Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Manufacturing and Civil Engineering

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Analysis of circular manufacturing strategies in the plastic industry using quantitative tools. Case of Plasto in Norway.

Master's thesis in Sustainable Manufacturing
Supervisor: Associate Professor Carla Susana A Assuad
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Abstract

This thesis presents a novel multi-agent simulation tool used to simulate recycling system for circular economy in plastic industry. Fish bracket orders are crucial for performance of recycling facilities, however different initial conditions move equilibrium of recycling system to different place, presented simulation address this problem based on user input and indicate when recycling system is the most stable. The simulation exercise allows to understand interactions between fish farmers orders and their influence on performance of recycling facilities which produce recycling granulate used for injection moulding production. Model is flexible tool which allow to indicate recycling system equilibrium based on user input. Give the pressure from industry for modern circular economy recycling system, simulation is one of the building elements which can led to establishing balanced circular economy recycling system.

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I would like to also address my sincere word of appreciation to coordinator of INMAN project Professor Kristian Martinsen, thank you for opportunity being part of INMAN program

I. Introduction

Growing expansion of polymer industry led to unsustainable management of natural resources which causes negative impact on environment. Todays, circular economy go in front of inefficient management of resources and allow us to use postconsumer materials as source from future production (Michelini *et al.*, 2017). Although industry already made big step towards circular economy, there is still a lot of problems which need to be address in order to make entire system more effective and easier to implement by new companies. Circular economy in opposite to classical linear production system take into consideration what happening to product after usage stage, it is caused by care for environment and common interest. In circular economy company need to reprocess and use this product for future production. This approach allow producer to take responsibility for their product through entire usage time from production till end of life (EoL). Simulation focus on recycling system of fish brackets which is main building block of fish cages used in aquaculture industry. In presented work fish bracket will be referred as component and Plasto will be referred as producer of injection moulded fish brackets.

Multi-agent modelling research question:

From context of this thesis the most important part of presented work is recycling system. In order to understand problem, multi-agent simulation try to present solution and answer following question:

How changes of fish brackets orders in Norway influence production of recycling granulate in recycling facilities and used by Plasto?

Result from agent-based model will allow to investigate performance of recycling facilities in each recycling scenario. Second it will allow to discover number of recycled components which will be collected by Plasto and third it will show in which conditions recycling facilities will be not effective. Not sufficient performance of recycling facilities will lead to their deactivation (which is equivalent to go bankruptcy). It will lead to sequence of consequences which will variety and depend on initial conditions of simulation.

Today's companies tend to focus on circular manufacturing in order to improve their production and create sustainable solutions which allow to create balanced and environmentally friendly future, companies want to find optimal solution which allow them to distribute they intellectual and economic resources between environmental, economic and social goals of company. Implementing circular economic require complete change how customers and producers think about product itself, it will lead to change in all logistic processes. There are different strategies which can be applied in order to achieve this goal, and the most commonly used are reuse, reduce, recycle, repair and cascading (MacArthur, 2013). It is proven that circular manufacturing present significant benefits especially for small and medium companies, which include Plasto (Rizos *et al.*, 2016).

Multi-agent simulation allows to investigate relation between fish farmers (customers) and recycling facilities, further it allow to understand relation between recycling facilities and Plasto. Model investigate different scenarios chosen by user, simulation is flexible and allow user to investigate recycling system in variety boundary conditions, abundance of fish farms (customers), not enough amount of customers, abundance of recycling facilities, few recycling facilities, abandonee of fish farms which are frequently supplied by new components etc. That is just part of recycling scenarios which will be investigated. True flexibility of model is represented by possibility to mix initial conditions with values between boundary conditions. Each scenario has equilibrium which is time when design scenario is the most stable. Obtained results show us that the most effective performance has system which were stable from the start, unbalance systems which high variation of values (too many recycling facilities in the start or not enough), caused long-term problems for entire recycling system through collection of too much components in initial time of simulation. It decreases pule of available components for rest of recycling facilities which rapidly decrease facilities “survival” capability. It is present even in situation when recycling system will achieve equilibrium. Noticed effect cannot be neglected. Model investigate time of 100 months which is equivalent to 100 months (approximately 8 years).

II. Literature review

1. Fish Farming in Norway

Norway is one of the biggest salmon producers in the world, in year 2019 produce 1357304 tonnes of salmon which value was estimated on 68.1 billion NOK., in year 2018 Norway produced 1 282 003 tons of salmon (*Statistisk sentralbyrå*, 2019), aquaculture still expanding which lead to increasing production every year. Fish farms are farmed in specially designed fish cages which minimize risk of escapes, there is variety of different fish farm constructions, but this study focus on fish brackets which are main component of plastic cylindrical fish cage. Cages are popular design alongside Norwegian coastline, one of the example cylindrical fish cage is "TUBENET" sold by AkvaGroup (*Akva Group*, 2020). Cages size vary from diameter of 90 up to 157m, cages are usually 15 up to 48 m deep (Holen *et al.*, 2019). Fish bracket is connector between floating pipes, it fulfils responsible role of assembling floating pipes and keeping them together through time when fish farm is in use. It needs to constantly resist harsh environmental conditions and waves on daily basis. Components are created by injection moulding process. Presented work focus on recycling process of those component and investigation of components collection procedure, collected components are used for production of recycled granulate used by Plasto for injection moulding process.

2. Injection moulding process

Injecting moulding HDPE components require significant amount of energy, usually traditional injection moulding process consume from 0.43 kWh/kg up to 2.3 kWh/kg of energy for HDPE material [12]. Plasto components reach up to 90kg which reach energy consumption per 1 fish bracket from 38.7 kWh up to 207 kWh. It is important to add that it is impossible to inject mould components with that weigh by commercially used machines and this is reason machines used by Plasto produce heavy components which require more HDPE, all this material need to be heat up for injection and then keep in the same temperature during the process and finally cooled down. It presumably requires more energy to produce 1 fish bracket because Plasto don't use traditional injection moulding machines. Plasto needed to modify commercially available machines according to they own need, it allowed them to achieve better performance and create 90kg injection moulded components. Plasto require higher production time per 1 produced unit caused by high weight and necessarity of longer cooling. Over 50% of energy used for injection moulding process is consume by drivers and machine motors, secondary 20% of energy goes for cooling system which allow to decrease temperature of the injection moulding form after process [13]. Additional disadvantage of production high weight components is potential risk of error, if any component will be with defect it will cause significant loss of material and time needed to operate machine, both errors have significant influence on energy consumption and resource management.

Today's modern injection moulding machines are made according to principles of environmental conscious design, this holistic approach is foundation for future development, it takes into consideration, how design product influence environment through entire product lifetime. It focuses on using low impact materials, energy efficiency and brings back end of life process to design stage, engineers start to think what will happened to the product after usage stage. Currently applied linear production models should take into consideration circular manufacturing approach in order to remove unsustainable resources management practises used in industry.

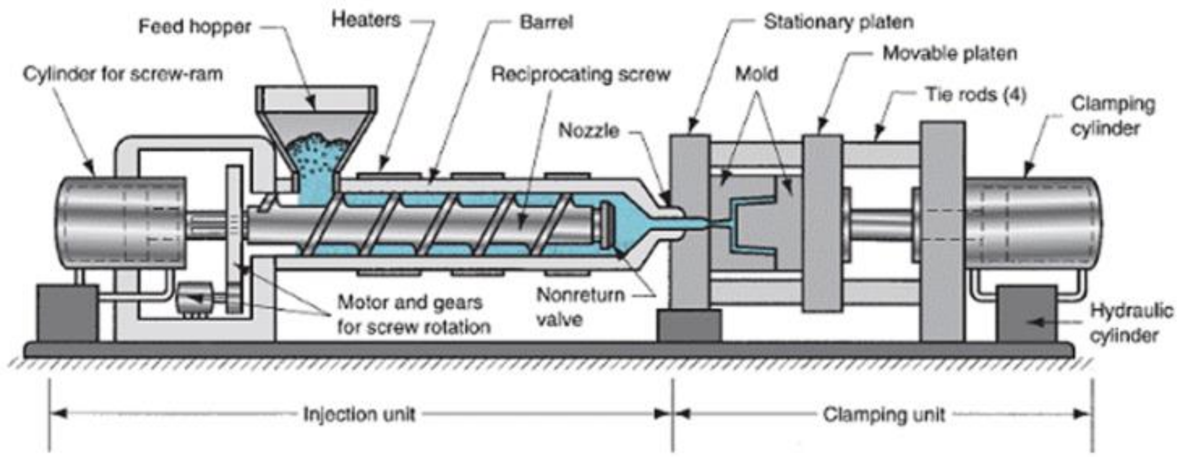

Figure 1 Plastic Injection Moulding Process (*Plastic Injection Molding Process*, 2020)

Injection moulding process require thermoplastic polymer e.g. HDPE in form of granulates which is possible to use in injection moulding procedure. The key steps of injection moulding process go as follow Figure 1, granulate is transported through hopper to barrel and then heated through friction by reciprocating screw. Additional heaters outside of the barrel allow to keep stable temperature and allow to avoid rapid change of temperature, change is homogeneous in entire section of barrel. When heated HDPE fill barrel then reciprocating screw push polymer to mould. Mould are predesigned usually made from steel form with shape of our desired component and cooling system on the outside of the form, the main goal of cooling system is control of component cooling process in order to avoid defects caused by uncontrolled or not homogeneous polymer shrinkage. Polymer pushed under pressure fill the mould, component inside of form is allowed to cool down and then component is going to be removed from mould, usually with support of vacuum caps.

3. Circular economy

It is difficult to understand current state of the resarch without using quantitive analysis tools, bibliometrics analysis of scientific resarch papers allow to find co-accurances of keywords. Method is not perfect but after adjustment allow to find common correletions between investigated topics of study . In order to minimize error, maps present keywords which was used frequently, at least 4 times for "Circular economy" bibliometric map presented at *Figure 2* and 5 times for "Circular economy recycling " bibliometric map *Figure 3* Different levels of keywords co-occurances allow us to understand main intrests of resarcher. Maps works as follow the heighest weight of the item the bigger circle and label of the item, items with smaller weight are represent by smaller circles. The same principle apply to relations between lines, if relation between keywords is stronge than line become thicker compare to other lines with smaller relation. If presented keywords are not connected at all than there keywords will be not connected by any line. Both maps are displayed in *"Overlay Visualization"* mode which allow us to cluster articles based on the month of publication, it allow us to observe changes in trends of reserchers intrests. The maps are highliy simplyfied versions of more complex counterparts, not simplified maps are compose of aproximetly 1000 keywords (e.g. 997 keywords for "Circular economy map" ,*Figure 2* present simplified version).It make result completely not redable and confusing. It is reason why this paper present simplified maps with keywords which appeared at least 3 times. It also eliminates problem of presenting keywords which appear in article only 1 time.

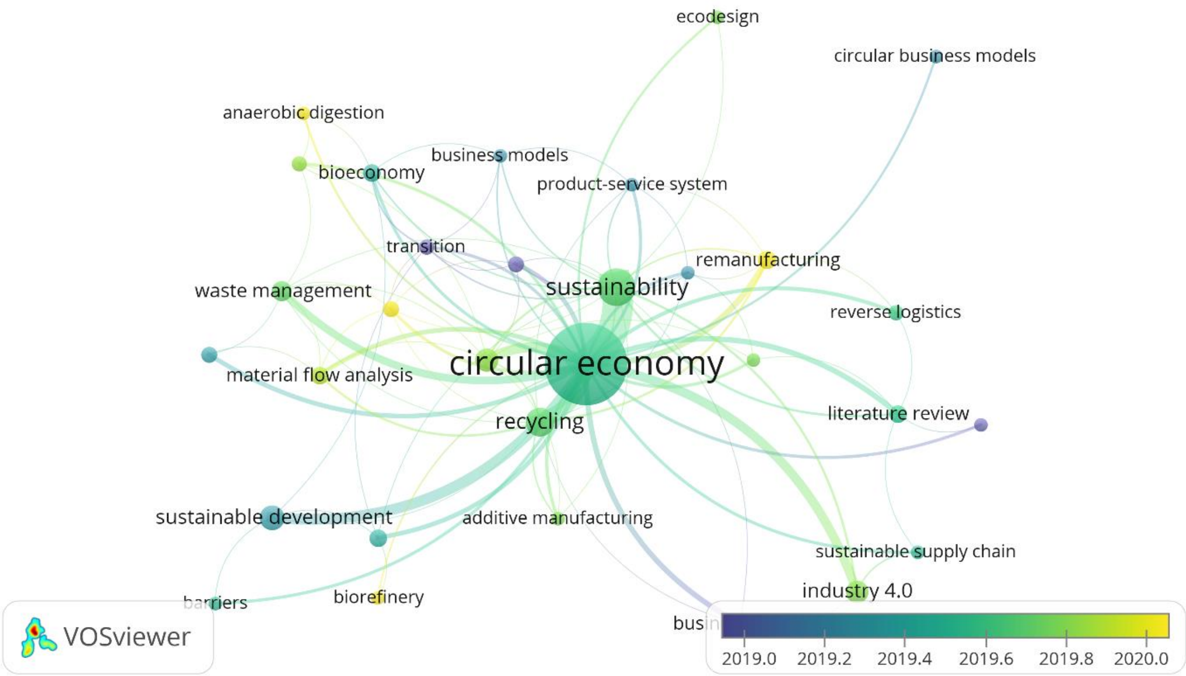

Figure 2 Bibliometric review of 300 relevant scientific papers in field of "circular economy", made with support of Vosviewer software

As expected first results all intrest in resarch on circular economy seem to have high connection with sustainability, but resarchers seem to connect circular economy directly with recycling. Suprisingly model don’t show any clustering of resarcher intrests based on the year of publishing, it mean that all keywords were equaly distribution in duration of 1 year and that was no any tendecies for resarch on specific topic. Reserchers also focused on recycling, remanufacturing of goods and reverse logistic, all those components are undauptable important part of circular economy. Map also include modern technologies e.g industry 4.0 which is closely interlink with sustainable supply chain, all those indicators show progress in resarch on topic of circular economy.

Further in presented thesis I explored corellation between resarch on *“Circular economy and recycling”* as it was presented at *Figure 3*, it is the most common resarch direction and it is reson why it needed more attention. Investigation lead to unexpected conclusion there are comon areas of resarch between *Figure 2* and *Figure 3*, in both cases resarchers focus on concept of *“sustainability”*, *“waste managment”, “material flow analysis (MFL)”* and *”additive manufucturing”*. Hovewer as expected that is some differences, resarch focused on circular economy from perspective of recycling tend to more focus on techniqes used for recycling and waste treatment, *Figure 3* contain articles which investigate *“chemical recycling”*, *“mechanical* recycling”, *“pyrolisis process”.* Further map also contains articules intrested in specific productes e.g. *“plastic packaging”, “generaly plastics”* and finally *“mechanical properties”* of recycled materials. There is visible change in trend, recently reserchers tend to be more intrested in moder technologies e.g. *“additive manufucturing”* and they connection to both circular economy and recyling. The most important finding from both maps is that majority of resarch directly connect *"circular economy"* with *"recycling",* reserchers tend to take circular economy problems from different perspective and investigate it in different domains, but reletions presented on map are intresting findings and are worth to be more intensively investigated in the future Maps allow us to observe current trends of resarch and predict future direction but what is more important it allow us to notice gaps in currently existing areas of resarch. It is visible on the maps by fields which are not connected, or are not connected enough.Those intresting areas should be focus on in the future, description of the gaps will be presented in the discusion.

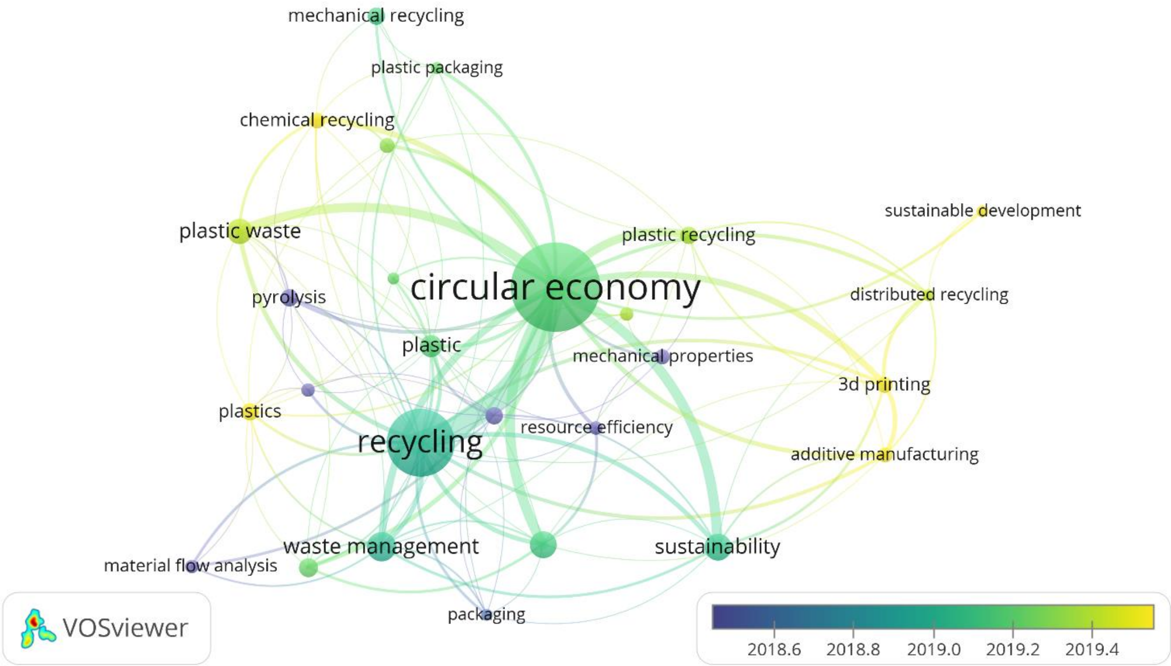

Figure 3 Bibliometric data of 300 relevant scientific papers in field of circular economy and recycling of plastics and polymers, made with support of Vosviewer software

Previous bibliometric review at *Figure 2* and *Figure 3* allowed to notice correlation between circular economy and recycling, however it didn't showed direct between circular economy and the simulation techniques. It was reason why it was important to investigate this area, Figure *4* allow us to visualise correlation between *"circular economy"* and *"simulation"*. Highlighted branch of the Figure *5* allowed to visualise correlation between circular economy and simulation in detail.

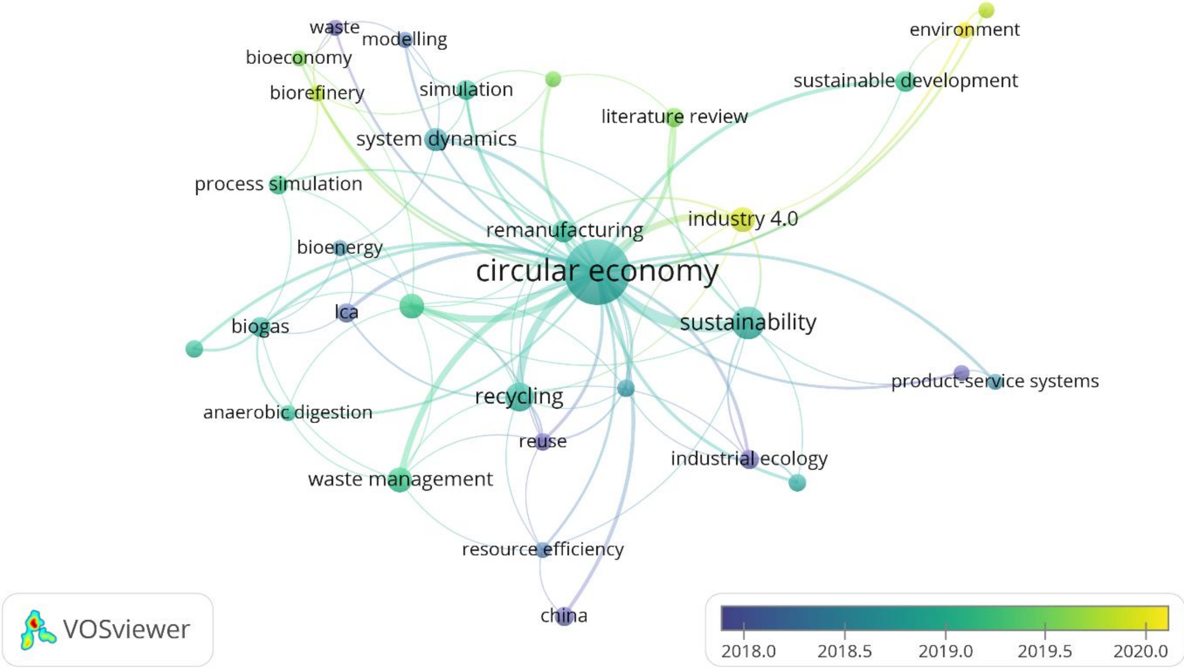

Figure 4 Bibliometric data of 300 relevant scientific papers in field of *"circular economy"* and *"simulation"* made with support of Vosviewer software

Surprisingly research dedicated tosimulation was not directly connected with research on *"recycling"* or *"remanufacturing"* of course all the concepts are indirectly connected by *"circular economy"* but in reviewed group of articles there are not direct connection between both. Perhaps increases number of reviewed articles would allow to find correlation in research between both topics, however there is noticeable trend noticeable on the map, researchers tend to focus on simulating *"circular economy"* as entire system and not a lot of attention is dedicated on creating separate simulation for *"recycling"* and *"remanufacturing"* respectively. It is not goal to proof if it is good or bad approach to the topic, but it is clear conclusion, visible on created maps *Figure 4* and *Figure 5*. As expected, research on *"Reuse"* topic is frequently investigated with problem of *"recycling"* and *"waste management"* , that are the most common direction of research as presented at Figure *6*. However, researchers often connect topic with *"resource efficiency"*, it is wonderful connection between area of research which should be more intensively investigated in future. Unfortunately only 3 articles explore *"Reuse"* and *"Resource efficiency"* relation. Those two components are two opposite sides of circular economy and their relation should be more intensively explored in the future.

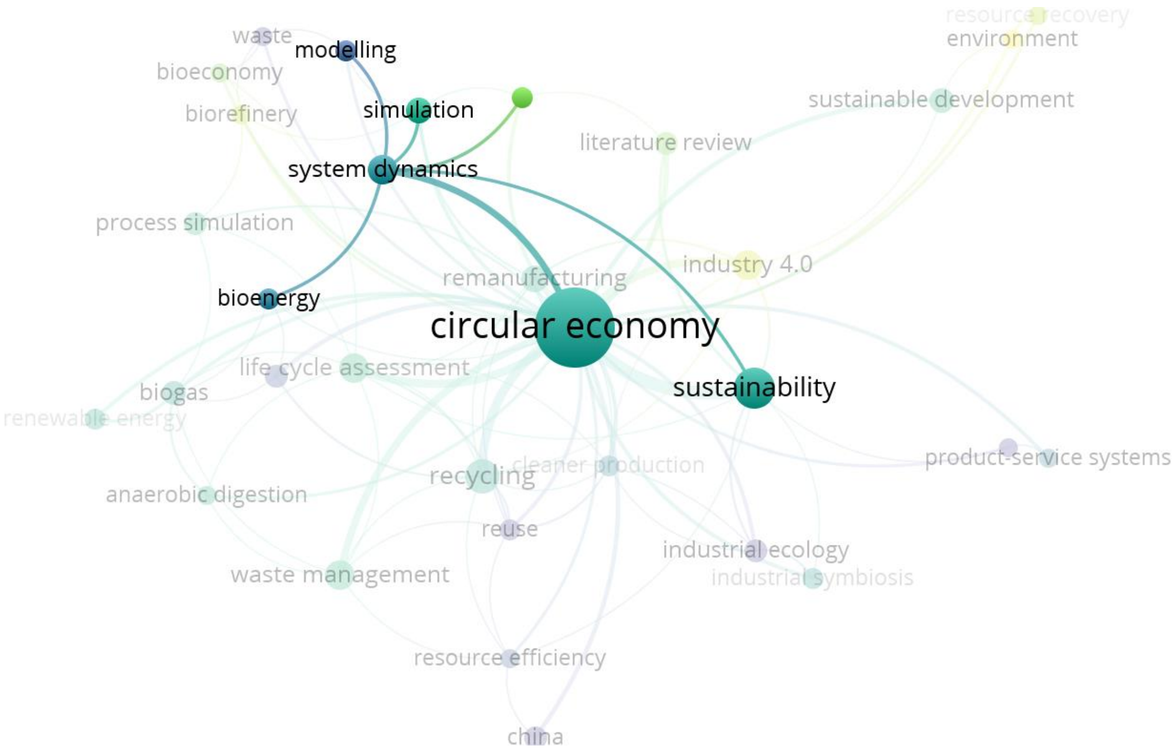

Figure 5 Branch of relevant research keywords related to *"System dynamic"* simulation, it is part of Figure 4

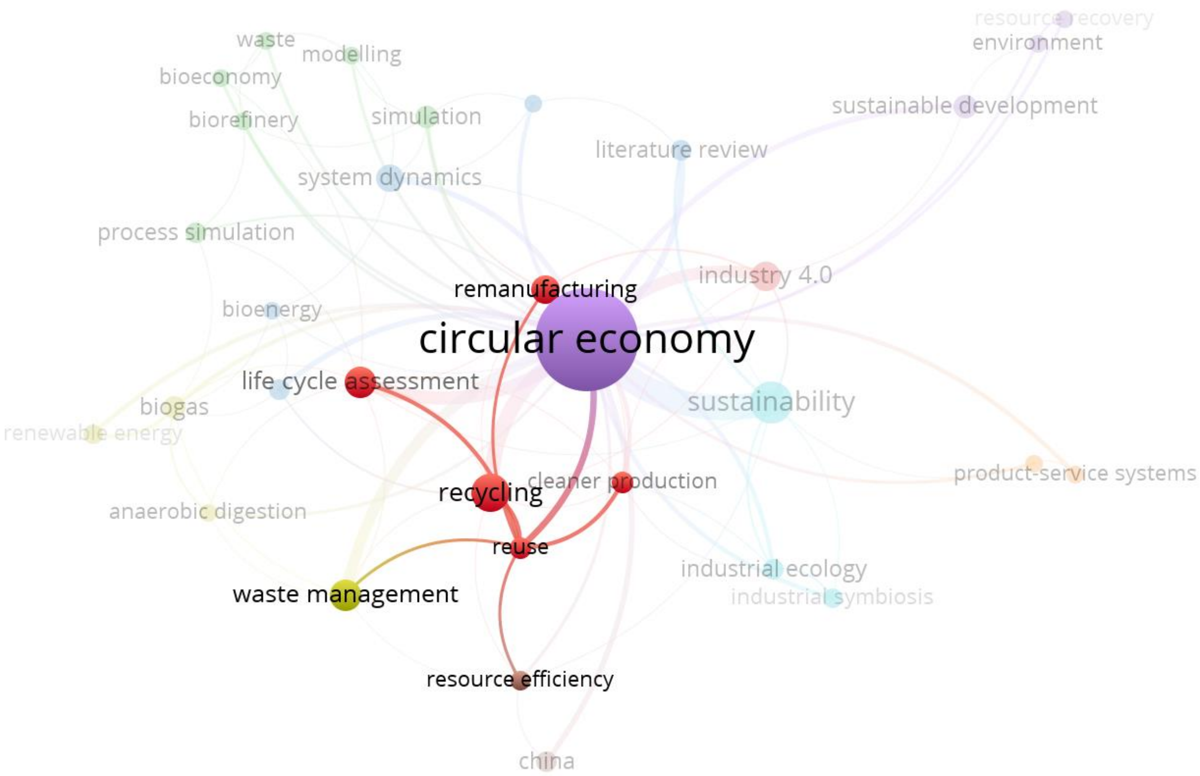

Figure 6 Branch of relevant research keywords related to *"reuse"*, part of Figure 4

Multi-agent simulation found its way for research about *"supply chain management"* and variety of interesting application. Although Netlogo is one of the most used software's for multi-agent simulation, there is plenty of different software which use agents-based modelling method, it is visualise at Figure *7*. One of examples is *"Matsim"* software. It is agent-based transport simulations software which allow user to use multi -agent based framework useful to simulate traffic, software is frequently used to simulate transport in variety of conditions (*MATSim Multi-Agent Transport Simulation*, 2020). Next software is *"Janus platform"* used to simulate traffic and land use modelling (Galland *et al.*, 2014), both software found it place in bibliometric map of *"Multi-agent simulation"* Figure 7.

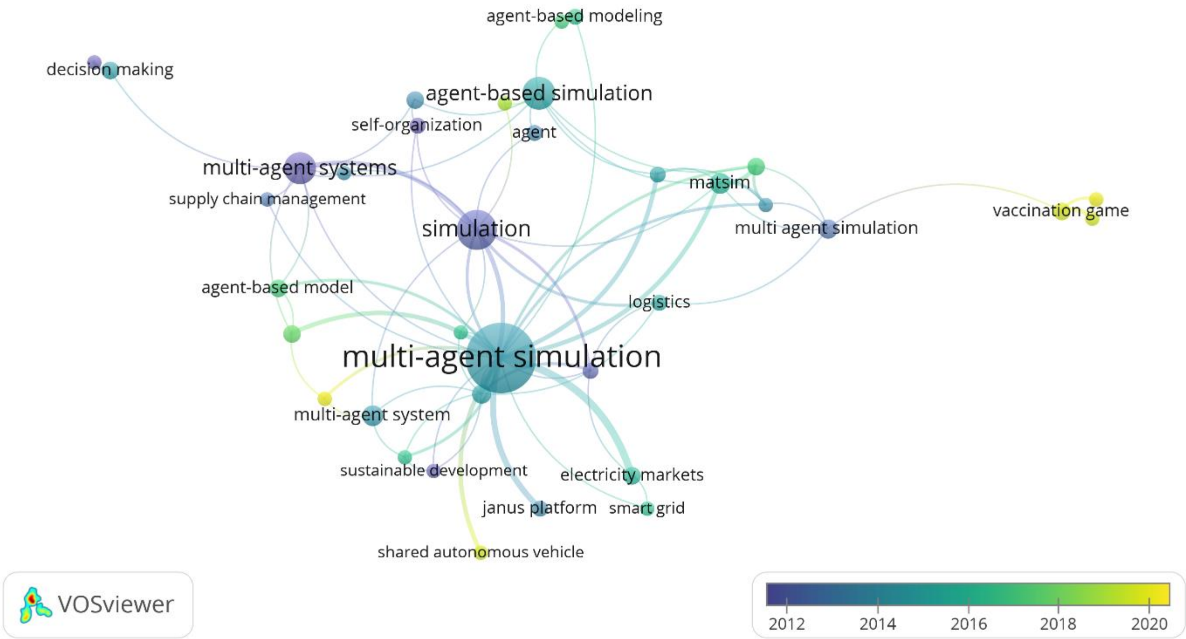

Figure 7 Bibliometric data of 300 relevant scientific papers in field *"multi – agent simulation",* made with support of Vosviewer software

Last branch of *"multi-agent simulation"* from *Figure 7* present system dynamic simulation which was directly connected with *"multi-agent system"*, *"multi-agent simulation"* and *"sustainable development"*. Finding system dynamic simulation here is good indicator of versatility of this method.

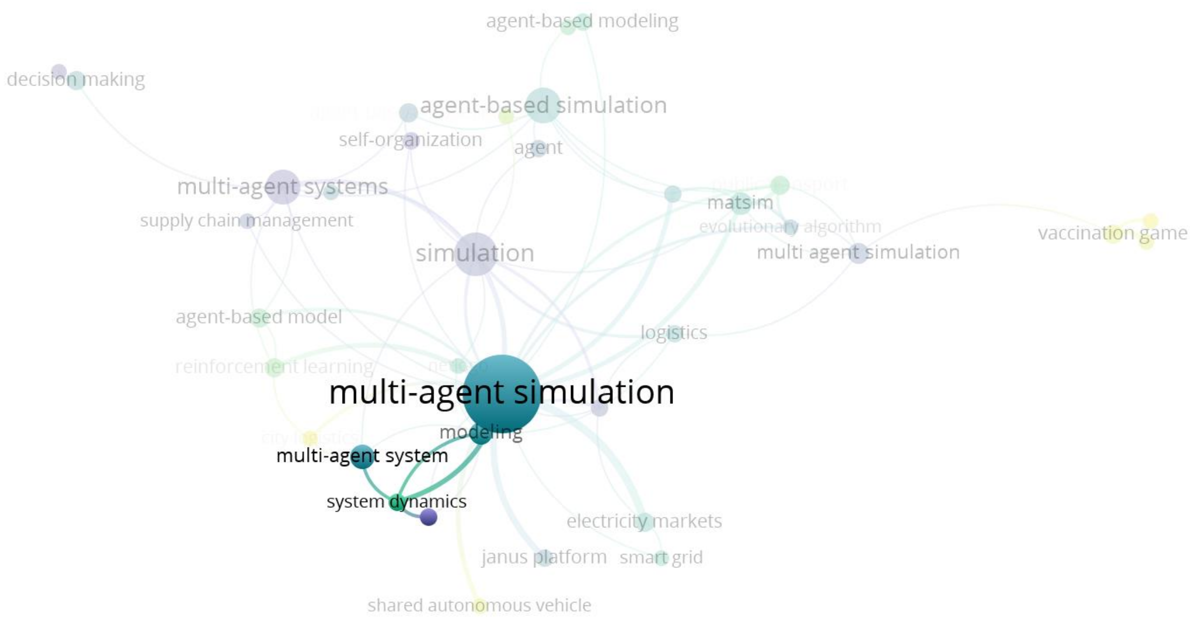

Figure 8 Branch of relevant research keywords related to *"system dynamic"* simulation, part of Figure 7

4. Circular economy-key features of concept

Circular economy is responsible sustainable economic model which focus on circular opportunities rather than linear processes. Although is not strictly defined and varied depend on source, general concept of model remains the same. From production company perspective it is important to mention main aim of circular economy which is reduction of using new material and output of waste material (Haas *et al.*, 2015). Presented definition allows to explain basic concept of circularity in more practical and tangible way to experts from linear manufacturing industry. Although it is good general definition it does not cover all aspects. It is important to explain that in circular economy system materials life cycle is controlled in the way which allow producer to know when product will be recycled. Recycled process takes shape of the closed loop. It is important to keep plastic components in the highest quality possible because through all the recycling cycles (Korhonen *et al.*, 2018). It allows to extend lifetime and quality of the products in incoming recycled cycles. In recent years there is growing interest in circular economy, it can be confirmed by regulations stated by European policy makers such as European Commission (*Closing the Loop - an EU Action Plan for the Circular Economy, Brussels(2015)*) and industry (Schulze, 2016).

As it was briefly mention before circular model highle differ from classic lineral model, both model treat resources in completely different way, it is well represented on Figure 9. The main issue with linear model is high flow of resources outside of production usege loop (green attowws), both renewable resources and non-reusable resources are barely used to create new products.The main flow of materials from usage stage go straight to disposal and incernation facility. In circular model resources are managed compleately different majority of them is used for production of new products which are further are sold to customers and in that way circle repeat.

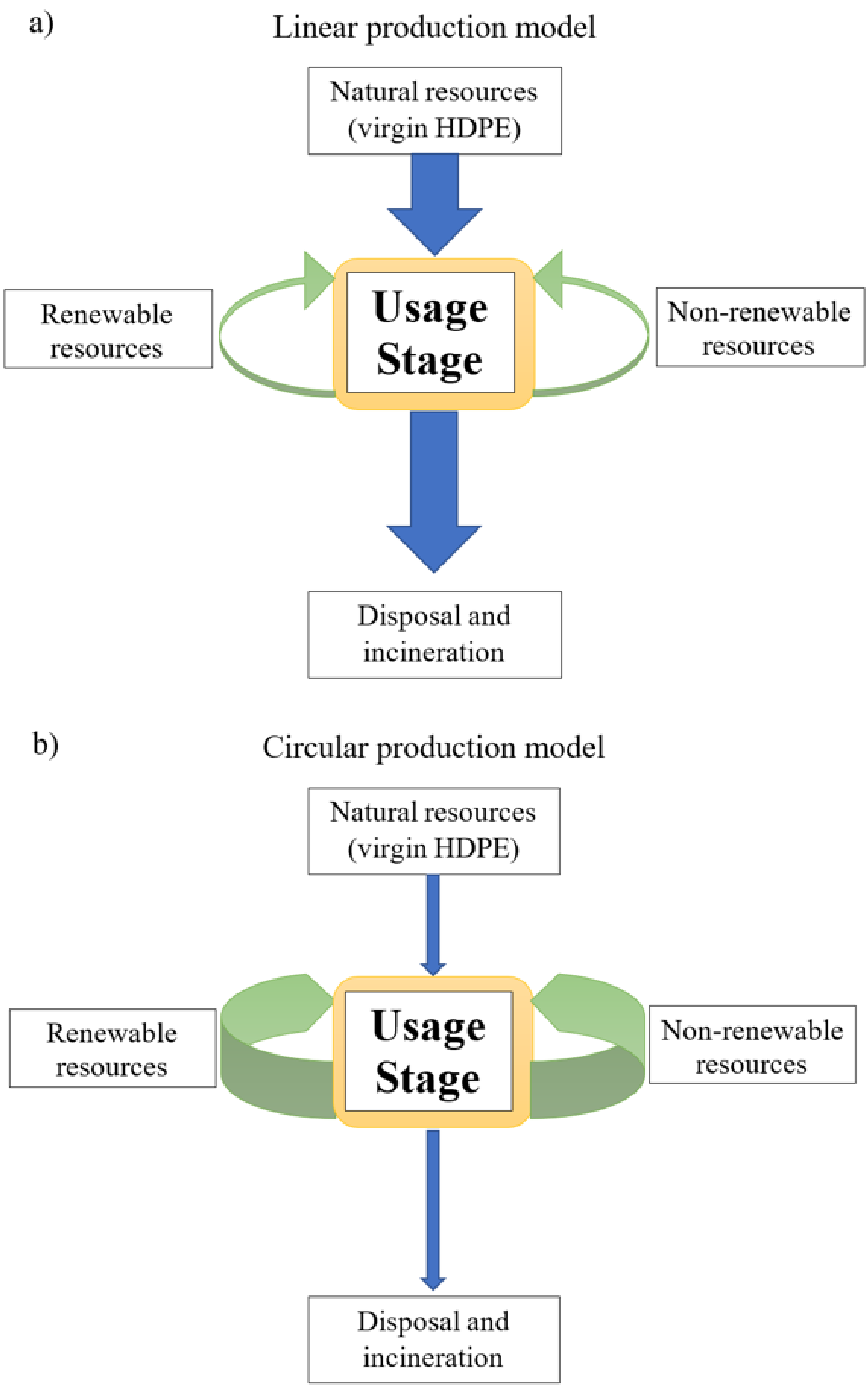

Figure 9 Flow of resources in in linear and circular business model adapted from (*Opportunities for a circular economy*, 2019)

Degradation of polymer chains lead to decreasing in value of recycled HDPE, after each of the processes after usage stage. Naturally already used components have lower mechanical properties than components before usage stage. It is undauntable nature of polymers and it don't require explanation. It is important to notice that after frequent recycling there will be moment when burning polymer product after usage stage will be more beneficial than keeping product in circular manufacturing recycling loop (Huysman *et al.*, 2017). The main reason behind this logic of thinking is that removing from the system extremely bad batch of material will positively influence on entire recycling system. Bad batch of material can significantly decrease properties of all the new products in the future which will lead to potential destruction of product. Circular economy focus on keeping quality of recycled granulate as high as possible in order to increase recyclability and long-lived of the product, keeping bad quality granulate in the loop go against main principle of circular economy and limit it future development which is highly dangerous for entire business model.

5. Environmental and economic advantages of circular economy

Circular economy forces companies to changes in their business models by focusing on circularity. Companies should rethink they linear way of thinking and shape it towards more sustainable approaches. Unfortunately, linear production model is highly focus on costumer consumption it is highly harmful relation between producer and customer and it can't be accepted in circular economy. The main emphasis should be focus on long-term relations with customers with will promote healthy trust-based relation. Producer need to be certain that he will have enough material from recycling in the future, it is impossible to achieve it without well-developed producer - customer relation

Materials scarcity seem to be increasing problem for modern companies, limited resources seem to influence company supply chain, there is increasing demand on resources crucial for production, fluctuating oil prices cause addition uncertainty which could easily become limited factor for further development of companies, circular economy can be solution for presented problem and contribute to financial performance of enterprises (Wang and Kara, 2019). Currently low oil price lead to decrease of the cost of virgin HDPE but, price tends to fluctuate and be depended on situation on the market and politics. It is important to mention that circular model can create new business opportunities which can be filled by production companies. Components need to be reprocessed and collected which require additional work, it can be done by companies. In addition to that company would gain full control over their entire supply chain.

Another significant benefit is reduction of greenhouse gases, majority of polyethylene is produced from petroleum which production caused significant pollution to environment in last few decades, currently production of ethylene cause CO_2 emission equal approximately 4-5t CO_2 eq/FU, data varied depend of research and amount of processes included in analysis (Zhao *et al.*, 2018). All this emission will be significantly reduced when circular recycling model will be implemented. It is important to mention that assigning higher value to postconsumer product will reduce import of the raw materials which will lead to decrease general cost of production.

It is important to notice that petroleum is non-renewable resource and will be depleted, it is impossible to renew it. It is necessary to conserve natural resources for further generations, perhaps they will create more sustainable way to use it.

6. Logistics in circular economy

Logistic system is based on feedback loop which provide new material to consumers but also warranty transportation of postconsumer goods from customer to producer in repeatable manner and as high efficiency as possible. It is important to minimize amount of processes and steps which product and post-consumer product go through in order to keep material as high quality as possible. It is important to plan logistic system and avoid all unnecessary steps in form of processes which are not necessary to produce recycled HDPE granulate.

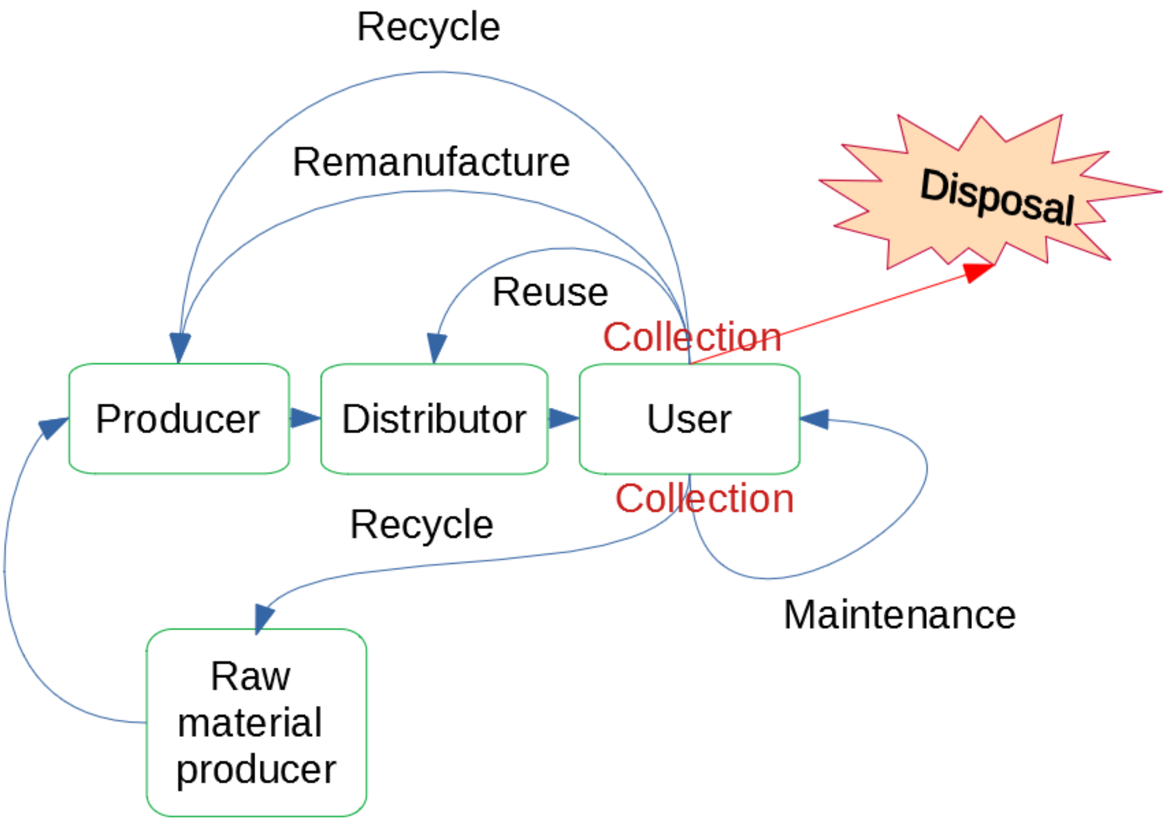

Figure 10 Path of product in circular economy

As it is presented at Figure *10* logistic take significant part in recycling process, well design waste management system is required in order to get all postconsumer products in right place and time. On the Figure *10* logistic is in the best represented by *"collection"* process, it begin all the recycling processes, postconsumer material is collected from the *"User"* and then respectively transported to distributor for *"Reuse"* process or fish bracket producer for remanufacturing process. User can also perform maintenance on components and use them for longer time which will delay recycling process. Product have also one more recycling pathway, components can be transported to *"Raw material producer"* and mixed with virgin material and then directly transported to producers. *"Producer"* can also recycle components on his own and manufacture recycled granulate which will be used for future injection moulding production. The last unwanted solution is disposal of product after usage stage, it is literal production model approach which we want to avoid.

Unfortunately, not all currently existing companies are prepared to fully implement circular economy approach, many companies lack necessary flexibility. Companies tend to be stagnated institution instead they should focus more on expanding into new markets. There are several approaches to evaluate company ability to change. Changeability classes are one of the ways to evaluate company ability to change. Companies can be evaluating by agility which refer to ability to find new markets for created products but also change way how they manufacture product. It is fundamental ability of company which allow to explore new areas and be competitive. Circular manufactures should easily adjust to changes researcher's at (Brunoe *et al.*, 2018) investigate flexibility of manufacturing workstation. It is referred as "changeover ability" and allow to investigate how fast company is able to organize workstation in order to produce different component. It takes into consideration only products which company already know how to produce and exclude all research and development stage and prototyping. It takes into consideration how fast and effective company is able to manage they equipment and know how in order to perform necessary tasks. It is key ability needed in manufacturing industry and should not be neglected in this evaluation. Similar ability is potential for transformability, it is ability to adapt entire factory to the most effective way to produce new component. It allows company to stay competitive and not being stagnated in the way how usually solve problems. This ability allow to make drastic changes in the workstation and factory in order to fit needs of new product (Brunoe *et al.*, 2018).

It is necessary to establish collaboration between companies with developed supply chains, sharing information about available pathways can improve cost-efficiency of recycling enterprise. There are cases where truck go not fully loaded and could take more materials, established collaboration between companies can reduce cost for companies which need to transport materials on the same paths. It will also significantly reduce emission of CO_2 caused by burning petroleum. In more advance stage, it will be possible to merge logistic circular models and create one interconnected model between few companies, it will allow to reduce time of the transportation and general cost spend in this field.

7. Measurement of circularity in circular economy and circularity indicators

It is difficult to clearly defined concept of circular economy which make even more complicated to correctly evaluate circularity level in companies. It creates uncertainty which require attention of researchers. Companies which start transition from linear model towards circular business model require indicators which will state on which stage they currently are. It is difficult to clearly estimate level of the progress but there are serious of factors which can be easily classify as suitable circularity indicators.

It was frequently proofed that product life cycle simulation are valuable tools used in to evaluate performance of circular economy (Takata, Suemasu and Asai, 2019). However even the best designed recycling system simulation is worthless if it doesn't have well defined performance indicators. It is even more important in complex systems. Data which is created from simulation should clearly indicate the result, it is important while performing simulation.

Fundamentally indicators can be divided in macro and micro indicators, majority of macro indicators take into consideration only usage of material and focus on recycling process on global scale. In order to do that they usually use techniques use to evaluate flow of material in recycling system, material flow analysis (MFA) and Input-Output analysis are commonly used (Moraga *et al.*, 2019). However, other simulations also seem to be suitable for this application. It allows to perform analysis and observe change in flow of material in specific weeks which allow to model behaviour of the system in long duration of time. Micro indicators go to the root of problem and take into consideration also life cycle thinking (Moraga *et al.*, 2019).

Although there were plenty attempts to evaluate validity of circularity indicators for circular economy, none of them fully describe all necessary characteristic, there is struggle to evaluate actual value of waste material. (Iacovidou *et al.*, 2017). It can be especially visible for plastic material which gradually degraded and change their value for producers. Using low quality polymer during injection moulding process significantly reduce longevity and mechanical properties of the final product. But also limit it recyclability potential in the future, if material will be one more recycle than its properties will decrease even more. Easy way to solve it is to add virgin polymer to mixture, but it increases final cost of component.

The most common circular economy performance indicators are based in environmental area and in that 193 indicators were connected to reducing negative impact of manufacturing process and reduction and restore philosophy (Kravchenko, Pigosso and McAloone, 2019).. Over 116 indicators from this group can be classified as environment indicators, and allow to indicate influence on environment and treat it as prior goal, rest of indicators 35 and 42 are classified as economic and social indicators respectively (Kravchenko, Pigosso and McAloone, 2019). Surprisingly almost 8 out of 10 mention sustainable economic strategies prioritize environmental based indicators, only two “Rethink business model” and “Recover“ prioritize social aspect indicators (Kravchenko, Pigosso and McAloone, 2019), none of presented model prioritize economically based indicators.

One of examples of circular economy systems is green supply chain management system which focus on transforming environmentally friendly inputs into output in form of processes which can be reused in the future or recycle when they will go out of use (Dube, Gawande and Coe, 2011). Reverse logistic is important part of the concept which allow to close manufacturing loop- It warranty that postconsumer product will go back to producer for recycling purposes. It allows to create completely reverse connection between producer and customer. Producer desire to not only sell product to customer but also receive it back in the future. It allows producer to manufacture more and sell more product in the future. It is wonderful advantages of circular economy over traditional production model. Components are collected from customers and then gather in one place; it requires transportation by truck which increase emission. Further components are shredded which lead to production of granulate. Further recycled granulate is transported to production facility where granulate is injected moulded, next cycle close and entire recycling process repeat, new product is sold to customers, producer - customer relation is perfectly presented at Figure *11*.

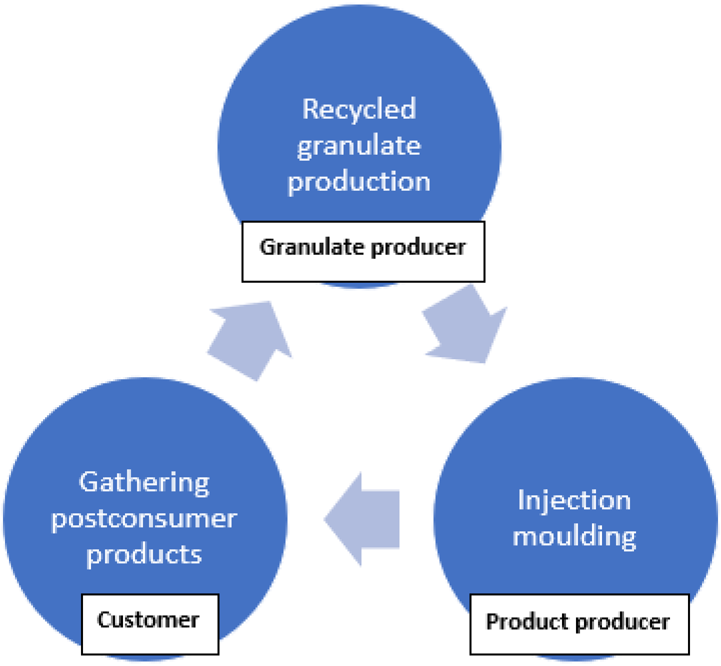

Figure 11 Relation between producer and customer in SSCM (Sustainable supply chain management) system

Another approach to tackle problem measurement circularity in circular economy is to investigate already existing circular supply chains. Green supply chain management (GSCM) is surprisingly similar to sustainable supply chain management (SSCM). Although both of them are classified as circular supply chain, comparing them allow to investigate what is important for them and how they deal with circularity evaluation problem. Topic already was explored and led to surprising result SSCM seem to have more wide definition, it can be argued that SSCM include all aspects of GSCM and expand it further. Green supply chain management system mostly focuses on environmental aspect of circular economy and efficiency of processes inside of the system. (Ahi and Searcy, 2013, 2015). The main bottleneck of GSCM seem to be lack concern over long term business sustainability, SSCM put emphasis on this aspect and don't ignore this problem. Supply chain management system in general strongly focus on long term economical aspect of supply chain management system. Sustainability characteristics are distributed completely different in both systems. Unfortunately the biggest concern which limit GSCM are aspects which are completely excluded from it characteristics and which are included into SSCM, first one is "Social focus" which include social aspects of broadly defined sustainability and second "Resilience focus" which take into consideration system ability to positively react to the unexpected negative change which will make work more difficult (Ahi and Searcy, 2013). It basically checks how system will work during crisis; it is valuable addition for supply chain system which visible is not present in green supply chain management system.

All economy aspects of sustainability in supply chain allow company to exist and expand circular economy to another companies, it cannot be neglected because in the end it allow company to be present and in the end will bring more good for the environment from long-term perspective.

As it was mention before lack of clear definition of circular economy lead to confusion which indicators are suitable to evaluation circularity. One of the most intuitive way to evaluate circularity is by indicators which allow us to evaluate performance of circular economy. It can include indicator which tell us how much recycled material is used compare to new material. In purely linear production system, all production material is new not recycle material. Additional indicator which allow use evaluate performance of circular economy is emission level compare to production the same product though linear production model. It can include both direct and indirect emissions. It takes into consideration entire LCA of production system and evaluate what is true impact of this product on environment (Elia, Gnoni and Tornese, 2017).

Another interesting approach is to evaluate recycling polymer based on its capability to exchange new polymer. It allows to estimate technical quality of waste and its usability. The highest quality postconsumer polymer presumable would be able to exchange new material in 100% it would be not necessary to adding any virgin material to injection moulding process and technical properties of created product are on per with product created from virgin polymer. It is perfect material for close loop recycling. Unfortunately, when polymer degraded in time there will be the moment when it will be necessary to add proportion of new polymer in order to increase mechanical properties of final product, it creates "semi-open recycling loop". It is simple and useful indicator of technical quality of postconsumer polymer (Huysman *et al.*, 2017).

8. Circular products and they influence on slowing down recycling loop

Environmentally friendly companies always try to close circularity loop, the shorter the loop the better benefit for environment. Circular manufacturing concept is based on using the same, postconsumer material for production without necessarity to implement new material to the system. However, it is the most basic approach for circular economy, it is possible to make loop shorter and avoid unnecessary processes and reprocessing which is harmful for environment. All processes require electrical energy or different form of energy, if it is possible to safe it then it should be done. If company implement to the system possibility of reusing products then the product circulation loop will be reduced, the product will immediately be transferred from primary customer to next customer. It will eliminate necessarity of producer participation in the process. concept is well visualised at Figure *10*. Although recycling process is wonderful asset for circular economy, it requires plenty of processes, product must be transported, cleaned, shredded and injection moulded. If product will be reused than part of this processes will be not necessary, it will minimize negative impact on environment, of course not all product will be in correct state to be reused but reusing even small percentage will be beneficial. Reusing and remanufacturing will have positive influence on environment but also will decrease volume of products with company sell. It is necessary to company to adjust to new way of the business, presented approach should be take into consideration (Brunoe, Andersen and Nielsen, 2019).

Circular product influence on manufactured significantly differs from influence of linear product on their producer, circular products are designed to last longer and be recycled in the future. There is significant difference in product development approaches for both models. Linear model focus on "cradle to grave" design but circular model treats all products as part of recycling system and use "cradle to cradle" approach. Products are design to slow down and close resources loop. Long-lived product last longer and delay recycling process, it slows down resources circulation loop, maintenance and remanufacturing also slow down material circulation loop. Products need to be easy to conservation and repair, further correctly design product should follow currently existing quality standards and be compatible and ready to be easily assemble and disassembled in time of need (Bocken *et al.*, 2016). However, it is not good information from producer perspective. Manufacturer will receive production material with some additional delay, it is good solution from environmental perspective because if product last longer in usage stage than customers don't have need to exchange it. It is wonderful example of small conflict of interest between customer and producer from economical perspective. Producer need to sell goods in order to sustain it business and if products last longer than customer will need to buy them less often. And that will be noticeable drawback for producer. It is important to highlight that solution for this can be easily solve in circular economy. If producer will keep ownership of the product through entire usage stage and only lease product to customer for predefine time than this small conflict of interest will disappear. If producer will keep ownership of product than in his interest it will be to design as good product as possible. And he will keep control when product will be recycled or reprocessed. This small change can eliminate designed conflict of interest between producer and customer.

Recycling process lead to closing resources loop and use postconsumer products to creating brand-new components. Usually producers put high emphasis on keeping high quality of raw material through all recycled cycles. From the start product is design to be recycled in the end of life, product designers take care of quality of used materials. Design take into consideration maintenance procedure and exchanging parts in product in order to extend component lifetime.

All production system requires usage of material; however, producers can decide which material will be used for production, linear production model require supply of new materials all the time which is relatively simple to organize for producers. Infrastructure for buying new material already is well established, unfortunately it is more challenging to buy good quality recycled material.

9. Alternative uses of fish brackets

Fish brackets are design to fulfil strictly determined function, there are one of main construction components of fish cages. Unfortunately, no literature was found on different application dedicated for fish brackets. Product is specialized in one branch of aquaculture industry and as lack of literature confirmed, it didn't receive enough attention. However, lack of literature is wonderful opportunity to investigate problems connected to alternative innovative uses of fish brackets. The most important is to take into consideration necessarity of product disassembly and then transportation Figure *12*. Disassembly is defined as a ordered process of separation components (Chang, Ong and Nee, 2017). It is highly important to performed it in correct way in order to avoid destruction of components which will be sold and reused in the future. After disassembling of components it is possible to perform all necessary maintenance, repair of components can be also performed when product is in "storage facility" *Figure 12.* All this time can be used to make product as good as possible before selling product to second customer.

Product will not find immediately customer, and this is reason why it is necessary to store it in storage facility and then transport it to second customer, it is important to highlight that reuse process is able to completely eliminate producer from entire process. Producer can be the company which take care of finding new customer for reused product, but company involvement is not necessary, it is possible to outsource process or find new customer to completely different company specialized in sale of reused components. Perhaps even better solution will be to leave process to prior customer which bought fish brackets (fish farmer). It is in his interest to find customer for his postconsumer product in order to receive additional compensation for his own company.

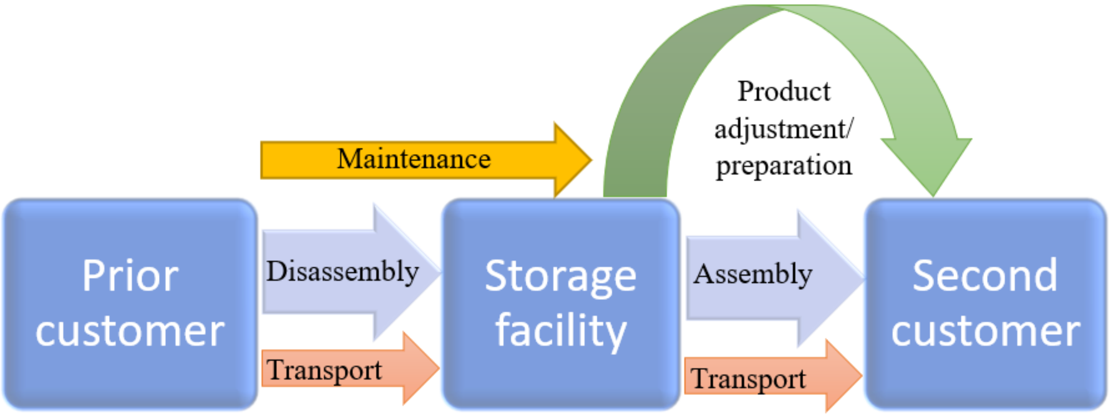

Figure 12 Reuse process- necessary processes

Depend on kind of new application components will need to be assembled again or adjust for new function. Perhaps reused fish brackets will be used for the same application but in less demanding environment e.g. in the lake where water is more peaceful and mechanical stress on component will be a lot smaller than in the sea. In that situation fish brackets will need to be transported from "storage facility" Figure *12* to "Second customer" and then assembled again in order to create fish cage with required size. Another interesting application is to use fish brackets in completely different application for example as construction of port buoys in the harbour, components will prevent mooring ships from heating port docks. It is wonderful application for those components. Fish brackets will be arranging in the same way as they are organised in fish cage. Reducing unnecessary scratches on the ship during mooring and departure of ships is important task which can be easily prevented by those elements. It is important to remember that fish brackets are solid elements which weight of almost 100kg each with connecting HDPE pipes between them (also available in fish cage) components can reduce impact of arriving ship. Design system should also protect ship from scratching pier (landing platform for the boats in the harbour). In order to be effective arrangements of fish brackets with HDPE pipes should be assembled alongside of the harbour in places where bots prepare for mooring , they can be placed on the water between boats Figure *13* a) and alongside of the dock Figure *13* b). That is wonderful possibilities to use those components in order to increase safety and unnecessary boat damage.

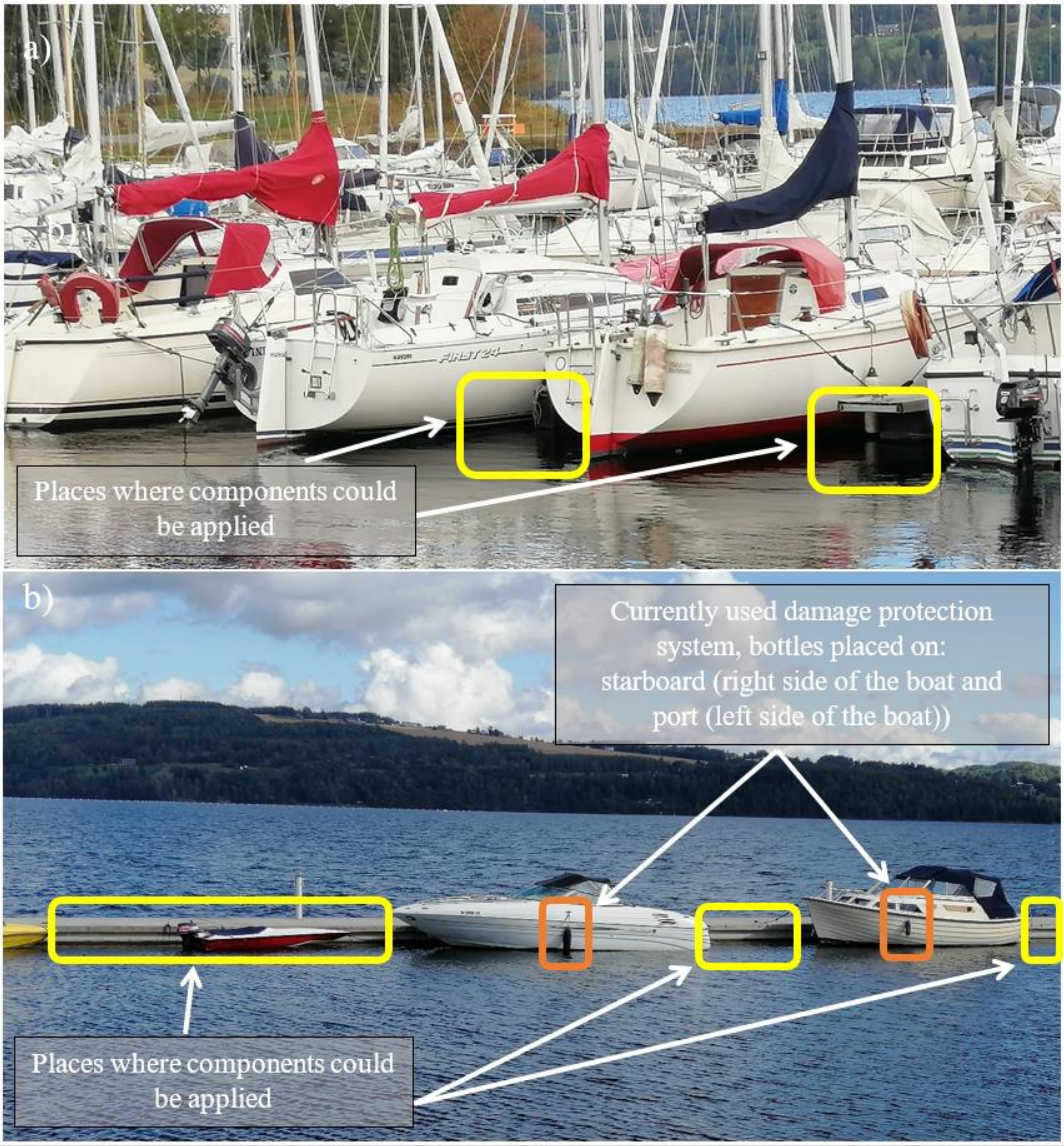

Figure 13 Gjovik harbour - places possible to install anti-scratch elements

Already existing solution don't allow fully protect boat, as presented at Figure *13* b) boats use specials bottle shape elements (marked by orange squares) which go between boat and dock presented at *Figure 13* a). Unfortunately, solution is not sustainable enough and is not always effective, this is reason why docks usually are equipped with dock impact bumpers which reduce risk of creating scratches or damage starboard (right side of the boat) or port (left side of the boat) presented at *Figure 13* b). As it is presented on *Figure 14* a) and b) not all docks are equipped with dock impact bumpers which is important to notice, applying fish brackets in those places could fully solve the problem. Fish brackets are good source of high-quality material and should be treated as valuable product for this application

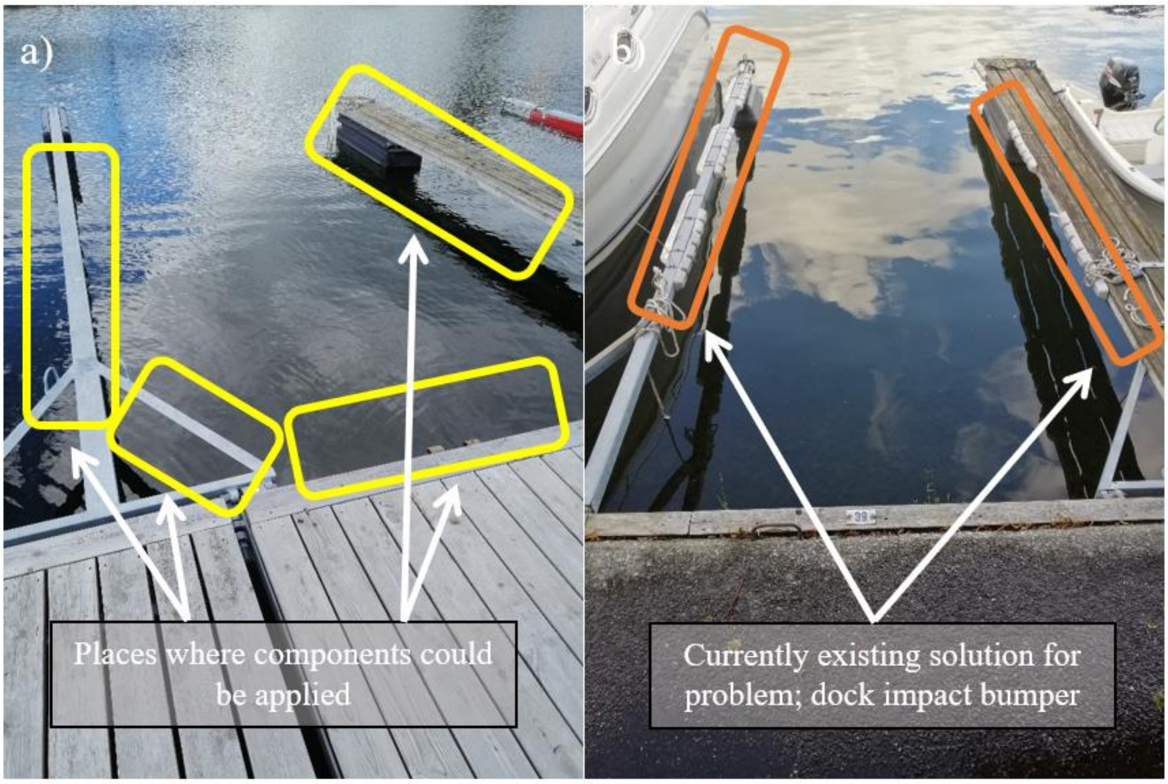

Figure 14 Boat dock in Gjovik a) dock without ant-scratch elements b) dock with currently existing ant-scratch protective elements

10.Recycling system fish brackets how is done today

It was reported in literature that problem of marine waste is not fully solved, unfortunately problem of waste from aquaculture usually investigate from general waste from marine industry. There are not many specific studies which address circularity problems of waste from one specific marine application. However that don't change the fact that problem exist today, Norway generate annually 4000 tons of waste from fishing gears and ropes (Deshpande *et al.,* 2020b). Although it was difficult to find specific number on how many fish farm HDPE waste is generated, this number is correlated to number of fish gears and net which are currently used, it allow to get estimated inside into amount of generated HDPE waste from aquaculture industry. Only 55% fish gears were recycled, approximately 19% was incarnated and rest 26% was landfilled (Deshpande *et al.*, 2020a). Presented evidence strongly suggests on unsustainability of currently existing recycling system and necessarity to implement change.

a. New HDPE compared to recycled HDPE

There are growing appeals for balanced production solutions it is possible by limiting amount of used material. Unfortunately, it is difficult to use recycled material because of loss of mechanical properties. High density polymer (HDPE) is thermoplastic polymer commercially used because of high density to strength ratio and resistant to many solvents. Thermoplastic properties allow to frequently recycled HDPE and use in variety applications e.g. chemical containers, pipe systems, aquaculture, bottles. It is important to remember that there always will be some difference of properties between virgin and recycled HDPE, during usage stage length of polymer chain become shorter which decrease properties of material however well controlled recycling environment can limit loss of properties due to recycling process, the main degradation mechanism are chain scission and crosslinking. However, the main degradation mechanism for injection moulding is crosslinking. Unfortunately using postconsumer HDPE lead to decrease of mechanical properties, decrease in properties is visible in tensile strength, but also aesthetic properties change in significant matter in respect to new HDPE (Mendes, Cunha and Bernardo, 2011). It is complex problem with variety of components, problem was narrow down to the level which allow to well describe it and create coherent discussion. Research include work on fish brackets for one kind of fish cage. Plasto produce fish brackets only for one version of fish cage and it would be illogical to include different designs of cages. Studies are dedicated to circular economy of Plasto components and don't include fish brackets produces by different competitors.

Using recycled HDPE will require continuous quality check of granulate which will be circulate in the system. Further work includes review of environmental impact of all processes which are necessary to produce fish brackets. It allows to understand why recycling is beneficial solution. Materials scarcity seem to be increasing problem for modern companies, limited resources seem to influence company supply chain, there is increasing demand on resources crucial for component production, fluctuating oil prices cause addition uncertainty which could be easily limited factor for closed loop production model, circular economy can be solution for presented problem and contribute to financial performance of enterprises (Wang and Kara, 2019). Currently low oil price lead to decrease of the cost of virgin HDPE but, price tends to fluctuate and be depended on situation on the market.

Using recycled plastic is necessity and cannot be avoided in the future, it is important to fully understand properties of recycled HDPE and adjust it performance for common good.

There is variety of studies dedicated to recycling HDPE (L. Simões, Costa Pinto and Bernardo, 2013, Associates, 2011, Alzerreca *et al.*, 2015), it is possible to use recycled HDPE in variety of innovative designs, material can be used in packaging industry, currently existing food safety regulations don't allow to use recycled HDPE in contact with food (Commission., 2008), however recycled HDPE can be used as middle layer of 3 layer packaging structure, outer layers can be produced from virgin HDPE (Radusin *et al.*, 2020). All materials used in packaging require to past rigorist safety requirements and it is long way to go before recycling materials will fulfil all necessary safety conditions. It is one of example where recycled HDPE can be used- In addition to that package material need to fulfil mechanical requirements which are easily provided by virgin HDPE. Additionally they are aesthetic problems between recycled and new HDPE(Mendes, Cunha and Bernardo, 2011), optical properties are not the same and difference can be noticed by common customer, it is important disadvantage from sale perspective and have to be taken into consideration while using recycling HDPE (Radusin *et al.*, 2020). Product may exceed satisfying mechanical performance but visual difference between components made of virgin and recycled HDPE may lead to bias towards completely new component. This problem needs to be solved in reasonable way before product will be send to customers.

b. Sustainable end of life treatment of postconsumer unusable Fish brackets (HDPE)

Quality check of postconsumer granulate will lead to rejecting part of granulate, unfortunately frequently recycled polymer degraded with time. It is reason why it is important to find end of life scenario for HDPE material. Although burning is the most common way to dispose waste, it is not the most sustainable solution, more study is needed in this field (Huysman *et al.*, 2017).

c. Logistics of fish brackets for recycling

Even the best design product require to be effectively deliver to customer and then in the end of his life take it away from customer and directed to right recycling path, it is well represented by "collection" at Figure 10. Supply chain need to be flexible and able to adapt to changes. System need to identify future bottlenecks and identify the best solutions. It is impossible to solve those problems without support of industry 4.0 technologies. Internet of things (IoT) is one of the most suitable technology for circular economy and can be applied in variety of circular economy areas(Rosa *et al.*, 2020). The most intuitive application is accelerating manufacturing process and reduce defects and quality of products in injection moulding process. IoT have more interesting technologies, it can be implemented especially in postconsumer product management system and monitoring of product during usage stage. If product would be embedded with low budget sensor which allow to track it location and time spend in water. Then evaluation of HDPE quality would a lot easier. Correctly design system would be able to estimate times and quantity of products which need to be recycled. System would be able to optimize recycling path and send components in correct recycling path, perhaps additional improvement of sensors would allow to estimate level of degradation of currently used components.

11.Multi-agent-simulation

Multi-agent-based modelling is one of simulation techniques which is often used to model complex systems which use of agents also called turtles in Netlogo software. Agents are autonomous entities which interact with each other and patches according to written code, each agent have assigned traits which allow to describe it current status or change of values caused by interactions with different agents or patches. In order to structure simulation, it is possible to introduce breeds of each which are specific group of agents (called turtles in Netlogo). Each agent with is part of breed can have assigned specific traits and can be invoke in order to do specific set of function or task, it allows user to differentiate between different group of turtles. Designing suitable interaction between turtles and patches are the main building block of well design simulation model (Soyler Akbas, 2015, Anosike and Zhang, 2009).

III. Methodology

The objective of study was to create tool which will support circular economy system of company which produce plastic components for aquaculture industry.

1. Methodology bibliometric overview

In order to understand current status of research on the in each of maps I choose 300 relevant *"Research articles"* and *"Review articles"* from ScienceDirect database and then export citation to RIS format. Brief analysis took place in order to evaluate relevance of article to the topic. Articles was segregated with support of Boolean operators available at website search engine (*ScienceDirect Support Center*, 2020). It allows to increase efficiency of review and minimize risk of unwanted articles which will increase potential error in overview of the topic. Then exported citation in the RIS format were upload and analyse in Vosviewer software (*Vosviewer software*, 2020).

Software provide 3 different modes of analysis maps in order to find solution this study include "*Co-occurrenc*e" analysis where, relatedness of articles is evaluated based on number of scientific papers where keywords appear together, I treated all keywords with the same significance and this is reason why I use *"Full counting"* method as medium, it allow to assign the same weight value to each of the links (*Vosviewer software*, 2020). In order to minimize error I choose only items which appear in citation at least 4 times (in software it is described as co-occurrence of keywords), it lead to creating 31 keyword items visible at *Figure 2*. If number of co-occurrences of keywords would be minimize from 4 to 1 than it was possible to visualise map compose of 942 keywords items, unfortunately overdose amount of information made it not readable and this is reason why map was reduce to the most significant 31 keywords, all maps were simplified to level which allow to clearly analyse the most valuable part of the map.

Circular economy map direct towards second investigation; *"Circular economy in relation to recycling"*, number of keyword "co-occurrences" was limited to 5 and allow to create map with 27 items presented at *Figure 3*. Next bibliometric overview limited to keywords which appear at least 4 times let to creating map with 34 items in area of "Circular economy and simulation", presented at *Figure 4*, during reviewing ScienceDirect database articles was limited by Boolean operator AND in the way "Circular economy" And simulation. Result allow to limit articles to group articles related to both concepts.

Last map allows to investigate research papers related to “multi-agent simulation”, map was in the same way as previous maps but this time occurrences of keywords was limited to 3 and lead to creating map compose of 42 items *Figure 7*.

Simulation of life cycle of the product frequently proved to be beneficial way to evaluate varied scenarios of circular manufacturing systems. Life cycle simulation are especially useful tool to evaluate varied paths of recycling the product. They allow to simulate capacity of each recycling possibility, then evaluate affordability and finally evaluate boundary conditions of our recycling system. Study allow to identify what is maximum input and limitations of designed recycling system scenarios. However the most important benefit of performing LCS simulation is possibility to optimise our recycling system before it will be actually implemented by company (Takata, Suemasu and Asai, 2019). Software allow us to freely adjust and move components of our circular system in order to achieve the most optimal solution. Evaluating different scenarios and investigate bottlenecks allow us to predict future problems and propose solutions before problems truly appear in real life.

2. Casual loop diagram - methodology

Presented system is relatively simple, “Production of Plasto” positively influence “Plasto sale”, if more components will be produced than it is possible to sell more product. Sold components are added to group of components in usage stage cold “New components in usage stage”. Adding new components to usage stage cause decrease “Customer demand for new products” which further decrease “Plasto sale”. Components stay with customers for time of usage time, after that delay components are send to group of “Components in EOL”, components in that group are ready to be recycled. In that phase components have 3 path ways, first they can be used in main path and just be used for production of recycled granulate “Recycled granulate production” and then sended directly to Plasto “Production of Plasto”.Second possibility is to be remanufactured and use in slightly different application “Remanufactured components” and then they will be shredded and use for production of granulate “Recycled granulate production”. The third option take into consideration reusing components by customer in the same application “Reused components”, it is important to highlight that reusing components will require intensive quality check before sending components to customer. All three component pathways; “Remanufactured components”,” Recycled granulate production” and” Reused components” lead to Plasto “Production of Plasto”, however only “Recycled granulate production” positively influence Plasto production, rest provide negative effect. Granulate production create recycled granulate which is further used by Plasto for production, it provides material for production, but both remanufacturing and reusing process delaying delivering of recycled granulate which lead to decrease amount of granulate which Plasto will be able to use for production. In addition, if more components will be reused for the same application “Reused components” than “Customer demand for new product” will be lower which will lead to slightly decrease on Plasto production.

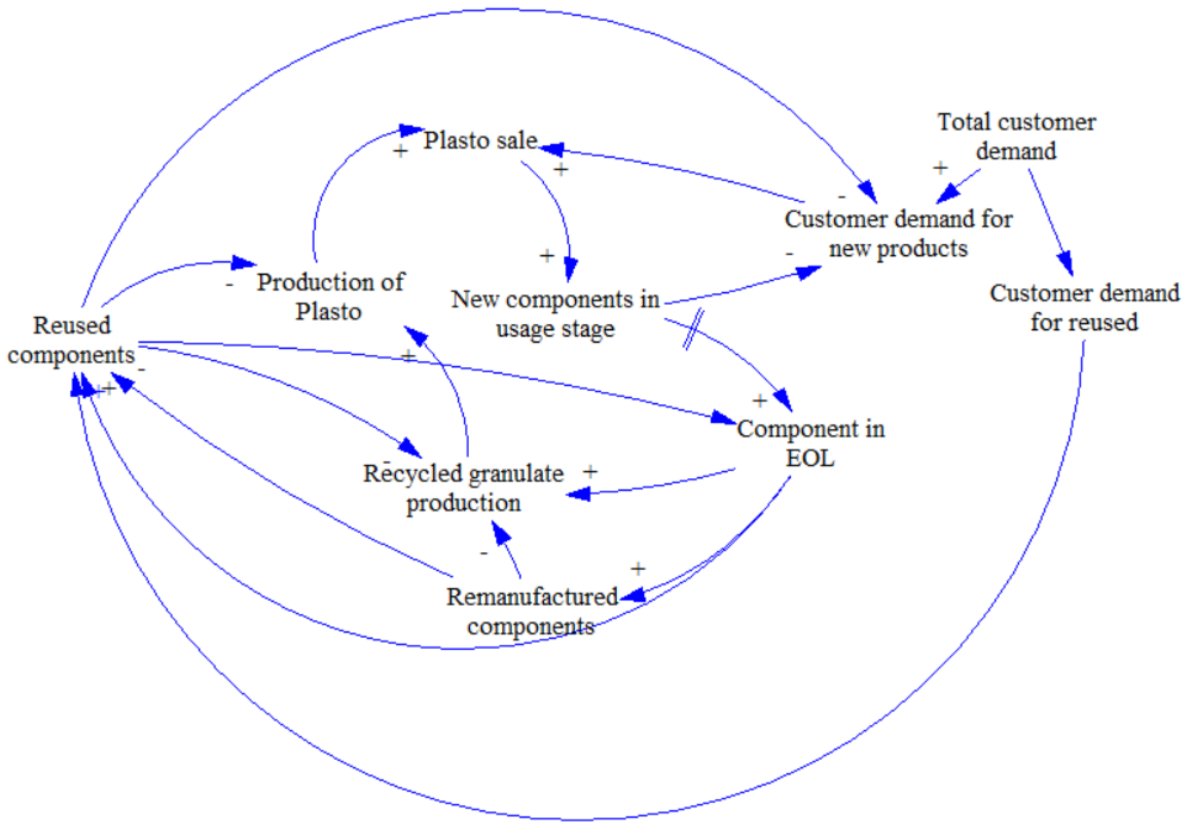

Figure 15 Casual loop diagram of system dynamic model

3. Multi-agent simulation – assumptions, verification and validation

Model contain series of unchangeable assumptions which need to be taken into account before evaluating final result, first new fish farms are added to system based on user input, than new fish farms are added only every 10 ticks (10 months) but user can decide how many fish farm will be added to the system, location is random and cannot be decided by user. Second assumption is that Plasto always collect all components from recycling facilities due to fact that presented recycling system represent Plasto close loop circular economy. Collection taking place every 25 ticks, it is equivalent to 25 months, but it allows to divide model on clear 4 quarters which make result clear and more transparent for the observer and for interpretation. It is important to remember that the most important level of simulation is performance of facilities because it influences performance of Plasto, it is assumed that Plasto will collect all components with company primarily produced. Plasto 25 tick's collection procedure allow us to easily visualise collection process and performance of all facilities in defined range of ticks (time). Next important assumption is that each truck can collect maximally 500 components, value is constant for all 6 scenarios, but simulation user can change this value. Each scenario is set of 10 simulation with the same initial conditions. Simulation continiu until achiving equilibrium or until all recycling facilities stop being active. If at tick 24 recycling facilities will not be able to collect at least 2000 components than facility stop being active.

As proofed in literature is difficult to fully validate multi-agent models and results should be carefully investigated (Takadama *et al.*, 2003). Each fish farmer owner need to have license from Norwegian government which allow to produce salmon in strictly defined amount and strictly defined region (Eby, Molnar and St. Louis, 2019). Norwegian government concisely choose how many licenses will be sold and although number of sold licenses increase from year to year it circulate in proximity of 1000, in year 2019, Norwegian government sold 1041 licenses (*Fiskeridir- Aquaculture-Statistics of Atlantic-salmon-and-rainbow-trout*, 2020). It is reason why user in initial stage of simulation can create up to 1100 fish farm through *"number-of-fish-farms"* variable. It allows to represent realistic values from chosen year. Unfortunately, due to program capacity limitations, maximum number of active fish farm in initial stage of scenario was limited to 700 fish farms. It is important to mention that 1 active fish farm is equivalent to 1 license. Model were verified by changing 3 variables, *"number-of-fish-farms"*, *"number-of-fish-farms"* and *"initial-number-of-facilities"*.

4. Methodology multi-agent simulation

Multi agent simulation was completely made in Netlogo software, all agents in software are called turtles and group of turtles is called breeds, software enviroment allows on versatile and clear wrriting simulation code. Simulation is bulid on 3 different group of turtles called breeds, they are implemented as follow breed [facilities facility, breed [Plastos Plasto] and breed [trucks truck]. Each of them allow the user to treat them as sepreate entities of turtles which allow to easy implementing them with sepreate procedures. Software allow to add specific traits to chosed breed. Breed facility represent recycling facilities which reprocess postconsumer fish brackets, breed truck represent group of turtles which collect postconsumer components from fish farms and prepare injection moulding granulate, the last breed, Plasto represent production compoany which collect injection moulding granulate from recycling facilities

In this simulation, each breed have the following characteristics (traits) :

- Plastos-own [total_collected_components]

Characteristic show us how many components Plasto was able to collect in the facility

- trucks-own [truck-load, home-facility, max-truck-load]

Truck series of describtieves telling us; truck-load, how many components truck currently transport.This value depend on components present in selected by truck fish farm. Next trait called *"home-facility"* allows to assign truck to specific recycling facility with , each truck allways deliver components to one specific facility marked with that trait. Last *"max-truck-load"* variable inform us what is maximum amount of components which each truck can collect from fish farm. It allow user interact with the simuation and increase efficiency of collecting components from fish farm-

- patches-own [fish-brackets-in-farm]

Last characteristic *"fish-brackets-in-farm"* is assigned for each pactch in the model. In simulation fish farms are represented by red, black,and yellow patches. Value of trait *"fish-brackets-in-farm"* for red and black fish farms is always bigger than 0, yellow coloured patches represent fish farms visited by truck, they always have value 0. Function is used to assign specific number of components to each fish farm. All different coloured e.g blue and green patches are used to describe world and always have value equal 0.

5. Procedures to “setup-world”

First function in model, *“setup-world”* function allows to setup simulation environment in Netlogo, first procedure use clean-all function to clean all leftover turtles and patches from previous simulation, then create representation of Norway map in Netlogo. Function implement vector map which was found at (*Vector map of Norway*, 2020), then it change colour of patches outside of the map on colour blue -025. In order to well visualize Norway land function change colour of all patches which are not blue-025 to green, in that way Norway map is implemented to software. It is important to notice that implementing vector map allow to differentiate between patches which are on map (Norway land according to country border) and ocean according to coastline, this small remark will be important for executing next procedure. Further simulation executing procedures; “*delete-svalbard”*, *“create-habitual-zone”* and *“create-random-facility”*, they will be described in further part of this chapter. The simulation creates habitual zone around Norway border, it creates future zone for creating fish farms, procedure exclude land region of Sweden *(“edit”* function). It is impossible to create fish farm in land region of Sweden; further Svalbard is also excluded from simulation. In the last step simulation create recycling facilities assigned in random locations on the map (they are represented by white house icons), user decide how many of them will be introduce to the system by choosing value on slicer *”initial-number-of-facilities”*. In the end of executing procedure function create “Plasto” which is separate breed from breed facilities. Plasto is created always in the same location and it is equivalent of its real address in Norway (Åndalsnes).

It is possible to add own recycling facility in any place on the map by clicking *“Add own recycling facility”* button in the interface, facilities created by user are represented by colour red house icons Figure 16. Double clicking on any “white” or black facility will allow to delete it and then create it in different place.

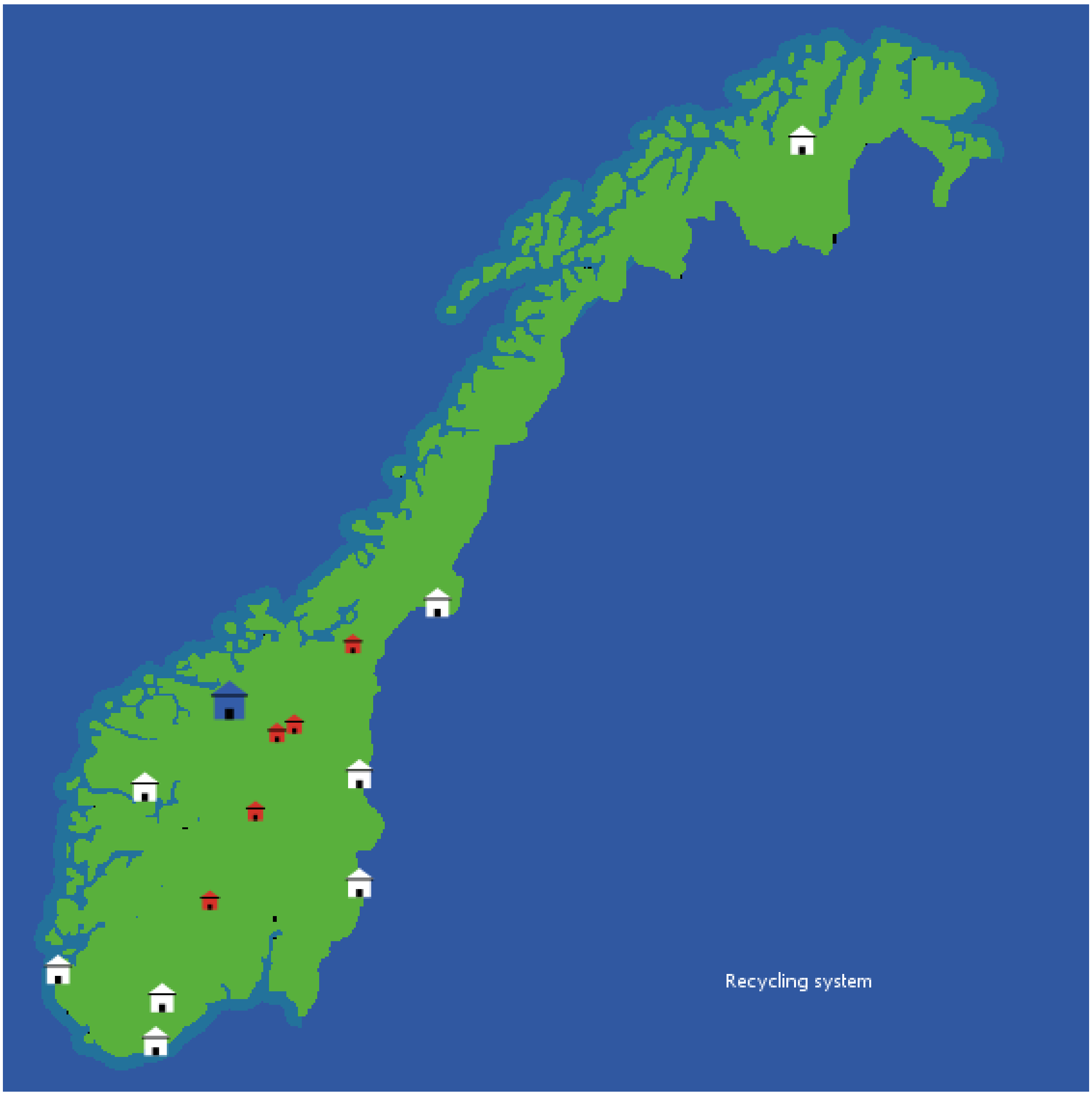

Figure 16 Simulation after executing "Setup world" procedure

6. Setting up simulations (set of executed functions)

In order to correctly understand interactions between designed procedure it is possible to perform 2 different simulations with use the same functions but execute them differently, first *"Simulate one conditions endlessly"* allow to set up simulation environment based on user input and then simulate those conditions endlessly second "*Repeatable endless simulation*" allow us to find system equilibrium and check, performance of recycling facilities frequently in the same predefined initial conditions set by user. The main functional unit of simulation is 1 month with is equivalent to 1 tick, because of chosen functional unit equal 1 tick some breed (trucks) move fast and they movement is not smooth, it is done on purpose. Trucks can't travel through few ticks to the destination (movement would be smooth) because 1 tick is equivalent to 1 month, this time would be not realistic, trucks are speed up in order to make simulation more equivalent to truth.

Basic for both is the same, user can decide how many fish farm will be in the beginning in the system by using slicer "*number-of-fish-farms*" , each created fish farm will have assigned random number of components in range 50 to 300, it is presented in simulation as variable *"fish-brackets.in-farm* "and it is patches-own variable). Slicer "*number-of-fish-farms*" is used as input for executing ”*create-fish”* procedure Figure 17, all fish farms are created in habitual zone around Norway coastline, habitual zone is express by light blue colour of patches. All fish farms created in the beginning stage on simulation are represented by red colour Figure 17.

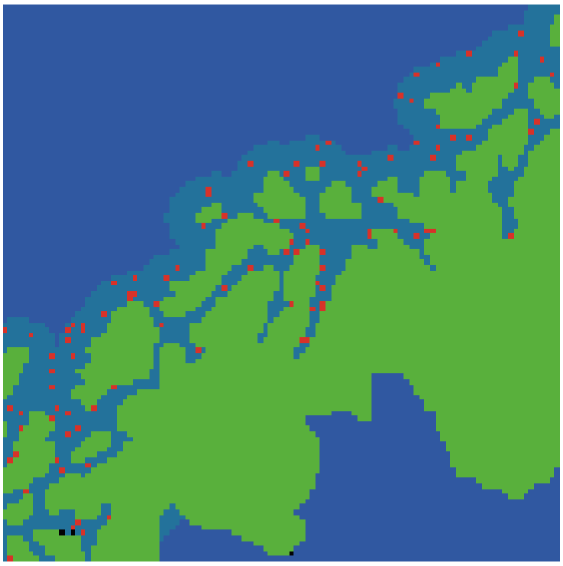

Figure 17 Executed function – *“create-fish”*

In the next stage simulation create number of trucks decided by user slider *“num-trucks”*, all trucks are randomly assigned to already existing facilities, it represent real-life scenario, not all facilitates have the same resources in the start, but if it is possible than facilities gather resources to be more effective. It is reason why when facility stopped being active than all trucks will be randomly distributed among active facilities. All resources are used in order to make process more effective. It is important to control numbers of facilities and trucks in the beginning stage of simulation. The correct relation between them is important part of stable recycling scenario, it allow to decrease or increase different amount of resources available for recycling facility Figure 18.

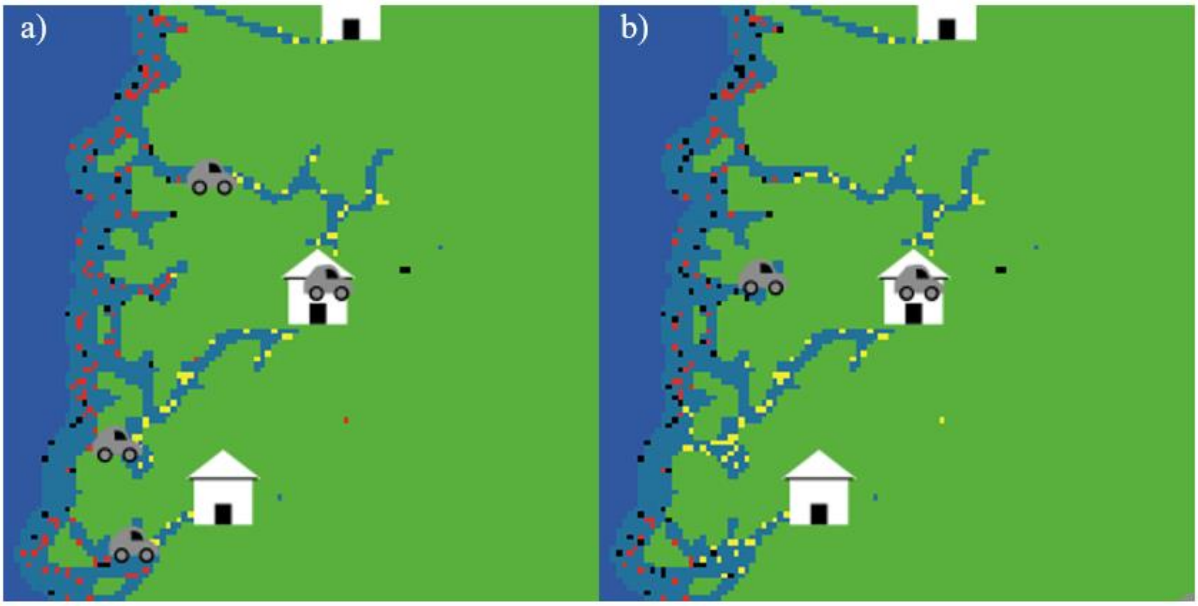

Figure 18 Collecting components area priories

Further components are collected from fish farms, it is executed by “find-fish-brackets” function which execute 3 subfunctions *“move”* Figure 19 b), *“collect-product”* Figure 20 a) and *“go-back-procedure”* Figure 20 b) first *“move”* function allow to target one of the fish farms with colour red or black. Trucks always target the closes fish farm to them; it is important limitations which adding structure to say how trucks collect product. In that way facility always will priories fish farms which are close to facility location and then if there will be not enough material facility will expand searching area.

If truck collected material from fish farm than fish farm change colour to yellow and set characteristic *“fish-brackets-in-farm”* equal 0. Truck increase his *“truck-load”* by the amount which was present in the fish farm. If *“truck-load”* will reach *“max-truck-load-capacity”* which is maximum capacity which is maximum truck payload, then truck go back to assigned *“home-facility”*. If truck didn’t reach it maximum payload than truck also goes back but with not fully loaded capacity. User can decide value of truck maximum payload by changing value on slider presented in interface *“max-truck-load-capacity”*. Function *“go-back-procedure”* contain safety mechanism which say that if *“home-facility”* stopped existing (stopped being active) than truck temporarily stop and don’t cause error for the simulation.

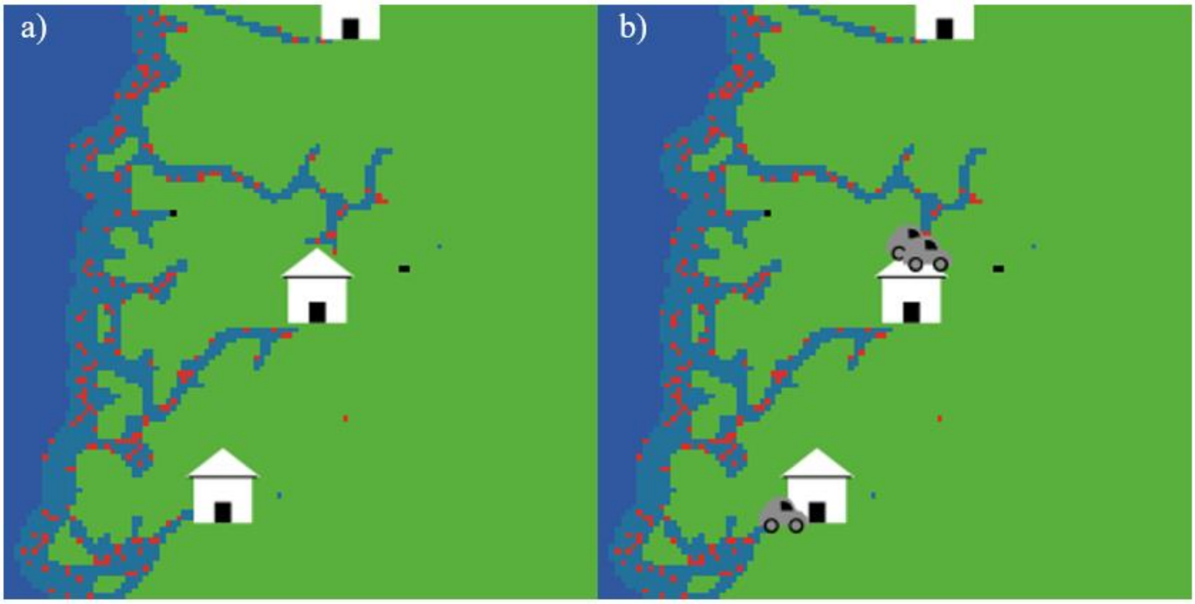

Figure 19 Execution function: a) *“create-fish-trucks”* b) *“find-fishbrackets*” (subfunction - move)

Every 10 ticks some yellow, red or black fish farms will increase number of components which they have by random value up to 300 fish brackets. User can decide how many fish farms will be supplied with new fish brackets: It can be control by slider*” number-of-fishfarm-supplied-at-10-tick”*. All fish farms which increase number of fish brackets change colour to black, it is visualise at Figure 20 a). It allows to visualize how function work and monitor changes in recycling system.

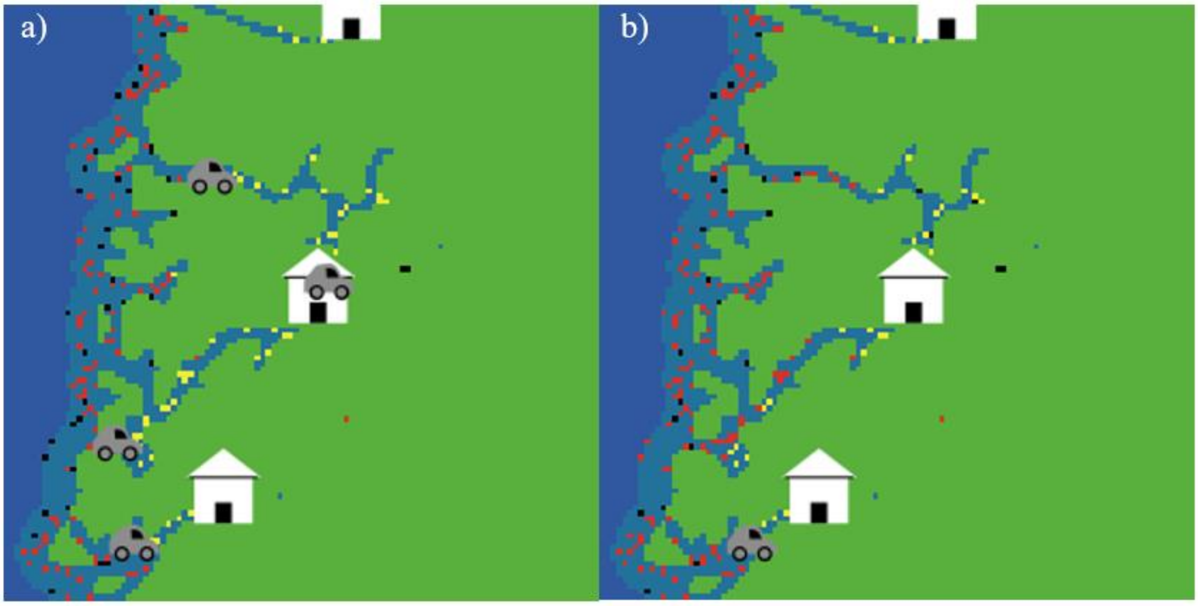

Figure 20 Execution functions: a) *"find-fishbrackets"* (subfunction - collect-products), b) *"find-fishbrackets"* (subfunction - go-back-procedure)

There are three conditions when *"find-fish brackets function"* will stop, first two conditions:

"if home-facility = false [stop]" and *"if home-facility = nobody [stop]"*

Those conditions allow us to stop representatives of truck breed when it loses recycling facility (when facility die/ stop being active), it allows to simulation to run even when it will happen. Last condition:

"if any? patches with [pcolor = red or pcolor = black] = false [stop],

Condition telling us that simulation will end when all red and black fish farms will be collected. In that time trucks will stop looking for new components to collect.

All recycling facilities are limited by important restrains, first every 24-tick facility which didn't manage to collect 2000 fish brackets will stop being active, it is executed by function *"death-facility"*. Second in tick 25 each facility transfer all collected fish brackets to Plasto, number of components in all recycling facilities is set to 0, it is controlled by variable *"facility-capacity"*. Further Plasto *"total_collected_components"* trait is equal to sum of previous number of components increased by amount of sended components. Plasto accumulate components and don't used them for production, presented trait allow us to visualize change in number of components collected by Plasto. Size of Plasto icon increase temporarily every time when company collect recycled granulate from recycling facilities. It allows to visualize changes in the system. First *"Simulate-one-conditions-endlessly"* simulation continue to work until all componenst will be collected or until all recycling facilities will die.

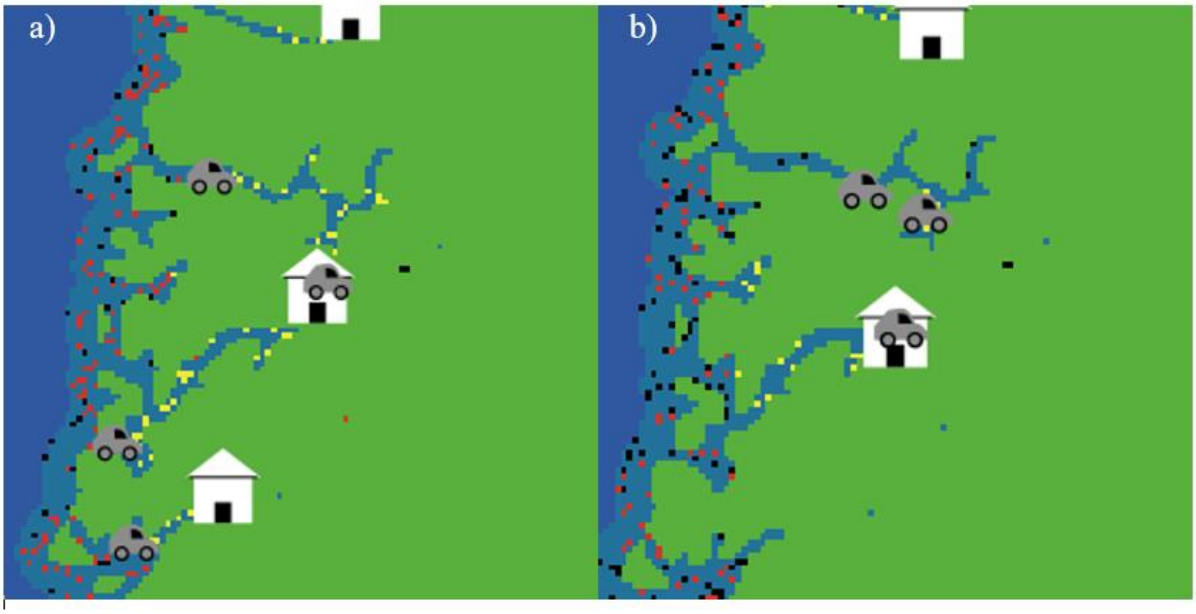

Figure 21 Simulation progress facility at: a) tick 23 before executing "death-facility" function, b) tick 30 after executing “death-facility” function

Second “Repeatable-endless-simulation” partially reset at tick 100 hundred, but recycling facilities which survived first 100 ticks remain on the map. All the values of facilities and Plasto are reduced to 0, location, values and colour of fish farms is completely deleted. Further simulation creates new fish farms and new fish farms according to initial user input. It is not necessary to interact with simulation; it will be done automatically. It allows to find simulation equilibrium and then after 100th tick test achieved simulation with user initial condition with slight variation. It is important to notice that location of recycling facilities remain the same due the entire simulation. Conditions to end simulation are the same as for previous simulation *“Simulate-one-conditions-endlessly”*.

7. How model work? - interactions between agents and patches

Model is build base on interactions between group of the turtles from different breeds, trucks can interact only with home-facility and home-facility can interact with their agents and Plasto with is separate breed *Figure 22* . Lines show connection between breeds and arrows indicates direction of interaction, patches can only interact with the trucks and truck can set value of components in patch to 0 (when components are collected). Only specific group of patches which is called *“fishfarms”* can interact with trucks, in contrary to turtles fish farms are not turtles (agents) but they are specific group of patches with distinguished value of descriptives, they are visualise by patches with patch colour (pcolour) red, black and yellow.

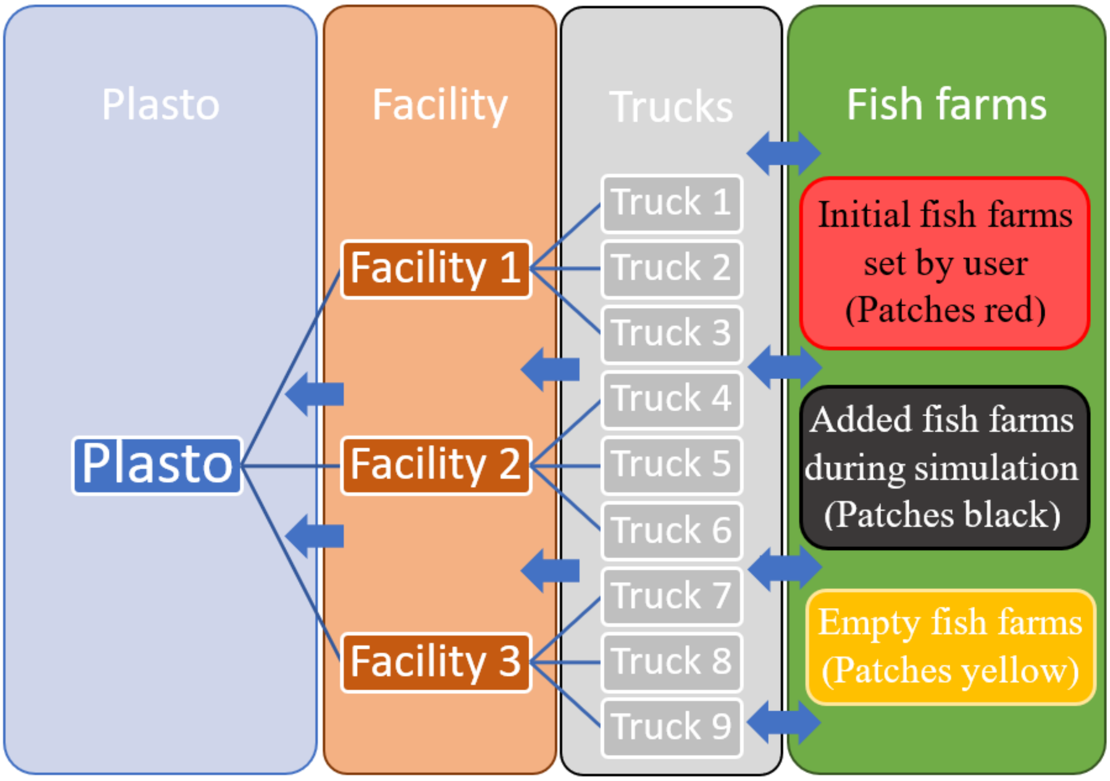

Figure 22 Hierarchy of interactions between breeds and patches

It would be simpler to define fish farms as another breed, but it would significantly slow down program because of significant number of fish farms in the system (usually above 700 - it depends on user settings). Initial attempt was made to do that, but fish farms frequently change they status lead to significant amount of calculations in simulation, much more effective solution was to treat fish farms as patches with specific group of descriptive (colour and value of traits). Additional argument for this solution is nature of fish farms, they don't move and can directly interact only with one breed "trucks" *Figure 22*.

Repeatable endless simulation consist of 10 simulation performed in the same initial conditions, simulation reset after 100 ticks which is equivalent to 100 months, the only difference between simulations is that if facility will go bankrupt (die) in Simulation 1 than it will not appear in the next simulations 2 or any other up to 10, the same principle is implemented for rest simulations. It is game of survivals which work in the same values of initial conditions but random distribution of initial conditions. For example, number of fish farms in first tick of simulation 1 is the same as number of fish farms in Simulation 2, 3 etc., the only difference is their location and new randomly assigned number of components, number close to each plot represent number of simulation .

8. Scenario description

There is variety of variables in the system and it is impossible to understand it correctly without identifying mechanism in the system. It is the reason why in following scenarios only 1 variable is change on the time in reference to first scenario RR1. In order to understand how model works additional simplification was implemented in scenario RR1, RR2 and RR4, it allows to understand how proximity of fish farms to recycling facility influence result (performance of recycling facilities) and shape of components collection plots. Fish farms in set of simulations RR1, RR2, RR3 and RR4 don't reset number of components after truck collect material from them, however of course after collection fish farm will stop being active which is marked by change of her colour to yellow. Then there is a chance every 10 ticks that fish farm will be activated again, then of course, truck will have more components to collect from reactivated fish farm. It allows to evaluate how proximity of fish farm influence performance of recycling facility. It is important to remember that trucks collect first components from fish farms in proximity to recycling facility. Set of simulation RR5 and RR6 is more complex and required result from RR1, RR2, RR3 and RR4 in order to understand it outcome, Fish farm reset number of components after truck collect components from them, in order to identified more complex scenarios they are marked by "set up 0" in the headline. RR5 and RR6 are more realistic scenarios in contrary to scenarios RR1, RR2 and RR4 which are used as a medium to simplify and understand mechanism inside of the model. There are 2 types of simulation in presented work, scenarios RR1, RR2, RR4, RR5 and RR6 use *"Repeatable endless simulation"* and scenario RR3 use" *Simulate one conditions endlessly".*

Scenario RR1

Scenario RR1 use *"Repeatable endless simulation"* and assume abundance of recycling facilities (17) which are randomly distributed in system with many fish farms (700), every 10 ticks recycling system is supply with 322 fish farms with new components, they are marked by black colour. Recycling system is not limited by number of components but by actual location of fish farms and recycling facilities. It is important to remember that fish trucks are always created in place of their own recycling facility, it allows us to investigate truck - fish farm relation. Scenario consist of 10 simulation performed in the same initial condition simulation reset after 100 ticks which is equivalent to 100 months, the only difference between simulations is that if facility will go bankrupt (stop being active) in Simulation 1 than it will not appear in the next simulations number 2 or any next up to 10^{th} , the same principle is implemented for rest simulations. It is game of survivals which work in the same values of initial conditions set by user but randomly distribution. For example, number of fish farms in first tick of simulation 1 is the same as number of fish farms in Simulation 2, 3 etc., the only difference is their location and new randomly assigned number of components. In case of confusion please find designed code of Netlogo simulation in appendix at page 75.

Table 1 Scenario RR1 - MODEL SETTINGS

number-of-fishfarm-supplied-at-10-tick	max-truck-load-capacity	initial-number-of-facilities	num-trucks	number-of-fish-farms
322	500	17	19	700

Scenario RR2

Second scenario RR2 is the same as scenario RR1 and use "Repeatable endless simulation" but decrease *"number of fish farms to reuse"* from 322 to 50 units and initial number of fish farms from 700 to 1000. All the changes in reference to Scenario RR1 are marked by blue text colour in model settings table.

Table 2 Scenario RR2 - MODEL SETTINGS

number-of-fishfarm-supplied-at-10-tick	max-truck-load-capacity	initial-number-of-facilities	num-trucks	number-of-fish-farms
50	500	17	19	100

Scenario RR3

Scenario RR3 use more realistic approach and allow all the fish farms they components when they are visited by truck. In addition to that scenario use second kind of simulation" *Simulate one conditions endlessly"* simulation which don't reset any conditions after reaching 100 ticks which is equivalent to100 months. All other function works the same. Simulation is built based on experience gained from results of simulations RR1, RR2, RR4, RR5 and RR6, it is strongly advice to look on those results in the end.

Table 3 Scenario RR3 set up 0 (Simulate one conditions endlessly) - MODEL SETTINGS

number-of-fishfarm-supplied-at-10-tick	max-truck-load-capacity	initial-number-of-facilities	num-trucks	number-of-fish-farms
50	500	5	19	700

Scenario RR4

Scenario RR4 was designed in line with model settings from scenario RR1, the only difference is reduced number of recycling facilities from 17 to 5, model is also simplified version of simulation which allow fish farms to accumulate components when truck collect components from fish farm (the same as in scenario RR1,RR2 and RR4).

Table 4 Scenario RR4 - MODEL SETTINGS

number-of-fishfarm-supplied-at-10-tick	max-truck-load-capacity	initial-number-of-facilities	num-trucks	number-of-fish-farms
322	500	5	19	700

Scenario RR5

Simplified model presented at Scenario RR1 allowed to understand relation between location of fish farm and performance of recycling facility in new arrangement of fish farms, next simulation RR5 allow to investigate the same initial condition as presented in scenario RR1 but in normal conditions. Fish farms will lose components when fish farm will be visited by truck.

Table 5 Scenario RR5 set up 0 - MODEL SETTINGS

number-of-fish farm-to-reuse	max-truck-load-capacity	initial-number-of-facilities	num-trucks	number-of-fish-farms
322	500	17	19	700

Scenario RR6

In the last multi agent simulation I used the same model settings as in Scenario RR2, but fish farms lost they components when track collect them. In opposite to Scenario RR5 number of fish farms is reduced to 100 and only 50 fish farms will be randomly added to system every 10 ticks.

Table 6 Scenario RR6 set up 0 - MODEL SETTINGS

number-of-fishfarm-supplied-at-10-tick	max-truck-load-capacity	initial-number-of-facilities	num-trucks	number-of-fish-farms
50	500	17	19	100

9. Simulation interface

The interface is divided into 4 main area *Figure 23*, left side of simulation is used to control input for the simulation. It is necessary to follow steps presented on interface, all options necessary to perform simulation are placed in area of called *"Simulation control buttons*" *Figure 23,* simulation start bottom fulfil role of start and stop. It is possible to modified simulation by sliders in area of *"Advance initial simulation setting sliders* ". Advance option are not necessary to perform simulation but giving user additional possibility to influence system. There are two cleaning options in simulation located in *"Cleaning options"* area, first *"Clean trucks, fish farms and ticks"* button allow to clean all results from current simulation and prepare program to do next simulation with recycling facilities currently existing in system. "*Clean all"* removing all gather data and initial setup. Area called *"Simulation map"* showing us current status of simulation, last area*" Simulation output"* present series of graphs which allow to monitor in real-time change in values of *"Total average of components in facilities"*, *"Distribution of fish farm in simulation"*, *"Distribution of components in the simulation"*, *"Average amount of components collected by Plasto from facilities"* and *"Total sum of components collected by all facilities"*

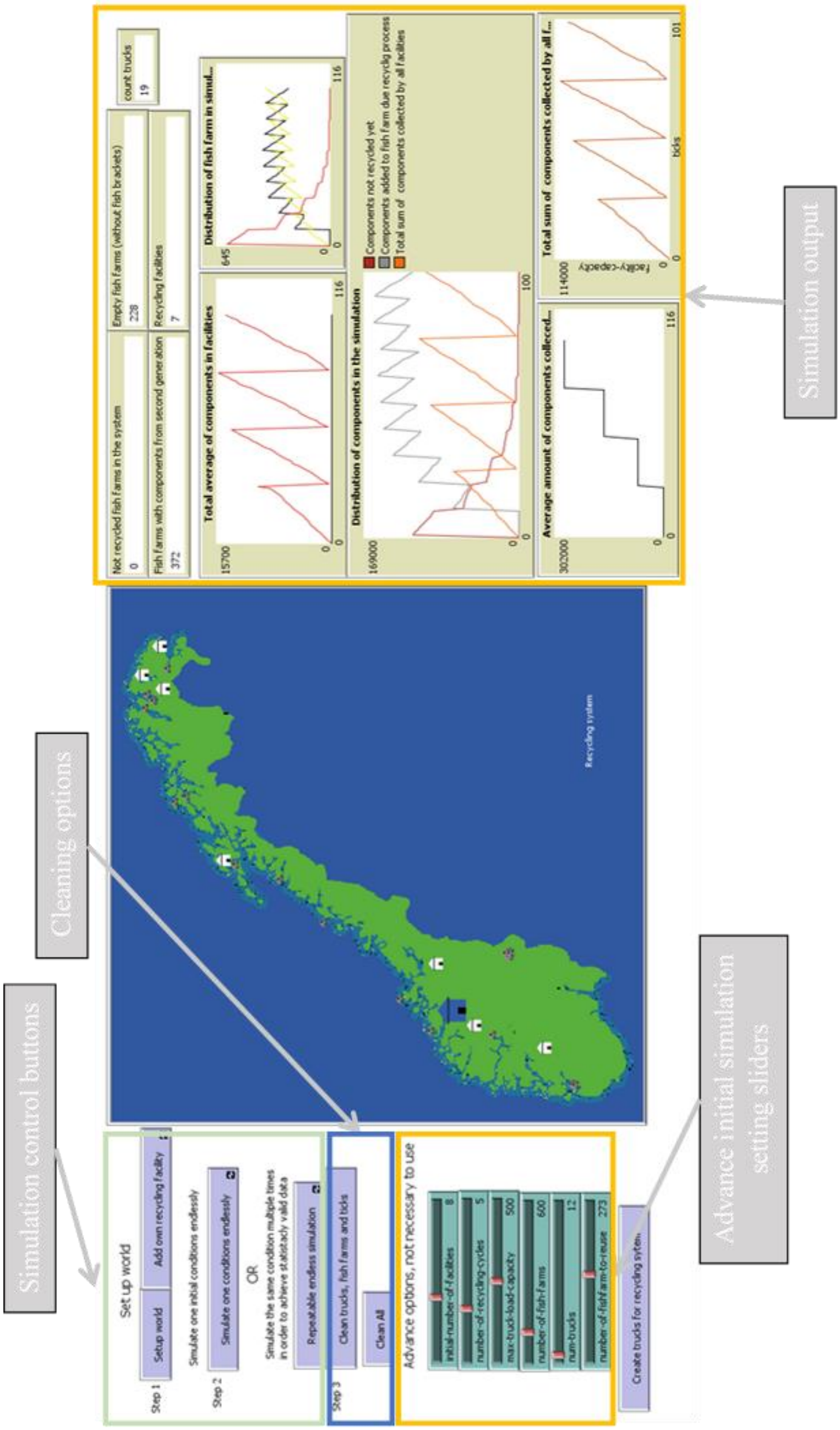

Figure 23 Multi-agent simulation interface

IV. Multi-agent simulations -results

The model allows to investigation possible configurations of user input, unfortunately it is impossible to investigate all of them, however one of the most important part is to investigate how agents interact with each other and patches. There is plenty of variables in the model which influence each other as presented at Figure *22*, part of them is randomly assigned with some limitations described in chapter 8.

In the beginning it was difficult to interpret result of the simulations because of too complex interaction between trucks and fish farms. It is reason why scenarios RR1, RR2 and RR4 investigate simplified conditions. Trucks prioritize one of fish farms which is in the proximity to the *"home-facility"*, however both recycling facilities and fish farms are randomly distributed in the system which lead in difficulty to understand how trucks exactly choose fish farm which they plan to collect components. Then if simulation continue truck choose other fish farm to collect product and process continue; it is impossible to truly understand truck - fish farm interaction. It is reason why Scenario RR1 and RR2 simplified this randomness and assume that each farm keeps all components after truck collect material from them (and then turn colour to yellow), it allows to investigate how initial configuration of fish farm influence performance of trucks. It is important because if marked fish farm *Figure 2* will be supplied with new components in one of the 10th tick than it will have in possession initial number of components assigned by *"create-fish"* function and components assigned by *"start-fish-farmers-supply-cycles"* function. Fish farm can be supplied with new material every 10 ticks (20th, 30th,40th etc. up to 100th) which can lead to significant accumulation at end of first simulation, try will visit this fish farm more frequently which will show us importance on fish farm location in relation to facility performance. However high accumulation don't matter in the end because truck can visit fish farm only once per every 10 tick and collect maximum *"max-truck-load-capacity"* which was set at 500 components, than fish farm change colour red and is ignore by truck in collection process, fish farm can be used again if *"start-fish-farmers-supply-cycles"* will assigned her new value and change colour to black , it is decided randomly and user decide how many fish farms will be assigned value every 10 ticks.

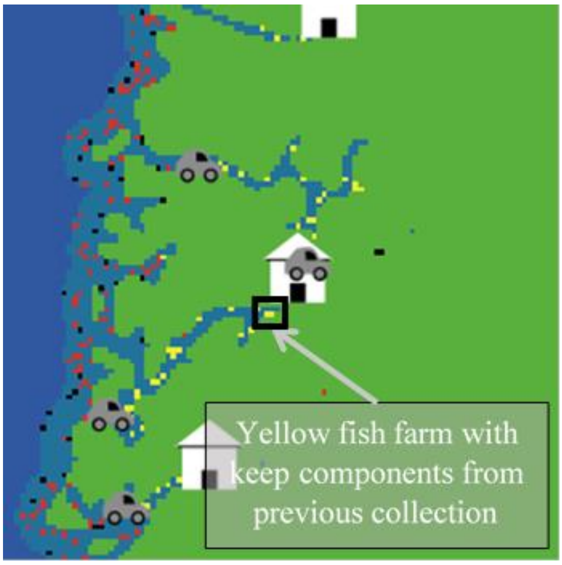

Figure 24 Explanation of main principle of simplified model

It is important to notice that performance of this interaction influence performance of facilities which further influence performance of Plasto *Figure 22*, it is the main building block of simulation and this is reason why it is separately investigated.

1. Set of simulations - Scenario RR1

First set of simulations allow us to investigate behaviour of facilities in abundance of facilities and material which will be collected.

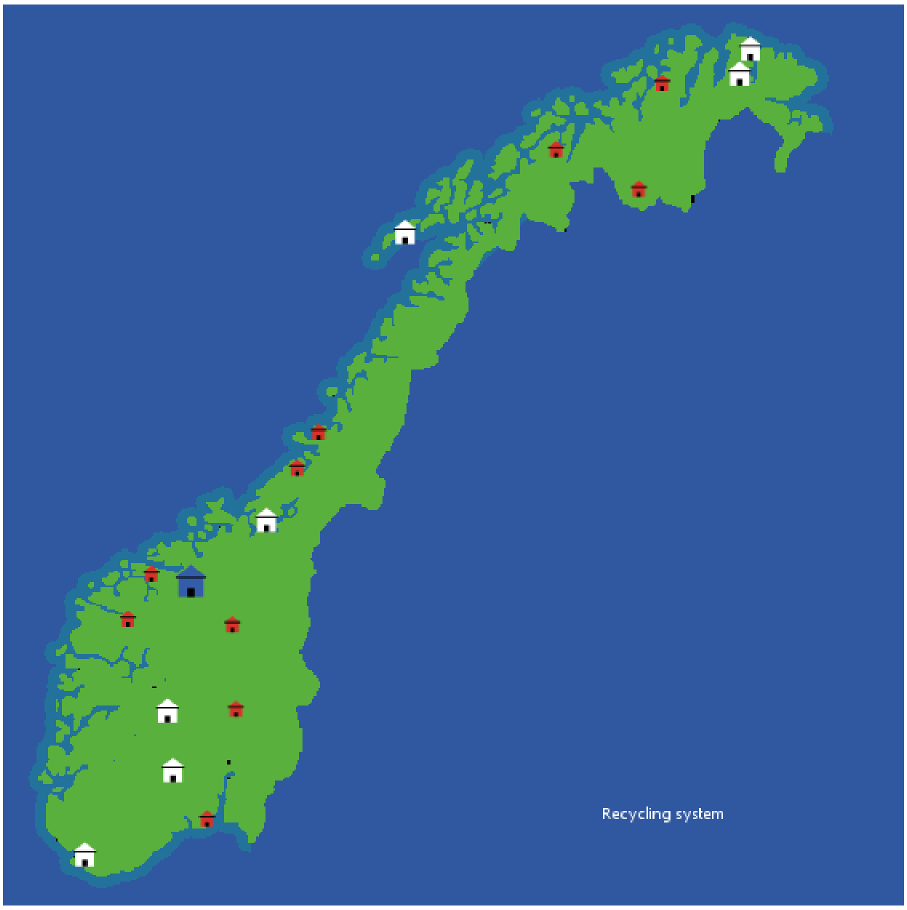

Figure 25 Scenario RR1 - Initial map

Map Figure 25 present initial distribution of recycling facilities, part of facilities were distributed in random location by Netlogo function (white houses) and part of them were chosen by user (red houses). It allows to distribute facilities more homogenously. First graph Figure 26 present average amount of collected by each facility.

Every 25 ticks all facilities transport all collected material to Plasto and set they value of collected materials to zero, it is reason why repeatable pattern have specific component collection pattern visible at Figure 26. Each line represents average amount of component collected by all active facilities in each tick. All components circulate in the close loop and this is reason why it is assumed that Plasto will collect all components from fish farms, collection every 25 allow to compare performance of Plasto in each 25 tick quarters, this visualisation make result more transparent and easy to understand. It is visible tended for each scenario, average increase when amount of facilities decreases. It is visible when we compare all plots in ticks 0-25 to next plot 25-50, 50-75 and 75-100,it is caused by slow elimination of not effective facilities which were the most vulnerable for change in location of available fish farms (they was barely able to collect enough components). Recyclied facilities which stopped being active were placed too far from fish farms which lead them to their inadequate performance in series of next simulations, they could survive few simulations by coincidention benefit conditions, but statistic shows that they were not effective enough.

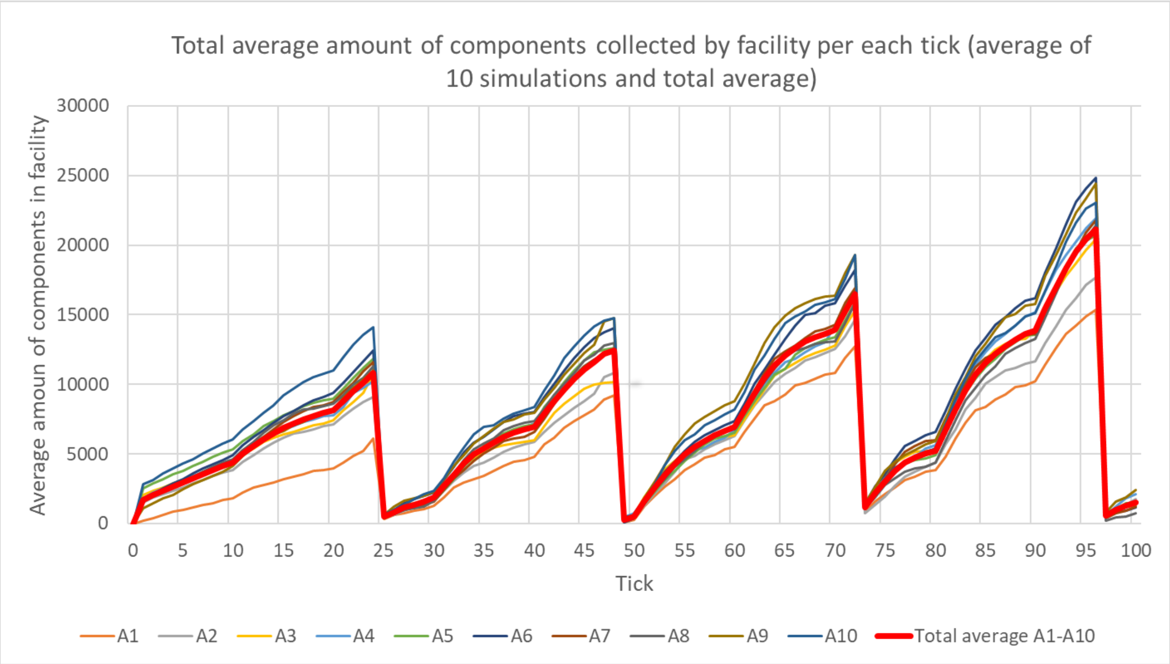

Figure 26 RR1 - Total average of components in facilities (average of 10 simulations and total average)

Every 10 ticks function supply one of the black red or yellow fish farms with new material, it is randomly and uniformly distributed, all the fish farms which were supply with new material change the colour to black *Figure 27*. In addition to that truck breed continuously collect components from red and black fish farms. It is reason why in repeatable range of 10 ticks values of black fish farms decrease and yellow fish farms increase.

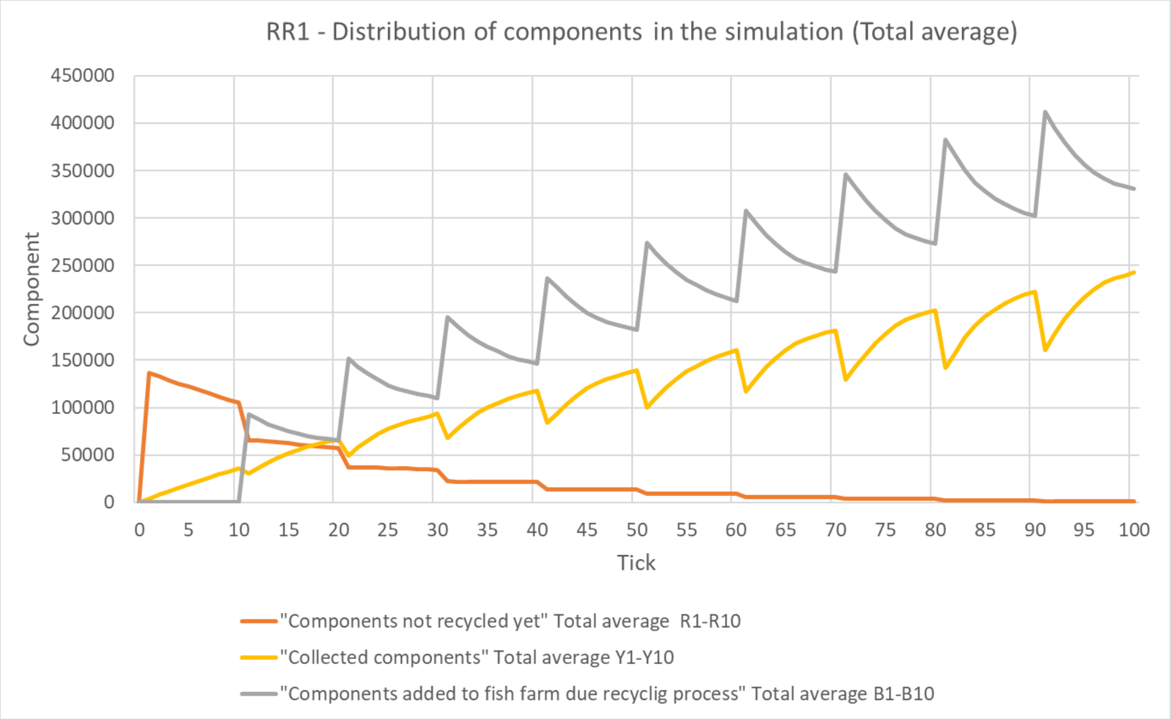

Figure 27 RR1 - Distribution of components in the simulation (Total average)

Collection of component by Plasto from facilities *Figure 28*, seem to have more homogenise nature than collection components by facility *Figure 27*, values varied less compare compared to average number of components collected by single facilities.

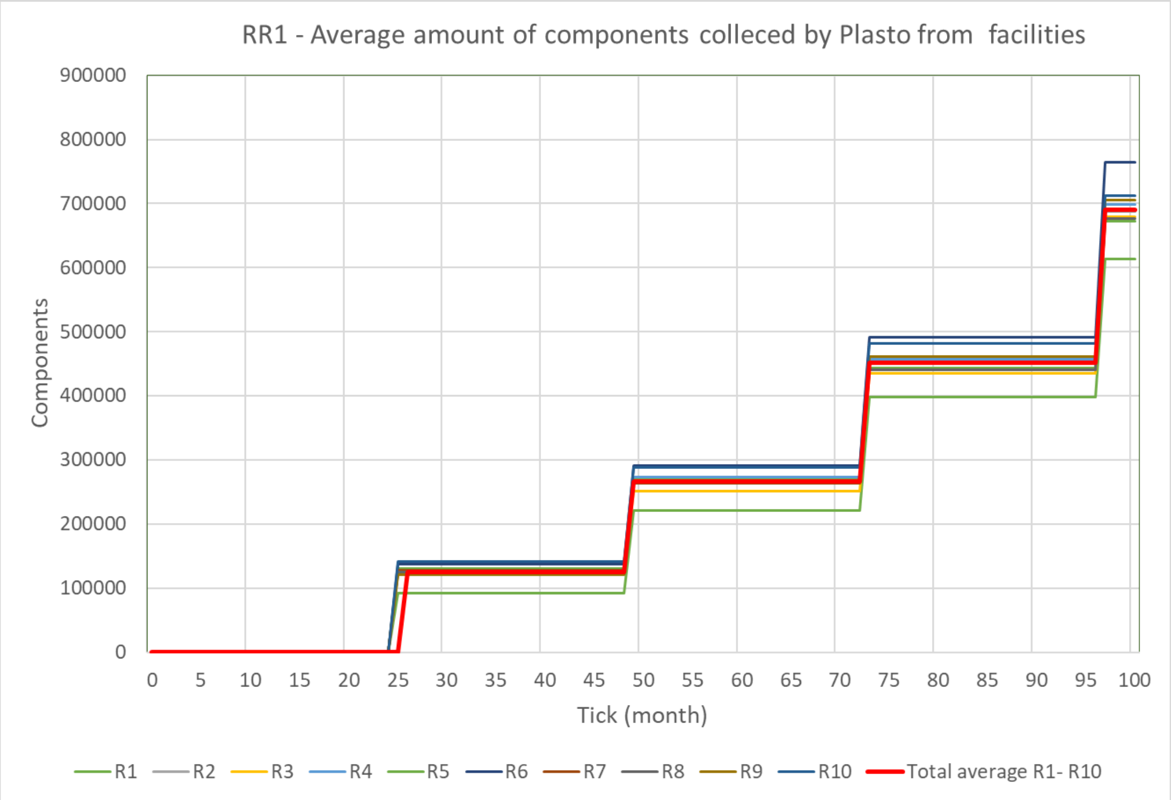

Figure 28 RR1 - Average amount of components collected by Plasto from facilities

Based on gather results it is visible that simulation 6 was the most sustainable, facilities gather the higher amount of components *Figure 29* which allow Plasto to collect the highest amount of material *Figure 29*. Although *Figure 26* and *Figure 29* look similar they represent different data *Figure 26* average amount of components collected by facilities in each simulation, it exclude facilities which were disactivated every at 24 tick (24 months) due to 2000 components survival condition. In the other hand *Figure 29* present summarize performance of all facility which is good indicator of general collective capability of all facilities as a system from global point of view.

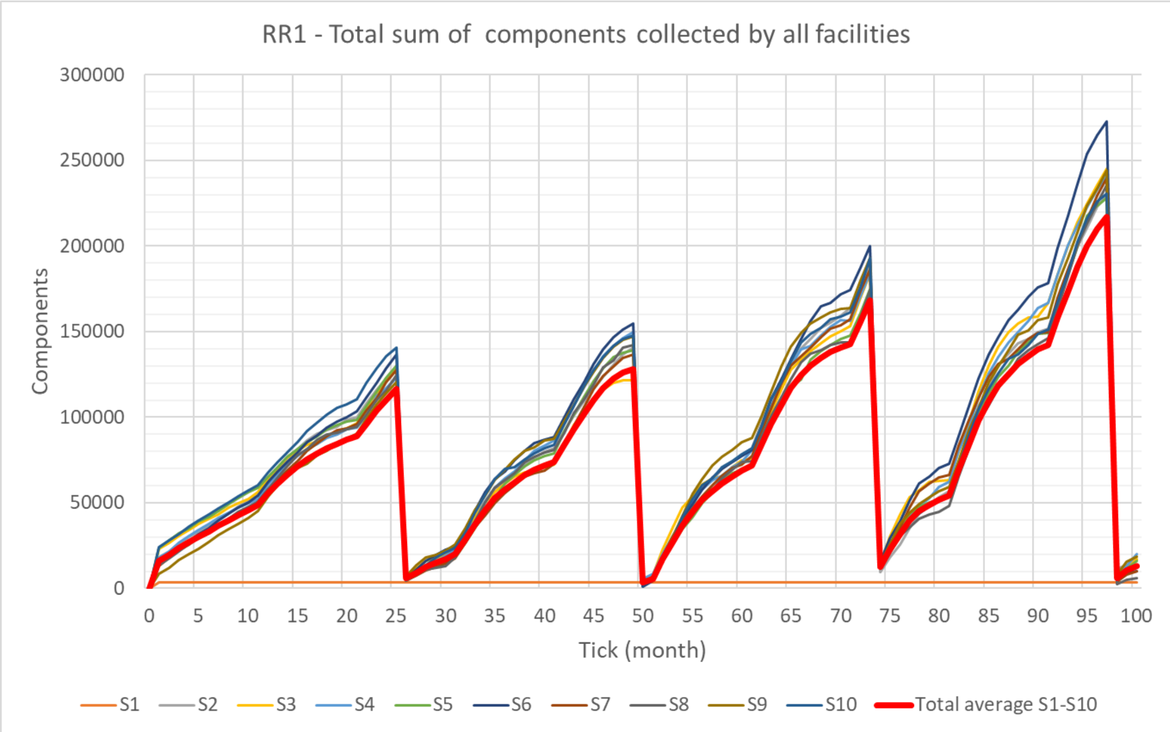

Figure 29 RR1 - Total sum of components collected by all facilities

2. Set of simulations – Scenario RR2

In next scenario facilities are accumulated in the south of Norway which lead to more competitive environment, 15 recycling facilities died after first 25 ticks of first cycle. *Figure 30* a) show initial distribution of recycling facilities and *Figure 30* b) show distribution after first 25 ticks. Only 2 recycling facilities managed to collect 2000 components during first 10 ticks (10 months), what is more surprising all facilities in region with accumulation of recycling facilities (south Norway) went bankrupt.

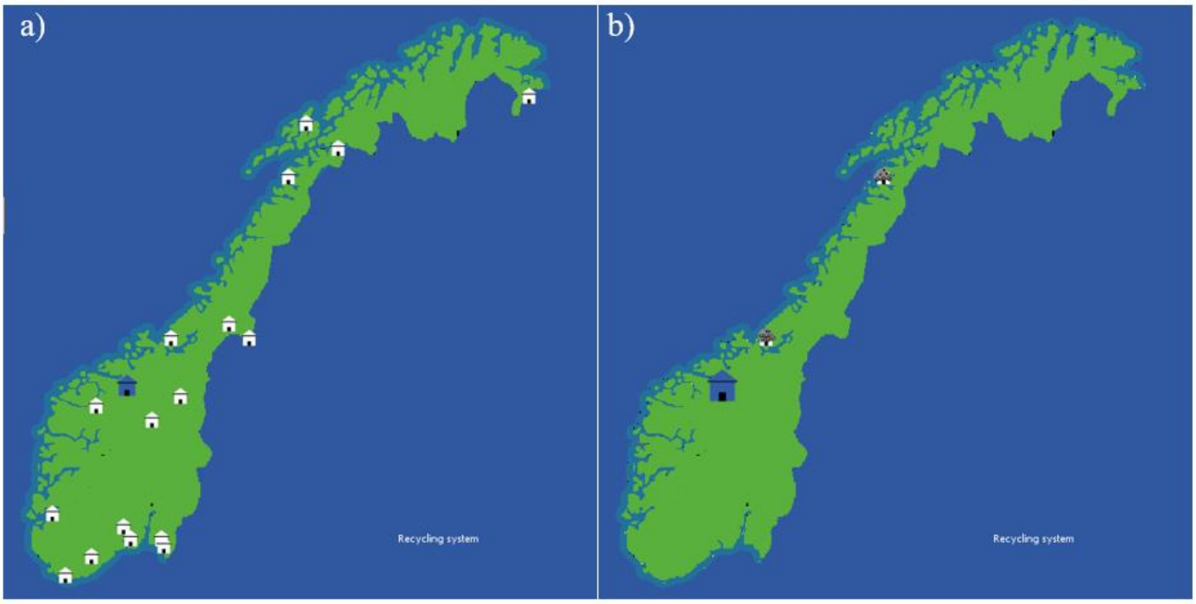

Figure 30 Scenario RR2 - a) Initial map- tick 0 and b) map at 25 tick

The only facilities which survived were facilities which were in remote areas with long coastline and small competition. *Figure 30* b). It is especially visible in first simulation A1*Figure 31* during time between tick 1 to 24, average amount of collected components by all 17 facilities is well below 2000 components, it is close to 1000 components which is not enough for good performance. Remaining 2 recycling facilities keep struggling in tick 25-50 and 50-75, they barely pass 2000 components limit but manage to be active. In the end of first simulation A1 in period between tick 75 to 100 system manage to accumulate enough material in order to allow companies to triple amount of collected material. We need to remember that without 15 facilities which died in 25 tick material keep accumulating in fish farm around Norway coastline. Next simulation A2, A3 and A4 because only 2 facilities were active the average amount of collected components by facility increased. In simulation A5 series of unfortunate circumstances caused not beneficial distribution of fish farms in area close to remaining facilities which caused they trucks to travel far away in order to collect components to production. It led to increasing collection time and bad performance; remaining facilities died but were close to reach condition to survive (2000 components at tick 24).

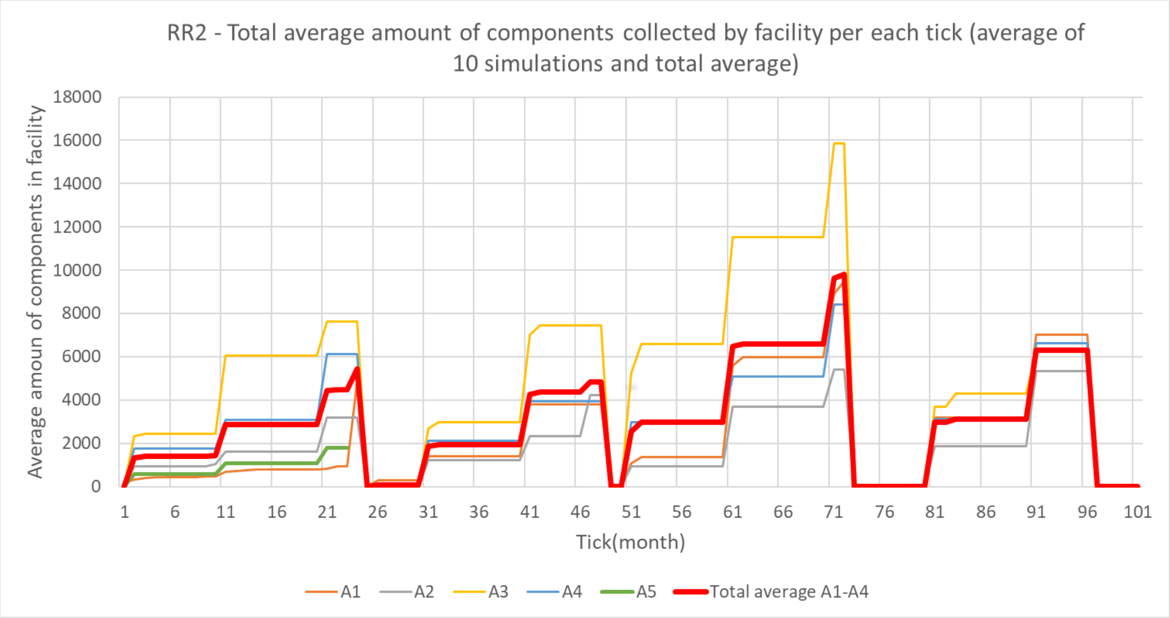

Figure 31 RR2- Total average amount of components collected by facility per each tick (average of 10 simulations and total average)

Figure 32 allow us to investigate how limited amount of fish farms in the recycling system influence their collection possibility, it is important to compare it with *Figure 27* from scenario RR1. Scenario RR1 have more rapid components collection pattern compared to RR2.

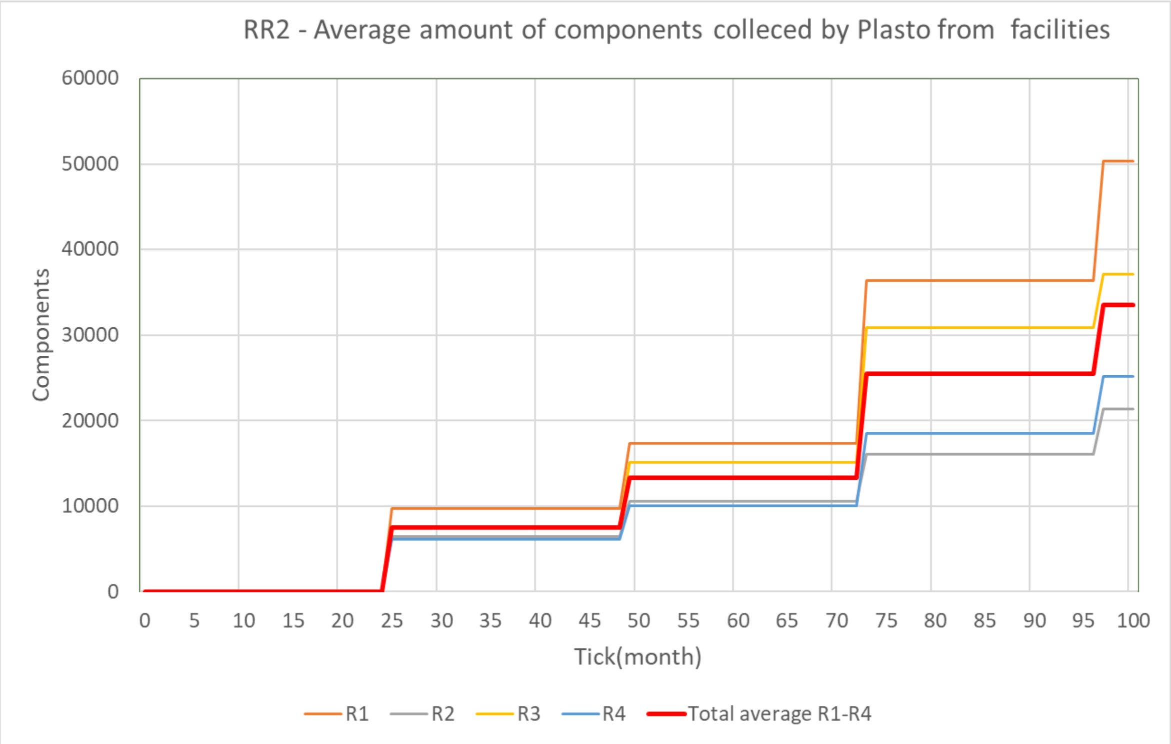

Figure 32 RR2 - Average amount of components collected by Plasto from facilities

Surprisingly all facilities collected the highest amount of components during simulation 1 *Figure 31*, time between tick 0-25 can be easily explain by amount of recycling facility which operate during this time (17 facilities), second part of the graph is more enigmatic. It is important to notice drop in collection of material in cycle between 25-50 for all simulations in scenario, it is well represented by total average S1-S4 (red plot). After low collection period material keep accumulating in more distant fish farms, not all fish farms were reached by trucks in cycle 25-50 and then when those full fish farms were reached, they significantly increased amount of collected components. The most surprising is that intime between 50th and 75th tick facilities collected the highest number of components. It is important to remember that in simulation RR1 and RR2 fish farms don't lose components after fish truck collect them and send them to facility which lead to high probability to visit the same fish farm which is in proximity of facility. Important detail need to be notices in simulation 1 (plot S1) *Figure 33* two facilities which achieved the best result between tick 75 -100 were the same facilities which survived first eliminations of facilities at tick 24. Those facilities survived because they have the best conditions among all 17 facilities, it is attributed mostly to fish farms arrangement, because in this scenario fish farms have infinite supply of components so number of components in fish farms is not important in not limiting factor in this simulation. After 100 tick's arrangement of fish farm change and facility losses main factor which allow them survive simulation 1. This scenario allows to proof how important is location of facility and its proximity to high number of fish farms. It is important remark from those simulation

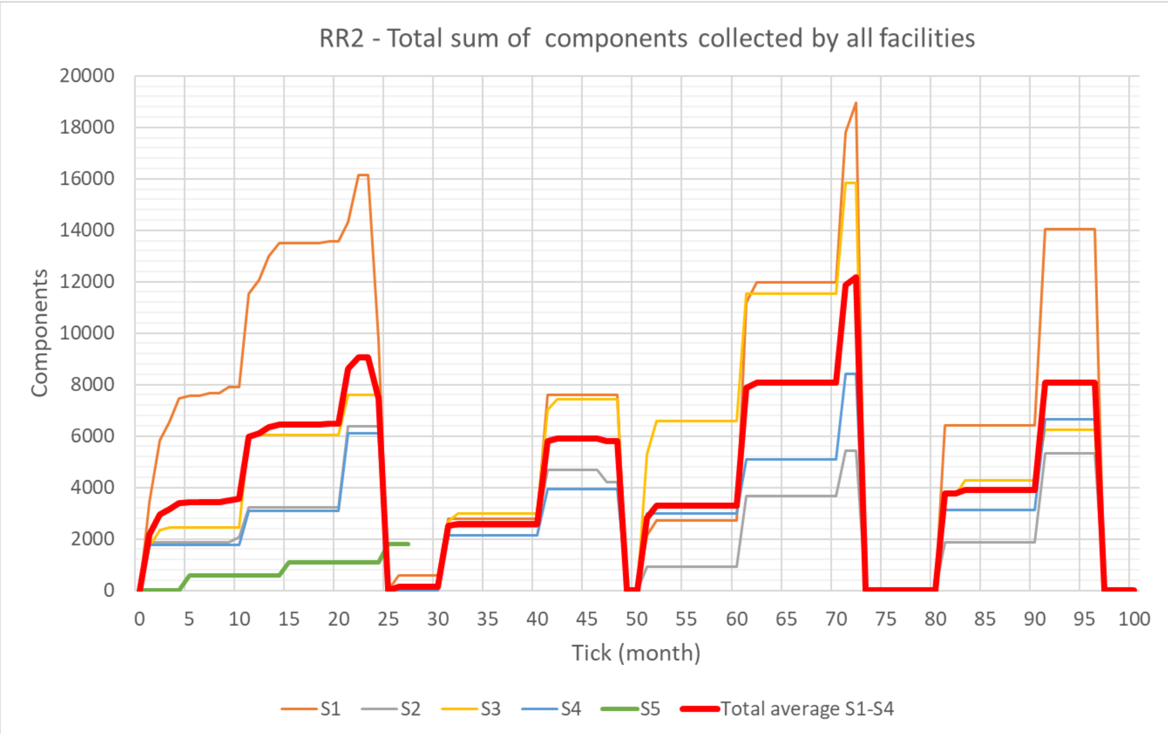

Figure 33 RR2 - Total sum of components collected by all facilities

3. Set of simulations – Scenario RR3

Simulation RR3 is the only simulation which use second type of simulation *"Simulate one conditions endlessly"*, in contrary to other simulation this simulation doesn't reset part of conditions at 100 tick. This simulation continues to work until all recycling facilities stop being active. Simulation assume abundand amount of fish farms the same as in scenario RR1 (700 fish farms) but decrease *"number-of-fishfarm-supplied-at-10-tick"* to 50 which mean that every 10 ticks 50 new fish farms is added to the system *Figure 34*.

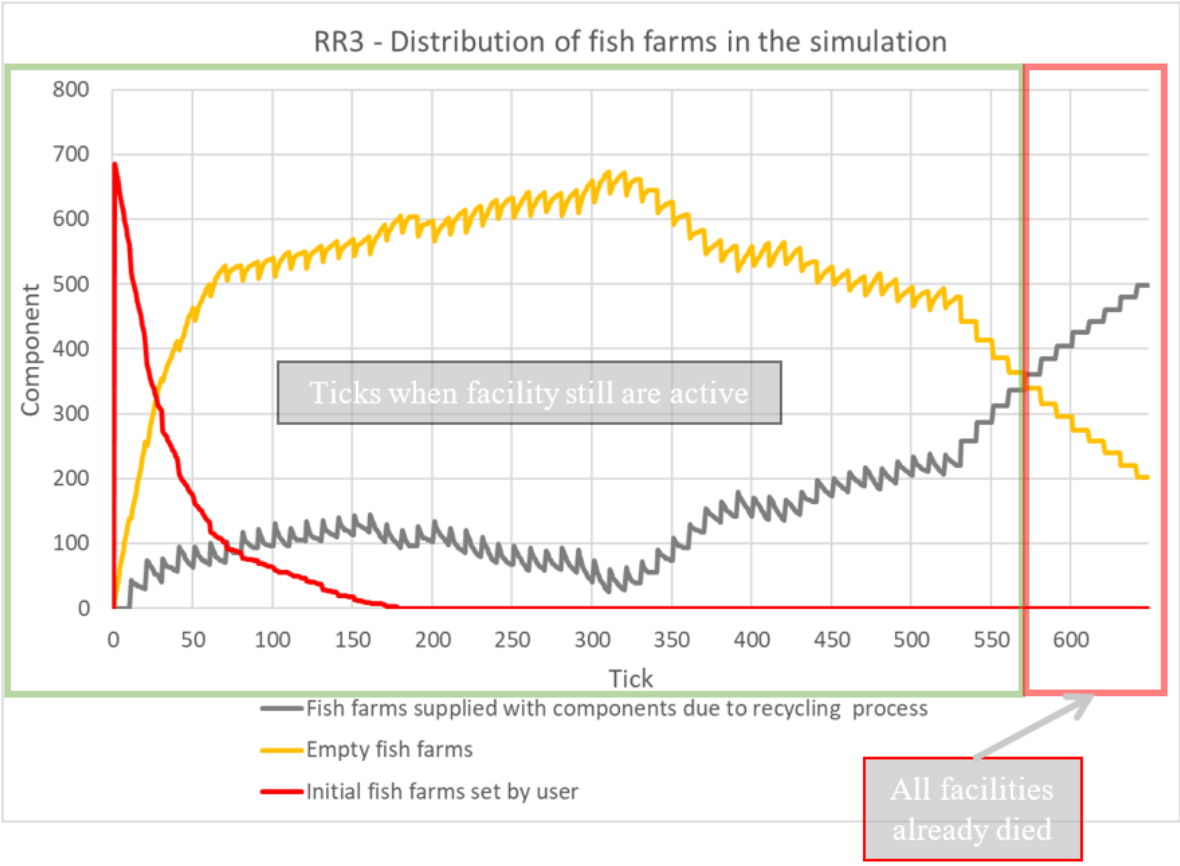

Figure 34 RR3 - Distribution of fish farm in the simulation

In that condition first facility died at 24th tick, next facility died at 99 tick, then 2 facilities died at 374 tick, suprisingly systm was not significantly effected by death of facilities before facilities reached they maximum collection capability at tick between 320-340 (maximuum values of yellow plot) at *Figure 34*. It seem that this scenario reached equilibrium with 3 recycling facilities *Figure 35*. It can be presumed tha if system contained from the start only 3 facilities than it would be more balanced and those facilities would survive collaspse at tick 374.

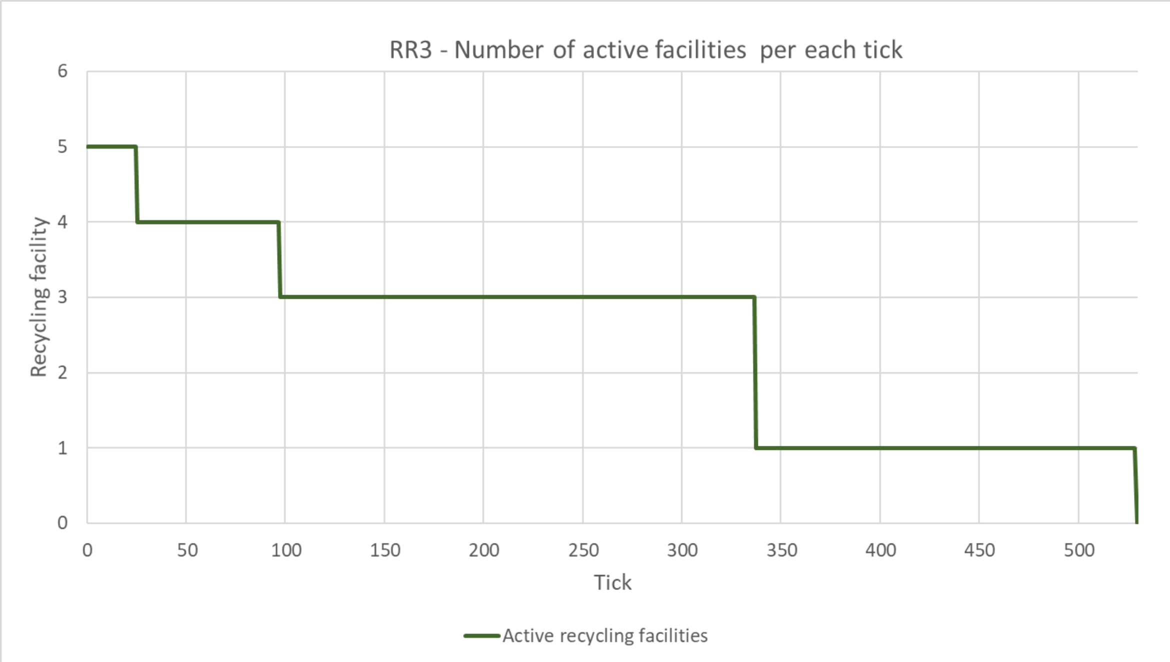

Figure 35 RR3 - Number of active facilities per each tick

Conclusion can be also confirmed by decrease collection of Plasto in the same range of tick between 350 and 375 *Figure 36* and *Figure 37*. As expected, the company manage to collect the highest number of components at tick 25, it is caused by high amount of facilities. It led to surprising outcome, if result is bad for recycling facilities than it doesn't mean that it will be reflected by performance of Plasto. In the end of the day for Plasto the most important is amount of components which it can get and high amount of facilities allow to collect high number of components, although recycling facilities will be on brink of survival (reaching collection of 2000 components every 24 ticks) *Figure 37* .

Figure 36 RR3 - Average amount of components collected by Plasto from facilities

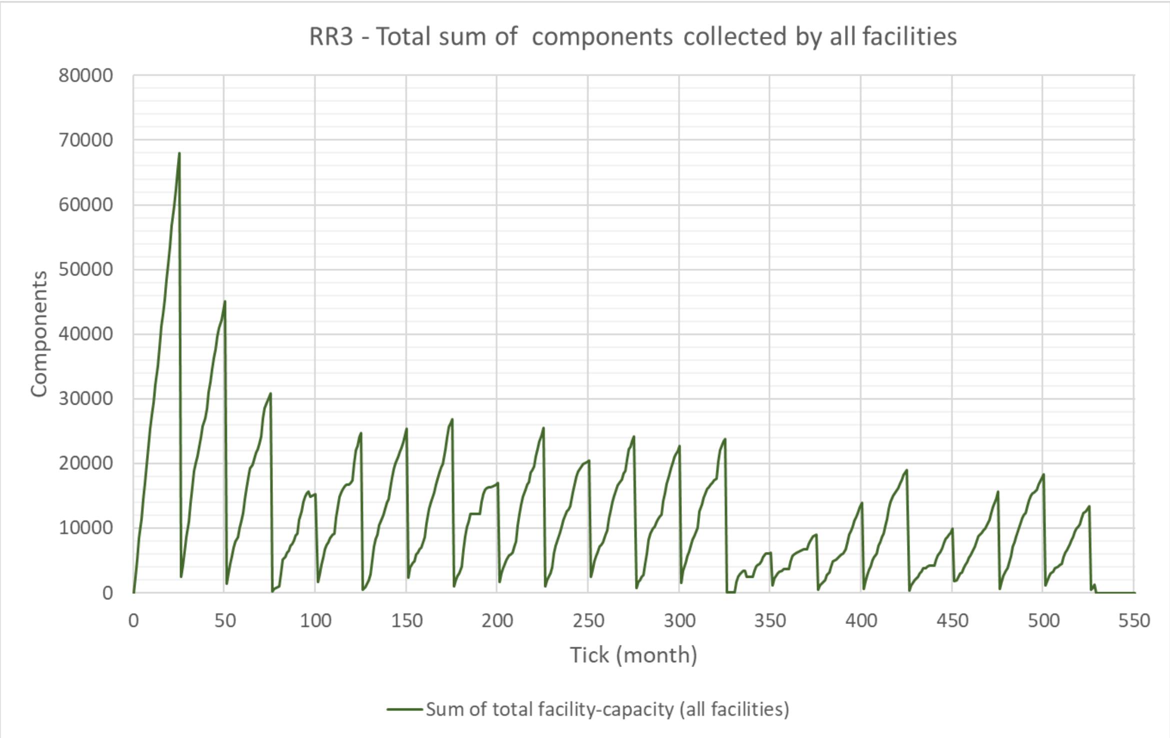

Figure 37 RR3 - Total sum of components collected by all facilities

4. Set of simulations – Scenario RR4

Presented set of simulation assume that there will in the start there will be only 5 active recycling facilities and abundance of material to collect.

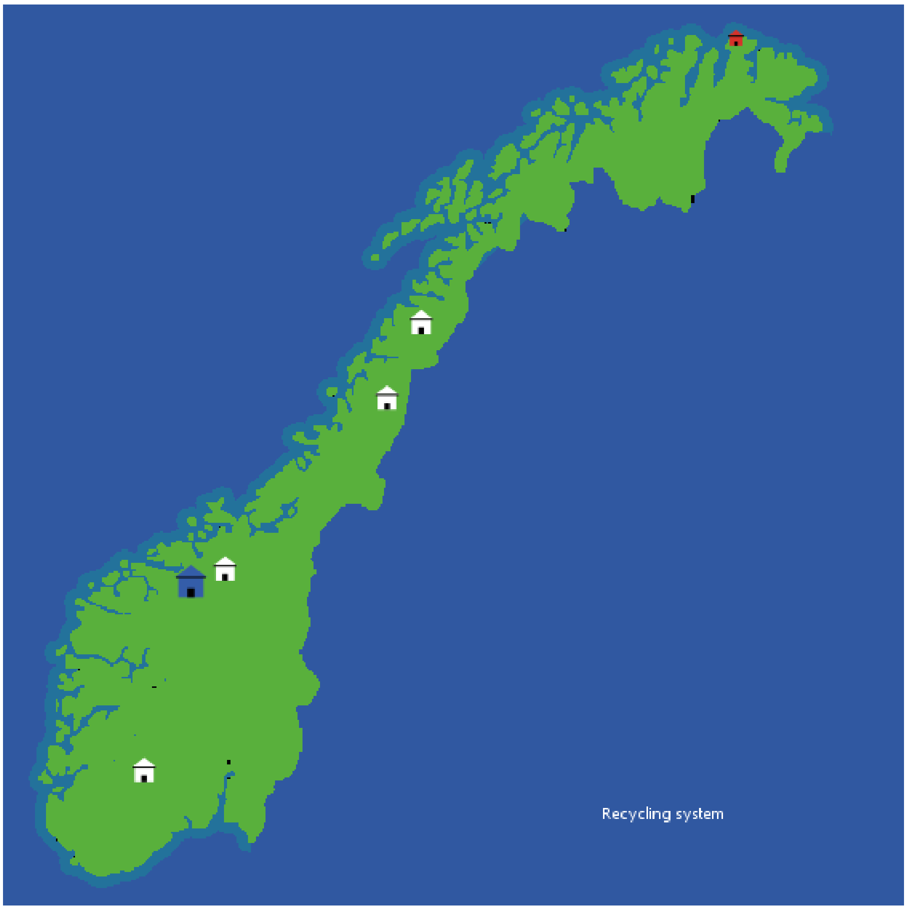

Figure 38 Scenario RR4 - Initial map

Surprisingly decreasing amount of facilities led to making components collection plots to increase by more discrete values *Figure 39*, compare to plots at scenario RR1 at *Figure 26*.

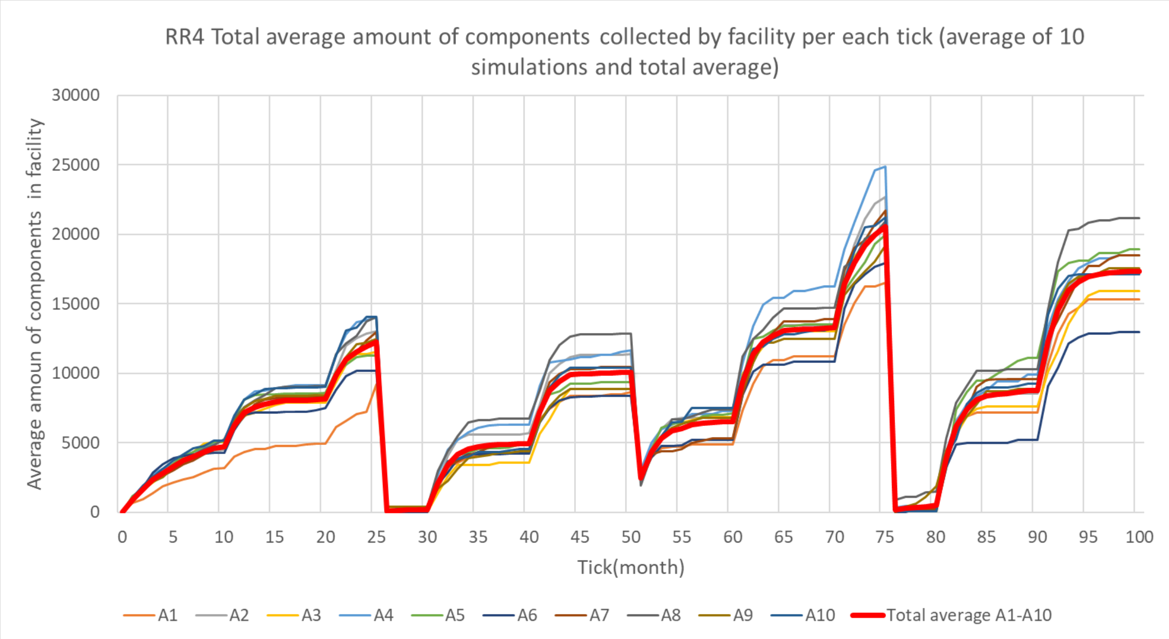

Figure 39 RR4 - Total average of components in facilities (average of 10 simulations and total average)

Low number of facility lead to decrease in collection capability of recycling facilities, more "Components added to finish farm due recycling " (black plot) at *Figure 40* decrease less in value in every batch of 10 ticks compare to the same graph in scenario RR1 presented at *Figure 27*.

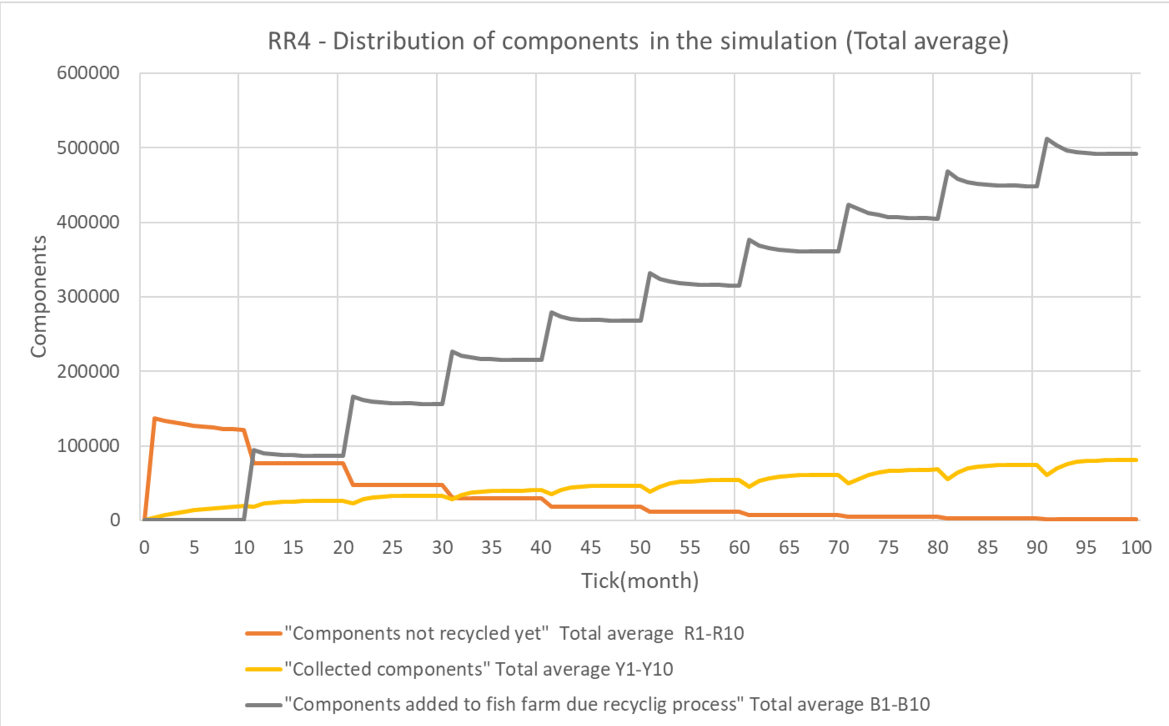

Figure 40 RR4 - Distribution of components in the simulation (Total average)

In presented scenario RR4 simulation 4 allow to achieve the best results both for Plasto (plot S4) at *Figure 41* and facilities (plot A4) *Figure 39*.

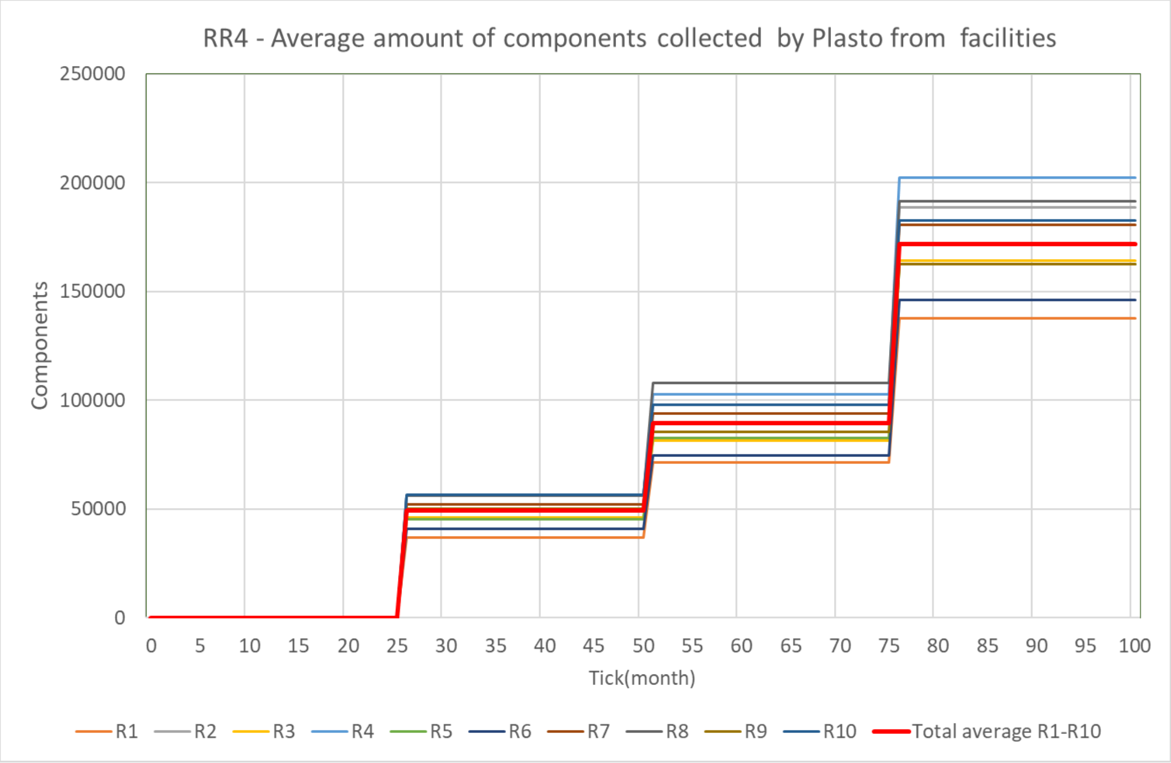

Figure 41 RR4 - Average amount of components collected by Plasto from facilities

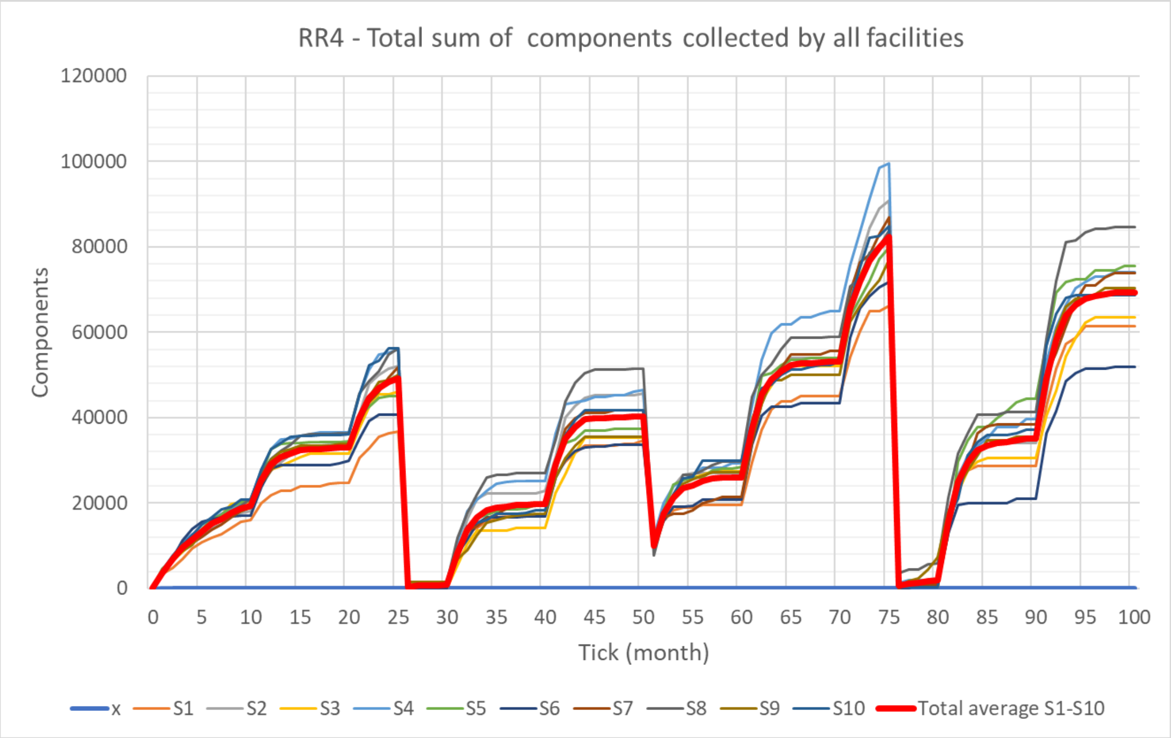

Figure 42 RR4 - Total sum of components collected by all facilities

5. Set of simulations – Scenario RR5

Results in all simulation 10 simulation with scenario RR5 seem to follow the same circular pattern, cycle 0-25 have the highest average collection value, then cycle 26-50 has the lowest value. Further cycle repeating itself for cycle 50-75 and 75- 100 but differences in values significantly decrease, average peak value in cycle 0-25 is 2500 components lower than average peak value at cycle 50-75 *Figure 43* (red plot).

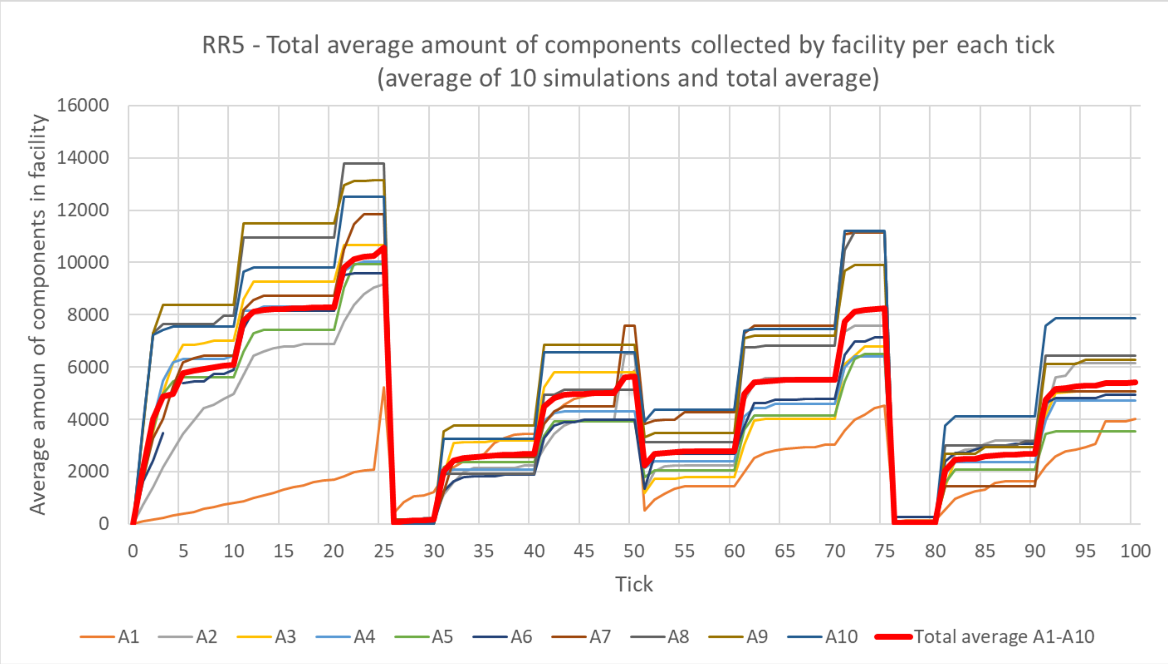

Figure 43 RR5 - Total average of components in facilities (average of 10 simulations and total average)

Majority badly located facilities died in tick 24 *Figure 44*, low collection capability at tick 49 *Figure 43* lead to bankruptcy of 1 recycling facility on average in all 10 scenarios. Surprisingly difficult conditions lead to stabilizing recycling system, at tick 74 all facilities remain active.

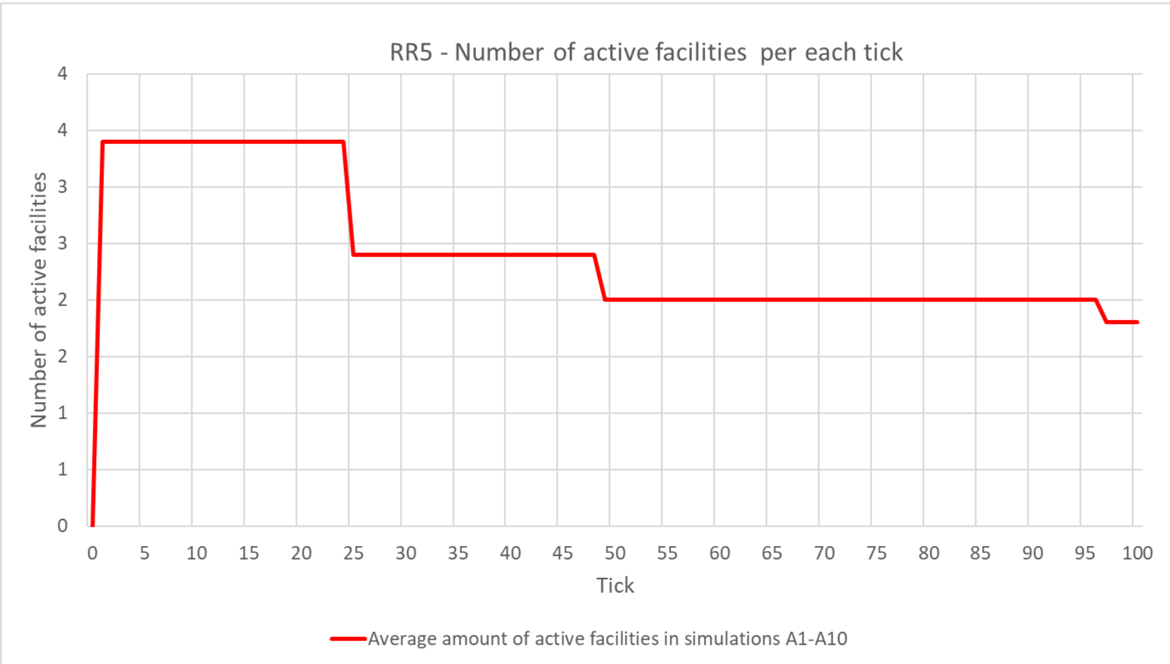

Figure 44 RR5 - Number of active facilities per each tick

As expected in scenario RR5, amount of collected components *Figure 45* (yellow plot) is significantly lower than in the same condition in scenario RR1 *Figure 27*, plots have completely different tendencies. In scenario RR1 values increase due to accumulation of components in fish farms. Second important finding is that distribution of the components in fish farms in 10 ticks cycles is more stable at *Figure 45* (system is supply with new components every 10 ticks due to *"start-fish-farmers-supply-cycles"* function).

At *Figure 27* black fish farms accumulated components from previous cycle of 10 ticks which allowed trucks always transport they full capacity every time when they reached fish farm (truck transported always 500 components). In case of RR5 scenario fish farms have only initial number of components to collect, initial values varied in the range range up to 350 components (red fish farm) and up to 300 for added fish farm during simulation (black fish farm). This simple principle lead to rapid decrease of components in cycle of 10 ticks in case of scenario RR1 and more stable decrease for scenario RR5 *Figure 45*. During majority of time of all simulations, from tick 10 to 100 there was always approximately 80 empty fish farms in the system *Figure 46* (yellow plot). It means that trucks and fish farm created balanced recycling system. In addition there was not huge variation in values of empty fish farms.

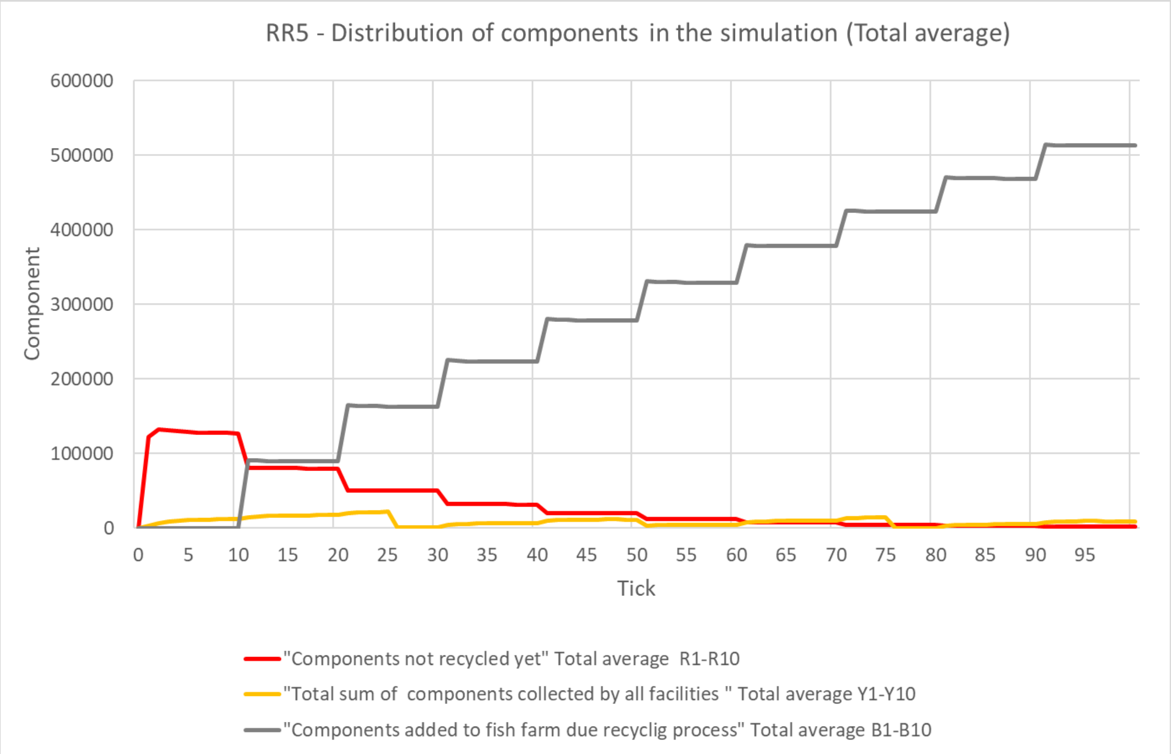

Figure 45 RR5 - Distribution of components in the simulation (Total average)

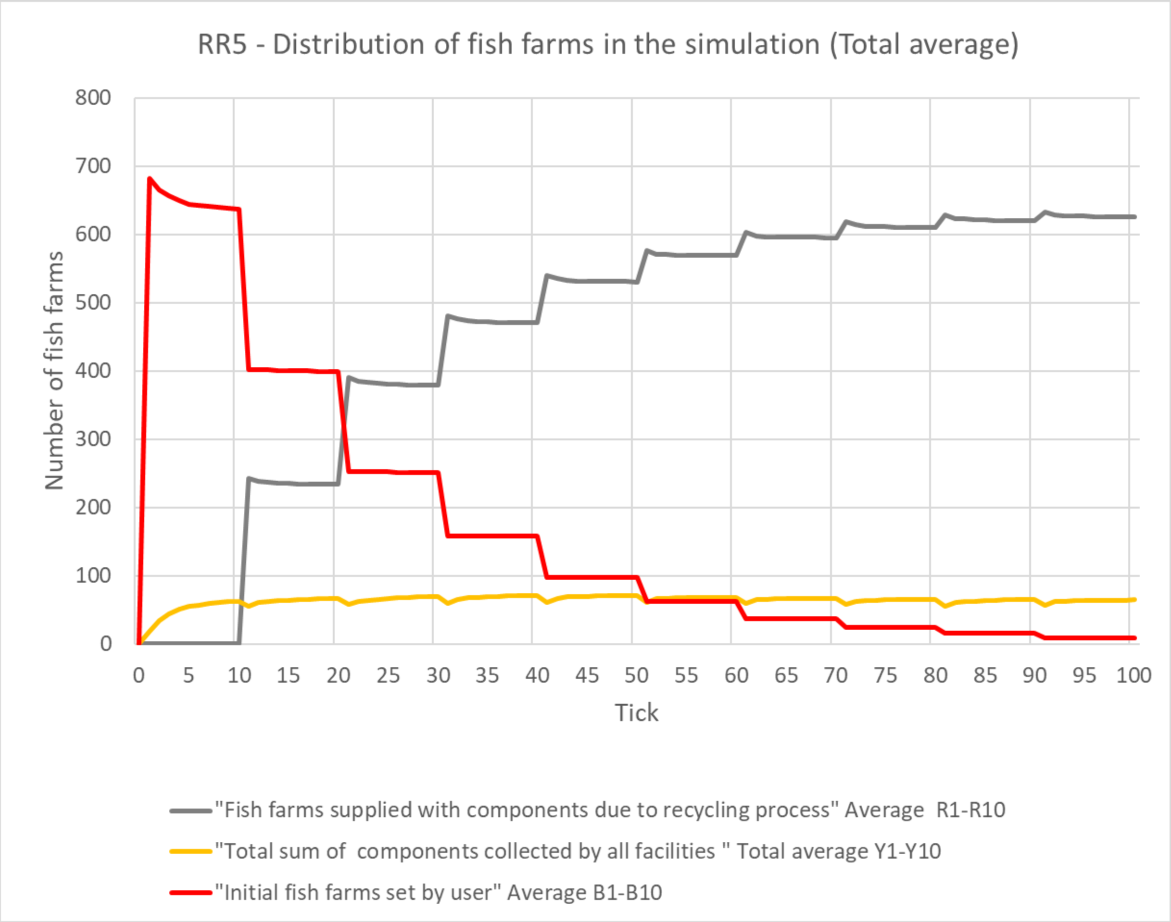

Figure 46 RR5 - Distribution of fish farms in the simulation (Total average)

Scenario RR5 is one of few simulations which allowed to create 10 simulations in "Repeatable endless simulation", usually unbalanced recycling system caused fast bankruptcy of majority scenarios in proximity of 6th or 7th simulation. In this scenario RR5 simulation 1 allows Plasto to collect the highest number of components. In next simulations collection decrease by almost 50% due to smaller number of active facilities.

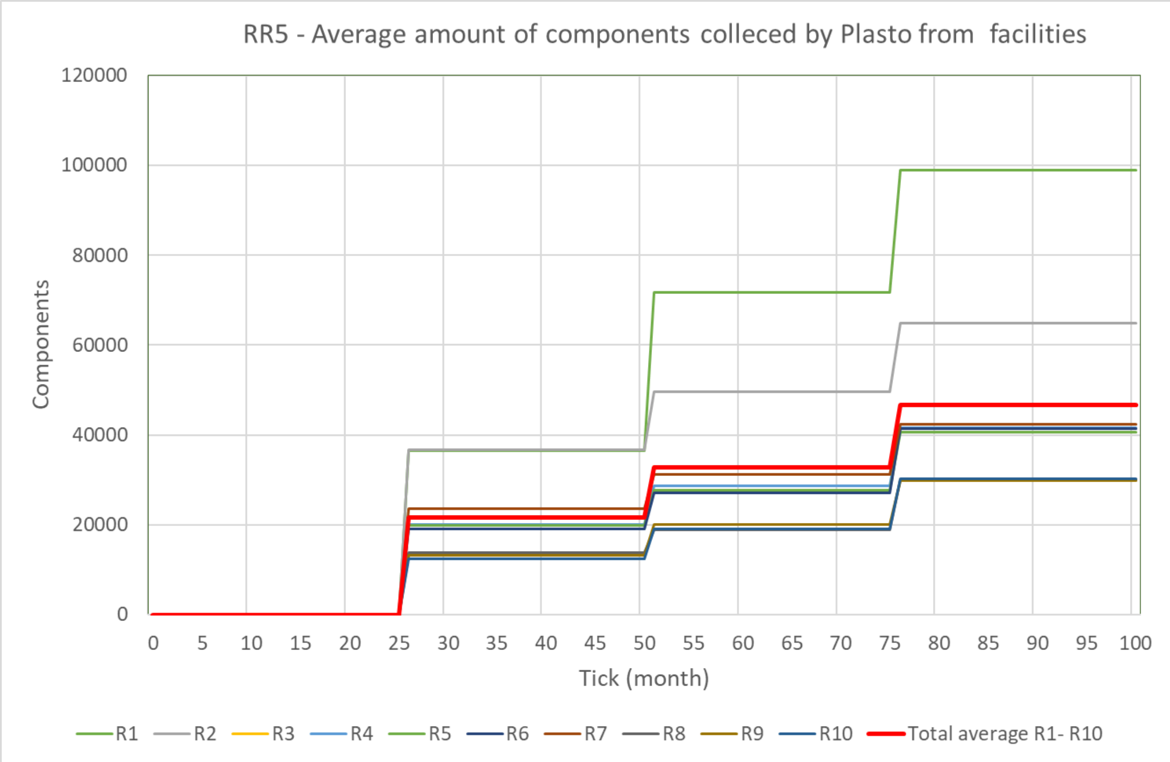

Figure 47 RR5 - Average amount of components collected by Plasto from facilities

In presented scenario components are commonly available, it is not surprising that in those condition simulation 1 with the highest amount of facilities achieving the highest components collection *Figure 49* (plot S1). However, the highest collection doesn't mean the most balanced recycling system.

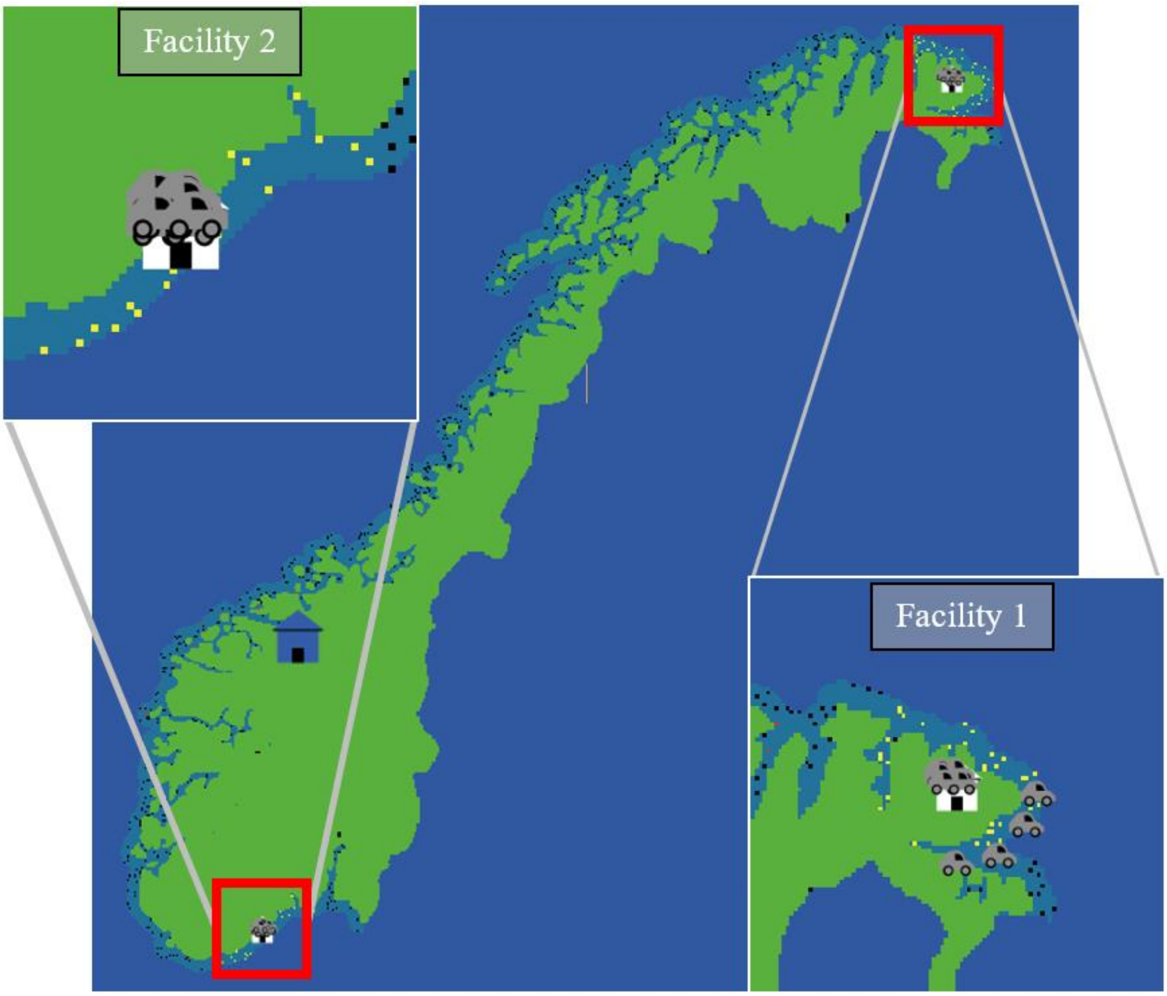

Figure 48 Location of 2 recycling facilities which remain from 2nd up to 7th simulation

Simulation 3 to 7 was able to work only with 2 recycling facilities located in remote area with long coastline *Figure 48*. It is balanced arrangement of facilities which allow to achieve equilibrium which lasted through duration of 4 simulations which is equivalent to 4 cycles of 8 years (100 ticks = 100 months). Two remaining facilities was tested in 4 different fish farm arrangements and survived unfortunately one of facility didn't manage to survive 8th simulation, but one Facility 1 with longer coastline manage to survive, it was attributed to higher number of fish farm available in near proximity to fish farm. Performance of facilities is visualise at *Figure 49*.

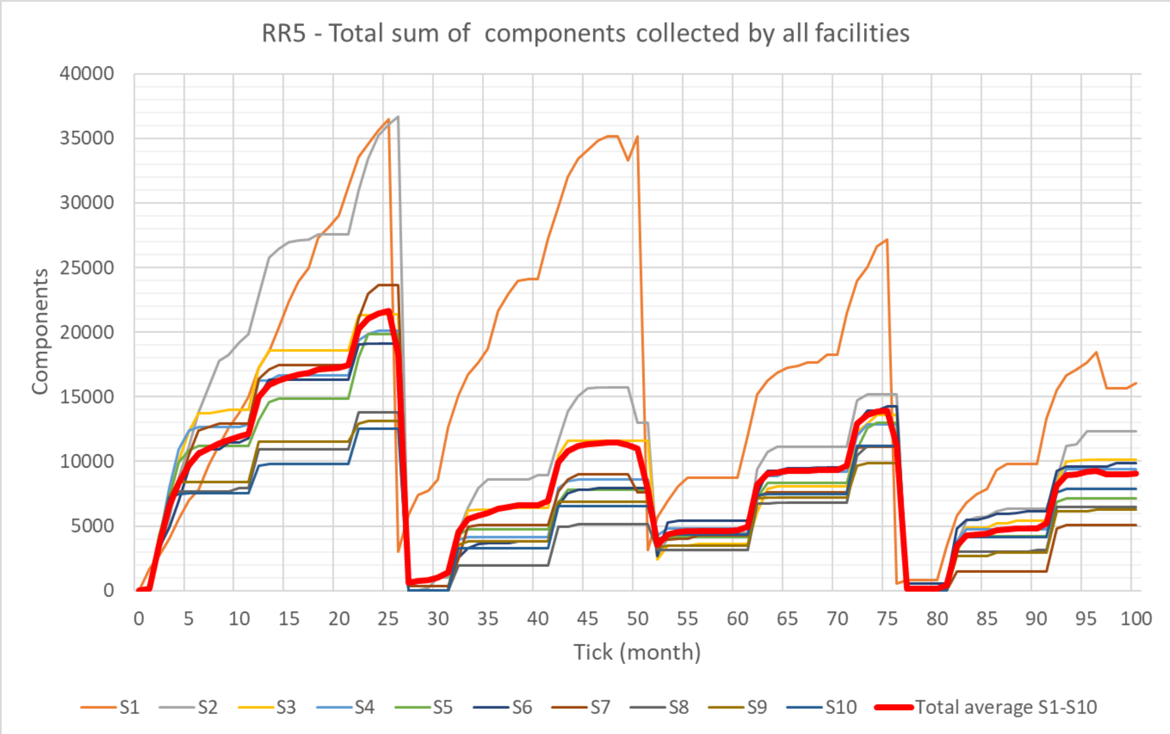

Figure 49 RR5 - Total sum of components collected by all facilities

6. Set of simulations – Scenario RR6

The data extracted from Scenario RR6 reveals significant differences in average amount of components collected by facilities, collected components in scenario RR6 are approximately 50 % lower compare to values achieved in scenario RR2 *Figure 26*.

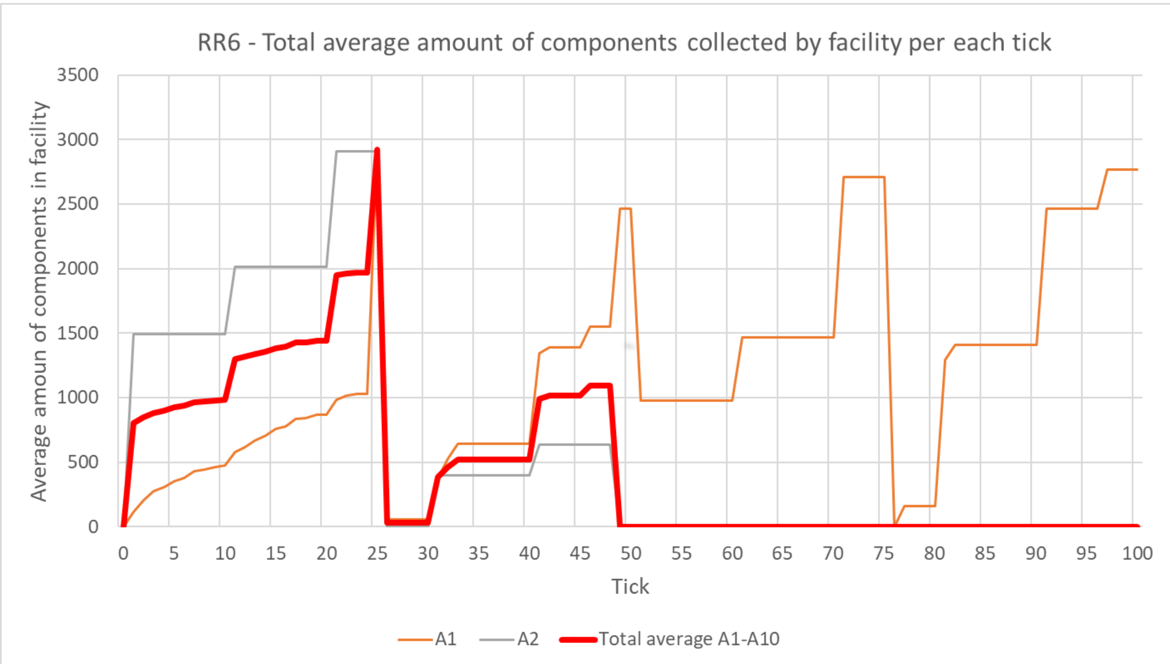

Figure 50 RR6 - Total average of components collected by facility per each tick

Result show that 12 recycling facilities didn't reached 2000 components survival limit and died instantly at tick 24 of first simulation 1 (plot A1) at *Figure 51*. Recycling system still was not balanced and didn't next 3 facilities didn't manage to survive next selection at tick 49. However, after that remaining facility manage to survive till end of first simulation and then till 49th tick of Simulation 2 (red plot - A2).

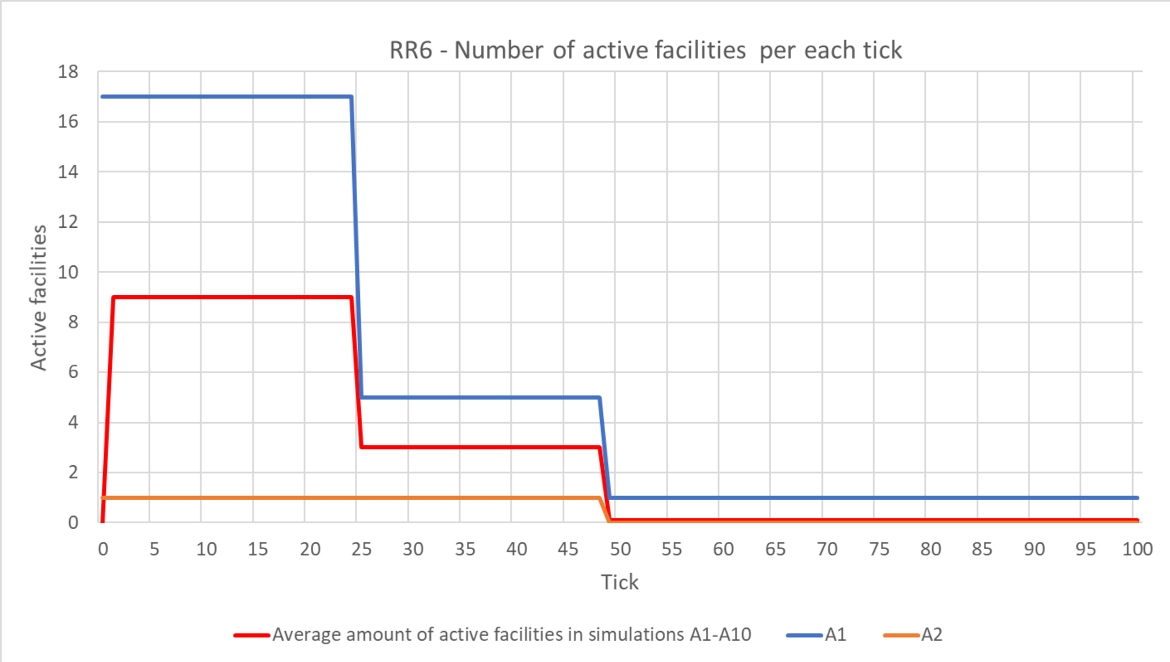

Figure 51 RR6 - Number of active facilities per each tick

There is significant difference in collection between simulation 1 (plot Y1 - black) and 2 (plot Y2 – dark green) at *Figure 52*. Collection of component especially varied in the beginning of simulations, and it is related to amount of facilities which were active in the beginning of each simulation .In the beginning of 1st simulation 17 facilities were active (Plot A1 - blue) at *Figure 51* and although 15 of them died at the 24th tick they collected significant amount of existing components. It is important to remark that facilities which stop being active don't contribute material to Plasto collection *Figure 54*.

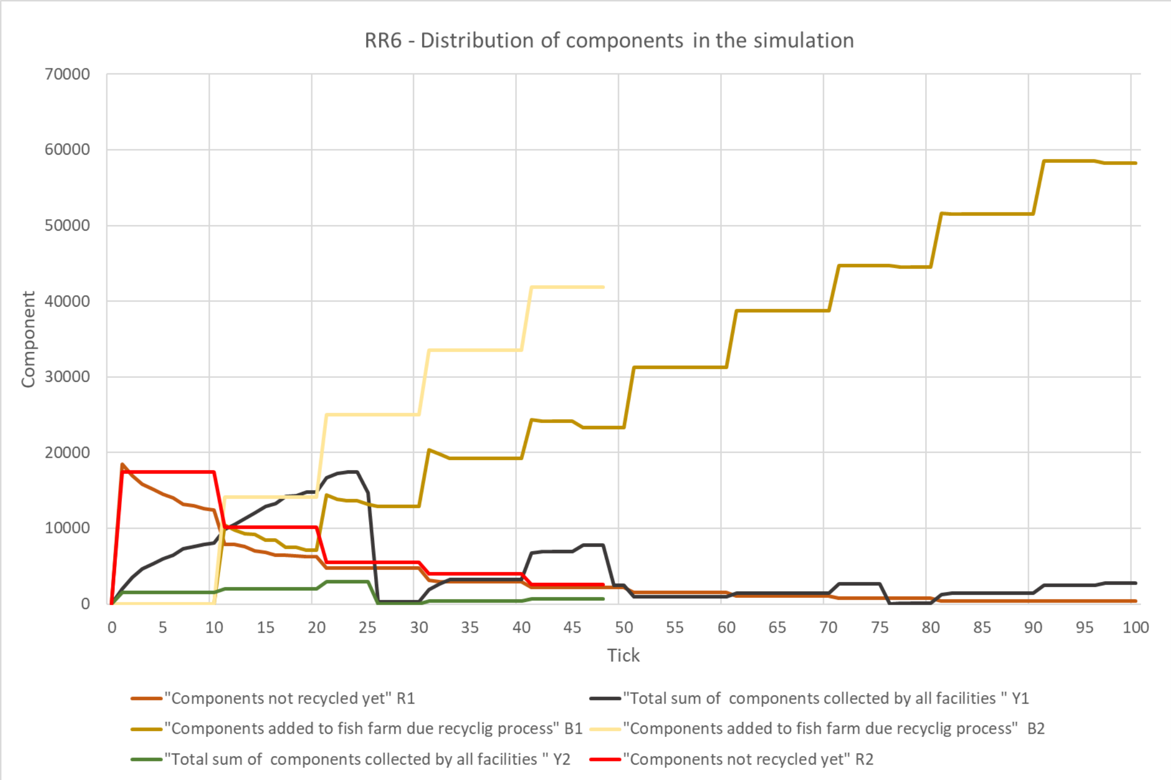

Figure 52 RR6 - Distribution of components in the simulation (Total average)

Facilities were active in collection components from fish farms *Figure 53* , the main reason of facilities failure was lack access to enough number of resources. Significant distances between fish farms lead to inefficiently long time needed for truck to travel from facility to fish farm and from fish farm to home-facility, facilities didn’t manage to achieve survival limit of 2000 components.

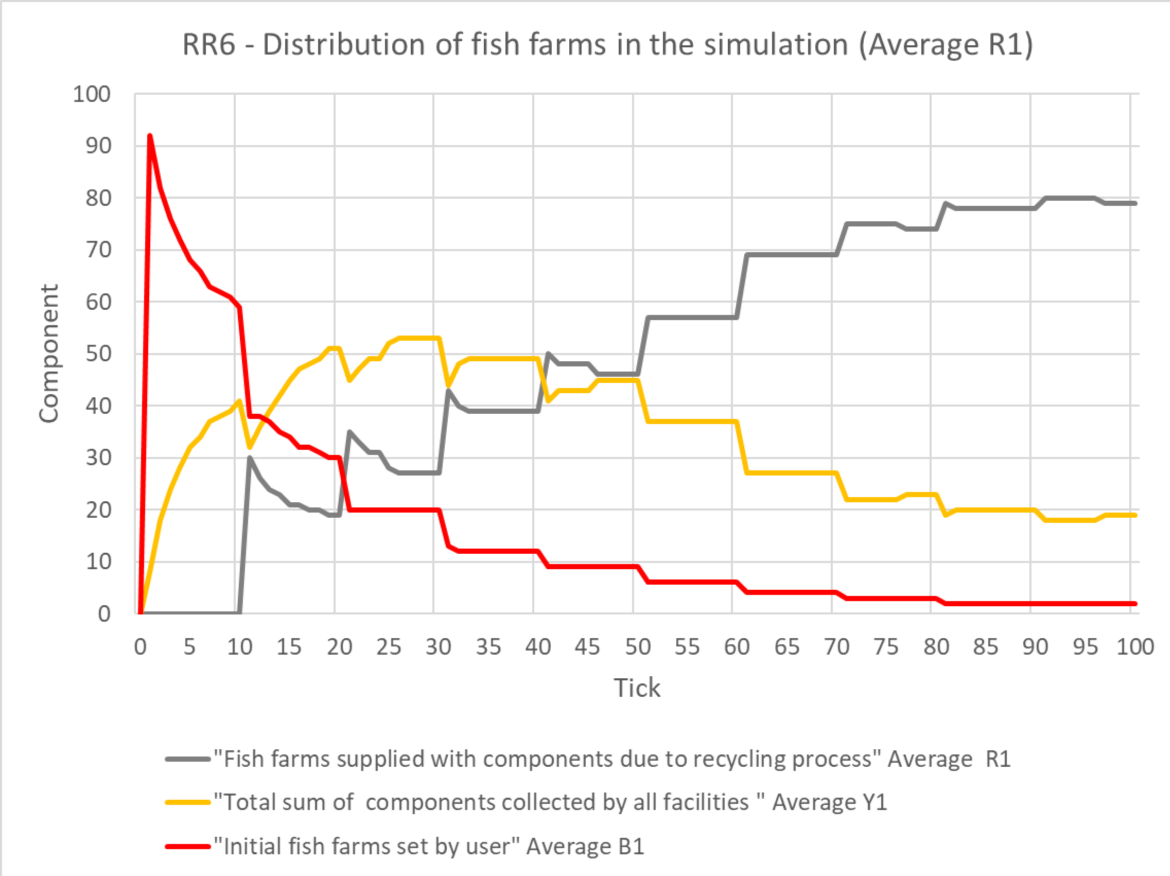

Figure 53 RR6 - Distribution of fish farms in the simulation (Average R1)

Assigning all remaining resources in form of 17 trucks at tick 24 lead to relatively good performance of remaining 2 facilities although they were not as much effective as 17 facilities (plot Y1 - yellow) at *Figure 53* which were homogenously distributed among Norway coastline which significantly reduced trucks travel time. Two remaining recycling facilities have enough resources to collect components, but they are not able to overcome problem of scattered and distributed customer network (fish farm), they collection slowly declining.

Recycling facility collection problem lead to problems of Plasto, company is not able to collect significant amount of material *Figure 54*. In first simulation from 0 to 24th tick facilities managed to collect almost 18000 components (plot S1 - orange) at *Figure 55*.

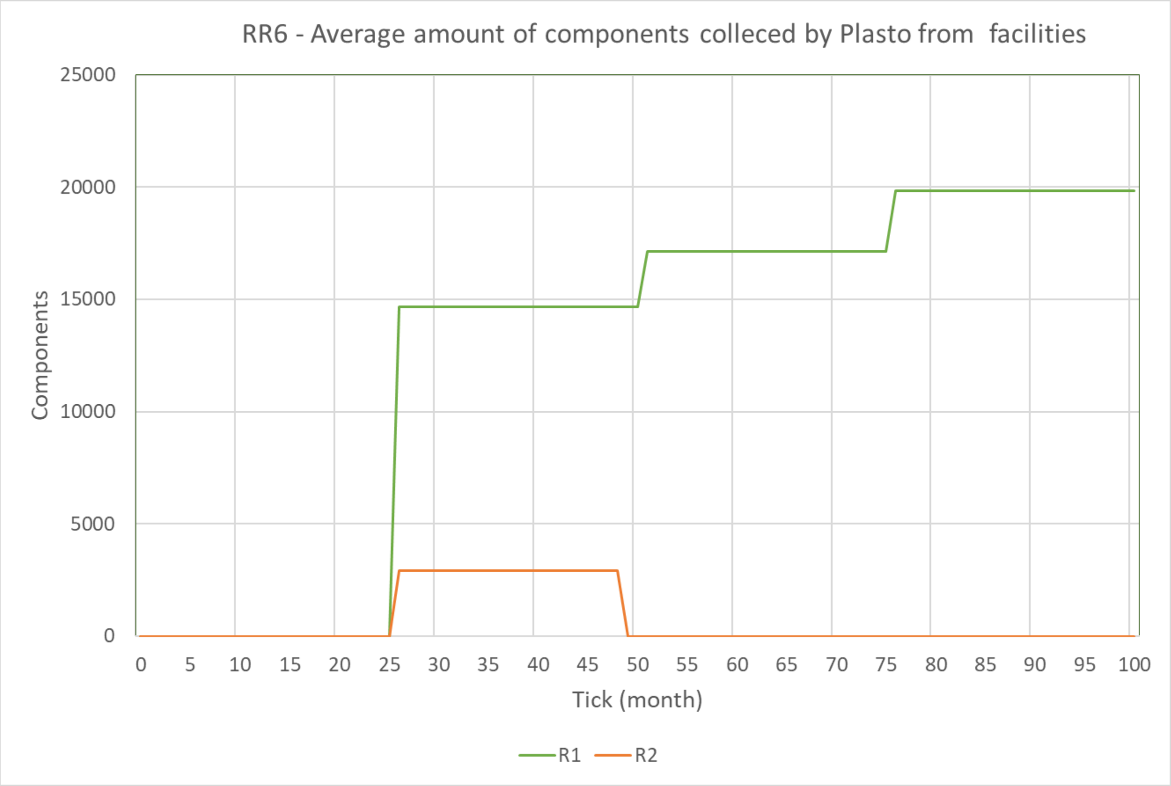

Figure 54 RR6 - Average amount of components collected by Plasto from facilities

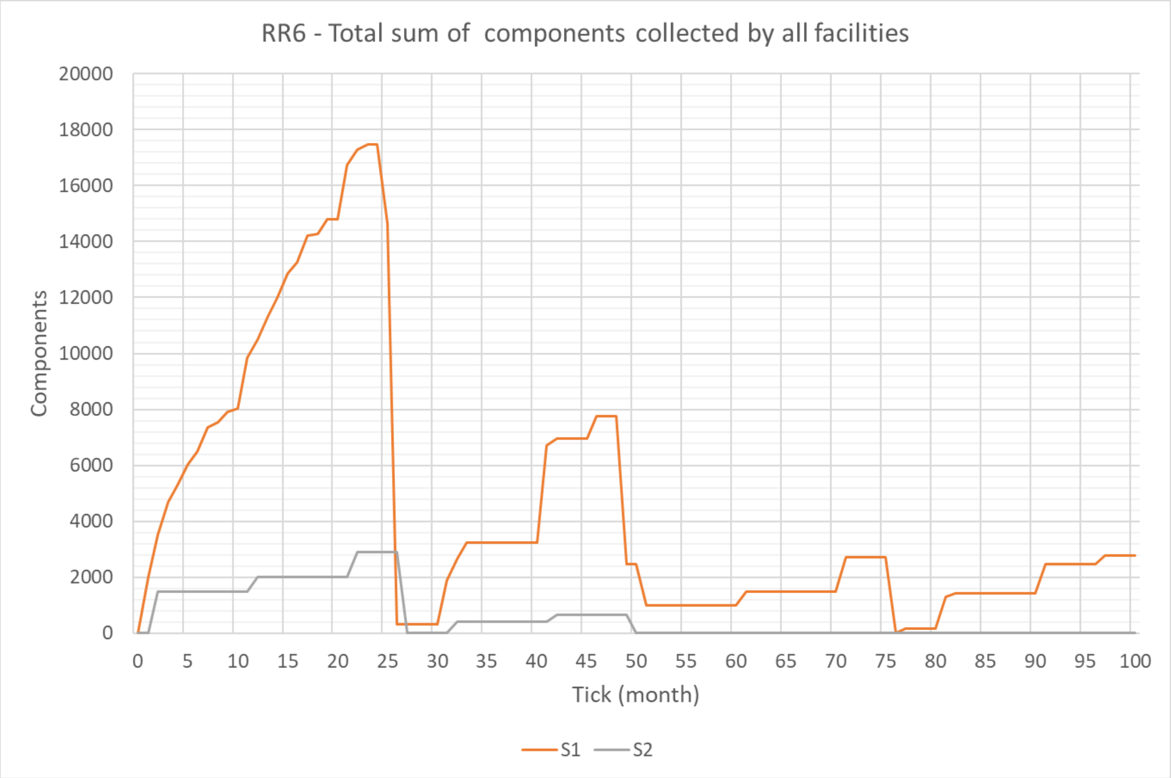

Figure 55 RR6 - Total sum of components collected by all facilities

7. Circular economy - what is needed to achieve it?

Stability is one of main indicators which allow to make Plasto new circular economy more reliable and affordable. Reliability is easy to explain company can be sure that there is enough material in the market and quality of material is easy to predict because company know how long fish brackets was in the sea. If components stay long in usage stage then components degradation increase, polymer chains shorten which further decrease mechanical properties of components. It is reason why it is important to know how long recycled fish brackets stay in usage stage. Mixing fish brackets from different years lead to mixing components with different mechanical properties. However mixing components from different years is unavoidable but it is strongly advice to recycle components in groups divided by year of usage.

It is good predictor of quality of recycled granulate and future quality of components created by mixing new and recycled granulate. Affordability means how many new granulate (not recycled with high quality) will be added to injection moulding mixture, cost of new granulate is few time higher than recycled granulate and quality of recycled granulate depends on how many years recycled fish brackets spend in usage stage, it is important to notice that quality of recycled granulate not always will be the same. Injecting moulding from recycled fish brackets which spent more years in usage stage will require higher addition of new material compare to recycled material which decrease affordability of process. If amount of new granulate will be not enough than properties of new fish bracket will be significant lower, and it may be reason for failure of component during usage stage which further make cause destruction of fish and unavoidable escape.

V. Discussion

Injection moulding process require high quality of granulate in order to produce high quality products, efficient collection system is needed in order to achieve it. Study proof that researchers are interests in variety of topic connected to circular economy, bibliometric overview was wonderful tool which allow us to visualise current state of the art *Figure 2*, studies were quiet surprising, bibliometric review of 300 articles on field of *"circular economy"* suggest strong interest in concept of *"sustainability"* and *"recycling"*. Concept of *"Industry 4.0"* and *"sustainable supply chain"* also find it way on the map. However, the most interesting part is secondary findings related to correlations between research topics. Although there is small link between research on *"sustainability"* and *"Industry 4.0"* there is none direct link between research on *"Industry 4.0"* and recycling. All research topics are indirectly connected through "circular economy" but there is no enough research which connect all three topics of circular economy, recycling and industry 4.0 are highly neglected, unadoptable there is plenty research which connect those 3 topics indirectly but as map *Figure 2* present those topics are not investigated together directly. It is truly remarkable gap in the knowledge which should be investigated in the future. It is difficult to evaluate why this gap exist, but it can be contributed to novelty of both concepts, circular economy and industry 4.0 are relatively new concepts. All problems related to both concepts recently start to be addressed and investigated by researchers. The problem seems to be even more interesting because of relation between *"recycling"* and *"material flow analysis"*, relation is visible into map *Figure 2Figure 3*. Material flow analysis is quantified stock and flow method used to analysis flow of components in production system and it is commonly known that gaining production data in manufacturing industry is highly based on concepts of industry 4.0. It seems to be surprising that research on topic of recycling is frequently indirectly connected to research on industry 4.0 but researchers don't investigate those topics directly.

From the results on first map *Figure 2*, it was clear that it was necessary to investigate next bibliometric map dedicated to *"circular economy"* and *"recycling"*- It is important to notice that first map led to research on second map. It is visible that second map tend to focus on practical mechanism used for waste recycling *Figure 3*. Result suggest more practical approach of researchers. Studies presented on map suggest that articles focused on practical recycling problems which are connected to circular economy and recycling. It is difficult to clearly answer why it happened, but it is clearly visualized on the map. Studies tend to connect both *"circular economy"* and *"recycling"* with *"pyrolysis", "mechanical recycling", "chemical recycling", "mechanical properties"* and *"distributed recycling"*. It is important to mention that those result are not coincidental, each of those keywords in order to be visualise on the map needed to appear at least 5 times together. It is clearly visible that those researches are not coincidental but truly represent researchers interests. Result can be contributed to reasons why those researches were performed. Although it is difficult to clearly clarified who was truly interested in obtaining result from those problems, but it is clearly visible that those problems are connected to recycling industry. There is high chance that that research was contributed to solve specific problem for specific company from recycling industry which collaborate with research institute, brief review seem to confirm that hypothesis. However, it is difficult to clearly confirmed that because companies tend to avoid adding their names to the research articles due to confidentiality concerns, homeware nature of problems support this hypothesis. Next interesting tendency seem to be recent interest in modern technologic e.g *"additive manufacturing"* and modern technologies relation to concept of "circular economy", it is emerging interest in those topics which seem to be especially visible in the middle of year 2019 *Figure 3*.

The main medium for presented research was multi-agent simulation it is reason why it was necessary to take into consideration relation between *"circular economy"* and *"simulation"*, map at *Figure 4* present next gap in research between *"recycling"* and *"remanufacturing"*. Connection between both topics is brittle and barely visible in contrary to research related to *"recycling"* and *"reuse" Figure 6*. There is significant tendency to address problem of reusing products, it can be explained by significant difference between reuse and remanufacturing processes, reuse process doesn't require additional postprocessing of the products. Product will be used for the same porpoise and it is not necessary to adjust product (beside necessary maintenance), of course quality check and correct maintenance procedure is necessary but that are all needed processes. In contrary to remanufacturing, process require additional work on product, it need to be adjusted for new application and prepared for different purpose. It requires more *"know how"* knowledge and quality check before remanufacturing process and after remanufacturing process. Additional processing increase chance to destroy components and rejection of product due to quality concerns caused by postprocessing. This can be main reason why researchers tend to focus in first place on reuse process and treat remanufacturing process as secondary topic. Remanufacturing process increase risk of product potential error compare to reuse process.

Other findings suggest that articles tend to focus on the problem connected to the waste in general through research on *"recycling"* and correct *"waste management"* and then secondary articles take into consideration actual possibilities for reuse or remanufacture postconsumer product. Presented lack of interest in reuse and remanufacturing processes is problematic for circular economy, because as proof at chapter "*8*. Processes of recycling, reuse and remanufacturing tend to influence circular economy in different way, slowing down recycling process in different degree. The main difference is time when postconsumer product will be sent back to producer. In recycling postconsumer product are directly send to producer and then they are reprocess and used for production of new components, while if we decide to reuse components than postconsumer product is send again to customer, product stay there for second usage stage cycle and avoid contact with producer. Then after second usage stage postconsumer product is send to producer for reprocessing and then material is used for production of new product. It is reason why reuse process slowing down circularity of product, in the end producer receiving material later in contrary to ordinary recycling process. It creates conflict of interest in circular economy, it appears between environmental benefit of reusing components and producer need for production material from recycling process. Hoverer there is way to address this problem and it can be done by correct postconsumer components management system. All production facilities require certain amount of material for production which can be predicted by correct production planning. Company can adjust production to the time when production material from recycling will be available. In next chapter simulation present recycling facilities collection capabilities and allow to simulate how much components will be possible to collect in variety of scenarios chosen by user. Simulation is flexible tool which can be freely used for design amount of fish farm in the system and amount of active facilities.

Created simulation are flexible tool which allow user adjust environment to desired conditions, user can choose location of recycling facility or chose amount of recycling facilities which will be distributed randomly. Additionally, user can decide how many fish farm will be active in initial stage of simulation, it allows freely design scenario initial environment. There is also possibility to choose amount of trucks and adjust their maximal payload, trucks will collect components from the fish farm, through entire simulation. In order to make simulation more realistic it is possible to allow fish farm to supply themselves in new components every 10 ticks, it add new components to the system, user is able to decide how many fish farm will be supplied with new components. It can be compared to real situation when fish farm owners decide to buy new components and, in that way, expand their business. It is not obligatory option in the simulation, but it is strongly recommended because it allow to make simulation more realistic. It was impossible to investigate all possibilities of the simulation it is reason why in study it was necessary to understand how simulation work and what are key indicators which led to result. In other to understand simulated model it was important to evaluate influence of proximity of fish farms on performance of recycling facility it is reason why set of simulation RR1, RR2 and RR4 are reference group which allow to address this problem, every time when truck collect components stay in the fish farm and are send to recycling facility. Basically, fish farm doesn't lose components when truck collected but also truck collect them from fish farm, they are duplicated, this preferential treatment allows to investigate how distance from fish farm will influence performance of the recycling facility, idea was success and lead to intrusting results. It is important to mention that after collecting components fish farm stop being active and change it colour to yellow. Hoverer trucks always first collect components from proximity of the recycling facility so if in next turn fish farm will be activated again due to "number-of-fishfarm-supplied-at-10-tick" variable than truck will have more components to collect from this location. It is important to mention that there is plenty not active fish farm in area of recycling facility due to truck collection procedure. Truck can maximally collect 500 components from 1 fish farm so it is impossible to exceed this value, than fish farm change colour to yellow again and fish farm need to wait again for chance to by activate again due to "*number-of-fishfarm-supplied-at-10-tick* " variable with this in mind we can compare result from those simulation. Mention above scenario are used are reference for set of scenarios RR5 and RR6, set of scenarios RR5 have the same model settings as set of scenarios RR1 and scenario RR6 have the same model settings RR2. However, when truck in set of scenarios RR5 and RR6 collect components from fish farm then amount of components is set on 0, components are not duplicated in the system, it is marked by "set up 0" in model settings *Table 5* and *Table 6*. This allow to compare them with set of scenarios RR1 and RR2. Results were surprising and differ dramatically although they have the same initial conditions. First of all recycling facility collection patter at set of scenario RR1 *Figure 26* is completely different than collection pattern in scenario RR5 *Figure 43*. The most visible difference is that patter at *Figure 43* is less continues compare to *Figure 26* have more "steps based structure". Collection of components at scenarios RR5 is more depended on circular supplied of new components every 10 ticks, it is clearly visible. Every time when new components are added to the system, collection drastically increase which lead to better performance of recycling facilities. In case of scenario RR1 it is completely different collection don't depend on supplied of new components into the system, it can be contributed due to already sufficient amount of components in to the system, it is important to remember that in set of scenarios RR1 fish farms don't "lose" components when fish truck arrive which led to saturation of the system and lack dependence on procedure which supplies fish farmers with new components every 10 ticks, basically there is always enough components, and trucks don't lack components to collect in the proximity of recycling facility.

It is important to remember that truck maximally can collect 500 components so even if there will be more components truck is not able to collect more than truck payload, this limitation also contribute to making collection pater more smooth in the range of every 25 ticks at *Figure 26* which is further called quarter of ticks. Another interesting finding is visible when we compare quarters of 25 ticks at *Figure 26* and *Figure 43*, in scenarios RR1 *Figure 26* collection in quarters of 25 ticks increase continuously, in quarter 0-25 tick collection of components is smaller than in quarter 26-50 ticks and this is smaller than collection in 51-75, process continues and is clearly visible. This phenomenon can be contributed to increasing accumulation of components in the fish farm in proximity of recycling facility, system seem to be stable. In case of scenarios RR5 *Figure 43* system seem to be more vulnerable on performance in previous quarters. Quarters in scenario RR5 have completely different collection pattern. Good collection performance in one quarter always lead to bad collection performance in next quarter, surprisingly further bad performance in one quarter led to good performance in next quarter *Figure 43*. Recycling facilities collection patter fluctuate in order to find stable conditions. Difference between maximum collection and minimum collection decrease in next quarters, system try to stabilize itself, it is visible in all 10 simulation and is the best represent by average value of all then simulation, it is represent by red line at *Figure 43*. Unfortunately, there were not enough components in the system and system was not able to find perfect equilibrium. Increase number of components in the system would lead to earlier stabilization of collection pattern in recycling facilities which would allow to stabilize entire recycling system. It would be visible by the same collection patterns in each quarter.

Distribution of the components in the system also is completely different in scenarios RR1 amount of fish farm with components in it rapidly increase just after supplying fish farms with new components every 10 tick and then start to rapidly decrease. *Figure 27*. It can be contributed to appearance of new fish farms in proximity to recycling facility which were activated every 10 ticks, accumulated number of components which led to huge amount of components available to collect in near proximity to recycling facility, trucks always transport all they capacity and go back to recycling facility, in next ticks when not a lot of fish farm is active in proximity to recycling facility, trucks need to travel further to collect components which led to further rapid decrease number of components supplied to fish farm (black plot) at *Figure 27*. As expected preferential condition in scenario RR1 allows Plasto to collect almost 10 times more components compare to scenario RR5, it is visualise at *Figure 28* and *Figure 47* respectively. It clearly shows how important is proximity of fish farm on performance of recycling facilities, it become one of the most important factors for recycling facility. simulation R1 at (green plot) *Figure 47* had the best performance from all 10 simulations. Plasto collection in set of simulations RR1 seem to be more homogenies during all 10 simulations, even first simulation R1 from scenario RR1, green plot R1 at *Figure 28*, it is especially important because during firs simulations in each scenario system need to adjust the most in order to find equilibrium. The main contributor to this difference can be attributed to amount of recycling facility which were present in first simulation, it was peak value of 17 facilities and although in scenario RR1 abundance of components allow all facilities to stay active through all 10 simulations, in scenario RR5 it was not possible and led to decrease number of active facilities *Figure 44*.

Set of scenarios RR1 and RR5 can be consider as system with abundance of components in the system, it is reason why next it is necessary to investigate behaviour of recycling facilities in situation when there will be limited access to components. The same as in previous experiments, all initial conditions for scenario RR2 presented at *Table 6* and RR6 presented at *Table 2* are the same. The only difference is that when in scenario RR2 truck collect components from fish farm number of components in fish farm is not subtracted, it is the same as in scenario RR1. It allows to investigate what is the influence of location of fish farm on amount of collected components by recycling facilities. As expected limited access to components had more dramatic influence on final result in scenarios RR2 and RR6, proximity of fish farm had even more significant influence on performance of recycling facilities at *Figure 31* and *Figure 50*. In both cases facilities managed to collect significantly less material. However, the most important fact is that in both cases recycling facilities didn't managed to survive all 10 simulations in opposite to scenarios with abundant number of components presented in scenario RR1 and RR5. In scenario RR5 last recycling facility managed to survive up to 5th simulation and in scenario RR6 up to 2nd simulation. Another promising finding was that scenario RR2 shape of components collection plot visible at *Figure 31* have a lot resemblance with *Figure 42*. It is important to remember that in scenario RR2 fish farms don't subtract components from them when truck collect components, it is the same as in scenario RR1.It was expected to have resemblance with scenario RR1 but not with scenario RR5. In contrary to scenario RR5 (presented at *Figure 31*) collection of components in scenario RR2 seem to be more stable, there is small variation in components collection between different quarters of ticks (0-25 tick, 26-50 tick, 51-75 tick and 76- 100 tick). It is contributed to high contribution of location of fish farm to result. It is important to mention that in scenario RR2 components are accumulated and activating fish farm again led to higher amount of available component to collect by recycling facilities. That is the reason why plot at *Figure 31* seem to be similar, system found equilibrium for initial set of conditions, there is small difference between performance in different quarters of ticks. The most surprising is that finding that facilities didn't manage to survive all 10 simulation even though recycling system found equilibrium which is proofed by homogenies collection of components through majority of scenario. Situation start to be more clear when we compare *Figure 31* from scenario RR2 with more realistic scenario RR6, presented at *Figure 50*. In the same initial conditions in scenario RR6 majority of facilities stopped being active before ending of first simulation *Figure 51* and last recycling facility stopped being active during 2nd simulation with this in mind it seem to be clear that result presented at *Figure 31* from scenario RR2 are the best possible outcome for set of chosen initial conditions and although system found equilibrium the main cause of failure was not enough amount of components in the system.

Last scenario RR3 only example of different type of simulation called *"Simulate one conditions endlessly*". In that model simulation work continuously, there is only 1 simulation which is based on initial condition not 10 simulation like in *"Repeatable-endless-simulation"*. Simulation don't reset any condition after 100 tick, it stop only in the moment when all recycling will not able to fulfil survival condition of 2000 components. Comparable to scenario RR5 and RR6 when truck collect material from fish farm components are subtracted from number of components available in fish farm. Experience gained from investigating collection system in scenario RR5 and RR5 presented respectively at *Table 5* and *Table 6* allowed to create simulation

RR3 presented at *Table 3*. Last recycling facility stopped being active at tick 541 which is clearly visible at *Figure 35*. It led to dramatic increase of accumulation of components as presented at *Figure 34*. Recycling system managed to work for almost 541 ticks on 1 initial set of conditions.it is equivalent to almost 45 years. That was the end of simulation but the most important is equilibrium which system was able to achieve at tick 100, system stabilize itself and was able to collect components homogeneously for 325 ticks as presented at *Figure 37*. It is good result because in simulation 200 ticks is equivalent to almost 19 years. It is important to notice that in this initial condition system balanced itself when they were only 3 recycling facilities available. Recycling facilities would last longer if in the beginning stage of simulation there would be only 3 recycling facilities. Two additional recycling facilities contributed to downfall of entire recycling system due to high collection of components in beginning stage of simulation in between ticks 0 to 75 as visible at *Figure 37*. Overconsumption of available resources led to long term effect on performance of all recycling facilities in the upcoming years. Although Plasto collect high amount of components in the beginning stage (Plasto always collecting all components from recycling facilities), it led to downfall of Plasto in the end because despite the fact that beginning quarters provided abundance of production material, company supplied ended when last recycling facilities stopped being active *Figure 36*. Model is good tool which allow to indicate when recycling system achieving equilibrium. Scenarios RR1 and RR2 allowed to understand what is main mechanism which created result in scenario RR5 and RR6. Further result from those simulation led to designing initial conditions for simulation RR3.

VI. Conclusion

From the study, key findings emerge, implementation of circular economy into production require change way of thinking about product. Product should be created by producer, but it is also important to design effective collective system which will allow recycling facilities collect components from the fish farm on balanced and constant basis. Customer orders are crucial for good performance of recycling facilities. Effective performance of recycling facilities is key for good and stable performance of Plasto. Important conclusion emerged; recycling system need to be stable from the start in order to increase longevity of recycling scenario. Too high consumption in the beginning simulation lead to catastrophic effects on performance of recycling facilities in the end of simulation, even if scenario manage to achieve equilibrium. Presented study suggest that that the highest chance of survival have facility which were part of balanced recycling system from beginning of the simulation. It is wonderful example how performance recycling facilities influence Plasto future. Each recycling system have different point when is the most balanced and significant amount of work need to be done to find it. Scenario RR3 seem to be closest to success and although in initial stage 5 recycling facilities was used for porpoise of the simulation, system found it equilibrium for 3 recycling facilities and it is reasonable to assume that result of scenario would be better for the same initial conditions with 3 recycling facilities. Although true potential of designed model is not visualised in the result, the highest value of model is its flexibility to design recycling system. Model allow to simulate amount of fish farm licenses in the beginning stage of simulation from 0 to 1300, defined amount of recycling facilities from 0 to desire number, chose freely location of each facility, adjust collection rate through control of amount of trucks in the system from 0 to desired number. And finally decide how many new fish farms will be activated in simulation every 10 ticks from 0 to desired number. This mobility makes model interesting tool which allow to explore possibilities of effective circular economy. Additional finding suggest benefit of using bibliometric overview as a tool to identify gaps in currently conducted areas of research.

VII. Future work

1. Bibliometrics- presented gaps and potential for future research

There are two ways to look on the gaps in the research, first as it was proofed *Figure 2* and *Figure 3*clusters of keywords with different colours are divided by the year of publication. There is visible trend to focus more on modern technologies like “additive manufacturing” and “industry 4.0” however link between “sustainable supply chain” and industry 4.0 is really brittle and barely visible *Figure 4*. Thin line indicates that only few articles from 300 articles addressed both problems directly. It is not enough, and more studies is needed. Next finding shows that unfortunately authors seem to not connect reverse logistic with industry 4.0 technology. Further industry 4.0 is also not directly connected to remanufacturing which was surprising finding. It can be argued that “sustainable supply chain” need to contain remanufacturing process and in that way, remanufacturing relates to industry 4.0 but researchers don’t address those problems directly which lead to not sufficient investigation of those problems.

2. Hybrid model

Multi-agent simulations and system dynamic are important tools for finding solutions for complex system: however, combining both tools would allow to improve validity of models, this synergic approach would use output from one simulation as input for other. This approach allows to use benefits of both multi agent and system dynamic simulation, although both tools are valuable resource, undoubtably system dynamic would introduce stock and flow and delays which are important part of the model if we try to imitate real life scenario (Lättilä, Hilletofth and Lin, 2010). Recently hybrid models start to be commonly applied to investigate supply chain system and supplier selection (Hilletofth, Aslam and Hilmola, 2010, Sevkli et al., 2008). Although presented multi agent have a little bit different goal, its proof validity of those method in context of research questions. Multi agent simulation allow to find equilibrium of recycling system, it shows us performance of recycling facilities based on user input, recycling facilities can survive only in balanced environment. Model could be expanded by system dynamic model and then result from multi agent simulation could be used as input for system dynamic simulation, although it is necessary to add input from real production company in order to made model truly deterministic.

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IX. Appendices

Multi agent simulation code

```
breed [facilities facility]
; it creates specific breeds, groups of turtles
breed [Plastos Plasto]
breed [trucks truck]
globals
; it creates global variable
[mouse-clicked?
create-facilility-cost
transportation-unit-cost
]
facilities-own
; create variable "facility-capacity" assigned only to breed
facilities
[facility-capacity]
Plastos-own
; create variable "total_collected_components" assigned only
to breed facilities
[total_collected_components]
trucks-own
; create variables "goal, truck-load, home-facility, max-
truck-load" assigned only
to breed trucks
[truck-load
home-facility
max-truck-load]
patches-own ;
create variable assigned to all patches in the simulation
"fish-brackets-in-farm"
[fish-brackets-in-farm]
; Setting up simulations

to Simulate-one-conditions-endlessly
; it create set of procedures - first simulation - Simulate
one conditions
endlessly
if ticks <= 0
; it allows to use "create fish" and "create-fish-trucks"
function only once in forever loop, used in the interface
[ create-fish
create-fish-trucks]
find-fish-brackets
death-facility
start-fish-farmers-supply-cycles
if ticks mod 25 = 0

; it allows to use function "update_Plasto_status" every 25
ticks
```

```
[ update_Plasto_status]
if ticks mod 27 = 0

; it allows to use function "change-Plasto_size" every 27
ticks
[change-Plasto_size]
End

to Repeatable-endless-simulation
; it creates set of procedures - second simulation -
Repeatable Endless Simulation

reset-create-fish-trucks
if ticks <= 0
; function create-fish is used only once every tick 0 (every
starting tick) -
condition allow to use this function in forever loop
[create-fish ]

; presented in interface
create-fish-trucks
find-fish-brackets
death-facility
start-fish-farmers-supply-cycles
if ticks mod 25 = 0
[ update_Plasto_status]
if ticks mod 27 = 0
[ change-Plasto_size]
if ticks mod 100 = 0
[ reset-create-fish
reset-Plasto_value
reset-ticks]
; it reset tick
End

; Procedures to setup world
to setup-world
clear-all
ask patches [ set pcolor blue - 0.25 ]
import-pcolors "Norway_counties_blank.png"
ask patches with [ not shade-of? blue pcolor]

; function work like, if you're not part of the ocean, you are
part of the
continent
[ set pcolor green
ask patch 400 50 [ set plabel "Recycling system" ]]
delete-svalbard
create-habitual-zone
create-random-facility
reset-ticks
```

```
end

to create-habitual-zone
; function create zone where future fish farm will be created,
in the radius of
coastline of Norway
ask patches with [pcolor = green]
[ask patches in-radius 6 with [pcolor = blue - 0.25]
[set pcolor 94]
]
edit
end
to edit
; function removing region of sweden from habitual zone, fish
farms cant be created
on land in Sweden
ask patches with [pcolor = 94][
if pycor > 0 and pycor < 372
and
pxcor - pycor - 30 > -85
and pxcor > 137 and pxcor < 250
[ set pcolor blue - 0.25 ]]
ask patches with [pcolor = 94][
if pycor > 300 and pycor < 430
and
pxcor - pycor - 9 > -100
and pxcor > 220 and pxcor < 460
[ set pcolor blue - 0.25 ]]
ask patches with [pcolor = 94][
if pycor > 280 and pycor < 444
and pxcor > 220 and pxcor < 431 and
pxcor - pycor - 30 > -100
[ set pcolor blue - 0.25 ]]
End

to delete-svalbard
ask patches [if pxcor - pycor < -300 [set pcolor blue - 0.25]]
; function deleting Svalbard from map and adding ocean in its
place, it is not
necessary for this simulation
end

; Fish farm procedures
to create-fish
; creating new fish farm
repeat number-of-fish-farms
[ask one-of patches with [pcolor = 94] [set pcolor red]]
ask patches with [pcolor = red]
[set fish-brackets-in-farm 50 + random 300]
end
to reset-create-fish
```

```
; setting value of all components in all fish farms equal 0,
it changes they colour to colour of ocean
ask patches with [pcolor = red or pcolor = yellow or pcolor =
black]
[set fish-brackets-in-farm 0]
ask patches with [pcolor = red or pcolor = yellow or pcolor =
black]
[set pcolor 94]
End

; Cleaning procedures
to clean-not-all
; cleaning fish farms and     trucks from the simulation, it
allows to perform second
simulation in the same conditions as first simulation
reset-create-fish
reset-create-fish-trucks
clear-all-plots ;
command clear all the plots in simulation
reset-ticks
end

to clean
clear-all
end

to start-fish-farmers-supply-cycles ;
function supply fish farm with new products every 10 ticks
if ticks mod 10 = 0
; function add-new generation of components to fish farm

; function is executed every 10 ticks

[repeat number-of-fishfarm-supplied-at-10-tick
; input telling us how many fish farm started to be supplied
with new components [ask one-of patches with
[pcolor = red or pcolor = yellow or pcolor = black]
[set fish-brackets-in-farm
fish-brackets-in-farm +(random 300)
set pcolor black
; black pcolor to check if function work
]]]
end

; Procedures related to breed facilities
to Add-own-facility
; adding facility in location chosen by user
set-default-shape facilities "house"
ifelse mouse-down? [
if not mouse-clicked? [
set mouse-clicked? true
```

```
ask patch mouse-xcor mouse-ycor [ toggle-facility]
]
] [
set mouse-clicked? false
]
End

to toggle-facility
let nearby-facilities facilities in-radius 4
ifelse any? nearby-facilities [
ask nearby-facilities [ die]
; if there is a facility near where the mouse was clicked,
then we remove this facility

; if there were no buildings near where the mouse was clicked,
we create building
] [ sprout-facilities 1

[set color red
set size 10
]
]
end
; procedure allow to create number of facilities chosen by
user, in random locations
set-default-shape facilities "house"
; all turtles which belong to breed facilities change shape to
house
let x 0
let y 0
create-facilities initial-number-of-facilities
[ set color white
set size 15
ask one-of patches with [pcolor = green] [set x pxcor set y
pycor]
set xcor x
set ycor y
]
create-Plasto-company
end

; it calls this function in the end of procedure
; all turtles which belong to breed facilities die in tick 24
if they didn't gather less than 2000 components (facility-
capacity)

to death-facility
ask facilities
[if (ticks mod 24 = 0) and (facility-capacity < 2000)
[die]
]
```

```
ask trucks;
trucks which lose home-facility stop
[if home-facility = false [stop]]
End

; it allows to create Plasto in predefined patch (always the
same location)
to create-Plasto-company
create-Plastos 1
[ set xcor 104
set ycor 180
set shape"house"
set size 20
set color blue
]
End

; function transfer number of collected components from
recycling facilities and
send them to Plasto
to update_Plasto_status
ask Plastos
[ set total_collected_components total_collected_components
+ sum[facility-capacity] of facilities
set size 30 ]
ask facilities ;
function reset number of components in Plasto
[ set facility-capacity 0]
End

;Function allow to increase size of Plasto icon
to change-Plasto_size
ask Plastos
[ set size 20]
end
To reset-Plasto_value
ask Plastos
[ set total_collected_components 0]
End

; Procedures connected to trucks
to create-fish-trucks
let x 0 let y 0 let homefacility 0
create-trucks num-trucks [
set size 9
set shape "car"
set color grey
ask one-of facilities [set x xcor set y ycor set homefacility
self]
set xcor x + random 5 - random 5
```

```
set ycor y + random 5
set home-facility homefacility
set max-truck-load max-truck-load-capacity
]
repeat num-trucks
[ask patches with [pcolor = white]
[
sprout-trucks 1
[
set color white
set size 9
]]]
end
to reset-create-fish-trucks
ask trucks
[die]
End

to find-fish-brackets
ask trucks [
if home-facility = false [stop]
if home-facility = nobody [stop]
move
collect-products
go-back-procedure
]
if any? patches with [pcolor = red or pcolor = black] = false
[stop]
tick
end

to move                         ; it go towards red patches
(fish farms)
rt random-float 100
lt random-float 100
face min-one-of patches with [pcolor = red or pcolor = black]
[distance myself]
let target-patch min-one-of (patches in-radius 25 with
[pcolor = red or pcolor = black]) [distance myself]
                                ; it collects fish brackets from
                                          fish farms
if target-patch!= nobody [
move-to target-patch
]
end
;

to collect-products
if pcolor = red or pcolor = black
[
set pcolor yellow
```

```
;just to see if truck truly coolect fish brackets
if truck-load <= max-truck-load-capacity
; truck go to homefacility when is full or more than full,
just in case of error in
simulation
[
set truck-load truck-load + fish-brackets-in-farm
if truck-load >= max-truck-load-capacity
[go-back-procedure]
set fish-brackets-in-farm 0
]
]

ask home-facility
[set facility-capacity facility-capacity + [truck-load] of
myself]
set truck-load 0
end

to go-back-procedure ; truck go
back to home facility and pass all the load to production
facility
ifelse home-facility != nobody [stop]
[set heading towards home-facility
fd 5
set truck-load 0
]
End

to die-truck; trucks
die if they lose home-facility
if any? home-facility = false [stop]
End
```

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