



Simulation Analysis

Comparison of various logistical concepts for offshore wind farm decommissioning

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Authors:

Marc Hillers (University of Applied Sciences Emden/Leer)

Prof. Dr. Marcus Bentin (University of Applied Sciences Emden/Leer)

Dr. Stephan Kotzur (University of Applied Sciences Emden/Leer)

Prof. Dr. Dirk Schleuter (University of Applied Sciences Emden/Leer)

Prof. Dr.-Ing. Jens Klussmann (University of Applied Sciences Emden/Leer) (†)

Amelie Bruns (University of Applied Sciences Emden/Leer)

Heika Ring (University of Applied Sciences Emden/Leer)

Jan Schneider (University of Applied Sciences Emden/Leer)



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List of Abbreviations

CLV	Cable Laying Vessel
DecomToolV	DecomTools Vessel
DES	Discrete Event Simulation
FV	Feeder Vessel
F_PbP	Feeder Part-by-Part
F_BunnyEar	Feeder Bunny Ear
F_Star	Feeder Star
HR1	Horns Rev 1
IV	Installation Vessel
MM	MetMast
OHVS	Offshore High-Voltage Substation
OWF	Offshore Wind Farm
OWT	Offshore Wind Turbine
P_PbP	Pendulum Part-by-Part
P_BunnyEar	Pendulum Bunny Ear
P_Star	Pendulum Star
WTIV	Wind Turbine Installation Vessel

1 Introduction

Most wind turbines are designed and certified for a service life of 20 to 25 years. After this period they must be decommissioned or have their accredited service life extended, often accompanied by repowering. While procedures for decommissioning and repowering of onshore wind farms are known, experience with offshore wind farms (OWF) is limited. There is no overall sustainable end-of-life approach to OWF. The transnational project "*DecomTools*" closes this gap by developing eco-innovative concepts, green products and various demonstration pilots in the areas of logistics, safety, vessel design as well as in up- and recycling. These new innovations help the entire industry to achieve a better eco-balance.

The pioneer OWFs in the North Sea Region are increasingly reaching the critical stage. The market analysis developed by Kruse (2019) shows that two decommissioning cycles can be expected in the North Sea region in the coming years. The first cycle with a smaller number of wind turbines to be decommissioned is already ongoing. The second cycle will start at the end of this decade, with a large amount of wind turbines to be decommissioned in almost all North Sea littoral states. While the first cycle is as a test case for different decommissioning strategies, the high volumes in the second cycle require mature solutions. To have enough preparation time, detailed simulations and analysis are need to be addressed now to define sustainable decommissioning logistic strategies.

This simulation analysis is based on the simulation models created in work package 5, deliverable 2. The models were created with the software "Plant Simulation" (Version 16) from Siemens. This is a "Discrete Event Simulation Software" for modeling, simulation and analysis of logistic systems (Siemens, 2022). Discrete Event Simulation (DES) is a simulation method for representing real systems, which can be divided into logical, temporally subdivided or sequential processes (Allen M, 2015). In the course of the development work, eight different simulation models were developed and implemented, which concretize different logistics strategies and dismantling configurations. These are presented in more detail below, including their results and their generated data. In addition to the dismantling of the offshore wind turbines, all models also include associated processes such as the pre-decommissioning activities, the removal of the offshore cables, and the dismantling of the MetMast (MM) as well as the offshore high-voltage substation (OHVS).

2 Offshore Logistic Strategies and Dismantling Configurations

A logistics strategy can be defined as a set of principles, settings and factors to consider planning, goals and relationships along a supply chain (Hill, 2017). The supply chain of offshore decommissioning can be divided into five different steps.

The first step is the offshore operation or are scenarios to decommission an OWT. Regarding the dismantling scenarios, three configurations can be identified. The product process model in Figure 1 shows the main components of offshore wind turbines and the configurations in which they can be dismantled. These dismantling configurations represent the (offshore) base of the developed simulation models.

The Star configuration describes the dismantling of the entire rotor including the three blades and the hub, followed by the nacelle, tower and substructure. The next operation involves the dismantling of the remaining two rotor blades, including the hub and the nacelle. The final dismantling operation consists of the removal of the substructure. In both removal configurations, 4 lifting operations are required.

The part-by-part removal provides a step-by-step dismantling of the individual components. The rotor blades are removed individually, followed by the nacelle incl. hub, tower and substructure, resulting in 6 lifting operations.

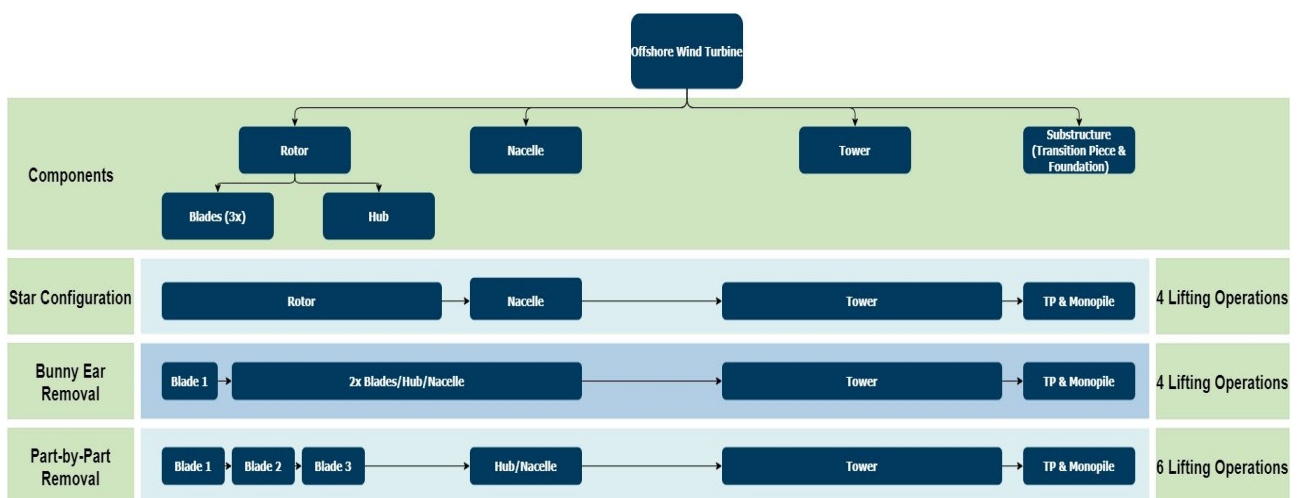


Figure 1: Product-Process-Model of main configurations for the dismantling process



In the second step, the dismantled components of a wind turbine are transported to the port. In terms of the supply chain for offshore decommissioning, two main logistics strategies can be defined: the pendulum system and the feeder system. The pendulum system describes a ship shuttle service between a port and the OWF. Here the installation vessel also performs the transport of the decommissioned components to the port. In the feeder system, on the other hand, the Installation-Vessel remains at the wind farm and a smaller vessel (feeder vessel) transports the components to the port.

At the port, the wind turbine components are unloaded and processed into smaller elements and prepared for further transport on shore in a third step. In the fourth step the materials are then transported to the hinterland by truck or rail to the recycling facilities, where the wind turbine components are recycled or repurposed in the final step.

3 The Logistic Simulation Model of the entire supply chain

To obtain useful optimization potential for decommissioning logistics, the offshore logistics strategies and dismantling configurations described in Chapter 2 have been mapped into different Plant Simulation Networks.

For clarity, the models consist of several networks. These are PlantSimulation modules, which enable the hierarchically structured construction of models.

The main network contains six subnetworks. These include the network for the offshore wind farm, a network for saving the simulation results, and four port networks.

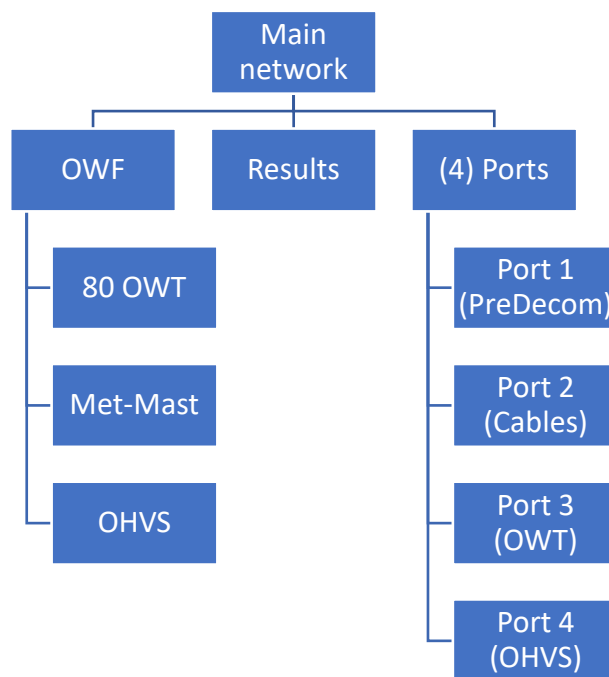


Figure 2: Network Levels

The OWF network is further composed of 82 subnetworks. Of these, 80 networks each represent one OWT. The remaining two networks represent the MetMast and the OHVS.

While the MM and OHVS networks are divided into topside and substructure removal, the OWT networks contain several process steps. These process steps are analogous to the dismantling configurations described in the previous chapter.

The offshore dismantling process is generally divided into several phases in which different types of vessels are used.

The pre-decommissioning stage comprises all activities to prepare the construction site for dismantling. This includes, for example, the seabed survey, the removal of hazardous materials and the removal of the wind turbines from the grid, including the cutting operations of cables and the installation of buoys at the cut ends. The second phase involves the recovery of all offshore cables (Inner Array Cables and Export Cable). This is followed by the dismantling of the wind turbines, the MetMast and the OHVS (Figure 3).

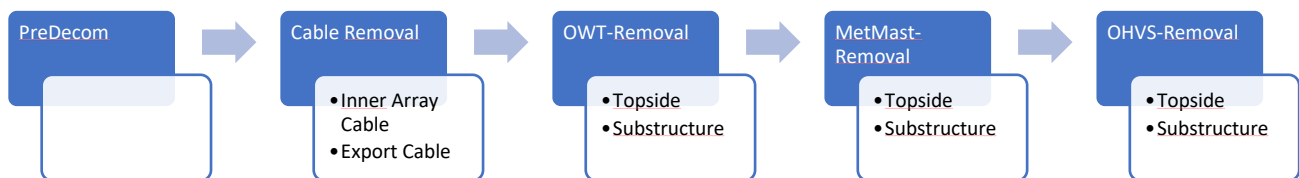


Figure 3: Offshore Process Overview

In addition to the offshore logistics, the simulation models also depict the onshore handling of the components. To consider different ports in terms of their activities and their geographical location a generic port-network was established. It consists of several sub-networks which are divided into “PreDecommissioning”, “Cable Removal”, “OWT Removal” and “OHVS Removal”. Accordingly, their operating principle and structure are similar. The components are unloaded from the ships, transported to a laydown area, and distributed further. They are then dispensed either to a station for further disassembly or for direct preparation for inland transportation by barges and trucks.

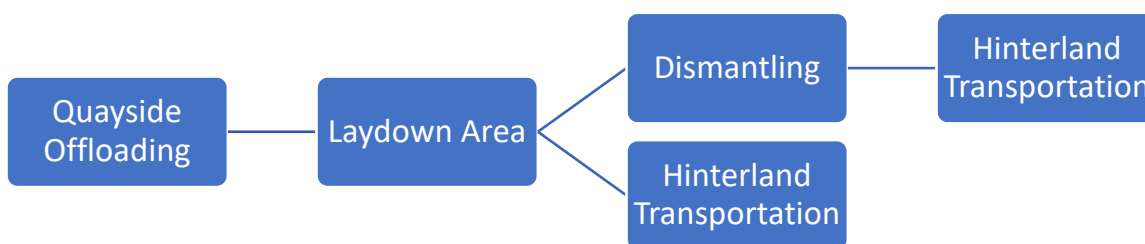


Figure 4: Onshore Process Overview



The results-network stores all data generated during the simulation. This information includes transit times, costs, and CO₂ emissions along the entire supply chain as well as more specific information on start and end times of the individual process phases including standby, transit and working times, etc.

4 Input Parameters and Model Descriptions

In the following chapter, the different input parameters of the simulation models will be specified in more depth. Furthermore, the models are considered in detail with regard to their structure and their special features.

4.1 Input Parameters

In terms of parameters, a large number are taken into account, which will be described in more detail in the following.

The wave height and the wind speed are to be mentioned as the main variables of weather influence on the offshore dismantling process. Our basis for this are data sets from the Danish Coastal Authority. The Danish Coastal Authority, which has positioned several sensors along the Danish North Sea coast, collects weather and wave information.

Based on these values, wind and wave information was defined in a 24-hour format for about 2 years (2018 and 2019) and used as a basis for the simulation.

All deployed vessels can be assigned specific attributes in advance via a table.

These attributes include day rates, fuel consumption in various modes, and speeds. The day rates plus fuel costs (average 650 €/ton at the time of simulation), average speeds and permissible wave heights and wind speeds are listed as examples in Table 1 and Table 2 for the Base Study.

It should be noted at this point that, as part of the project, consideration was given to possible optimized vessels in the dismantling process. In this context, a ship model was developed, which can be used both as a feeder vessel as well as a (de-)installation vessel. For example, it would be capable of recovering the cables and removing the monopiles as well as storing dismantling segments of the offshore wind turbines, taking into account the CO₂ emissions.

For a deeper insight, please refer to the document titled “DecomTools Vessel Design – An Eco-Sustainable approach to Decommission Offshore Wind Farms by designing a New Ship, new tools and efficient and reliable procedures” on the DecomTools project homepage.

Table 1: Vessel Information - Day rates, Speeds, Max. Wave Heights and Wind Speeds

Stage	Vessel	Day rate [€]	Average Sailing Speed [kn]	Average Infield Speed [kn]	Max. Wave Height [m]	Max. Wind Speed [kn]
PreDecom	Survey-Vessel	100,000	10	1	3	20
Cable Removal	CLV	150,000	10	1	3	20
OWT-Removal	WTIV	200,000	10	1	4	15-20
	FV	50,000	10	1	-	-
OHVS-Removal	IV	200,000	5	1	3	30
	FV	50,000	10	1	-	-

Table 2: Vessel Information - Fuel Consumption in different modes

Stage	Vessel	Fuel Consumption [t/d]			
		Sailing	Operational	Standby	Mobilization
PreDecom	Survey-Vessel	10	4.0	2	0
Cable Removal	CLV	12	10.0	4	0
OWT-Removal	WTIV	16	6.0	4	8
	FV	10	7.5	2	0
OHVS-Removal	IV	16	6.0	4	8
	FV	10	7.5	2	0

The dismantling times in the simulation models are essentially based on the erection times. They were also assigned to the deployed vessels in the form of attributes. For the baseline study, which is based on the Horns Rev 1 wind farm, an erection time and therefore also the deconstruction time of about six days per wind turbine was determined. (Roberto Lacal-Aránategui, 2018)

The Dismantling of OHVS-Topside is estimated to take two days and the removal of the OHVS-Substructure is also estimated to take two days.

Additional process times for different configurations on which the models are based on can be found in Table 3.

Table 3: Dismantling times of OWT through different configurations

Dismantling component	Dismantling time of different configurations [d]		
	Bunny-Ear	Part-by-Part	Star
Hub/Nacelle/2Blade	1.21	-	-
Blade	0.25	1.00	-
Rotor	-	-	0.71
Nacelle	-	1.00	1.00
Tower	1.21	1.00	1.00
Substructure Removal	3.17	3.18	3.18
Total Removal Time	5.84	6.18	5.88

The onshore parameters include the offloading times of the individual components at the quay, the transfers from the quay to the designated laydown area using parameterized means of transport, dismantling times and the transport to the hinterland by barge or truck including the respective distances.

Table 4 displays the duration and offloading of the wind turbine components through different configurations.

Table 4: Offloading and onshore dismantling times through different configurations

Component	Part-by-Part		Bunny-Ear		Star	
	Offloading Time in h	Dismantling Time in d	Offloading Time in h	Dismantling Time in d	Offloading Time in h	Dismantling Time in d
Blade	2	0.67	2	0.67	-	-
Hub/Nacelle /2Blade	-	-	4	14	-	-
Rotor	-	-	-	-	4	2
Nacelle	4	10	-	-	4	10
Tower	4	2	4	2	4	2
Substructure	4	3	4	3	4	3

Table 5 shows the removal (offshore), offloading and onshore dismantling durations for inner array cables and the export cable.

Table 5: Duration of cable removal, offloading time and onshore dismantling time

Component	Inner Array Cable Removal	Export Cable Removal
Days per 1 km	1	1
Offloading time in h	24	24
Dismantling time in d	10	25

The offloading and onshore dismantling durations for OHVS are displayed in Table 6.

Table 6: Offloading and onshore dismantling duration - OHVS

Component	OHVS (Topside)	OHVS (Substructure)
Offloading Time (h)	6	6
Dismantling Time (d)	56	14

Table 7 depicts the different relevant routes and onshore distances

Table 7: Onshore distances

Route	Distance (km)
Quayside ↔ Laydown Area	0.5
Port ↔ Hinterland (Street)	50.0
Port ↔ Hinterland (Waterway)	100.0

The Laydown costs per square meter comes to 0.5 €. Expenses for internal port transportation are composed of a daily rate and fuel consumption. A day rate of 4,5000 € and an average fuel consumption of 35 t per day are expected.

Table 8 shows the Onshore means of transport, fuel consumption and transport costs.

Table 8: Onshore Means of Transport (Generic)

Vehicle	Costs per 1km (€)	Fuel Consumption per 1km (t)
Truck	25	0.3
Inland Vessel	20	0.1

4.2 Basestudy

The base study concretizes the wind farm Horns Rev 1, consisting of 80 OWT, one MetMast, one OHVS, around 40 km inner array cables and 22 km export array cables. This wind farm has been installed about 20km off the Danish coast, west of Esbjerg.

During the baseline study, one vessel was simulated for pre-decommissioning activities, one for cable recovery, three installation vessels and one feeder vessel.

Unlike the other models, it should be emphasized that both the pendulum and feeder systems were used for the erection of HR1. The OWT foundations were placed in the feeder system. The installation vessel remained in the wind farm for this period, while the smaller transport vessel brought the monopiles to the wind farm (MTHojgaard, 2010, S.18; Vattenfall, 2014). In the further course, the OWT top structures (tower, hub, rotor blades) were installed in the Pendulum system. In this phase, two installation ships were used, each carrying 2 turbine sets in the bunny-ear configuration (Modern Powern Systems, 2005).

Analogous to this erection, the dismantling of the wind farm is realized in reverse order in this base line scenario. The first steps include the pre-decommissioning activities and the disconnection of the wind turbines from the power grid. To reduce the risk of jacking operations in the wind farm, the next step is to remove all cables. Subsequently, two vessels will dismantle the topsides of the OWT followed by an installation vessel and a FV for the purpose of dismantling and salvaging the foundations including the transition pieces. The last stage is the dismantling of the OHVS. Again, the topside will be dismantled first before the foundation can be removed.

The onshore processes start as soon as the first components are unloaded at the quayside. These include onward transport to the designated laydown area, from where the components are further distributed. For the portside onshore process, costs for storage are calculated in the simulation, in the same way as CO2 emissions and costs of the transport carriers used. Unfortunately, further cost structures could not be integrated due to the sensitivity of the data. There are two main options for the stored components, either they are further dismantled or transported on as "complete components". The transports to the hinterland are carried out via barge and/or truck depending on

the respective capacity of the transport carrier. The assumed costs and fuel parameters can be seen in table 8 of the previous chapter.

4.3 Pendulum-Systems: Part-by-Part-, Bunny-Ear- and Star-Configuration

The logistics simulations of the Pendulum systems are similar to the baseline study, the main parameters, such as number of wind turbines, fuel consumptions, distances, etc. are the same.

The parameters of the simulated ships are also identical. These include the process times, the fuel consumptions, vessel speeds etc. Further, the simulated WTIV was able to carry 2 complete Sets of OWT, analogous to the vessels used in the base study.

However, one major difference is the total number of ships. Since primarily installation vessels are used to shuttle between the wind farm and the port, there are no feeders here, except for the OHVS-Removal.

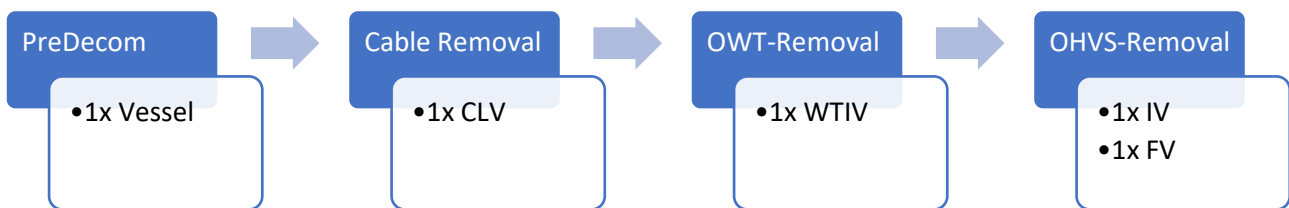


Figure 5: Pendulum-Systems: Stages and simulated Vessels

In addition, the pendulum models assume only one installation vessel, which dismantles the turbines, and not two vessels as in the base study.

On the process level, the pre-decommissioning activities are followed by the removal of the submarine cables. In the next steps, the turbines are dismantled. In the part-by-part configuration, the components are dismantled as individual parts. This results in 6 lifting operations (3x blade, 1x nacelle, 1x tower, 1x substructure). For the bunny-ear configuration and the star configuration, there are 4 lifting operations each. The different dismantling times can be seen in Table 3. The final steps include the disassembly of the OHVS.

With the arrival of the first dismantled components in the port, the onshore processes start here as well. After storage in the laydown area, possible further disassembly occurs. The onshore

dismantling times of the respective components differ in the individual dismantling configurations. For example, dismantling the rotor is more time-consuming than dismantling individual rotor blades, which can be seen in Table 4.

4.4 Feeder-Systems: Part-by-Part-, Bunny-Ear and Star-Configuration

In the feeder models, the main parameters regarding the OWF and the ships used are the same as in the baseline study. The total number of ships used in the different phases of the dismantling process along the supply chain is also lower here than in the baseline study. For the OWT dismantling process, only one installation vessel including one FV is thus simulated in these models, as it is shown in the figure 6 below.

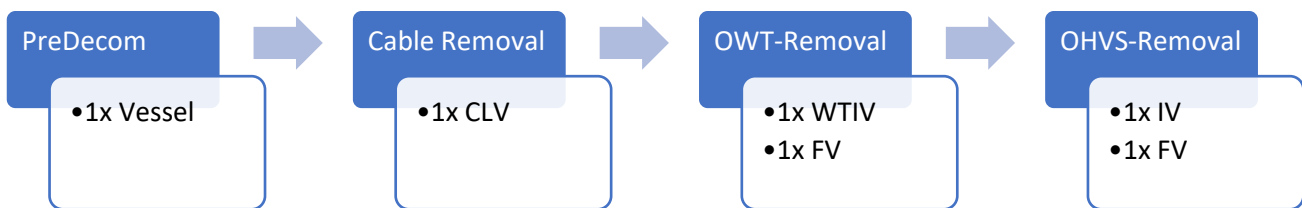


Figure 6: Feeder-Systems – Stages and simulated Vessels

During the OWT dismantling, the installation vessel remains in the wind farm. The dismantled components are brought to the port by the FV.

The land-based processes related to handling, storage, dismantling and onward transportation start when the feeder vessel reaches the port. In the port itself, after storage, the components are dismantled or further transported to the hinterland by simulated truck and barge transports.

5 Results and discussion

In the following chapter, different scenarios are presented with regard to their effects on runtime, costs and CO2 emissions. The results are presented in a separated form. On the one hand, the entire supply chain is observed and, on the other hand, explicitly the offshore processes for dismantling wind farms.

5.1 Scenarios with increasing distances for Complete Supply Chain

In the following, the impacts of parametric changes (here: distance to coast) for the whole supply chain are presented and the different configurations described above are compared.

5.1.1 Runtime

Figure 7 shows the average runtime of different configurations as a function of increasing distances. The baseline study curve ranges from a value of 618 days at 18 kilometres to a value of 1050 at 250 kilometres. The values of this curve remain lower over the increase in distance than the other compared configurations. The feeder Bunny Ear and the feeder Star configuration have the same curve progression. The pendulum Bunny Ear and pendulum Star configuration have a similar curve progression and differ only by about 30 days throughout the increasing distances. Pendulum Part-by-Part and feeder Part-by-Part start with very similar values but diverge towards the end, with feeder Part-by-Part having the lower runtime. The DecomTool vessel (DecomToolV) has the closest runtime compared to the base study. The curve starts with lower values than the feeder Bunny Ear and feeder Star configurations, intersects at 250 kilometres and then rises above the average runtime of the other two configurations. Up to a distance of 250 kilometres, the DecomToolsV comes closest to the base study, which has the lowest average runtimes.

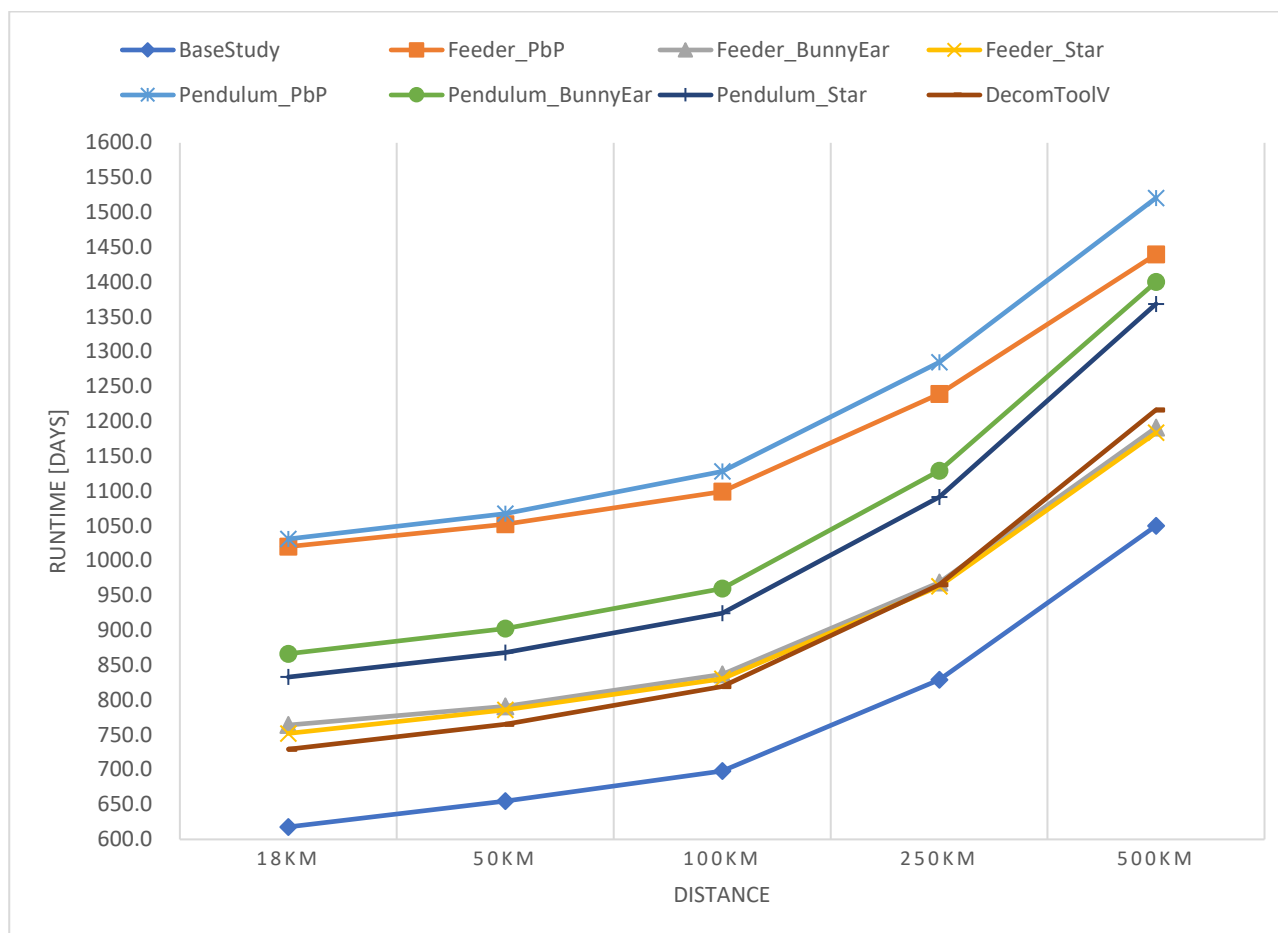


Figure 7: Parameter with increasing distances for Complete Supply Chain – Average Runtime in days

5.1.2 Costs

Figure 8 shows the average costs of different configurations as a function of increasing distances. The configurations feeder Bunny Ear, feeder Star, pendulum Bunny Ear, pendulum Star and base study all move in a very similar curve progression. From this group, Pendulum Star is the cheapest variant, which intersects with the other curves at 250 kilometres and then runs more expensive than the base study. The feeder part-by-part configuration is also significantly more costly than the other logistics systems for longer distances. Above a distance of 100 km, the Feeder Bunny Ear and Feeder Star systems generate costs roughly similar to those of the base study. The pendulum part-by-part configuration is in average about 30 Mio. € higher than the base study. The DecomToolsV turns out to be the cheapest configuration with a margin of 20,000,000 € from the grouping.

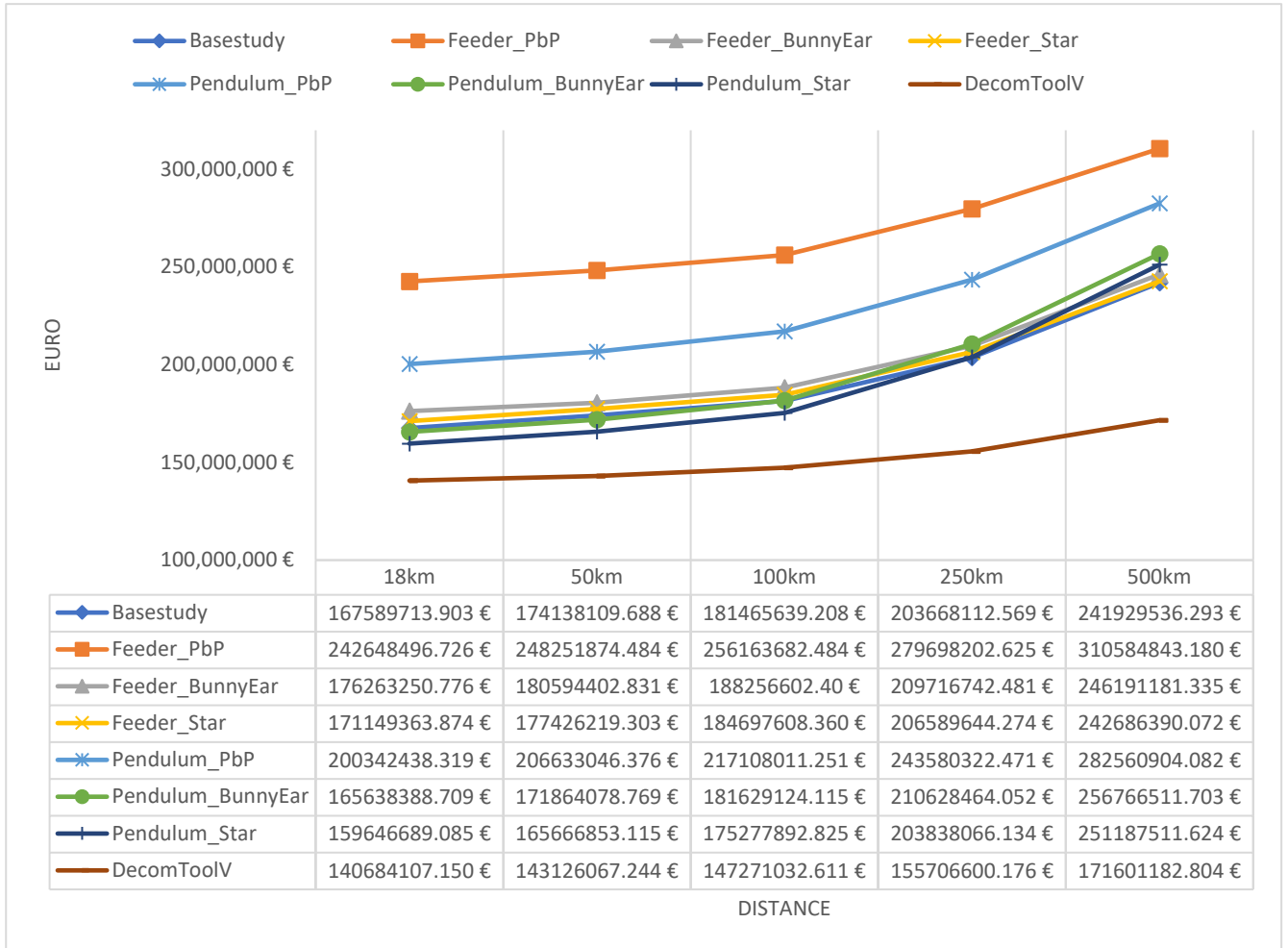


Figure 8: Parameter with increasing distances for Complete Supply Chain – Average Costs in €

5.1.3 CO₂-Emissions

Figure 9 shows the average CO₂-Emissions of different configurations as a function of increasing distances.

The lowest CO₂ emissions are emitted by the pendulum Star, pendulum Bunny Ear and DecomToolV configurations. The curves of these pendulum configurations initially run lower than DecomToolV, intersect it at 100 km. The curve of the DecomToolV runs relatively constant, but rises slightly more after 250 km. Pendulum Part-by-Part and the base study have a similar curve progression. They intersect at 100 km after which the pendulum configuration emits more CO₂ than the base study. Feeder Bunny Ear and feeder Star have a higher CO₂ emission than the before mentioned configurations. Feeder Part-by-Part has the highest CO₂ emissions ranging from 40,000 to over 50,000 tons.

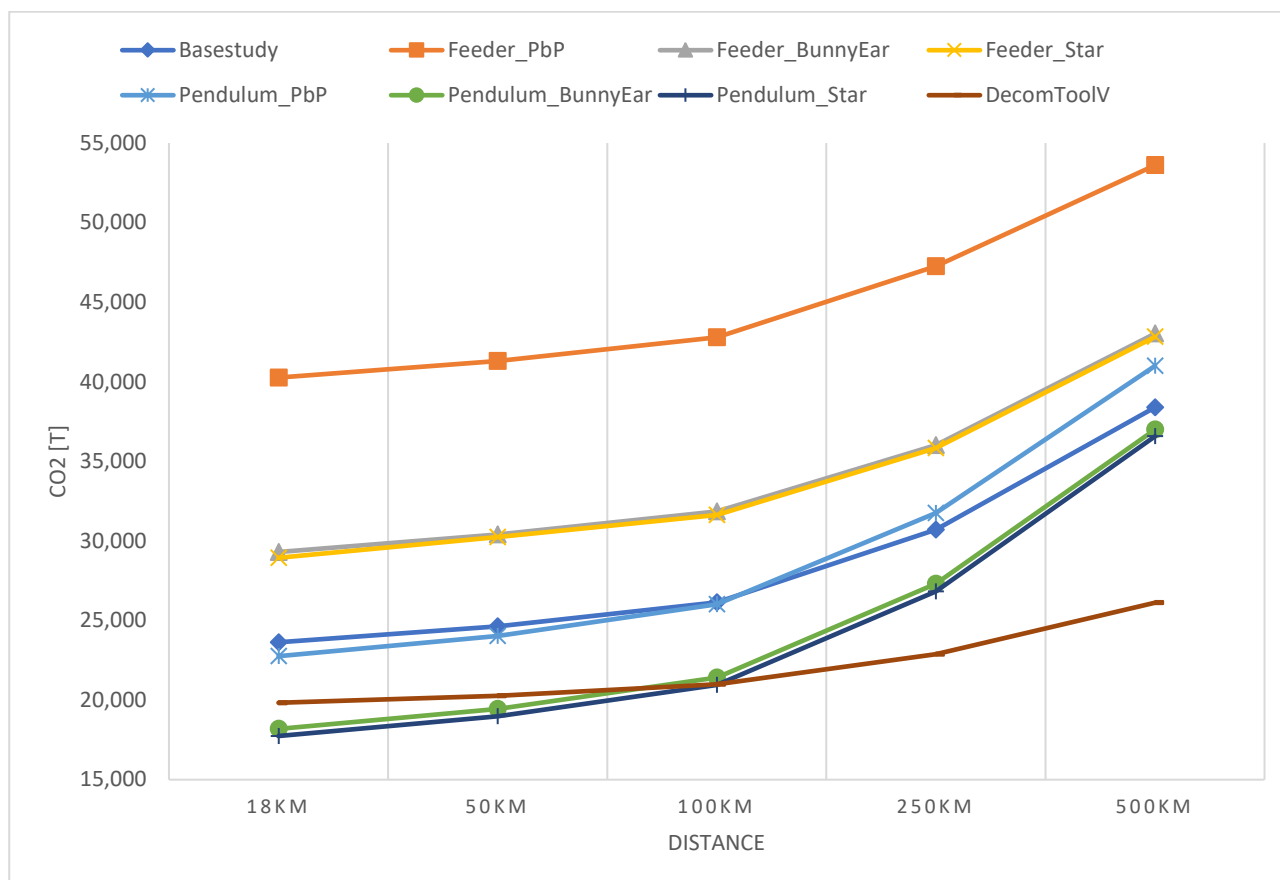


Figure 9: Parameter with increasing distances for Complete Supply Chain – Average CO₂-Emissions in tons

5.1.4 Annual Changes

In the course of the simulation, more than 1.000 simulation runs were performed per scenario and configuration. The start time of these was randomly selected and subsequently clustered by months. In the following, the running time, costs and CO₂ emissions are shown over the period of a year. The graphs are shown and explained for a distance of 50 km. Since the graphs for the other distances (100 km, 250 km and 500 km) look very similar, they are not included in the main text in order to maintain a structured overview. The graphics can be found in appendix 1.

Figure 10 shows the progression of the average runtime of different configurations at a distance of 50 km from the coast over a period of one year.

Over the course of the year, the runtime for the base study remains quite even, with a fluctuation of less than two percent. This is similar for the other configurations. With the exception of the pendulum Bunny Ear configuration, where the fluctuation is slightly below three percent, and DecomToolV with a fluctuation of 2.5%. Both configurations have the highest durations in September and October and the lowest at the beginning of the year (January and February,

respectively). However, there is no discernible pattern here, the values seem to increase towards the end of the year and decrease towards the summer, although this is not consistent.

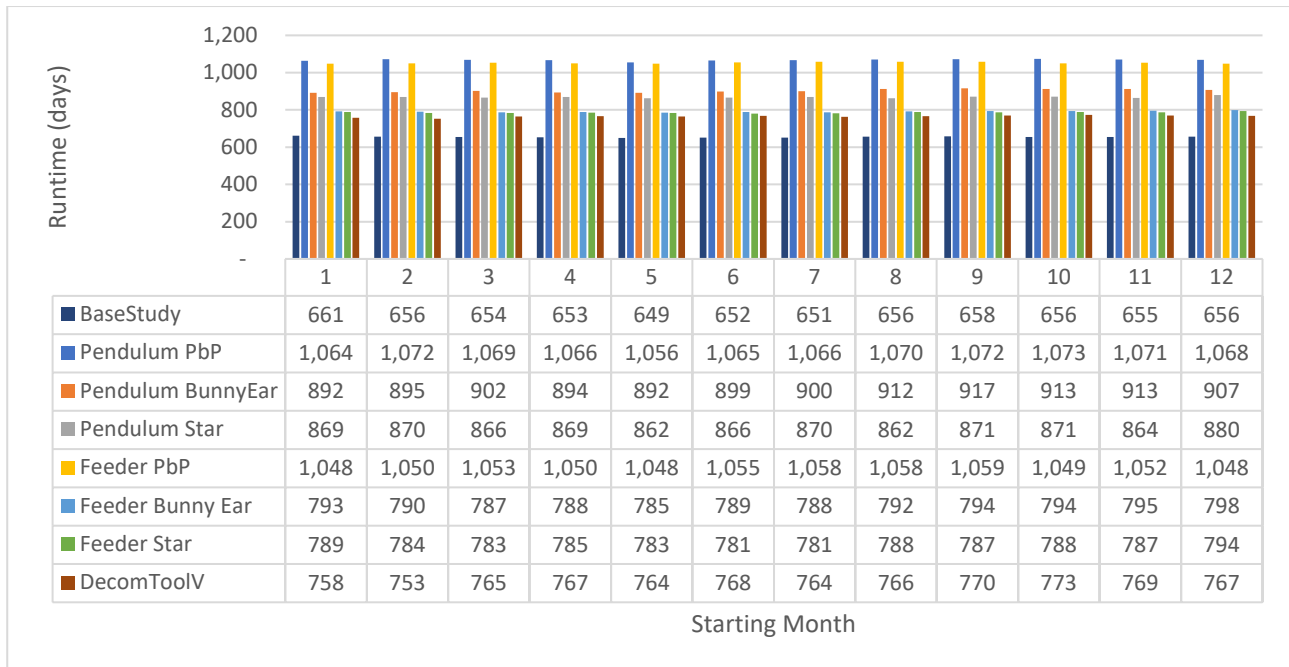


Figure 10: Average runtime of different configurations at a distance of 50 km over a period of one year – complete supply chain (1-12 equals the months from January to December)

Figure 11 shows the progression of the average costs of different configurations at a distance of 50 km from the coast over a period of one year.

As with the runtime, the costs over the time span of one year are in a very similar range with a fluctuation of under two percent. Here, too, the pendulum Bunny Ear configuration has a slightly higher fluctuation of under three percent. DecomToolV has a fluctuation of 3.5%. The highest value is in July and September (pendulum Bunny Ear) and the lowest value is in February and January (pendulum Bunny Ear).

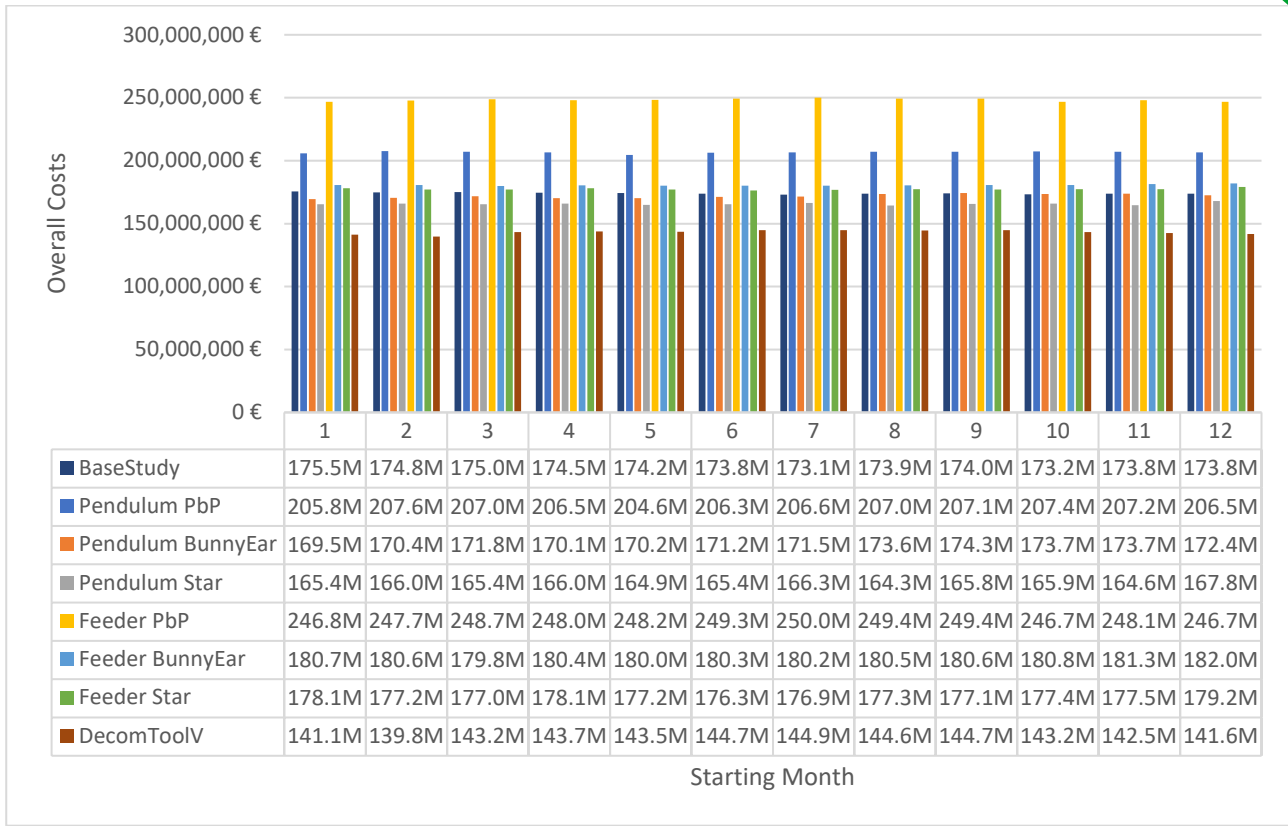


Figure 11: Average costs of different configurations at a distance of 50 km over a period of one year – complete supply chain (1-12 equals the months January-December; M stands for Million €)

Figure 12 shows the progression CO₂ emissions in tons of different configurations at a distance of 50 km from the coast over a period of one year.

All configurations show fluctuations of less than 1%. It is not evident that the CO₂ emissions are dependent on the seasons.

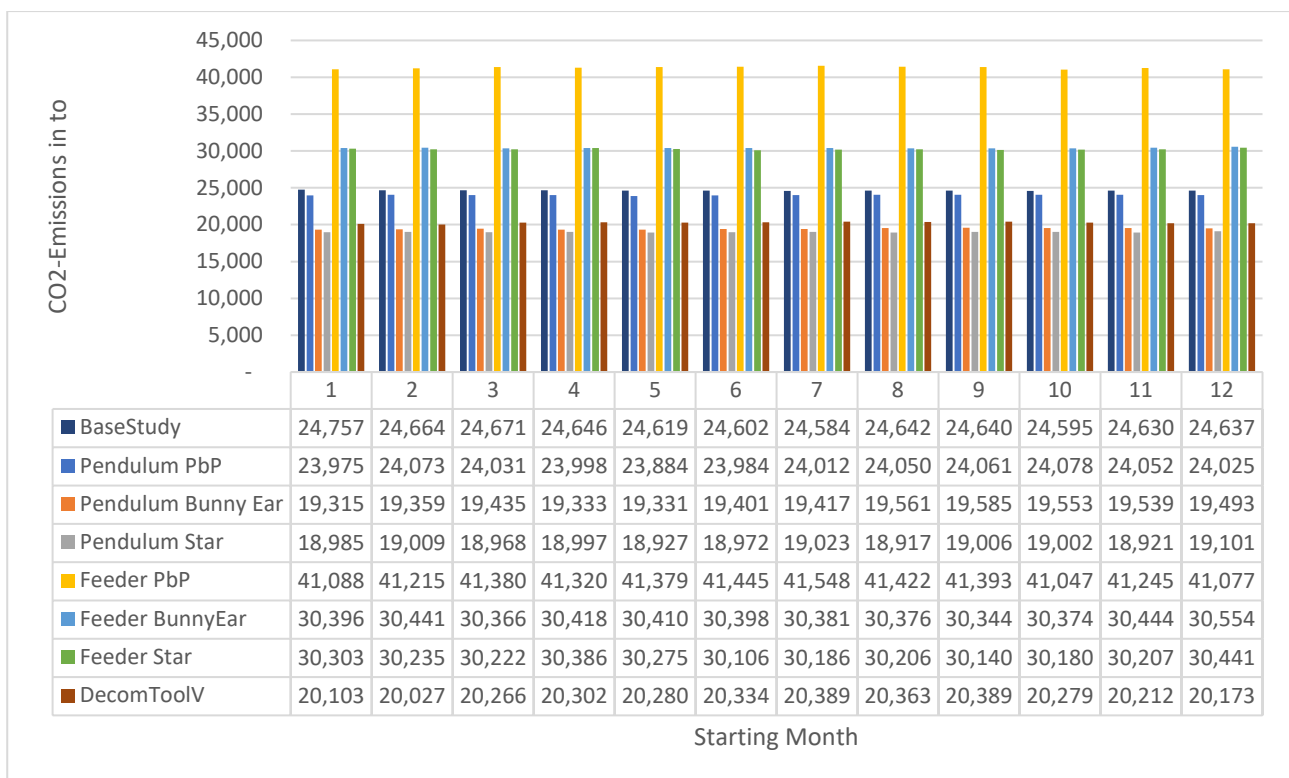


Figure 12: Average CO₂-Emissions of different configurations at a distance of 50 km over a period of one year – complete supply chain (1-12 equals the months January-December)

As already mentioned, the graphs for the evaluation aspects considered at 100 km, 250 km and 500 km are very similar to those at 50 km. Again, the deviations range from <2-3 %.

5.2 Parameter with increasing distances offshore

In the following, the impacts of parametric changes (here: distance to coast) for the offshore processes are presented and the different configurations described above are compared. Since the offshore processes are assumingly the ones with the biggest impact on runtime, costs and co₂-emissions a more detailed look gives further information.

5.2.1 Runtime

Figure 13 shows the average runtimes of different configurations as a function of increasing distances.

The runtimes of the base study are the lowest of all configurations over the distance range of 18 to 500 kilometers. The feeder Star, feeder Bunny Ear and DecomToolV configurations come closest to the runtime of the base study. The two feeder configurations run very similarly. The DecomToolV variant initially runs slightly below the other two, but at 250 kilometers the curves intersect and after that the DecomToolV has a higher runtime. Pendulum Bunny Ear and pendulum Star have parallel curves, with Star having a shorter runtime over the course of the curves. Pendulum Part-by-Part and feeder Part-by-Part have the longest running time, although the two curves initially have a similar course, the course of the pendulum Part-by-Part configuration increases more rapidly after 100 kilometers.

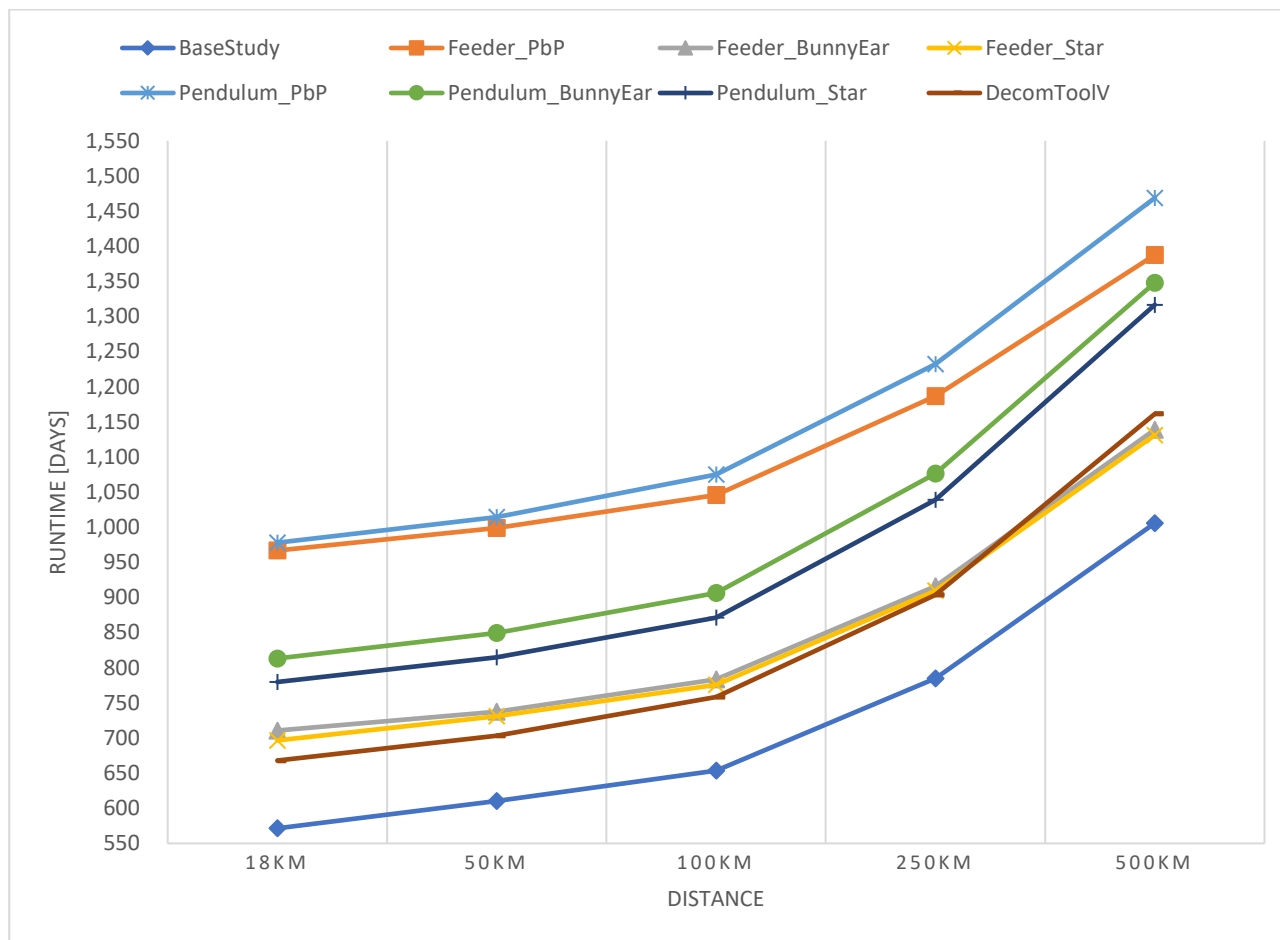


Figure 13: Parameter with increasing distances Offshore – Average Runtime in days

5.2.2 Costs

Figure 14 shows the average costs of different configurations as a function of increasing distances.

As with the complete chain, the DecomToolV configuration has the lowest average cost. After a gap of about 20,000,000 €, some configurations settle in a similar range. Thereby feeder Star and Bunny Ear have a very similar course at the upper end of this cluster. The base study and pendulum Bunny Ear run identically at the beginning, but from 100 kilometers pendulum Bunny Ear increases significantly and is the most expensive configuration from this grouping. Pendulum Star is the least expensive configuration up to 250 kilometers (after DecomToolV), where it intersects the curve of the base study and is more expensive thereafter. Pendulum Part by Part runs with a distance of

30,000,000 € to the clustering. Parallel to it runs the most expensive configuration feeder Part by Part.

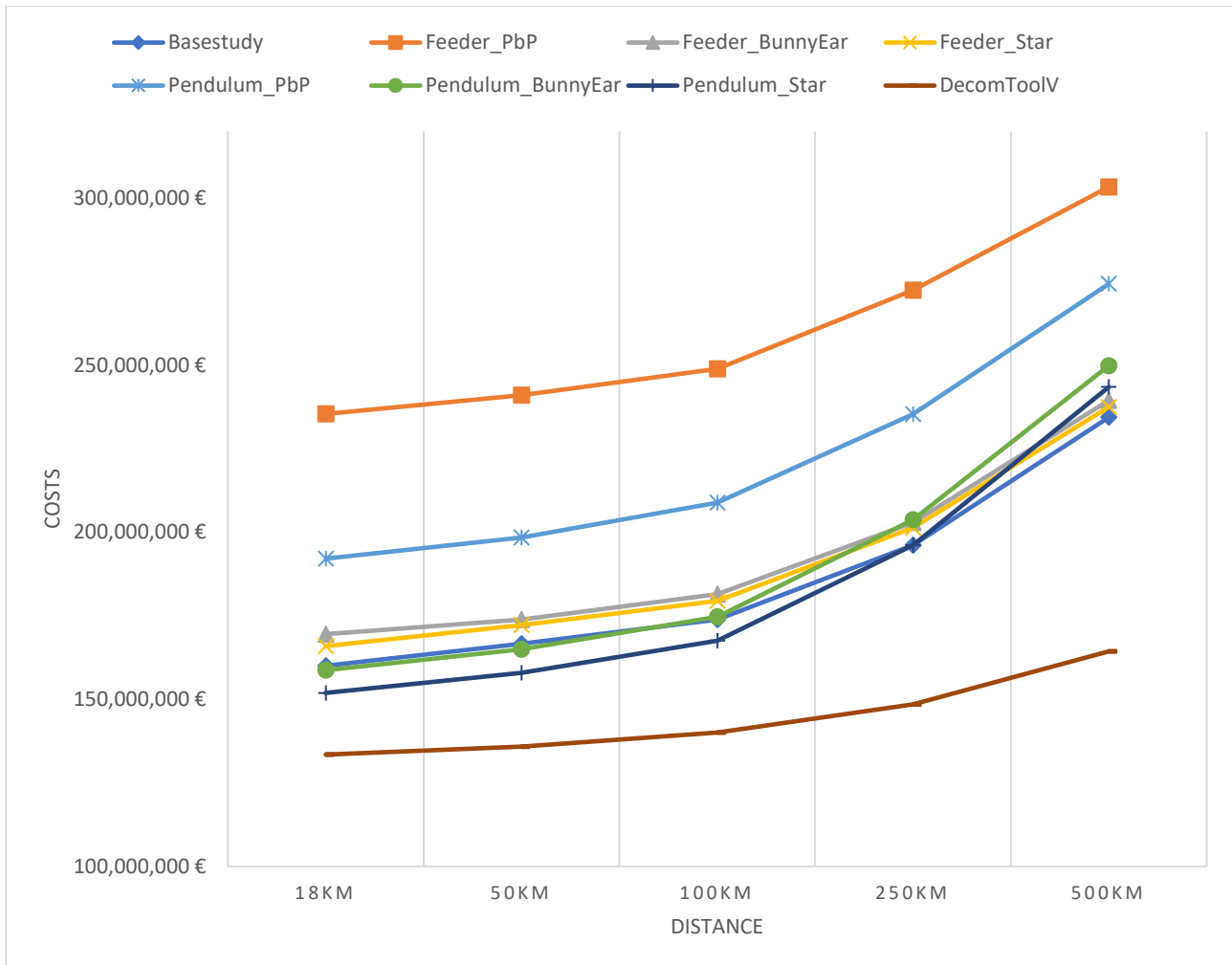


Figure 14: Parameter with increasing distances Offshore – Average Costs in €

5.2.3 CO₂-Emissions

Figure 15 shows the average CO₂-Emissions of different configurations as a function of increasing distances.

The configuration that emits the least CO₂ over the range of 18 to 500 kilometers is with the DecomToolV. Pendulum Star, pendulum Bunny Ear, pendulum Part by Part also have lower CO₂ emissions than the base study. At 18 kilometers, the pendulum Bunny Ear and Star configurations are in the same range as DecomToolV. However, these curves then rise almost identically and have

significantly higher CO₂ emissions. The base study and pendulum Part by Part initially run parallel, from 250 km the distance becomes smaller and at 500 km they cross. Feeder Star and Bunny Ear run identically, with a distance of 5,000 tons from the base study. The configuration with the highest CO₂ emissions is feeder Part-by-Part with a distance of 14,000 tons to the base study.

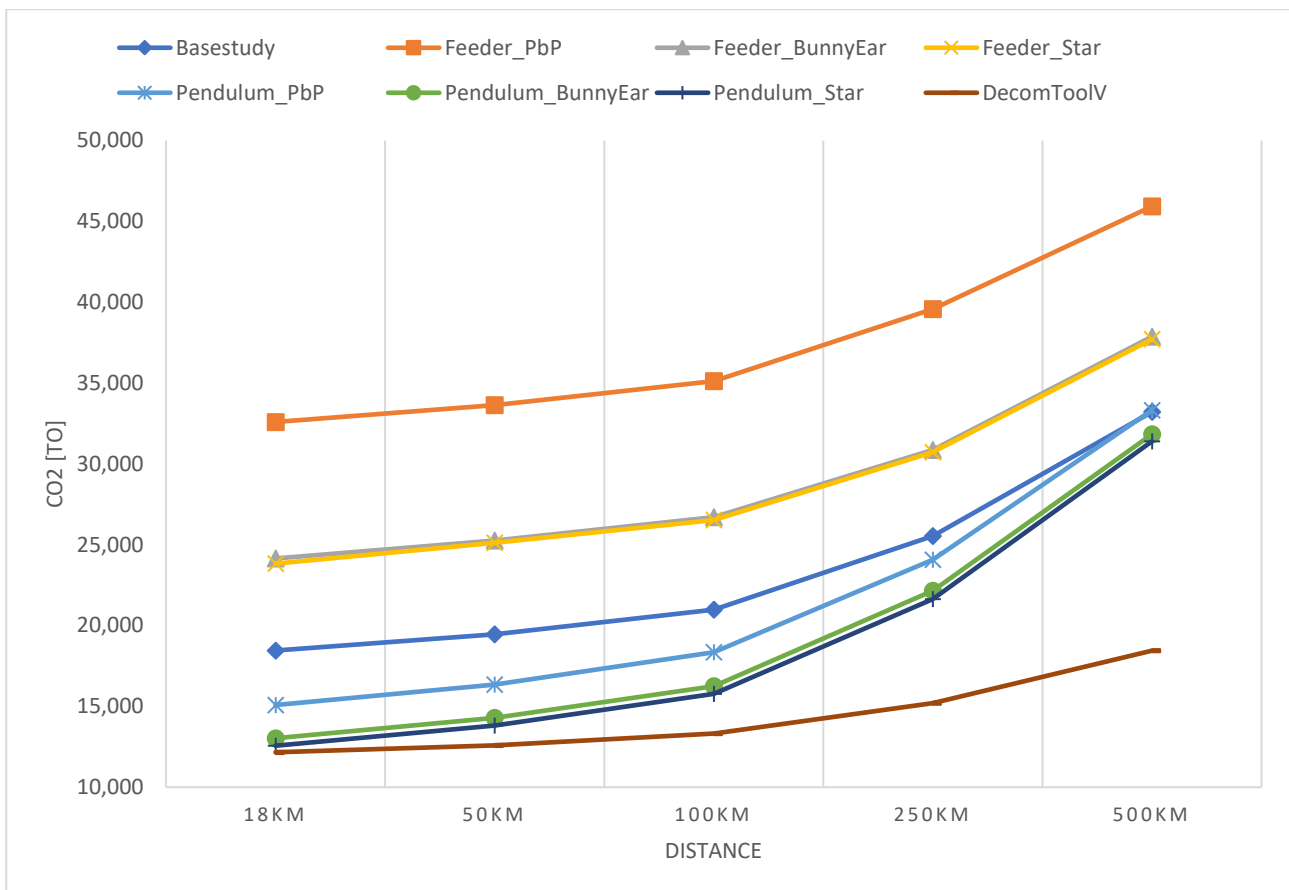


Figure 15: Parameter with increasing distances Offshore – Average CO₂-Emissions in tons

5.2.4 Annual Changes

In the following, the running time, costs and CO₂ emissions are shown over the period of a year. The graphs are shown and explained for a distance of 50 km. Since the graphs for the other distances (100 km, 250 km and 500 km) look very similar, they are not included in the main text in order to maintain a structured overview. The graphics can be found in appendix 2.

Figure 16 shows the progression of the average runtime of different configurations at a distance of 50 km from the coast over a period of one year.

The course of the average runtime follows the same pattern as described in chapter 5.1.4. The values are slightly lower, which is due to the fact that only offshore processes are considered. The deviations vary between 2-3% over the year as well.

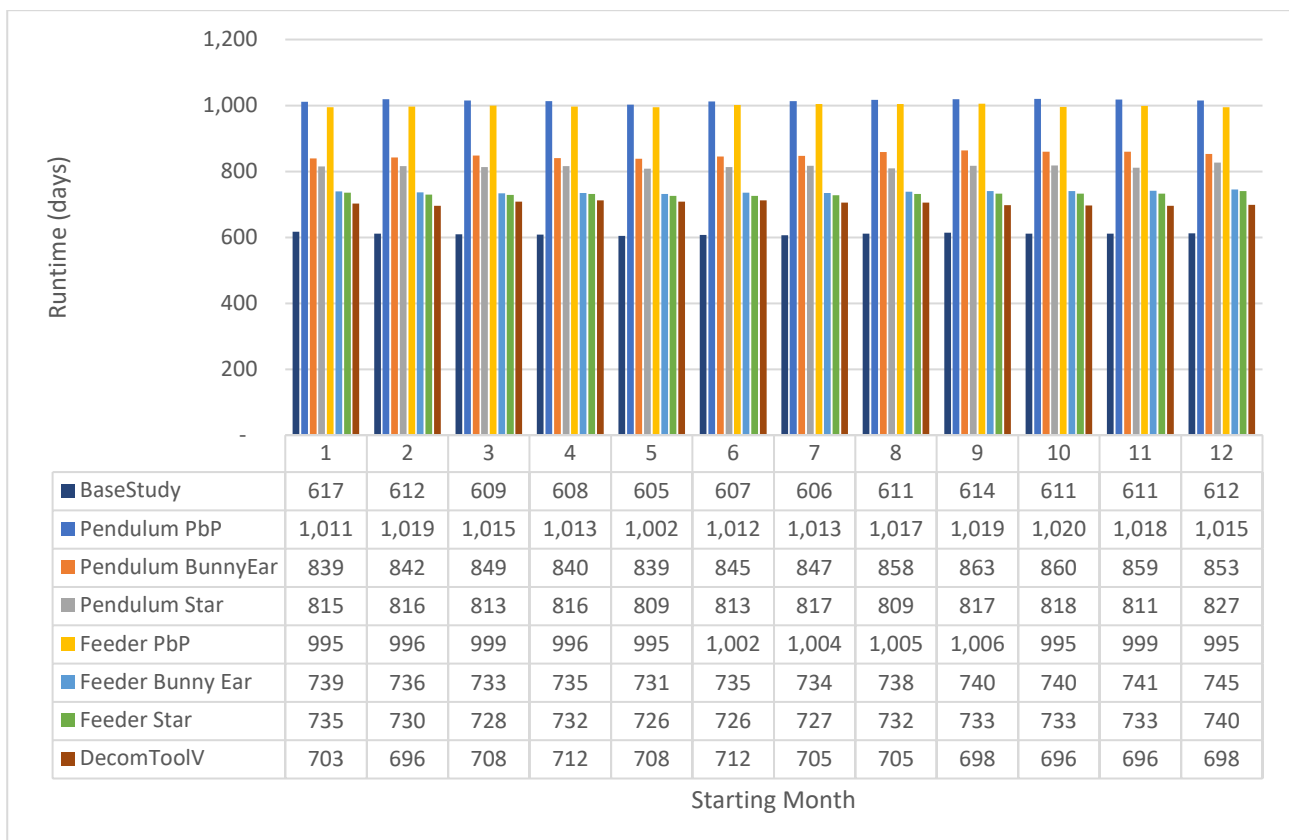


Figure 16: Average runtime of different configurations at a distance of 50 km over a period of one year – offshore (1-12 equals the months from January to December)

Figure 17 shows the progression of the average costs of different configurations at a distance of 50 km from the coast over a period of one year. The course of the average runtime follows the same pattern as described in chapter 5.1.4. Here, too, the values are lower, as described in the previous graph. The deviations vary between 2-3% over the year as well.



Figure 17: average costs of different configurations at a distance of 50 km over a period of one year – offshore (1-12 equals the months January-December; M stands for Million €)

Figure 18 shows the progression of the average runtime of different configurations at a distance of 50 km from the coast over a period of one year. The course of the average runtime follows the same pattern as described in chapter 5.1.4. Here, too, the values are lower, as described in the previous two graphs. The deviations vary between 2-3% over the year as well.

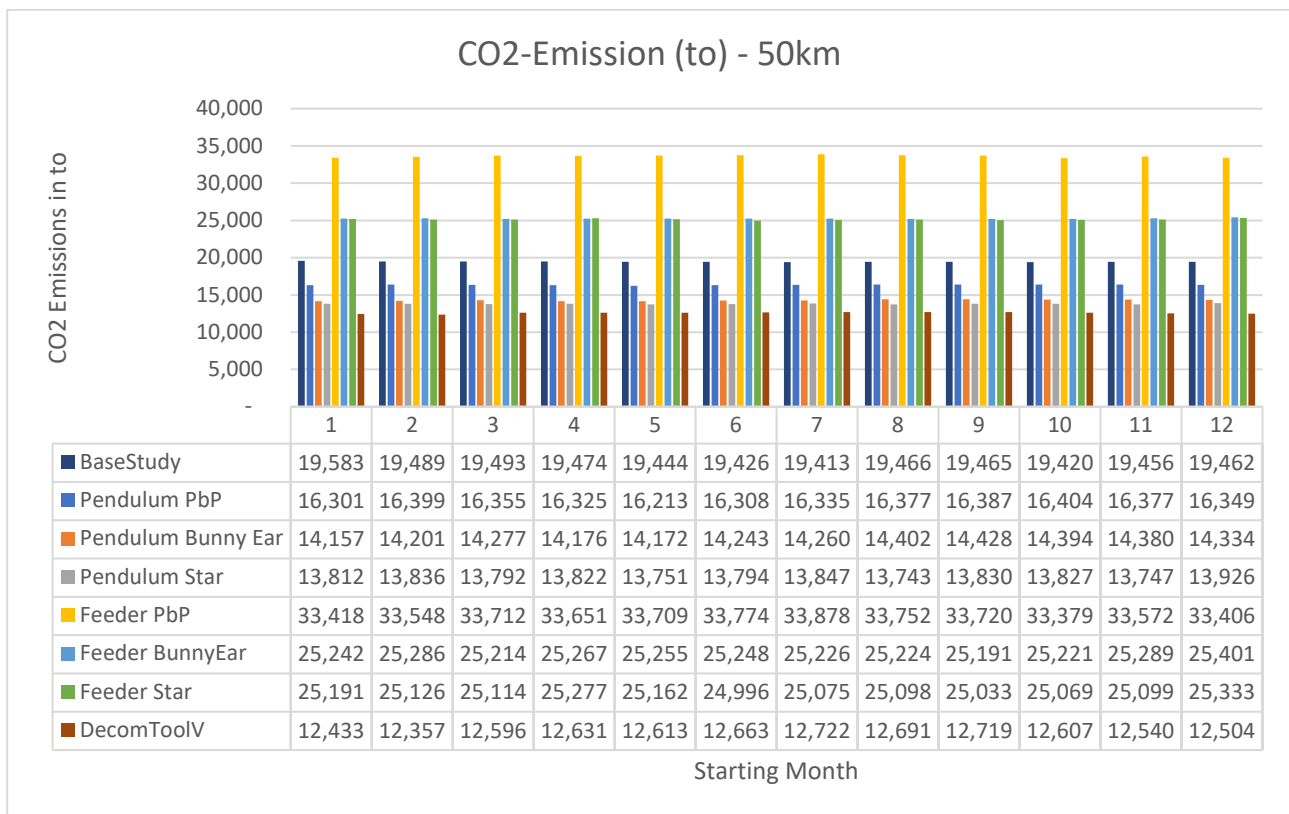


Figure 18: average CO₂-Emissions of different configurations at a distance of 50 km over a period of one year – offshore (1-12 equals the months from January to December)

As with the annual graphs of the complete supply chain, there is no correlation of run time, cost, or CO₂ emissions with the seasons.

5.3 Cost development with increasing vessel day rates

5.3.1 Complete Supply Chain

Figure 19 shows the cost developments of the different scenarios with increasing vessel day rates of the complete supply chain.

Simulations were performed at 10%, 25%, 50% and 100% increased day rates starting from the base (0%). As day rates increase, costs also increase in a nearly linear way, with no change in the positions of the different scenarios. The DecomTools vessel remains the least expensive scenario and Feeder Part-by-Part the most expensive scenario.

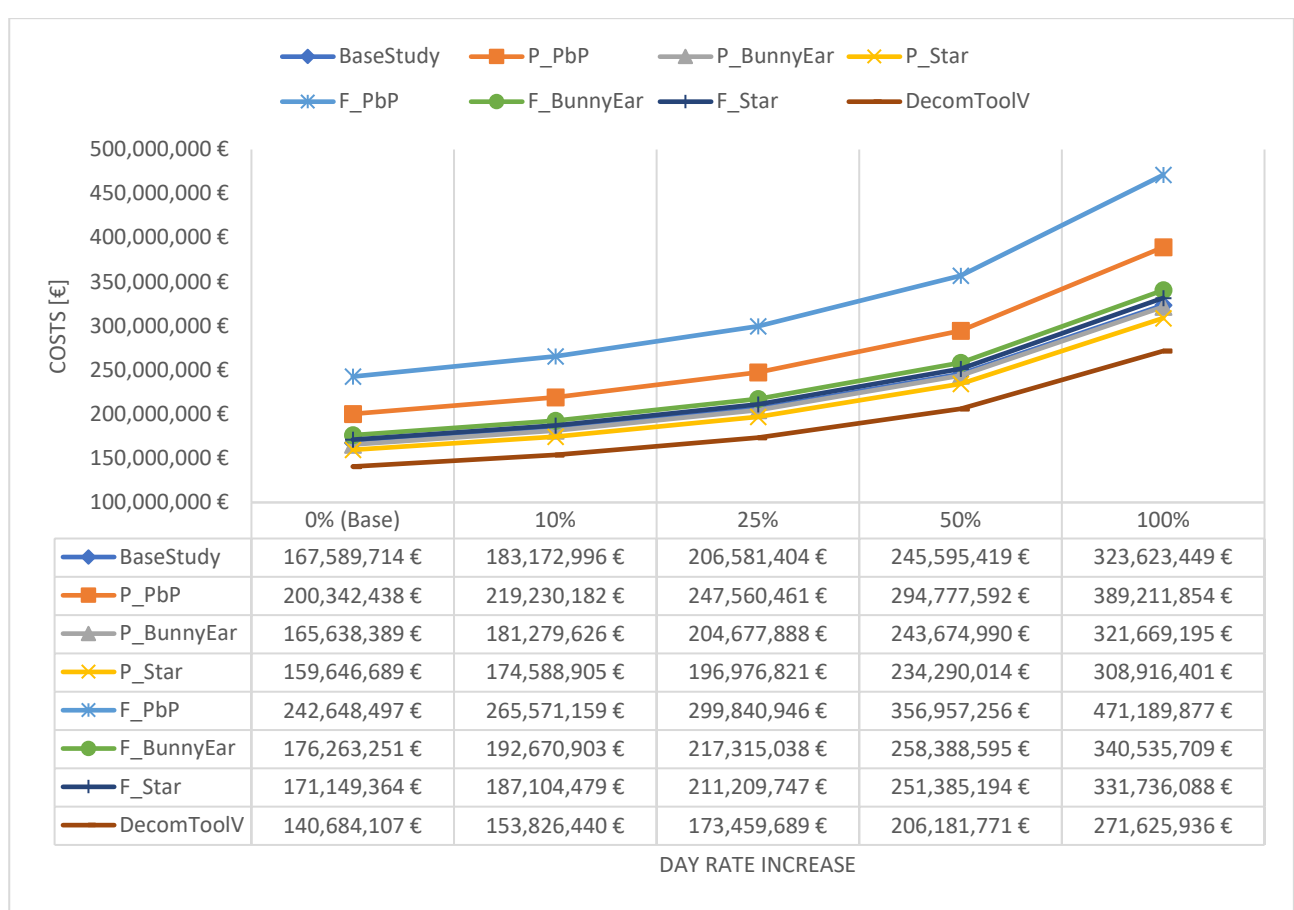


Figure 19: Cost development with increasing vessel day rates – complete supply chain

5.3.3 Offshore

Figure 20 shows the cost developments of the different scenarios with increasing vessel day rates of the offshore processes.

As with the cost development of the offshore process, the total costs increase with increasing day rates. The positions of the scenarios remain the same over the increase in cost. The least expensive scenario is DecomTool Vessel and the most expensive scenario is Feeder Part-by-Part.

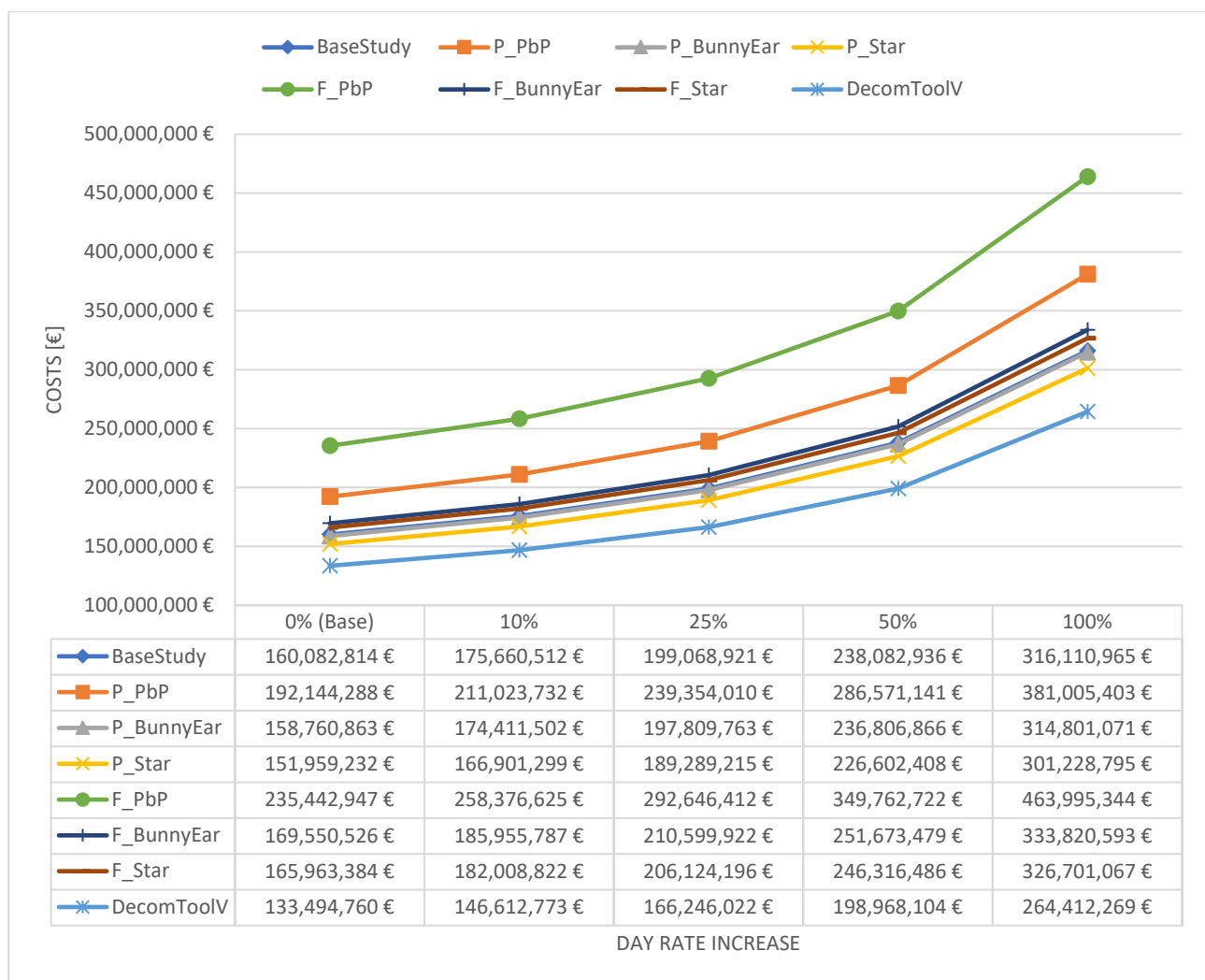


Figure 20: Cost development with increasing day rates – offshore

5.4 Cost development with increasing fuel costs

5.4.1 Complete Supply Chain

Simulations were performed at 10%, 25%, 50% and 100% increased fuel costs starting from the base (0%).

Figure 21 shows the progression of costs with increased ship fuel costs. Increasing fuel costs results in only a minimal increase in costs over the course of the curve. With a 100% increase, total costs are only about 3% higher than the initial condition. The increase in fuel costs therefore has minimal to no impact on total costs when the wind farm is at an 18 km distance from the coast.

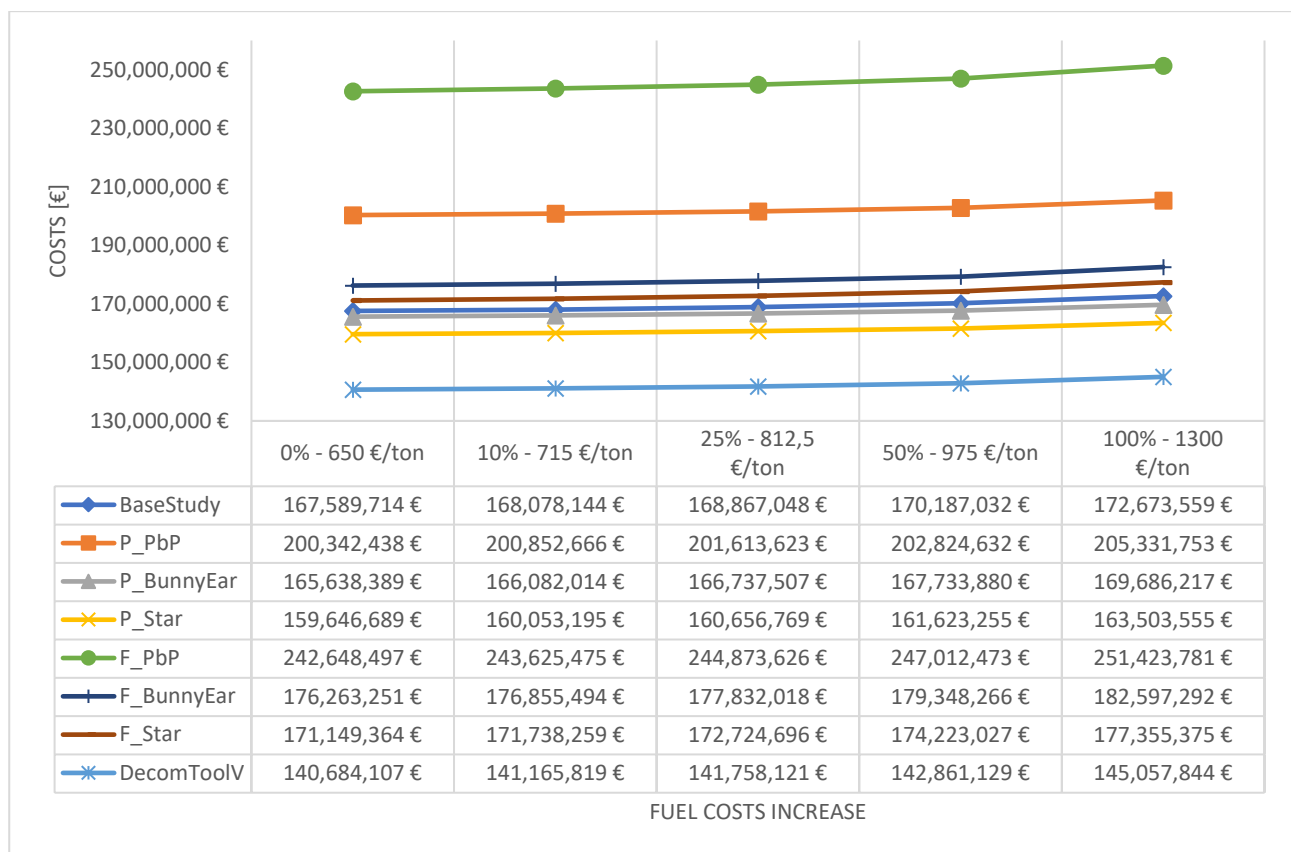


Figure 21: Cost development with increasing fuel costs per ton – Complete supply chain

5.4.3 Offshore

Figure 22 shows the progression of costs with increased ship fuel costs. Increasing fuel costs results in only a minimal increase in costs over the course of the curve. With a 100% increase, total costs are only about 3% higher than the initial condition. The increase in fuel costs therefore has minimal to no impact on total costs when the wind farm is at an 18 km distance from the coast.

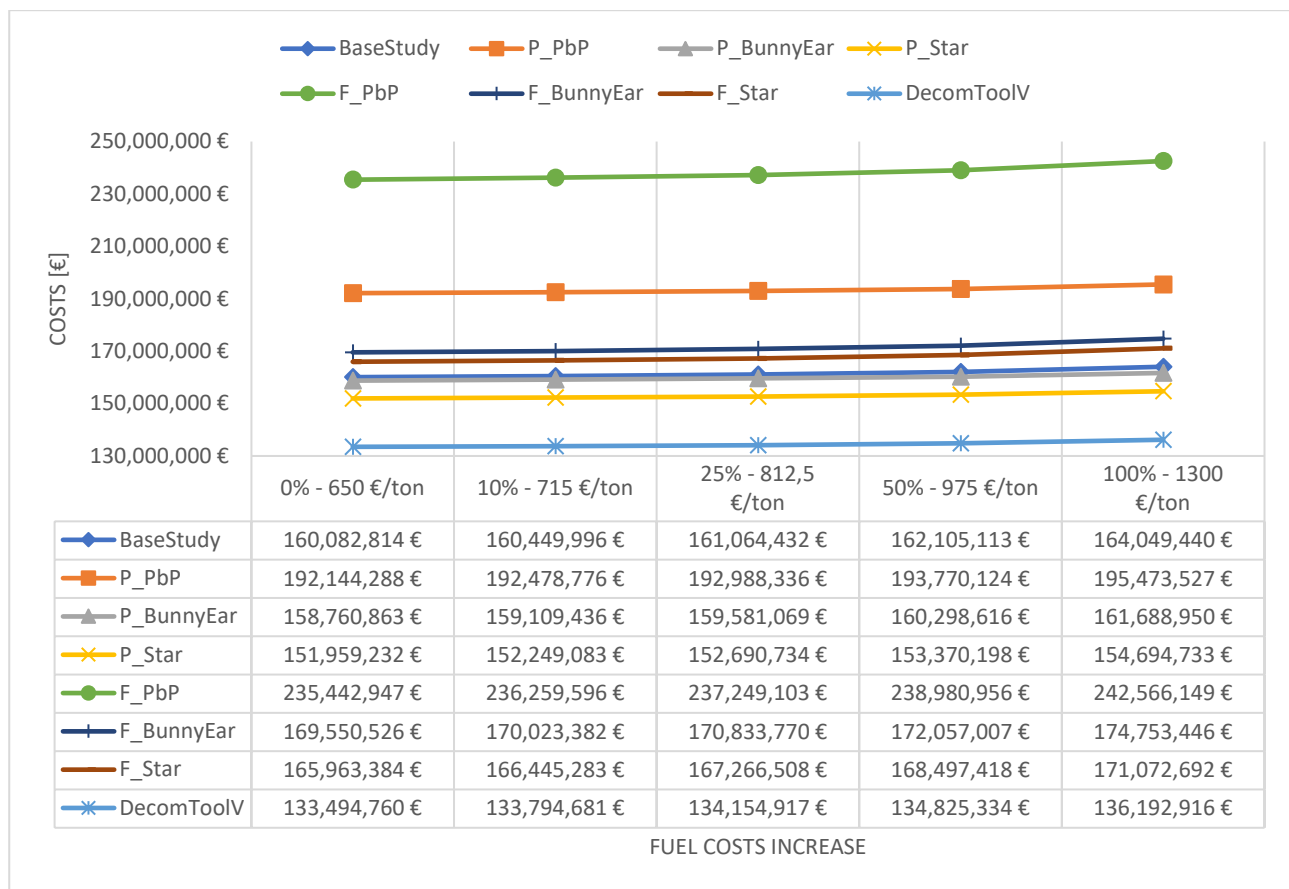


Figure 22: Cost development with increasing fuel costs per ton - Offshore

6 Conclusion

Table 10 shows the differences of the examined parameters runtime, costs and CO₂-Emissions compared to the base study in percent at a distance of 18 km to the coastline.

All configurations have a longer runtime than the baseline study. The pendulum Part-by-Part scenario has the largest discrepancy from the baseline study at 66.90%. DecomToolV has the lowest deviation with 18.05 %. DecomToolV also has the lowest cost with a difference of -16.05% from the baseline study. The pendulum bunny ear and pendulum star configuration costs are below those of the baseline study. The feeder part-by-part configuration is the most expensive one with 44.79% higher costs than the baseline study.

Pendulum Star has the largest negative divergence at -24.92%, and thus the lowest CO₂ emissions. The scenario pendulum BunnyEar has a similar deviation with -23.03%. The DecomToolV and pendulum Part-by-Part also have negative offsets, i.e. lower CO₂ emissions than the baseline study. The other scenarios have significantly higher CO₂ emissions compared to the base study.

All in all, neither of the scenarios reviewed has better values than the baseline study in all aspects. The scenarios P_BunnyEar, P_Star and DecomToolV come closest, as they all three have two aspects each that have better values than the base study. Of these, DecomToolV has the best values. In terms of runtime, this scenario comes closest to the baseline study, and in terms of cost, it has the lowest cost of all configurations. CO₂ emissions are also significantly lower than in the baseline study, at around -16%.

Table 9: difference of average runtime, cost and CO₂-Emissions compared to base study

Scenario	∅ Runtime in %	∅ Cost in %	∅ CO ₂ -Emissions in %
P_PbP	66.90	19.54	-3.69
P_BunnyEar	40.24	-1.16	-23.03
P_Star	34.82	-4.74	-24.92
F_PbP	65.12	44.79	70.38
F_BunnyEar	23.66	5.18	24.00
F_Star	21.72	2.12	22.47
DecomToolV	18.05	-16.05	-16.08

Table 10 shows the differences of the examined parameters runtime, costs and CO₂-Emissions compared to the base study in percent at a distance of 18 km to the coastline. With regard to the distances of the complete supply chain, the scenarios F_Star, F_BunnyEar and DecomToolV come closest to the baseline study in terms of average runtime over the course of 18 to 500 km.

In terms of costs, DecomToolV has the best values, which fall below the values of the baseline study. Up to a distance of 100 km, the P_Star, P_BunnyEar and DecomToolV scenarios are the best, with values below those of the baseline study. After that, the values for P_Star and P_BunnyEar increase and DecomToolV has the best values for CO₂ emissions.

When looking at the offshore processes, it is the same as for the complete supply chain with the exception of CO₂ emissions. There DecomToolV has the lowest values over the entire course of the distances. The difference in offshore and the complete supply chain in this case affects the course of the curves. For the other scenarios, the curves are very similar, but have lower values for offshore. This is not the case for CO₂ emissions. Here the values for P_Star and P_BunnyEar are minimally higher than DecomToolV at the beginning. For the complete supply chain, the values are lower than DecomToolV, and are only higher after 100 km, as already described. Whether the differences affect DecomToolV and the values are therefore lower or the other scenarios and they are therefore higher cannot be deduced from the results.

Increased ship day rates lead to an increase in the total cost of all simulated scenarios for both the complete supply chain and offshore, this has no effect on the ranking of the scenarios. DecomTools vessel remains the least expensive scenario and Feeder Part-by-Part the most expensive.

Increasing fuel costs does not significantly increase total costs offshore or in the complete supply chain (18 km offshore). This can be attributed to the fact that the share of fuel costs in the total costs is very low at this distance.

Looking to the future, this generic tool can be used to conduct interesting studies using a wide range of parameters from different stakeholders. The aims here can be of a cost-saving nature, as well as with regard to the reduction of CO₂ emissions. This parameter therefore has a significant impact on costs. The use of alternative, cleaner fuels would have a positive impact on CO₂ emissions, but would also lead to an increase in costs. However, a higher “CO₂ price”, would further equal this costs increase and create a fundamental incentive for climate-friendly and alternative fuels, which will have an overall significant positive effect on technology development.

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Appendix 1: Complete Supply Chain

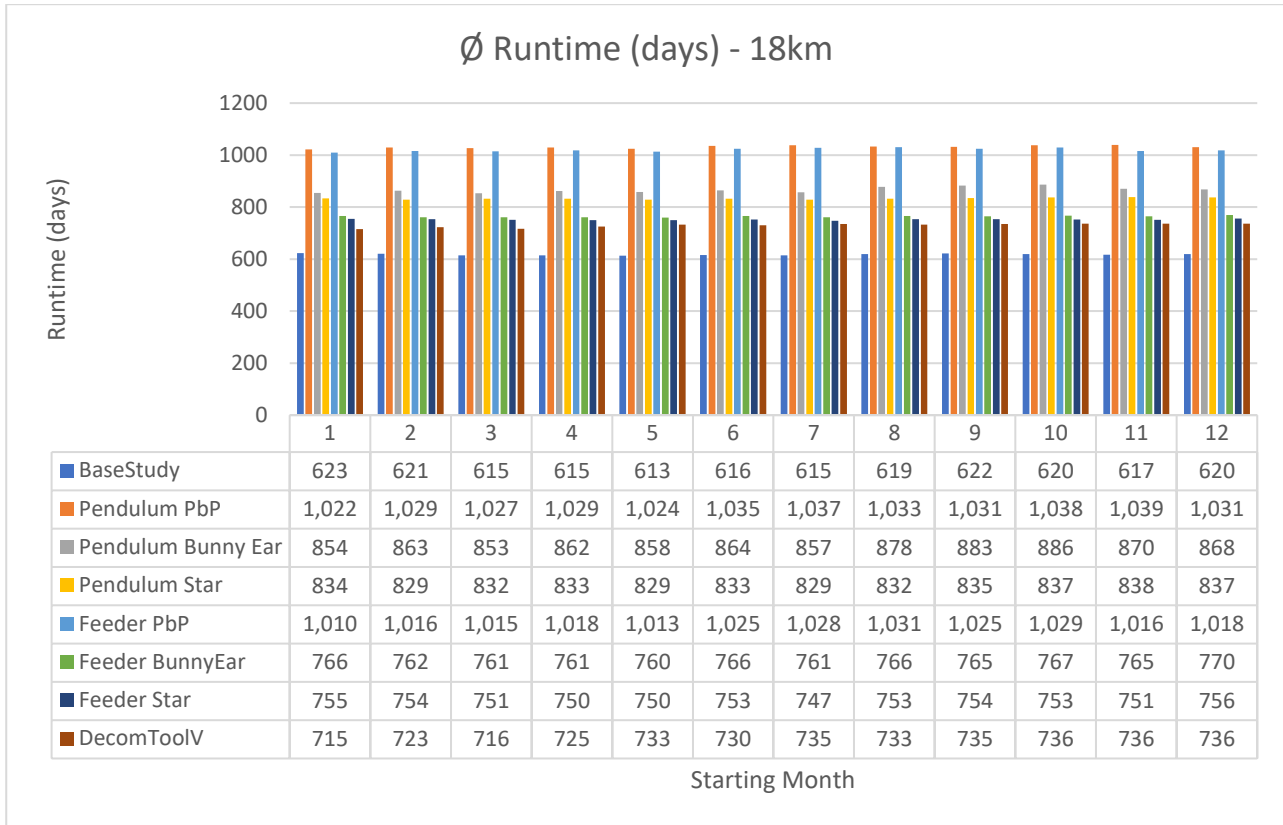


Figure 1: average runtime of different configurations at a distance of 18 km over a period of one year - complete supply chain (1-12 equals the months from January to December)



Figure 2: average costs of different configurations at a distance of 18 km over a period of one year – complete supply chain (1-12 equals the months from January to December)

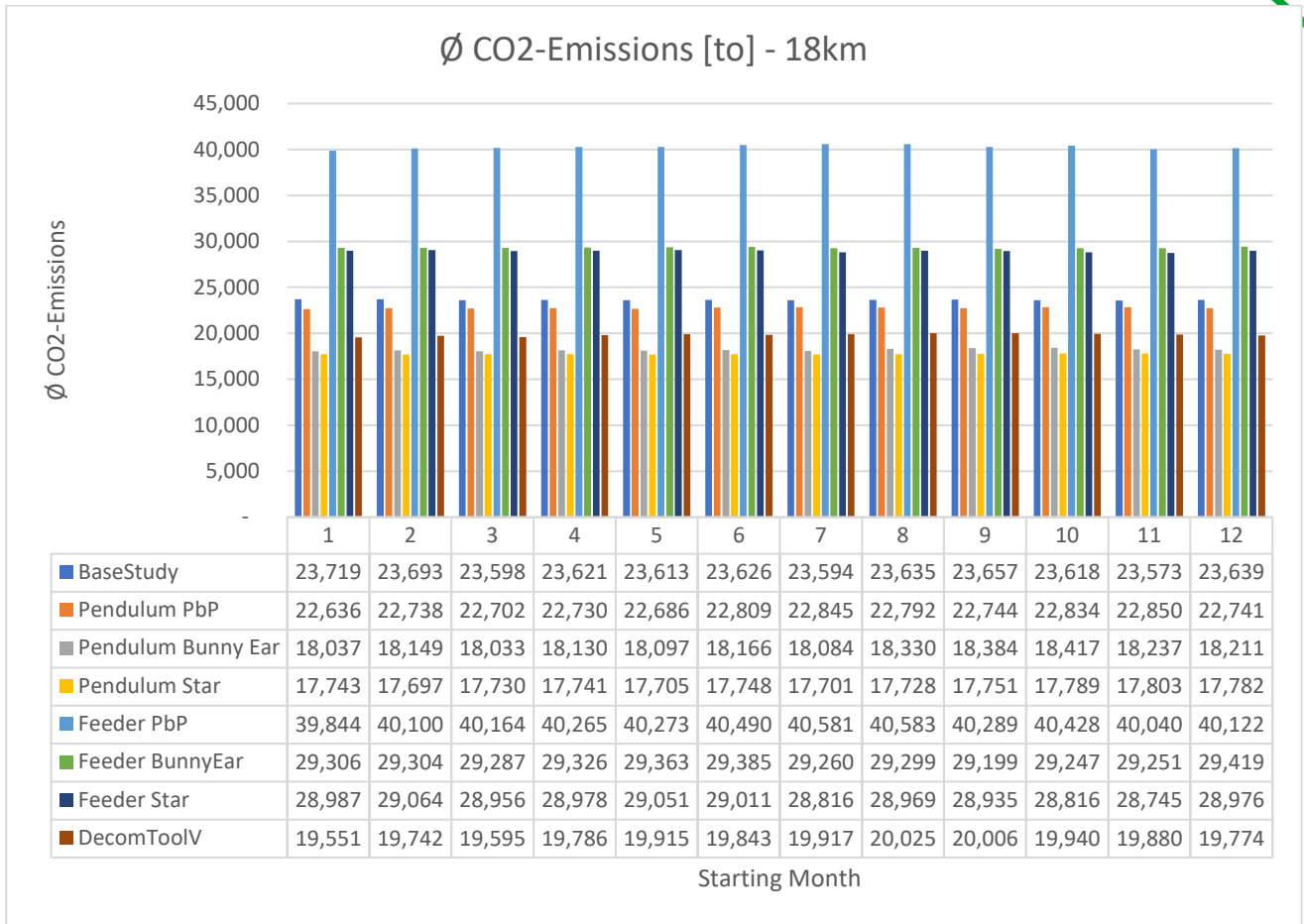


Figure 3: average CO₂-Emissions of different configurations at a distance of 18 km over a period of one year – complete supply chain (1-12 equals the months from January to December)

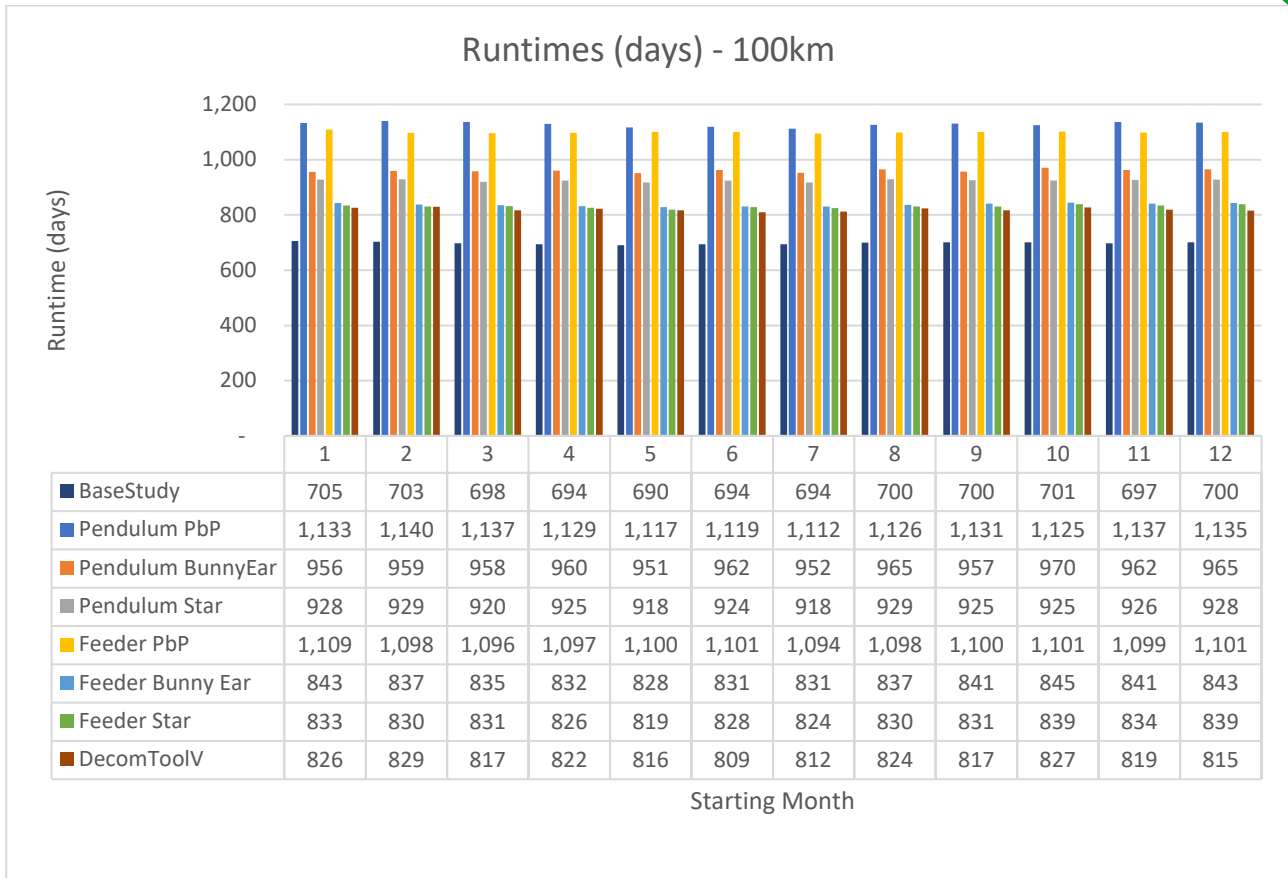


Figure 4: average runtime of different configurations at a distance of 100 km over a period of one year – complete supply chain (1-12 equals the months from January to December)

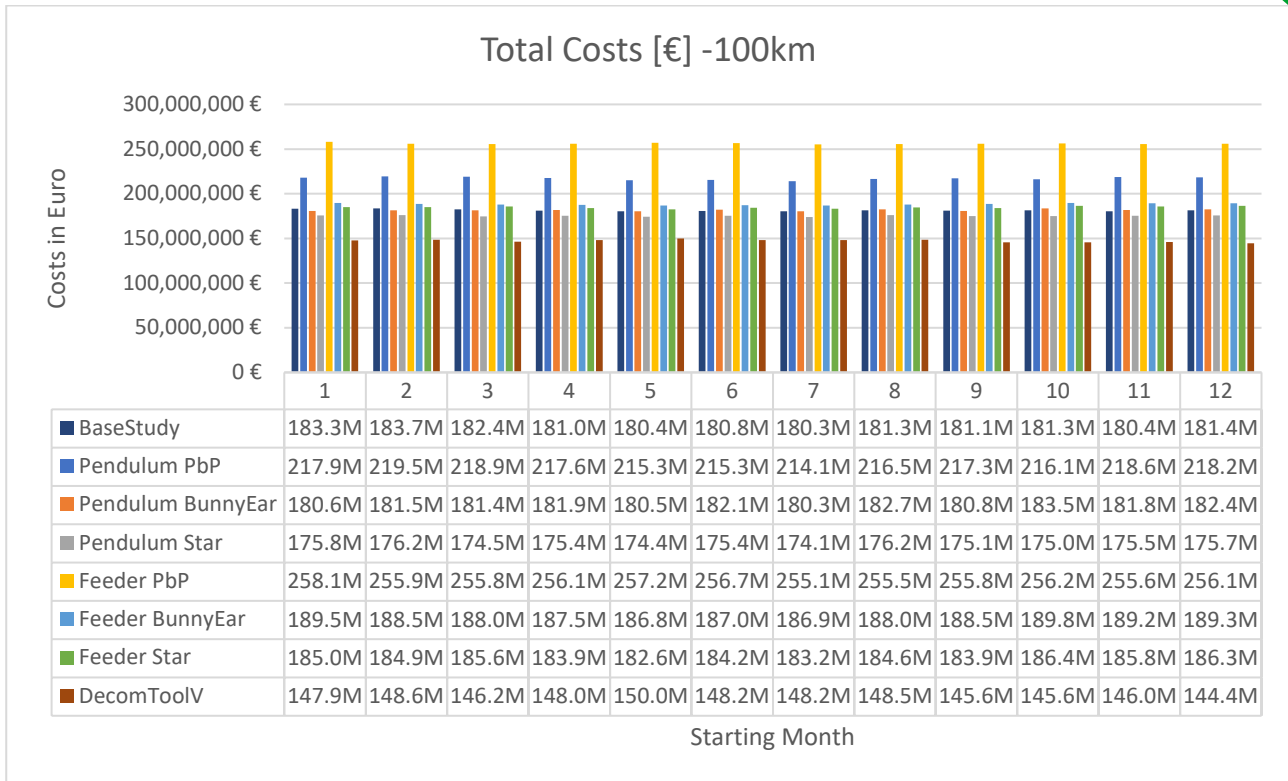


Figure 5: average costs of different configurations at a distance of 100 km over a period of one year – complete supply chain (1-12 equals the months from January to December)

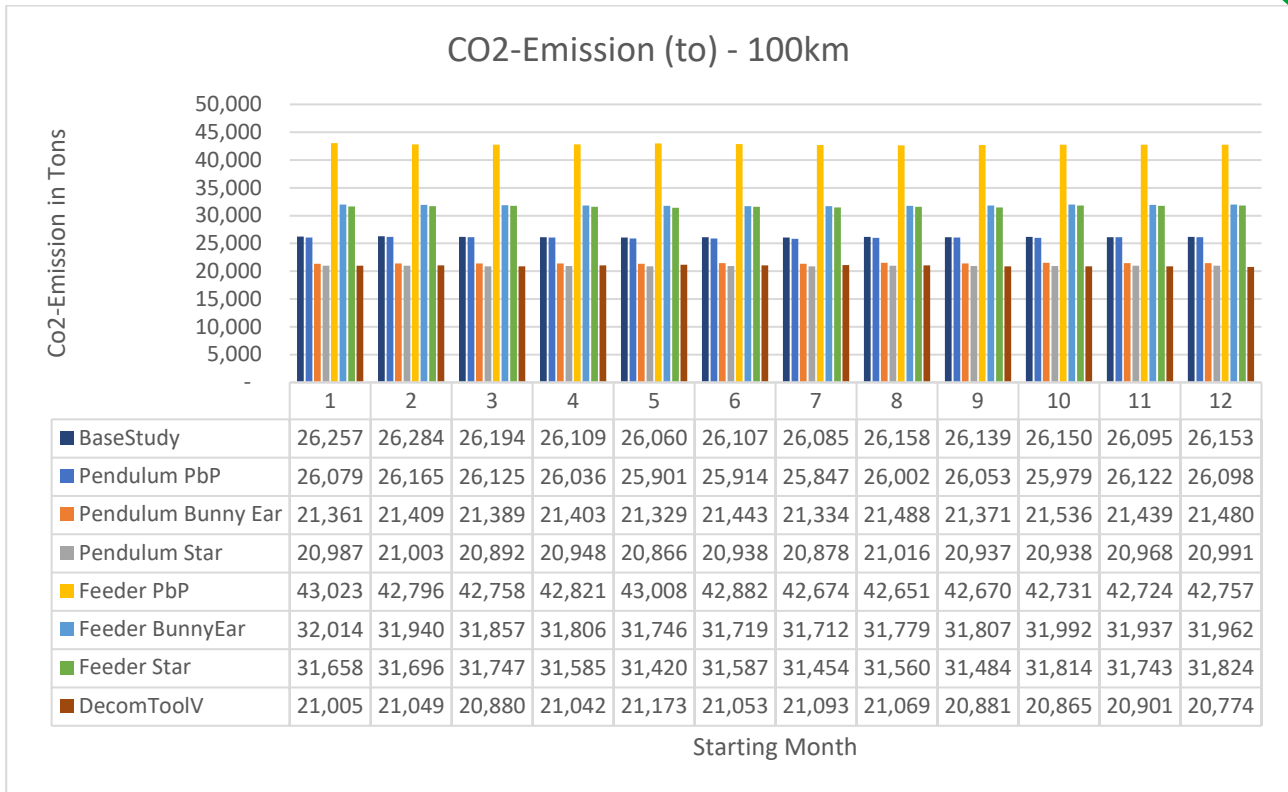


Figure 6: average CO₂-Emissions of different configurations at a distance of 100 km over a period of one year – complete supply chain (1-12 equals the months from January to December)

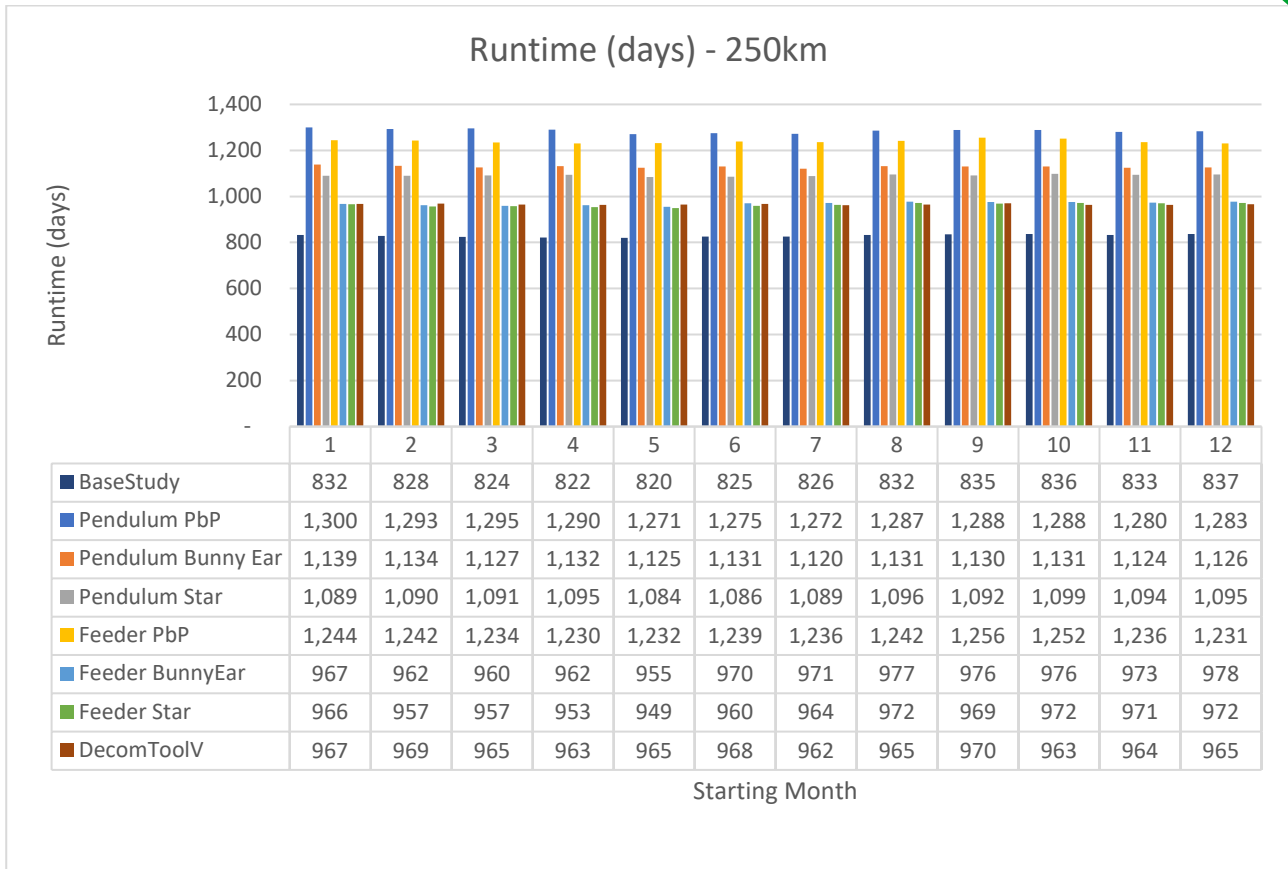


Figure 7: average runtime of different configurations at a distance of 250 km over a period of one year – complete supply chain (1-12 equals the months from January to December)



Figure 8: average costs of different configurations at a distance of 250 km over a period of one year – complete supply chain (1-12 equals the months from January to December)

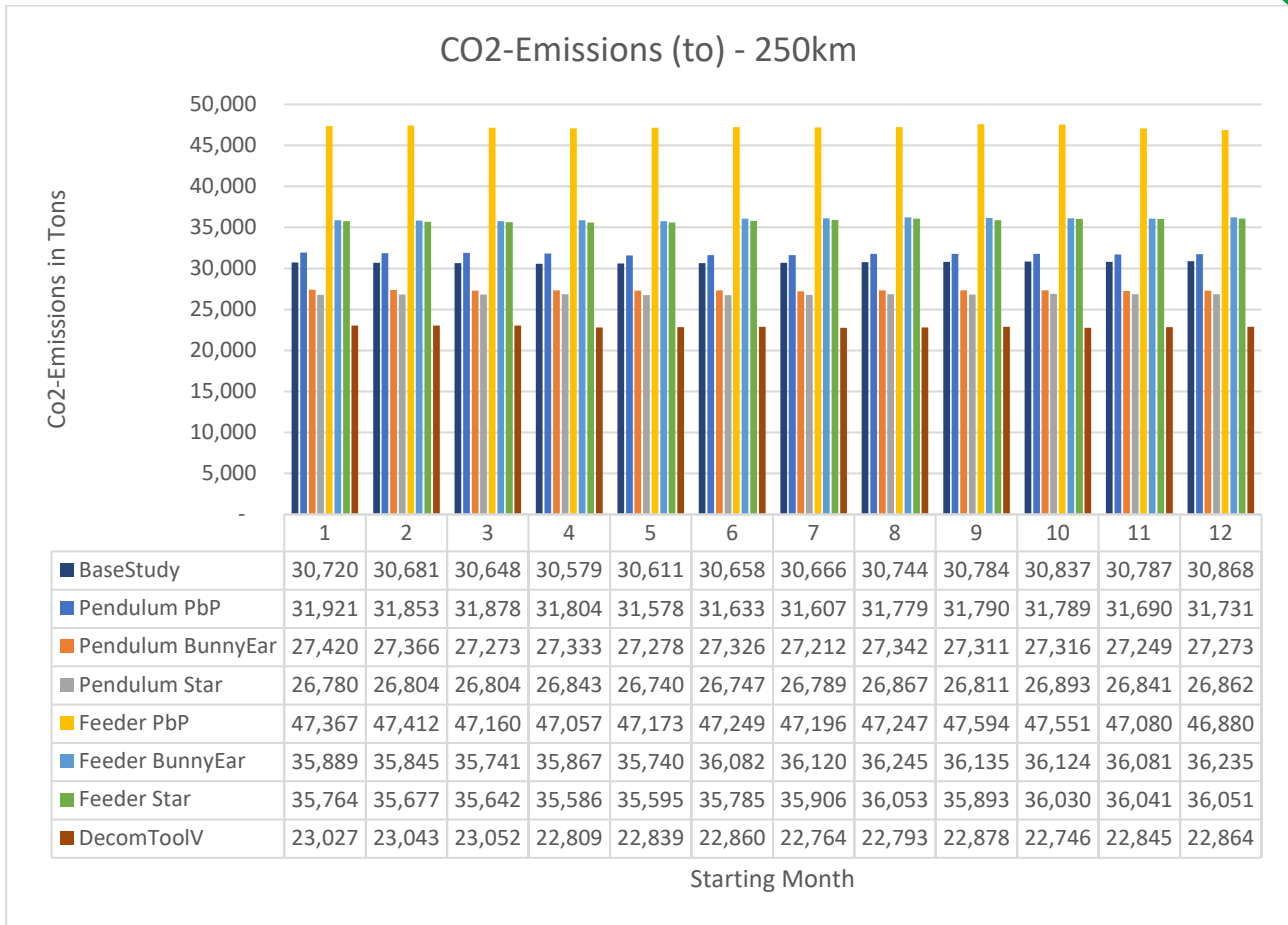


Figure 9: average CO₂-Emissions of different configurations at a distance of 250 km over a period of one year – complete supply chain (1-12 equals the months from January to December)

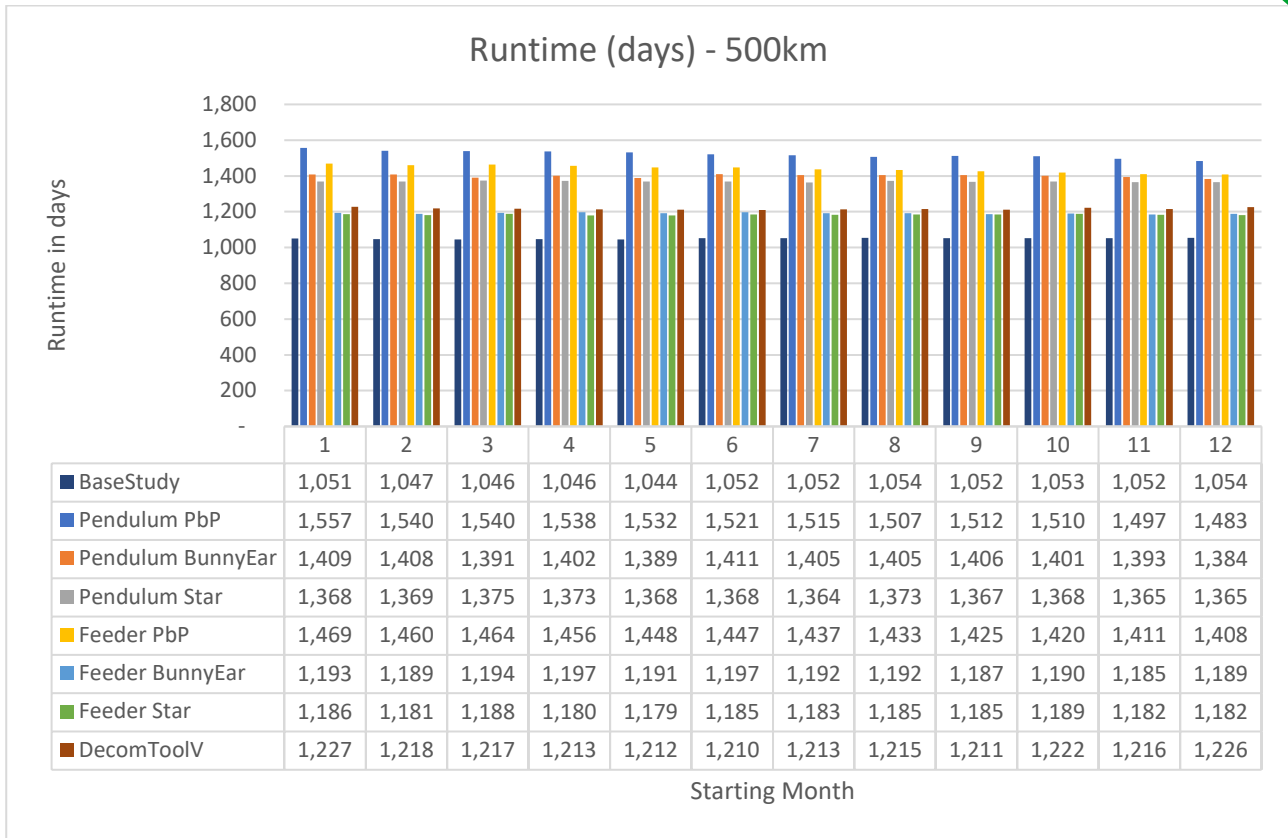


Figure 10: average runtime of different configurations at a distance of 500 km over a period of one year – complete supply chain (1-12 equals the months from January to December)



Figure 11: average costs of different configurations at a distance of 500 km over a period of one year – complete supply chain (1-12 equals the months from January to December)

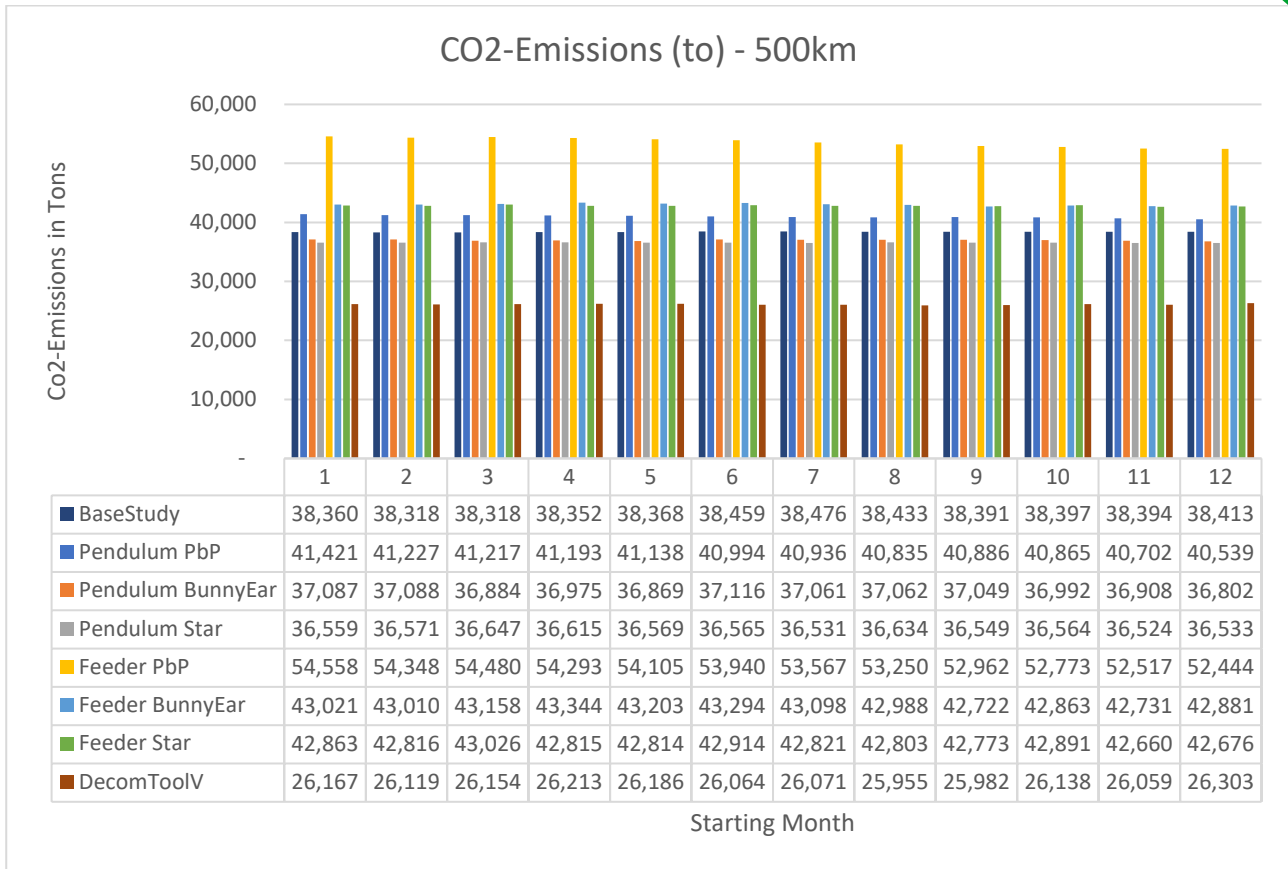


Figure 12: average CO₂-Emissions of different configurations at a distance of 500 km over a period of one year – complete supply chain (1-12 equals the months from January to December)

Appendix 2: Offshore

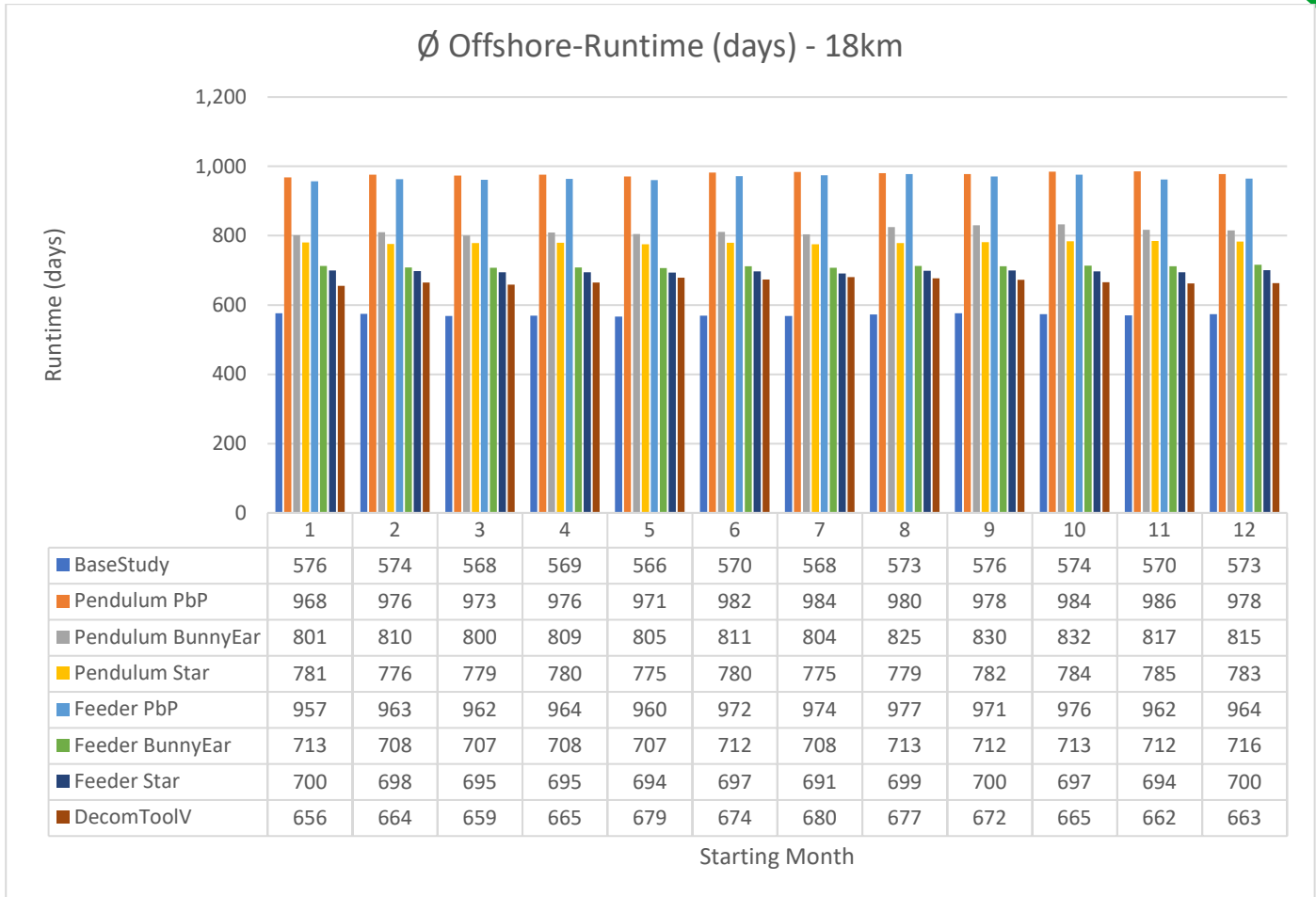


Figure 13: average runtime of different configurations at a distance of 18 km over a period of one year – offshore (1-12 equals the months from January to December)

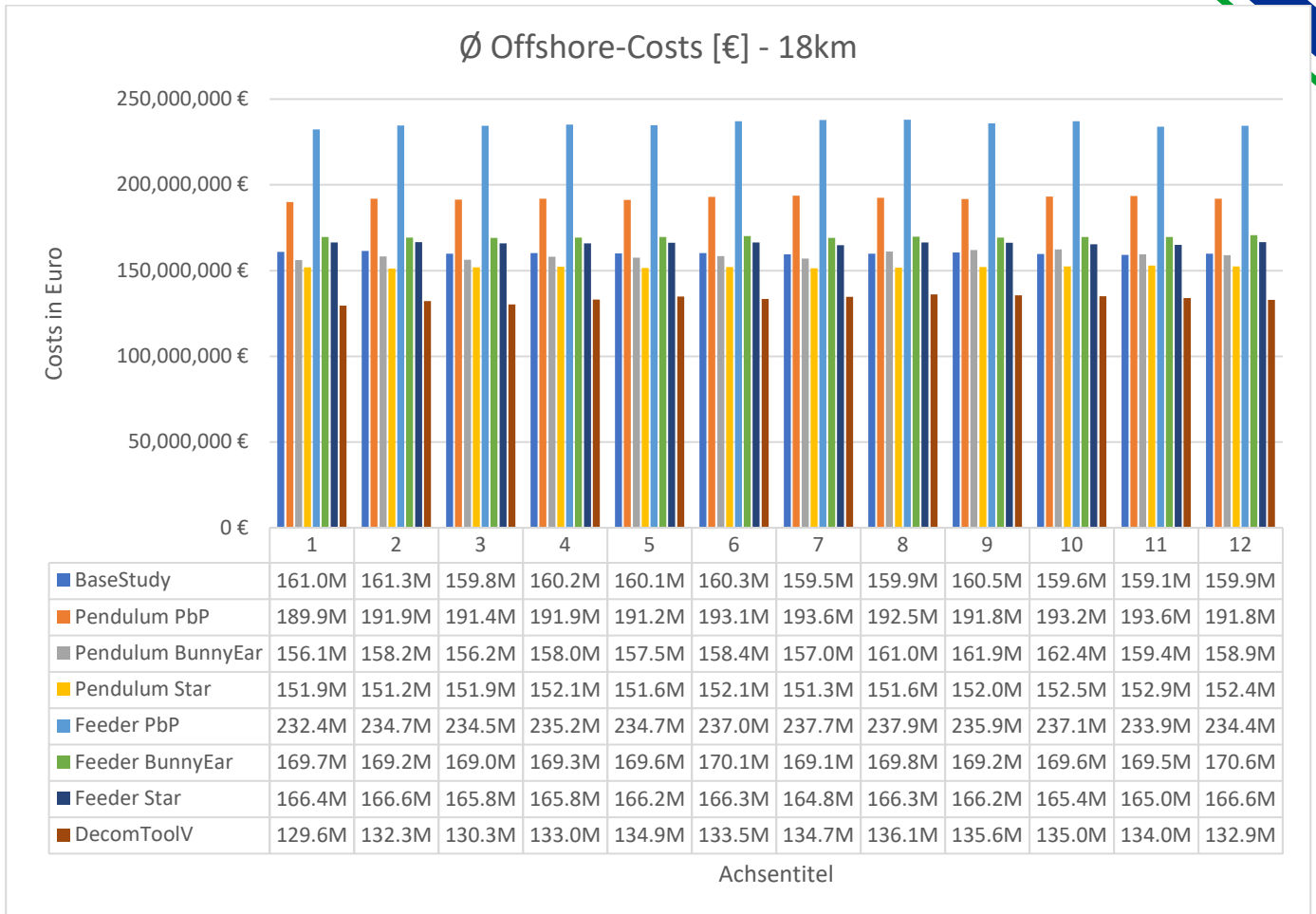


Figure 14: average costs of different configurations at a distance of 18 km over a period of one year – offshore (1-12 equals the months from January to December)

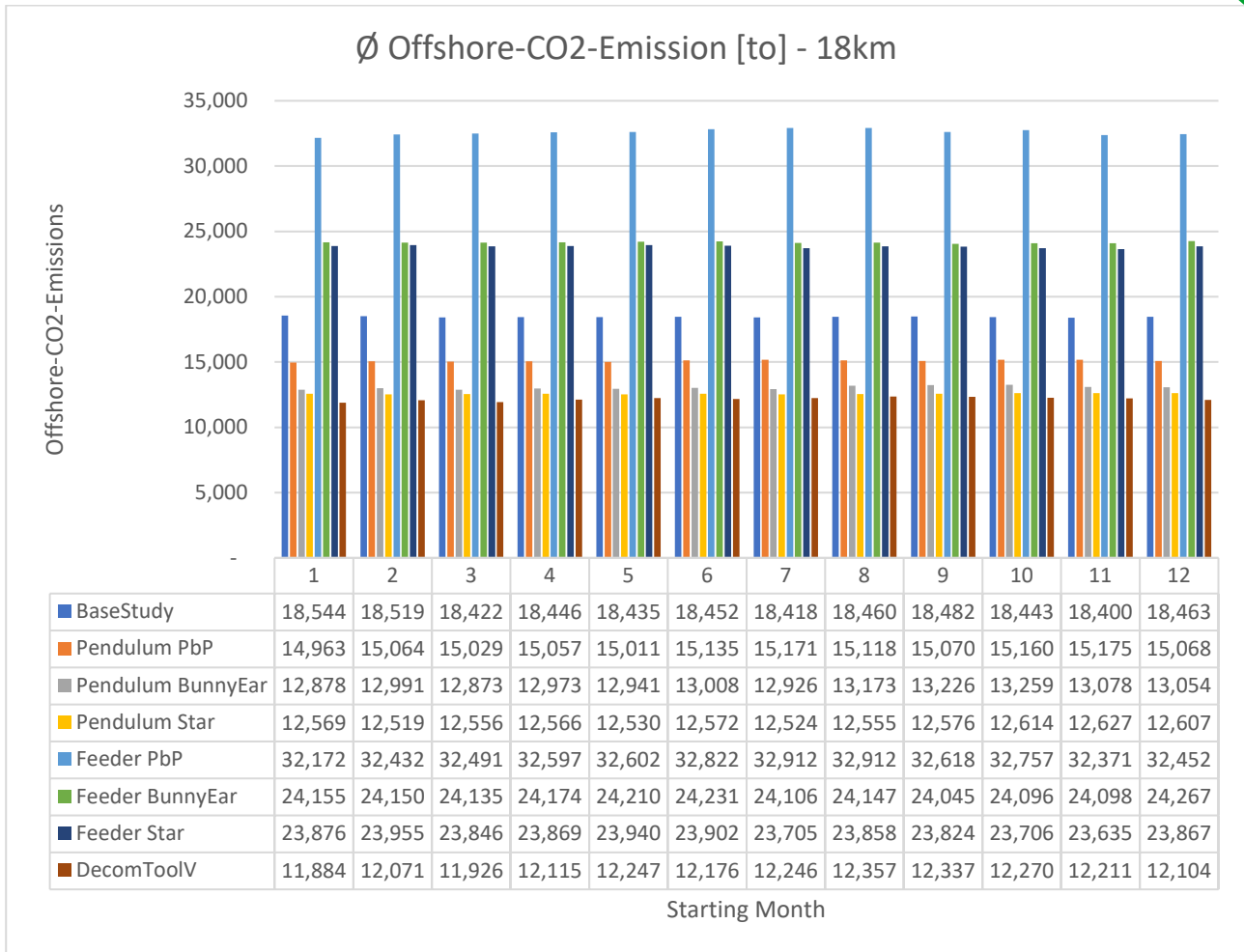


Figure 15: average CO₂-Emissions of different configurations at a distance of 18 km over a period of one year – offshore (1-12 equals the months from January to December)

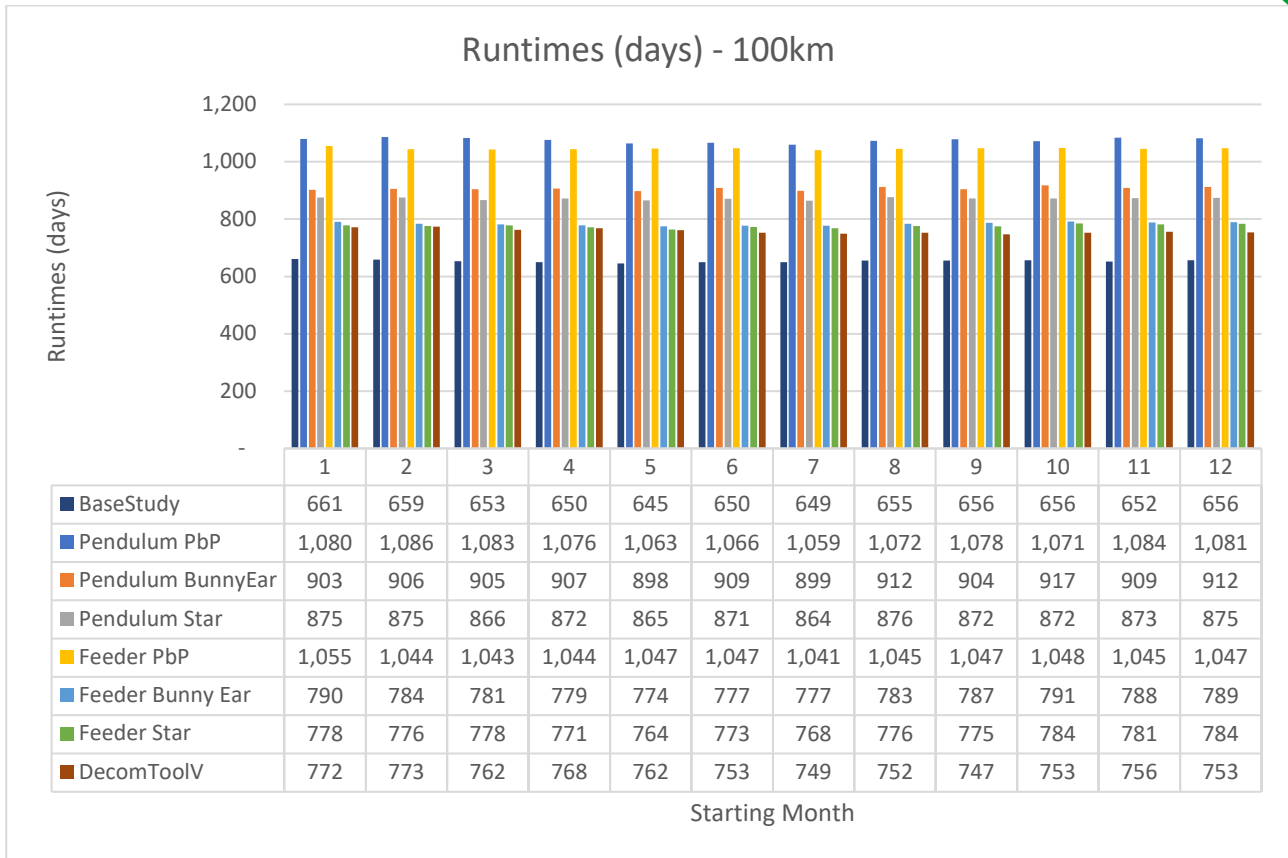


Figure 16: average runtime of different configurations at a distance of 100 km over a period of one year – offshore (1-12 equals the months from January to December)

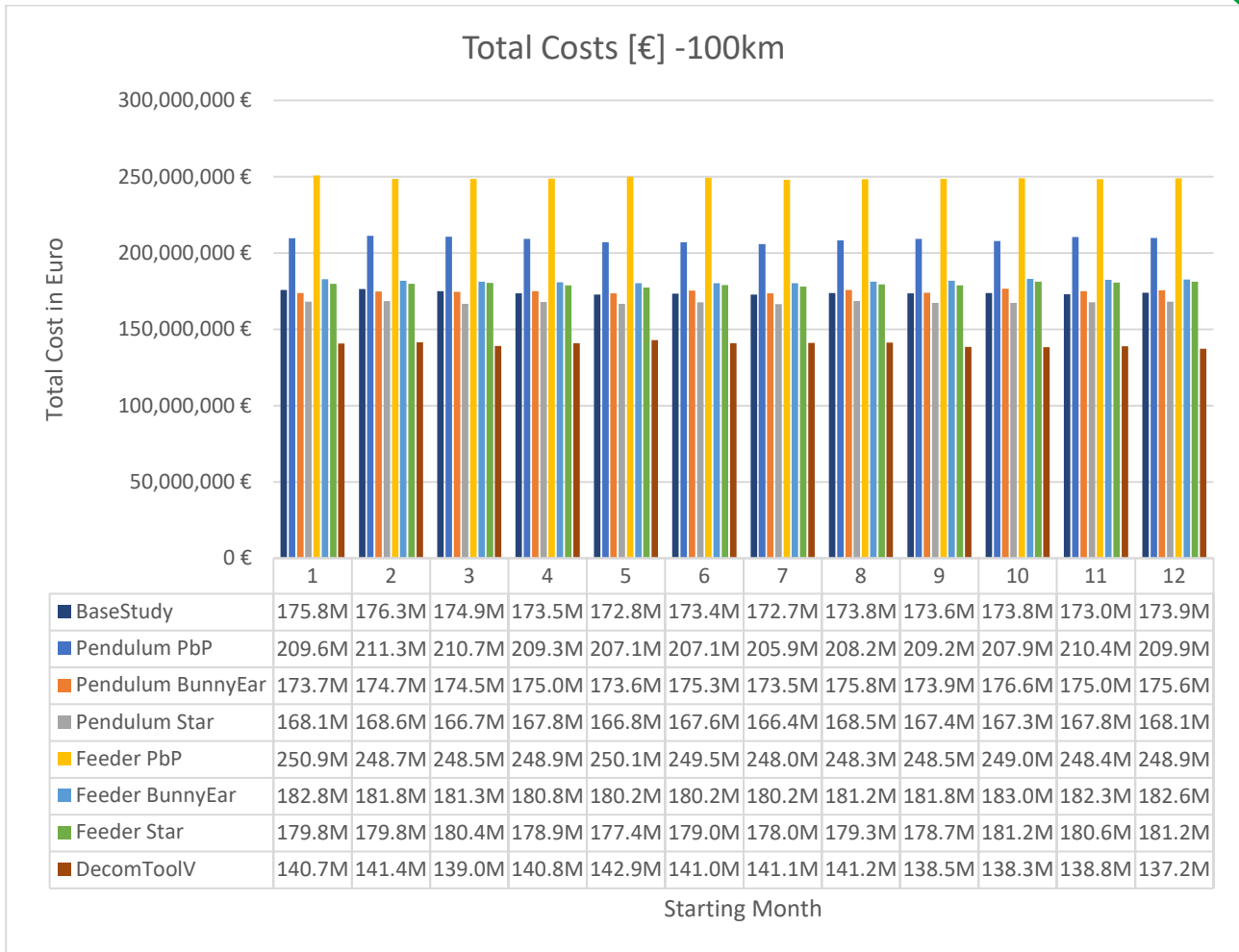


Figure 17: average costs of different configurations at a distance of 100 km over a period of one year – offshore (1-12 equals the months from January to December)

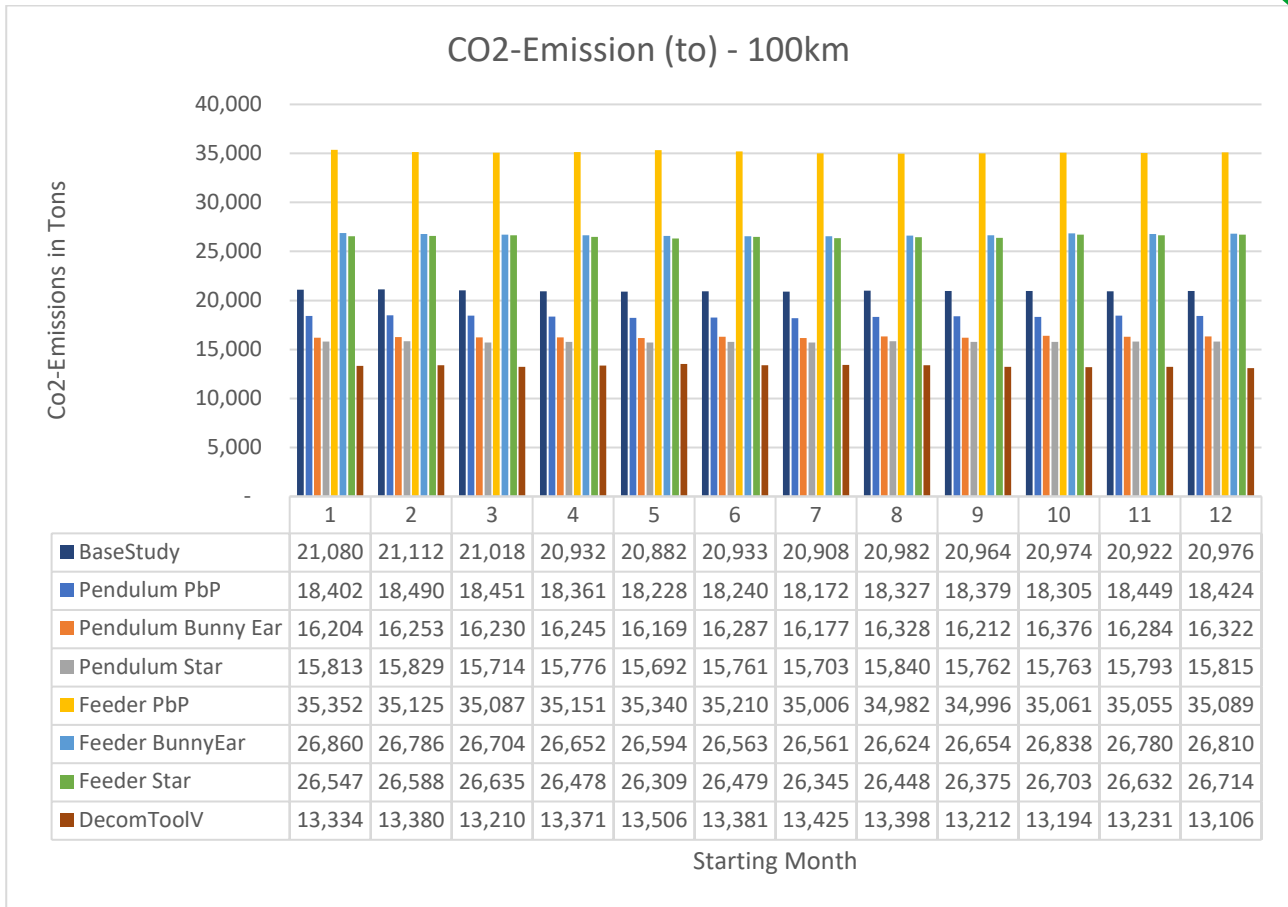


Figure 18: average CO₂-Emissions of different configurations at a distance of 100 km over a period of one year – offshore (1-12 equals the months from January to December)

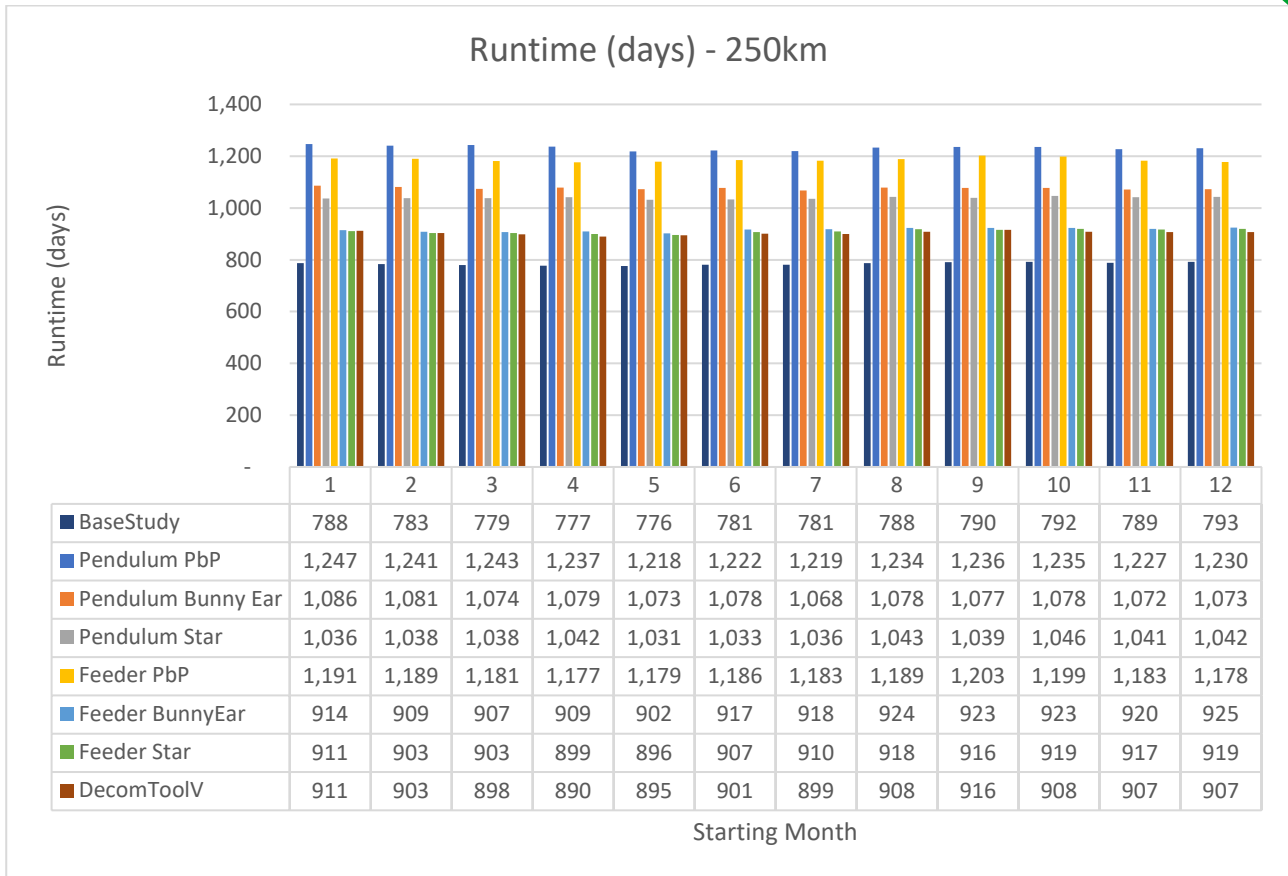


Figure 19: average runtime of different configurations at a distance of 250 km over a period of one year – offshore (1-12 equals the months from January to December)



Figure 20: average costs of different configurations at a distance of 250 km over a period of one year – offshore (1-12 equals the months from January to December)

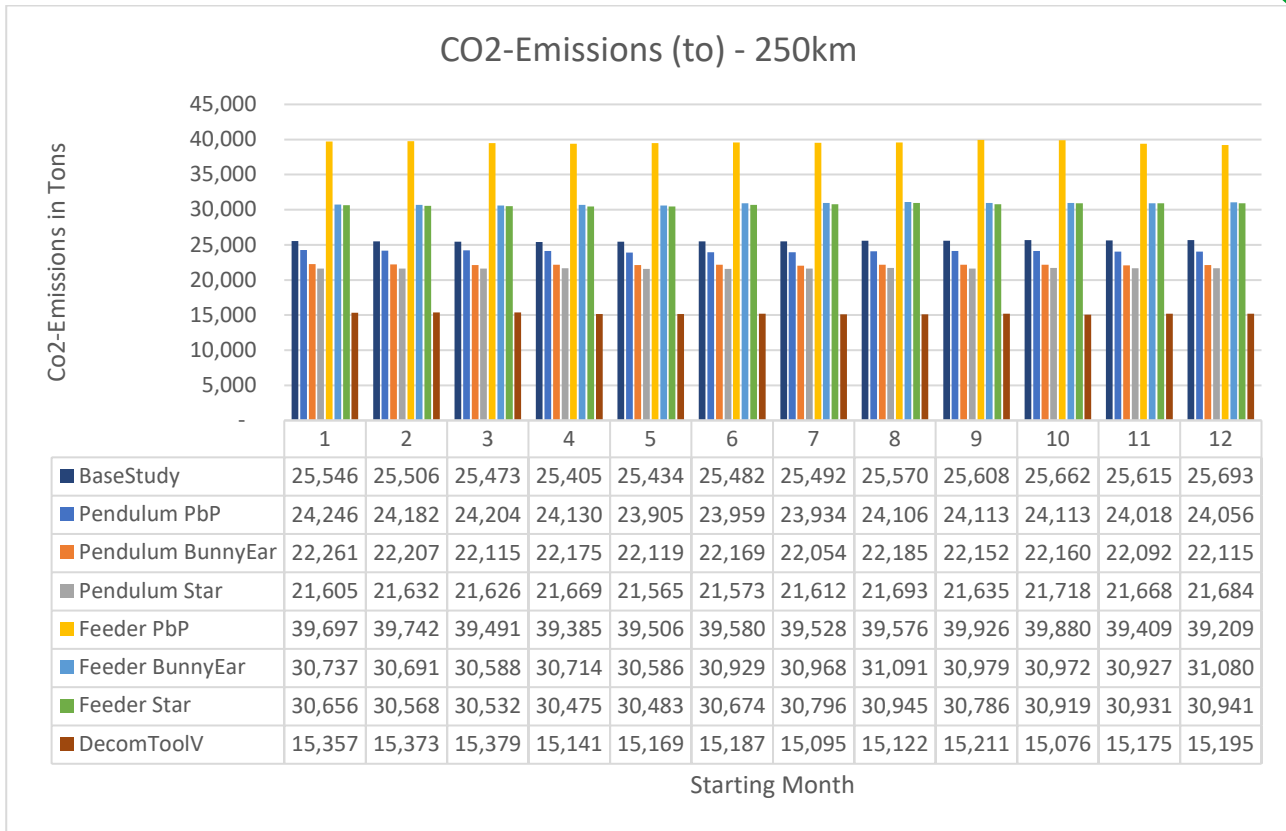


Figure 21: average CO₂-Emissions of different configurations at a distance of 250 km over a period of one year – offshore (1-12 equals the months from January to December)

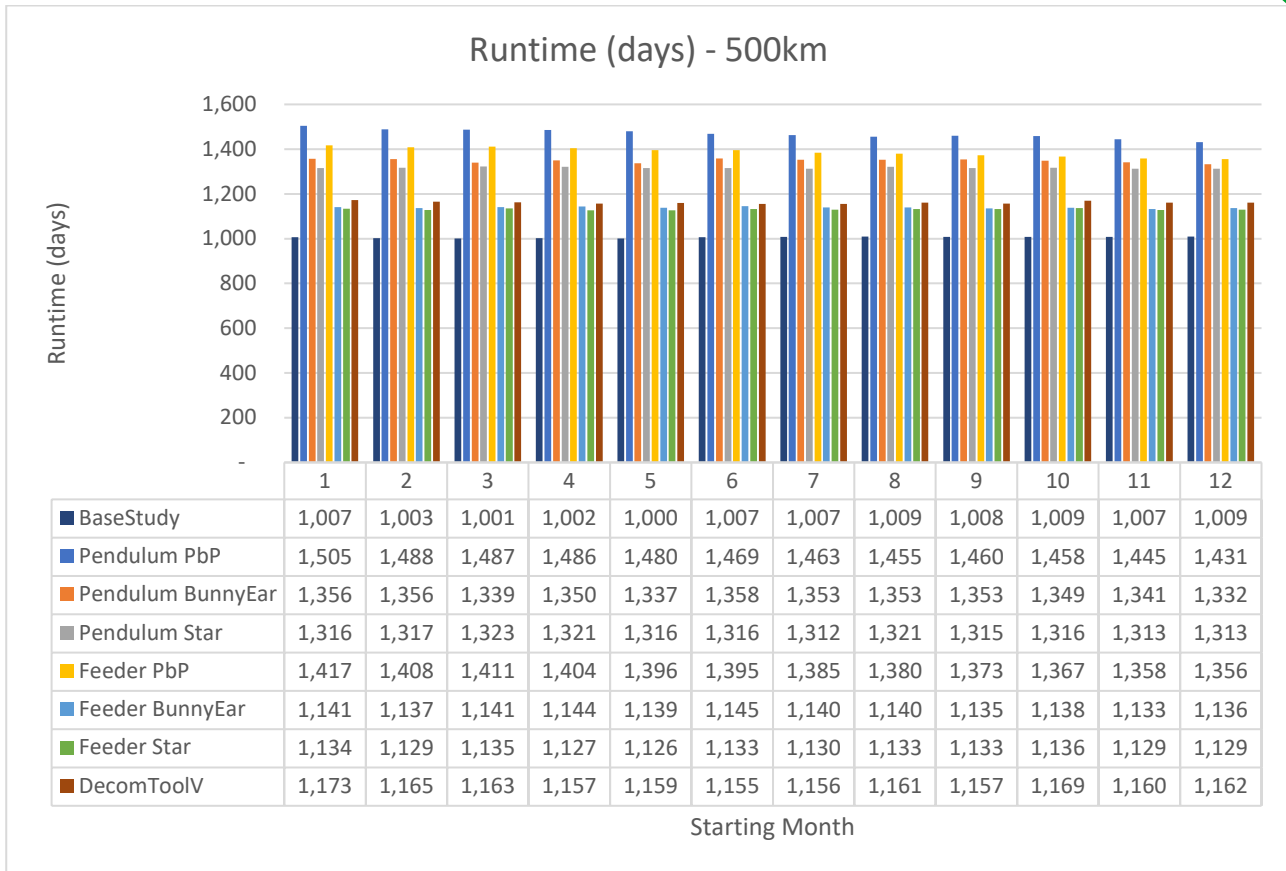


Figure 22: average runtime of different configurations at a distance of 500 km over a period of one year – offshore (1-12 equals the months from January to December)

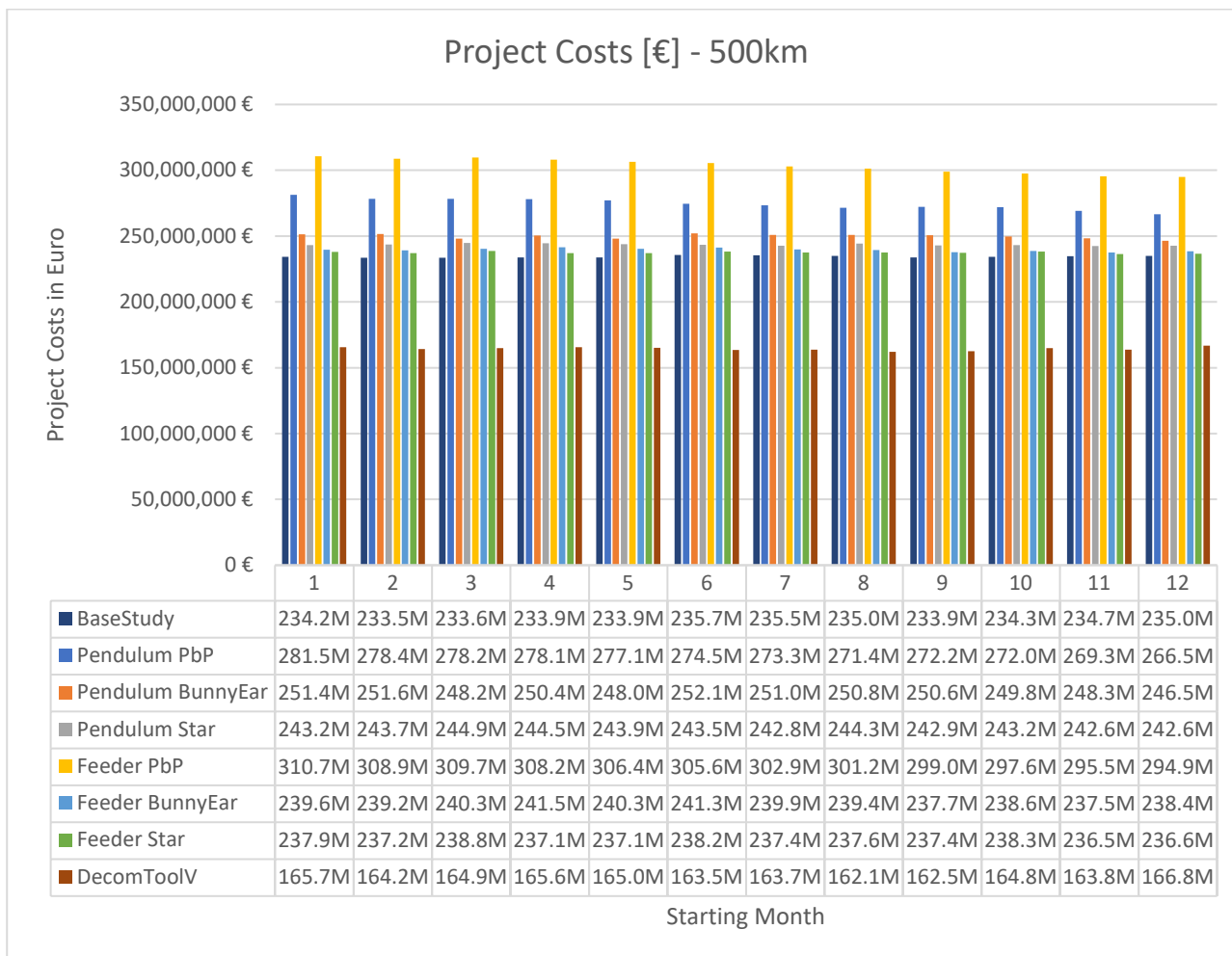


Figure 23: average costs of different configurations at a distance of 500 km over a period of one year – offshore (1-12 equals the months from January to December)

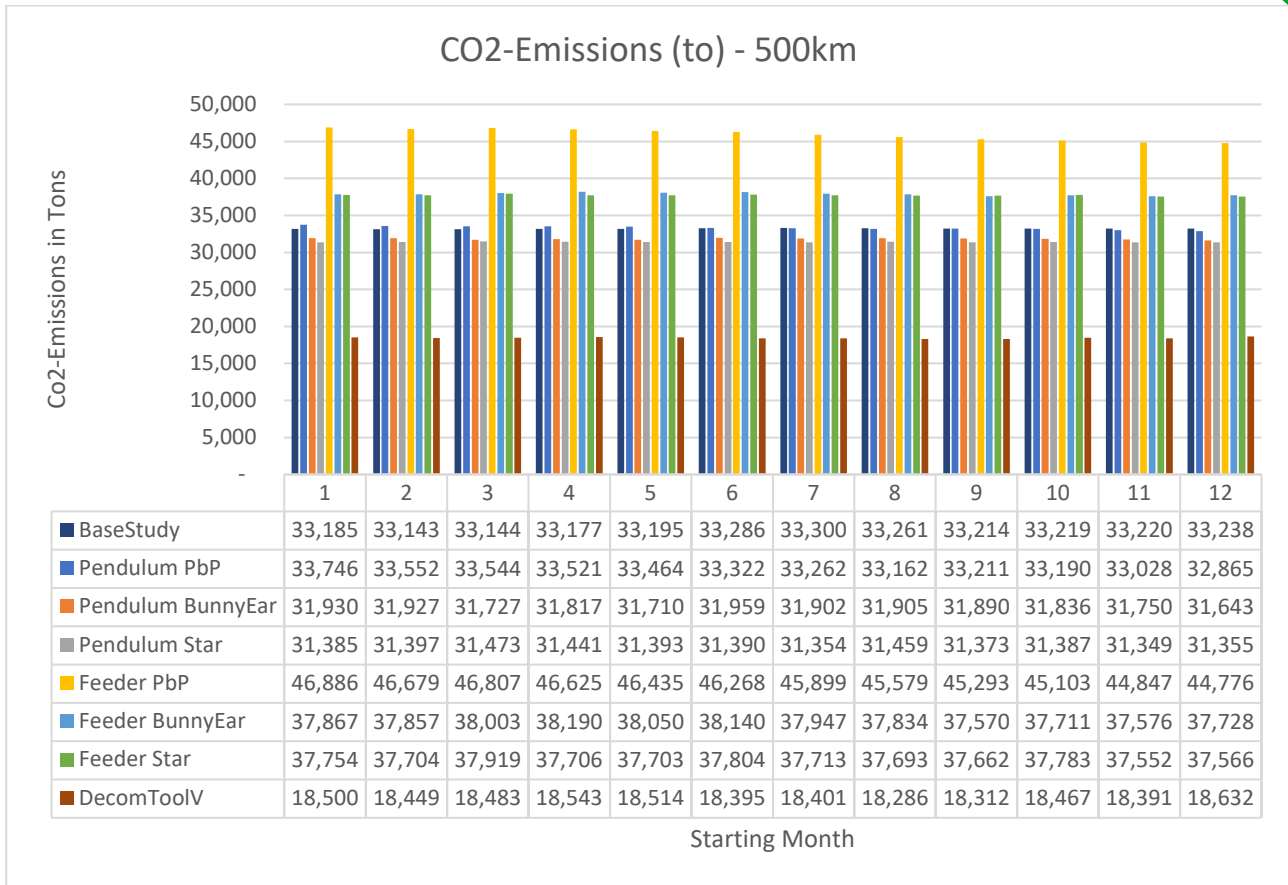


Figure 24: average CO₂-Emissions of different configurations at a distance of 500 km over a period of one year – offshore (1-12 equals the months from January to December)