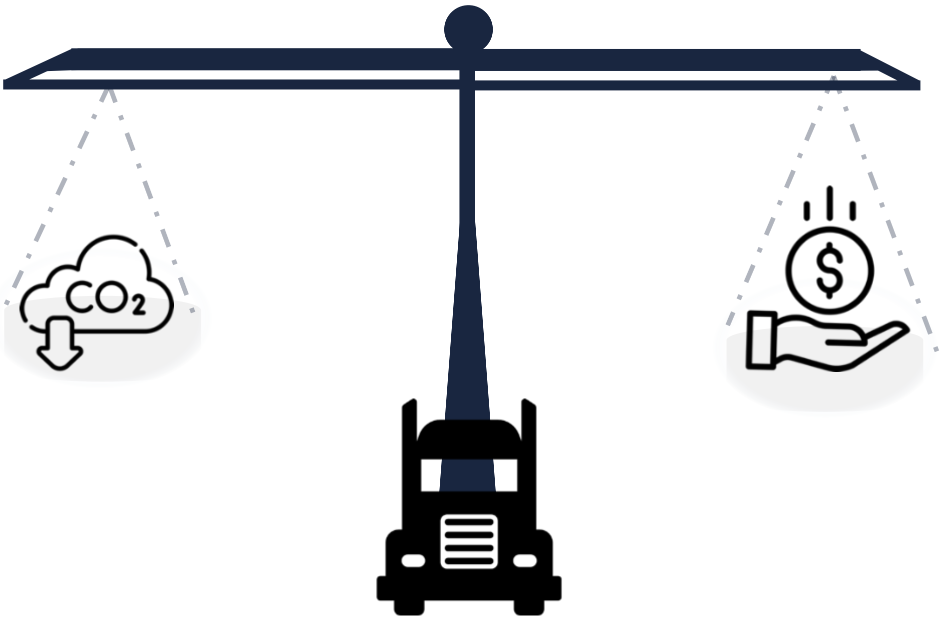
UNIVERSITETET I BERGEN

Mammoet case study: Carbon vs Cost
Analyzing optimum fleet transition to reach carbon reduction goal



Isis Hammer
GEO-SD 304
System Dynamics Modelling Process
Department of Geography
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Introduction and Reference Mode

As more information is made available to the global community about the effect of carbon emissions on the environment and the future ramifications this implies (IPCC report, 2022) an increasing number of governments have set goals to reduce their overall emissions in hopes to mitigate these effects (Paris Agreement, 2018). The Dutch government has pledged to reduce their greenhouse gas emission by 49% by the year 2030 compared to 1990 levels (Ministerie van Economische Zaken en Klimaat, 2019). It is estimated that 16% of the total emissions in the Netherlands come from transport (OECD, 2021). This brings transport to be the fourth largest source of emissions in the Netherlands, and an important sector to contribute to reducing total emissions.

Mammoet is a global leader in engineered heavy lifting and transport company based in the Netherlands (Mammoet, 2022). Their total fleet is predominantly fueled by diesel, and their trucks are their main source of emissions from their fleet in the Netherlands (Mathias Hoogstra, personal communication, November 21, 2022) The company has decided to reduce their emissions by 30% by 2030 compared to their 2021 emissions, and they are specifically concerned about their carbon emissions. (Mathias Hoogstra, personal communication, December 6, 2022). Currently Mammoet maintains their diesel fleet and is not reducing their emissions from their fleet in any other way. Considering their goal, this is a problem for the organization. By maintaining their current carbon emissions and diesel fleet they will not be able to reach their 2030 goal. This information was used to create a reference mode of feared behavior which is shown in Figure 1 and 2.

Figure 1: Feared carbon Emissions Reference Mode

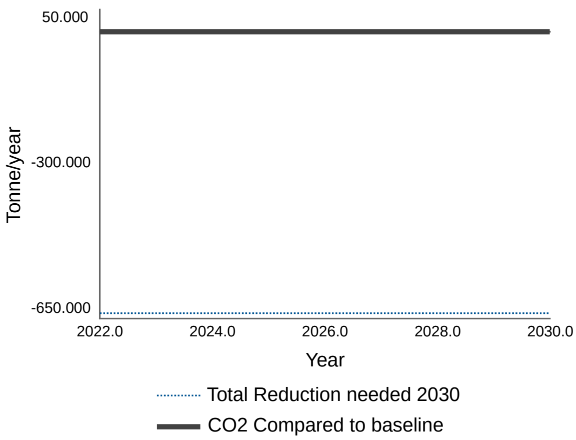
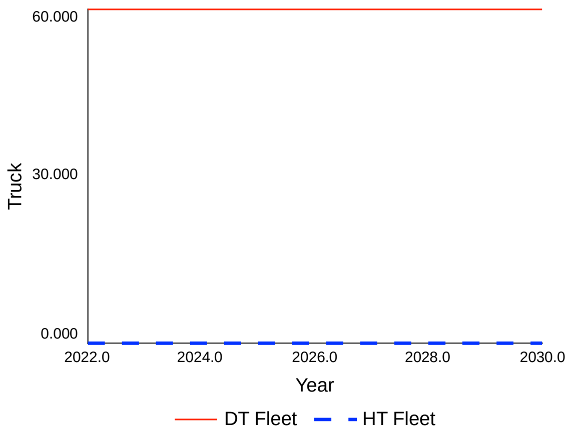


Figure 2: Feared Fleet Reference Mode

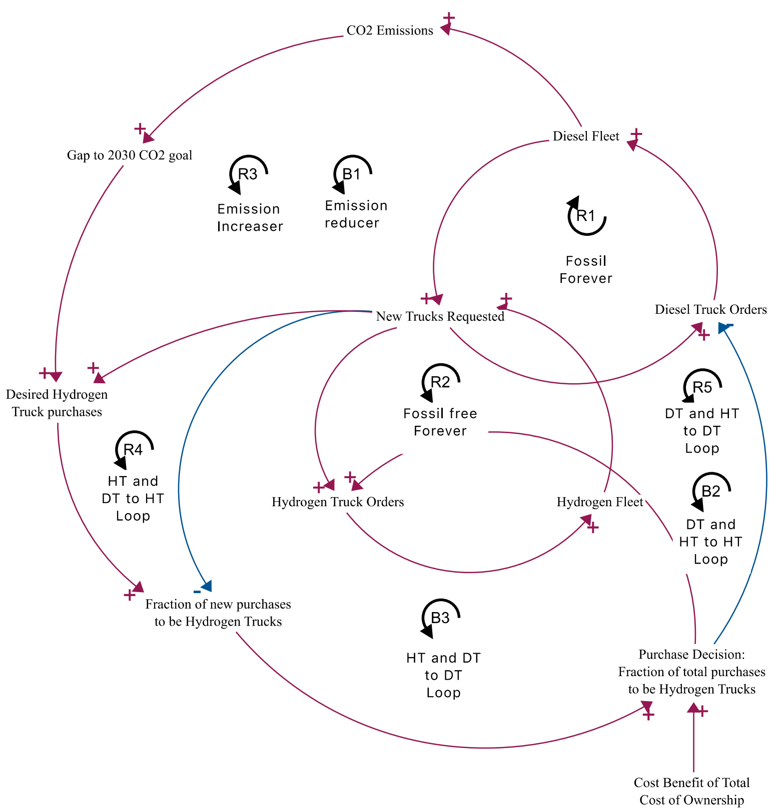


Green hydrogen is perceived to be the only viable long-term alternative to their diesel trucks (DT) besides alternative drop in fuels like Hydrogenated Vegetable Oil (Mathias Hoogstra, personal communication, November 21, 2022). The company does not see drop-in fuels as true sustainable alternative to diesel and they require more information about hydrogen. The aim of this problem analysis is to help the company understand the dynamics and consequences of their decision space, and what decisions will help them reach their emission reduction goal at the lowest cost.

Hypothesis

The company makes an implicit decision each time they purchase a DT: They choose not to buy a hydrogen truck (HT). Each year the company has access to information about their emissions in their yearly report as well as the costs of hydrogen and HTs. The dynamics of this problem surround the purchase decision the company makes each year. Mammoet's company policy currently states that their DTs are sold ten years after purchase. A new truck is purchased to replace the old truck within the same year. The same policy would be in effect if they maintained a fleet of hydrogen trucks (HT).[6] This information has been translated into a 'Fossil Forever' and 'Fossil Free forever' loop in the CLD structure in Figure 3. The sale of a truck causes a request for a new truck which leads to an order.

Figure 3: CLD Structure



Each year they measure their emissions and compile a report. Currently the company decides that every new purchase is a DT despite their level of emissions. A policy needs to be introduced to decide what fraction of new purchases will be HT to change this. Currently the purchase decision fraction is zero since no HT are purchased.

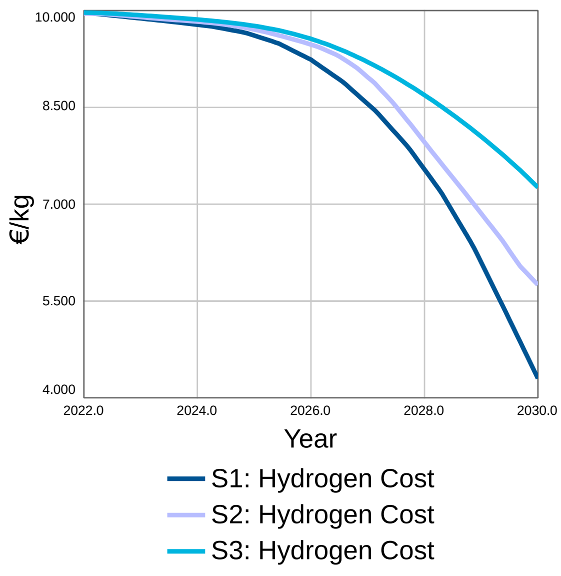
The hypothesis of this analysis lies in the additional structure which informs the decision regarding what fraction of new trucks are HT. This hypothesis assumes the company can track their progress towards their goal based on information in their yearly report. By tracking how many tonnes of carbon dioxide they need to reduce, and the number of diesel trucks responsible for this amount of carbon dioxide, Mammoet can calculate how many hydrogen trucks they should purchase. Since they also have information about the number of new trucks that are requested each year, they can calculate what fraction of new trucks should be hydrogen. This informs their decision and decides how many of the truck orders are HT and how many are DT.

The loop 'Emission reducer' emerges from this structure, which decreases the level of emissions when active. 'Emission Increaser' does the opposite when the company emits less than their desired level of emissions. The other loops act antagonistically. The effects of B3 and R5 are entangled in the variable 'New Trucks Required'. When trucks from the HT fleet and sold and a new truck is requested, in B3 this results in reducing the number of new hydrogen trucks purchased, but this decrease results in an increase in diesel trucks in R5. The same counts in the opposite direction for B2 and R4.

Since the company aims to maximize profits, their decision can also be influenced by the cost benefit of purchasing HT. Since HT will be more expensive to own than DT in the duration until 2030, this decision will always be to only buy DTs. A weight is used to test the dynamics of the priority the company gives to reaching the goal or maximizing profit.

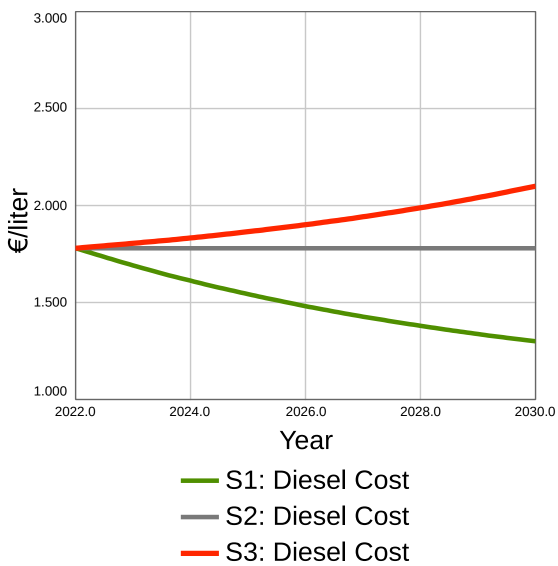
Assumptions

Figure 3: Hydrogen Price Scenarios



The model assumes that hydrogen fuel prices will decrease from ten euro per kilogram to between five euros and forty cents and seven euros and twenty-six cents (Leguijt, C., Rooijers, F., van den Toorn, E., 2022). Three scenarios are implemented to test the effect on total cost of ownership of a HT as shown in Figure 4. Scenarios are also made to test the effect of changes in diesel prices. The average price of a liter of diesel in the Netherlands was calculated using an archive of data.[7] From this baseline the price was decreased, kept stable and increased between 2022 and 2030 as shown in Figure 5. This affected the total cost of ownership of DTs.

Figure 4: Diesel Price Scenarios



The total cost of ownership was also based on estimates, and considers the purchase cost, fuel cost, maintenance and sales value. The purchase cost of HTs is expected to also decrease: This is included in the form of a table function based on visual data (ICCT, 2022). The model assumes that market demand, employee resistance, innovation progress and access to hydrogen fuel does not affect the decision. Other assumptions include that every DT emits the same amount of carbon dioxide each year, that the company has an infinite budget, and that truck are always sold for the same price. These assumptions were made to focus on the dynamics of elements of interest to the company currently: Their response to estimated prices and information about their emissions.

Validation and Sensitivity Analysis

Structure confirmation test

The structure of fleets was based on the processes described by the company. The additional structure representing the emissions feedback to the purchase decision was hypothesized by the author, described to and validated by the contact at Mammoet (Mathias Hoogstra, personal contact, December 15, 2022). The structure was considered realistic and the information is accessible for the company. Additionally, the assumption that the company would not invest in HTs if the cost is higher than DTs without considering the emissions goal was also validated.

Parameter confirmation test

The parameters used were sourced from Mammoet, online estimates from reliable sources or estimated by the author and checked with the company (Mathias Hoogstra, personal contact, December 15, 2022). The 'time to report' was adjusted after feedback from the company. The assumption that the company would not invest in HTs if the cost is higher than DTs without considering the emissions goal was confirmed. The main liability of this analysis are the estimates of prices. However, these assumptions allow the model to reveal the dynamics of the company's decision space which is the aim of the analysis.

Extreme condition test

An extreme condition test was conducted and revealed no unexpected behavior.

Dimensional consistency test

The units of the model are consistent with the equations. This is confirmed by the Stella software used for this analysis.

Integration error test

The model was tested for integration errors. Given the important of the number of trucks purchased and sold, and the oscillatory behavior of the model as a result of the information delay, RK4 was selected at 1/32.

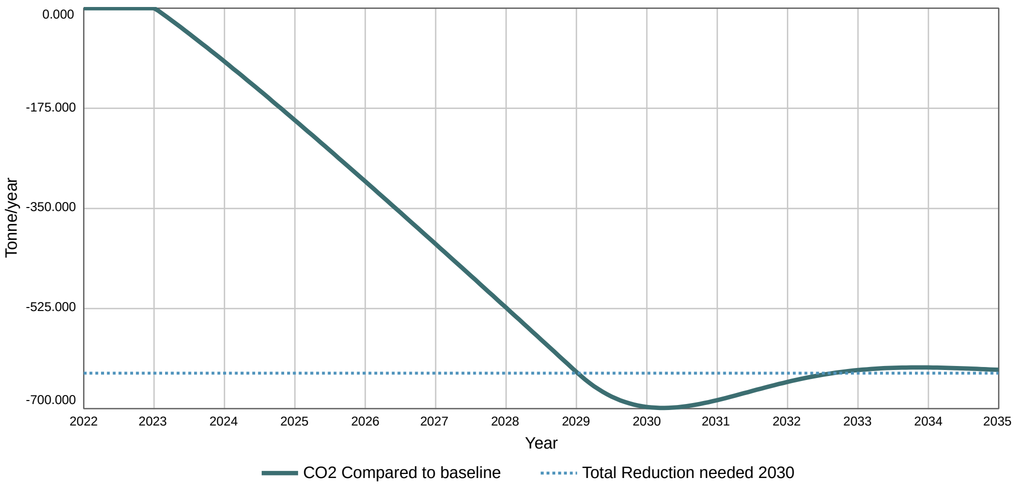
Behaviour sensitivity test

The model behavior was appropriately sensitive to parameters and did not reveal unexpected responses.

Model analysis

The first model run was done with the weight of focus completely on reaching the emissions goal, the policy switch on, the policy start time at 2023 and both fuel scenarios on scenario two (HS2 and DS2). The carbon reduction result can be seen in Figure 6.

Figure 6: Run 1 Emission Reduction Result



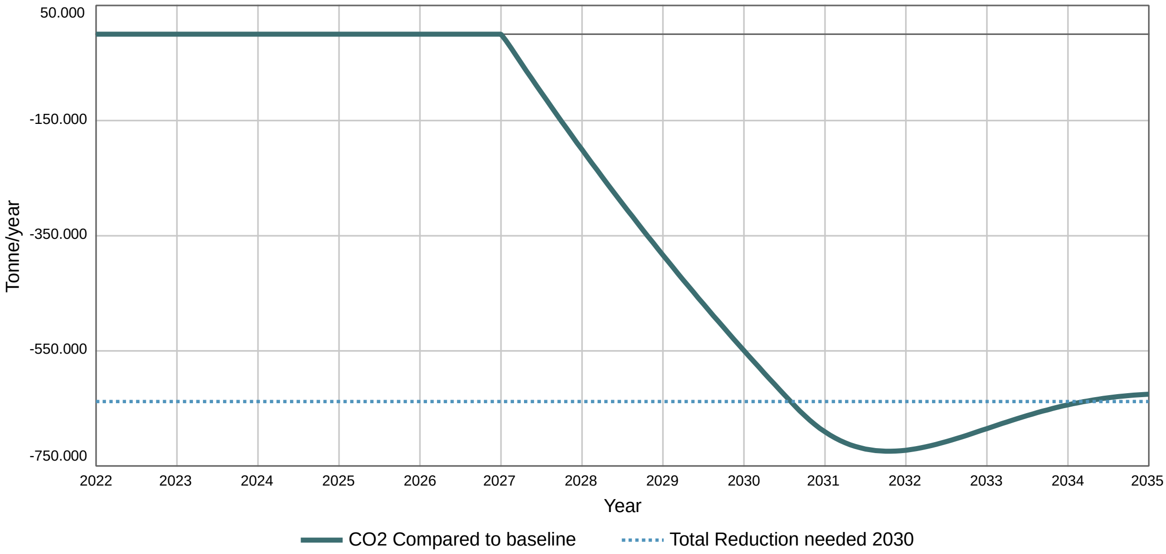
The behavior shows that between 2022 and 2023 the 'Fossils forever' loop is dominant before the policy is active. This analysis also reveals a steady decline in emissions revealing that the 'Emission Reducer' loop is strongest between 2023 and 2029. However, once the emissions are reduced below the desired level, as a result of the delay of data reporting, the 'Emission increaser' loop gains strength, but is not dominant. In 2030 the 'Emission increaser does become dominant, and the emissions increase towards the desired level. These two loops create a dampening oscillation that tends towards the desired level of emissions. When the Emission reducer loop is dominant, the 'Fossil free forever' loop, 'HT and DT to HT' loop and 'DT and HT to HT' loops strengthen the effect of the dominant loop. Oppositely, when the emission increaser is dominant, the 'Fossil forever' loop, 'DT and HT to DT' loop and 'HT and DT to DT' loop strengthen the effect of the dominant loop.

This analysis also shows that this decision would cost the company roughly 26.8 million euro extra by 2030. When adjusting the fuel scenarios in a second run to a small gap in prices (HS1 and DS3), this cost drops to an additional 24.8 million euro. And in a third run when the fuel scenarios are switched to a large gap in prices (HS3 and DS1) the additional cost increases to 29. million euro.

This analysis shows that the company can reach their goal gradually, but it would cost roughly over 25 million euro. The analysis also reveals the effect that using the report data has on the stability of the behavior once they reach their goal. This oscillation increases the cost of reaching the goal in run 3 from 29.7 to 36 million euro.

The second set of runs was conducted to test until what year they can introduce a policy and reach the goal, given they focus completely on reaching the goal and the fuel prices are at their average levels (HS2 and DS2). The latest they can implement a policy and reach the goal is 2026. The result of their carbon reduction is shown in Figure 7.

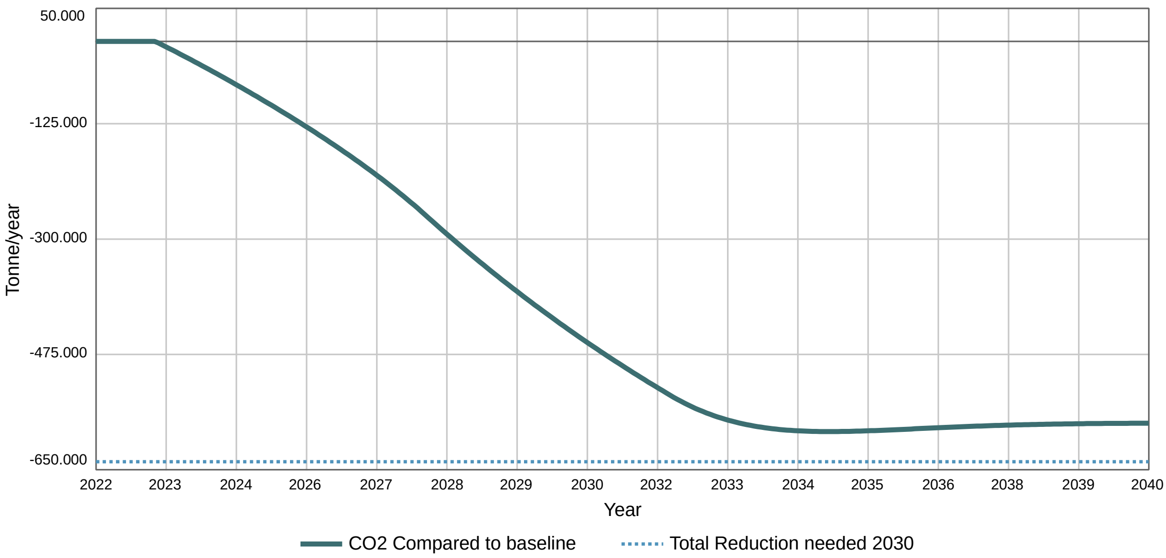
Figure 7: Run 4 Carbon reduction result



The behavior shape does not change, but the structure drives stronger behavior resulting in a steeper slope of decline in emissions. The same oscillations occur, but are slightly larger as a result of the same stronger behavior. This shows that the effect of policy start year on how much the emission reductions are spread out across the policy time period has a strong strengthening effect on the 'Emission reducer' loop. The additional cost resulting from this decision sums up to 20.3 million euros by 2030. This increases to 25 million by 2035 as a result of the oscillations. When the fuel price gap is small (HS1 and DS3) this drops to 17.8 million in 2030 and 20.6 million in 2050. This increases to 23.9 million and 30.7 million respectively if the fuel price gap is large (HS3 and DS1).

A final set of analyses were done to test what the consequence would be if the company would give 50% focus to the goal and 50% focus to the cost and start the policy in 2023. The fuel prices were at HS2 and DS2. The result of the emission reduction is shown in Figure 8.

Figure 8: Run 7 emission reduction result



The behavior is different to the previous runs. The decline in emissions is not a constant slope. The slope increases as the goal deadline approaches. This is explained by the dampened effect of the 'Emission reducer' loop by increasing the weight on cost priority which desires all new trucks to be diesel trucks. Another interesting change is that the emission reduction settles above the desired level of emission reduction. The time horizon was extended to examine the behavior further. This difference is also caused by the dampening effect of the lower weight on the goal. The effect weakens the 'Emission reducer' loop to the extent that it does not retain its strength to continue a decrease beyond a certain point. When the weight is increased, the emissions are reduced more, and when the weight is reduced further, the emissions are reduced less. In this run the additional cost amounts to 15.6 million euro. In this case they do reduce their emissions significantly, but fail to reach their goal by 2030, or any year after that. With a small gap between the prices (HS1 and DS3) the cost is 14.3 million, and with a larger gap (HS3 and DS1) the cost rises to 17.6 million euro.

Policy

The model analysis was conducted to support policy making by building understanding about the dynamics of the decision space. The results of the analysis remain speculative and are not purposed to provide certainty. The following insights from the model and the analysis were considered during policy making.

Insight 1: Implementing a policy closer to the goal allows the price of hydrogen and HT purchase cost to decrease. This lowers the total cost of ownership, and in turn the additional cost resulting from reducing emissions. However, there is a limit to how long the company can wait to still be able to reach their goal,

Insight 2: To reach the goal the company must sacrifice profit.

Insight 3: If the company does not change their focus from costs to reaching their goal, they will not reduce their emissions from their fleet of trucks sufficiently by 2030 to reach their goal.

Insight 4: 18 trucks are responsible for 30% of their emissions.

Additional real-world consequences of these insights were also taken into consideration:

1. Implementing a policy later, and investing in a technology that is still in early stages of market adoption late can also restrict the availability and progress of the technology. In this case hydrogen trucks, and the infrastructure for hydrogen fuel.

2. Another consequence is that implementing this policy later would lead to a period of only hydrogen trucks being added to the fleet. Investing in one technology for any period of time can be a risk, especially when it's a new technology, though the same could be said for continuing investments in only diesel. Another implication is that there is a shorter period of time to encourage adoption within the organization: With specific focus on the drivers of the trucks.

3. The company is likely to prioritise profit. However, this model does not factor in demand and the insights into decreased profits due to market share lost due to not offering emissions free heaving transport services.

4. It is tough to change one person's opinion: To do so for a whole company in a short period of time is even more challenging. Issuing a management of change project would add additional cost. Not doing so and expecting employees to accept a policy change without management can lead to other consequences such as a higher

resignation rate due to not feeling aligned with the organizations mission. It is important for the company to assess the effect of their organizational culture when it comes to fossil fuels and emissions reduction.

5. An easy fix would be to get rid of 18 diesel trucks, but this would cost the profits of those trucks. This strengthens Insight 1 from the analysis, that reducing the emissions will always cut profits.

Three optional policies were creating considering these insights, each weighing different costs and benefits. The three policies are the Heavy Lift the Goal policy, Hope for Hydrogen policy and Fossil Forever policy.

Policy 1: Heavy Lift the Goal

This policy would lead to decision to reach the goal, but to minimize the cost on hydrogen technology the policy is implemented in 2026. They will put a heavy focus on reaching the goal and reduce their emissions rapidly while solely investing in hydrogen trucks until 2030 when they can return to maintaining their fleet. By following their exact calculations, they could ensure that they avoid the oscillations in their diesel fleet, by switching to maintaining each fleet by replacing HT with HT only and DT with DT only.

This policy would need support from the organization to ensure the policy is not a shock to the perceived culture for the drivers in the years leading up to the policy. Another important implication of this policy is that Mammoet should be in contact with producers of HT and hydrogen fuel suppliers. Since the emission reduction goal could also be important for their market share, it is important that Mammoet's clients are aware that they will honor their goal and reduce their emissions.

Policy 2: Hope for Hydrogen

If Mammoet adopts this policy they would implement it as soon as possible to start investing in hydrogen. They could still focus a little on the cost, but it would be vital that they prioritise the emissions goal. This policy implies that Mammoet is hopeful about the future of hydrogen technology. They would bare the initial cost to secure a share of a future market for emission free heavy transport and enjoy cheaper overall fuel prices if hydrogen fuel does become cheaper than diesel after 2030.

This policy would create pressure on the technology development for heavy transport hydrogen trucks and create demand for hydrogen fuel in the Netherlands. This demand could speed up the process of cheaper supply of hydrogen fuel. If their hoped situation becomes a reality this could be a boost to the reputation of Mammoet in a world where emissions and fossil fuels become a part of the past and secure their position in their field for the future. This policy also gives the organization more time to adapt to a different culture surrounding emissions.

Policy 3: Fossil Forever

Profit is important to every business, and taking risk also means you can lose. This policy could be one of two things: either no policy and Mammoet retains their emissions and diesel fleet, or cutting losses and reaching the goal by reducing their fleet to the size it was before acquisitions. Not investing in hydrogen could avoid stranded assets if demand does not increase for emission free heavy transport and costs remain much higher than diesel.

The consequences are either losing capacity to provide services or hurting their reputation by not reducing their emissions. They would risk losing a share in a future market, but they could retain their current culture surrounding emissions and profit.

Conclusion

Mammoet has set a difficult goal which costs profit to reach. The results of the analysis revealed three policy scenarios regarding their decision to address their goal. Each scenario considers a different set of objectives, ranging from staying with what is known to embracing change in the industry. The main difficulty that faces the company is managing the uncertainty of the future and minimizing their risk. To combat this, it is important for Mammoet to stay informed about changes in hydrogen technology and price developments. This analysis will remain relevant until 2030 since it allows them to estimate what the implications are of certain price shifts in hydrogen. The insights to the dynamics of their predicament will be an aid to the organization in understanding the decision necessary for their emissions goal, and what their options are to reach their goal.

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Documentation

Acquisition_Fleet_expansion = STEP (5, 2017) - STEP (5, 2021)

UNITS: Truck/year

DOCUMENT: This flow represents the additional diesel trucks that were added to the fleet as a result of acquisitions between 2017 and 2020.

Additional_cost_of_Transition(t) = Additional_cost_of_Transition(t - dt) + (Calculating_cost) * dt

INIT Additional_cost_of_Transition = 0

UNITS: €

DOCUMENT: This stock represents the total additional cost of investing in hydrogen trucks based on the estimation of their total cost of ownership in the year that the trucks are purchased.

Additional_TCO_of_HT = TCO_Estimation_Hydrogen-TCO_Estimation_Diesel

UNITS: €/truck

DOCUMENT: This variable calculates how many euros more the total cost of ownership is for a hydrogen truck compared to a diesel truck.

Average_km_per_truck_per_year = MM_km_per_year/MM_Trucks_tracked

UNITS: km/truck/year

DOCUMENT: This variable calculates what the average kilometers driven is per truck in the fleet of Mammoet in a year.

Baseline_CO2_emissions = Trucks_in_Fleet_2021*_per_truck_per_year

UNITS: Tonne/year

DOCUMENT: Baseline emissions calculates how many tonnes carbon dioxide was emitted from the fleet of trucks in the year the company has chosen as a baseline for which they have set their carbon dioxide reduction goal.

Calculating_cost = HT_Purchase*Additional_TCO_of_HT

UNITS: €/year

DOCUMENT: This flow calculates each year how many more euros will be spent in the total cost of ownership of a truck as a consequence of investing in hydrogen trucks instead of diesel trucks.

CO2_Change_desired_per_year:_CO2_Goal = -(Current_Gap:_CO2_Goal)/Policy_adj_time

UNITS: Tonnes/Years^2

DOCUMENT: CO2 change desired per year calculates each year how many tonnes CO2 the company wants to reduce per year based on how many years the company has to close the gap to their 2030 goal.

Since the goal is to reduce CO2 emissions, the desired change in CO2 is negative.

CO2_Compared_to_baseline = IF TIME>2022 THEN Yearly_CO2_Emissions-Baseline_CO2_emissions ELSE 0

UNITS: Tonne/year

DOCUMENT: This variable calculates how many tonnes of CO2 more of less the company emits compared to the tonnes of CO2 they emitted in their baseline year from which they have set their reference for their goal.

CO2_Emission_Goal_2030 = Baseline_CO2_emissions-Tonnes_to_Reduce

UNITS: Tonne/year

DOCUMENT: The CO2 Goal calculates the maximum tonnes CO2 the fleet of trucks can to emit in 2030 to reach their CO2 reduction goal.

CO2_per_truck_per_year = (MM_km_per_year*(MM_liter_diesel_per_100_km/km_per_100_km)*Liter_Diesel_to_Tonne_C02_Converter)/MM_Trucks_tracked

UNITS: tonne/truck/year

DOCUMENT: CO2 per truck per year calculates how many tonnes CO2 is emitted by a truck using diesel fuel each year.

Conversion_Reference_usage_to_MM_usage = (MM_liter_diesel_per_100_km/Reference_liter_diesel_per_100km)

UNITS: dmnl

DOCUMENT: This variable creates a conversion factor which allows for conversion from the amount of fuel used to drive 100km with the truck used in the referenced study to the amount of fuel used per 100 km by the trucks in Mammoet's fleet.

The trucks in this study used less fuel per 100km than the trucks in Mammoet's fleet. Therefore this parameter is used to calculate the conversion between Mammoet's usage and the usage reported in this study.

Joshi, A. (2022, July 8). *H2 Ice Truck cost of ownership vs Diesel and fuel cell vehicles*. Mobility Notes. Retrieved December 10, 2022, from https://mobilitynotes.com/h2-ice-truck-cost-of-ownership-vs-diesel-and-fuel-cell-vehicles/

Cost_benefit_Purchase_Decision = IF Cost_parity_TCO_HT_vs_DT<1 THEN 1 ELSE 0

UNITS: dmnl

DOCUMENT: This variable denotes the decision rule of the company that if the cost benefit

Cost_parity_TCO_HT_vs_DT = TCO_Estimation_Hydrogen/TCO_Estimation_Diesel

UNITS: dmnl

DOCUMENT: This fraction shows whether the total cost of ownership of hydrogen trucks and diesel trucks are at parity with eachother.

1 meaning at parity.

>1 indicating that hydrogen is more expensive, than diesel.

<1 indicating that diesel is more expensive than hydrogen.

Current_Gap:_CO2_Goal = IF TIME >2022 THEN Yearly_C02_Report-CO2_Emission_Goal_2030 ELSE 0

UNITS: Tonne/year

DOCUMENT: This variables calculates each year how many tonnes CO2 from the fleet has yet to be reduced to reach the 2030 goal.

Desired_DT_purchase:_CO2_Goal = Net_change_desired_DT_fleet:_CO2_Goal+DT_Sold

UNITS: Truck/year

DOCUMENT: The desired DT purchase for CO2 goal calculates how many diesel trucks can be purchased in order to ensure that Mammoet reaches the CO2 reduction that is required that year.

This is done by calculating how many trucks are discarded, and adding this to the desired net change in the fleet.

Considering the desired net growth, and the information available to the company at the time of decision, the desired max purchase is calculated by adding the discarded trucks to the net growth, since the trucks discarded is already decreasing the fleet size.

Desired_HT_Purchases:_CO2_Goal = New_Trucks_requested_per_year-Desired_DT_purchase:_CO2_Goal

UNITS: Truck/year

DOCUMENT: This variable calculates how many hydrogen trucks should be purchased that year to ensure that Mammoet reaches their CO2 goal.

Diesel_Cost = IF Diesel_Scenario_Switch = 1 THEN S1:_Diesel_Cost ELSE IF Diesel_Scenario_Switch=2 THEN S2:_Diesel_Cost ELSE S3:_Diesel_Cost

UNITS: €/liter

DOCUMENT: { The model has 97 (97) variables (array expansion in parens).

In root model and 1 additional modules with 8 sectors.

Stocks: 3 (3) Flows: 6 (6) Converters: 88 (88)

Constants: 36 (36) Equations: 58 (58) Graphicals: 7 (7)

There are also 5 expanded macro variables. }

Diesel_Scenario_Switch = 1

UNITS: dmnl

DOCUMENT: This switch can be adjusted to show different diesel fuel price scenarios.

DT_Fleet(t) = DT_Fleet(t - dt) + (DT_Purchases + Acquisition_Fleet_expansion - DT_Sold) * dt

INIT DT_Fleet = Initial_DT_Fleet

UNITS: Truck

DOCUMENT: This stock represents the number of diesel trucks that are part of Mammoet's fleet in the Netherlands.

DT_Fleet_Lifetime = 10

UNITS: Years

DOCUMENT: This parameter represents a company policy regarding truck lifetime in the fleet of Mammoet in the Netherlands.

The policy states that a truck must be sold after 10 years of being part of the fleet.

Source: personal contact with the Head of Sustainability at Mammoet, 2022

DT_Fuel_Cost_per_year = DT_Fuel_use_per_year*Diesel_Cost

UNITS: €/truck/year

DOCUMENT: DT Fuel Cost per year calculates how much diesel fuel for one truck costs each year based on diesel fuel price estimates and how much fuel is estimated to be consumed by a diesel truck each year.

DT_Fuel_use_per_year = (MM_liter_diesel_per_100_km/km_per_100_km)*(Average_km_per_truck_per_year)

UNITS: Liter/truck/year

DOCUMENT: DT Fuel use per year calculates how many liters of diesel a truck uses in a year based on the average kilometers driven.

DT_Ordered = New_Trucks_requested_per_year*(1-Purchase_decision:_Fraction_of_total_purchases_to_be_HT)

UNITS: Truck/year

DOCUMENT: DT Ordered calculates how many diesel trucks are ordered by procurement each year based on how many trucks are requested by the drivers and any other conditions decided by the company.

DT_Purchases = DT_Ordered

UNITS: Truck/year

DOCUMENT: This flow represents the number of diesel truck purchased and added to Mammoet's fleet in the Netherlands each year.

DT_Sold = DT_Fleet/DT_Fleet_Lifetime

UNITS: Truck/year

DOCUMENT: This flow represents the number of diesel trucks sold per year from Mammoet's fleet in the Netherlands each year.

The company policy states that trucks must be sold at the end of their lifetime in the company.

Fraction_of_total_purchases_to_be_HT:_CO2_Goal = IF (Desired_HT_Purchases:_CO2_Goal/New_Trucks_requested_per_year)>1 THEN 1 ELSE (Desired_HT_Purchases:_CO2_Goal/New_Trucks_requested_per_year)

UNITS: dmnl

DOCUMENT: This variable calculates what fraction of new purchases should be hydrogen trucks.

Goal_focus_vs_cost_focus = .5

UNITS: dmnl

DOCUMENT: This is a parameter than can be used to test different comapny focuses which will guide their decision making.

1 means total focus on the carbon reduction goal and 0 means total focus on minimizing costs.

Goal_Reached_before_2030 = IF CO2_Compared_to_baseline<Total_Reduction_needed_2030 THEN 1 ELSE 0

UNITS: dmnl

DOCUMENT: This is a parameter used for the interface to check whether the emissions are reduced by the desired amount by 2030

Goal_Reached_before_2031 = IF CO2_Compared_to_baseline<Total_Reduction_needed_2030 THEN 1 ELSE 0

UNITS: dmnl

DOCUMENT: This is a parameter used for the interface to check whether the emissions are reduced by the desired amount by 2031. It is useful to know whether the goal is being reached before the end of the goal year.

Gram_CO2_per_liter_diesel = 2640

UNITS: grams/liter

DOCUMENT: Given the information from this source there is 2640 grammes of CO2 in a liter of diesel.

Source: https://ecoscore.be/en/info/ecoscore/co2

Grams_per_tonne = 1000000

UNITS: grams/tonne

DOCUMENT: This constant denotes how many metric grams are in a metric tonne.

HT_Discarded = HT_Fleet/HT_Fleet_Lifetime

UNITS: Truck/year

DOCUMENT: This flow represents the number of hydrogen trucks sold per year from Mammoet's fleet in the Netherlands each year.

The company policy states that trucks must be sold at the end of their lifetime in the company.

HT_Fleet(t) = HT_Fleet(t - dt) + (HT_Purchase - HT_Discarded) * dt

INIT HT_Fleet = 0

UNITS: Truck

DOCUMENT: This stock represents the number of hydrogen trucks that are part of Mammoet's fleet in the Netherlands.

HT_Fleet_Lifetime = 10

UNITS: years

DOCUMENT: This parameter represents a company policy regarding truck lifetime in the fleet of Mammoet in the Netherlands.

The policy states that a truck must be sold after 10 years of being part of the fleet.

Source: personal contact with the Head of Sustainability at Mammoet, 2022

HT_Fuel_Cost_per_year = Hydrogen_Cost*HT_Fuel_use_per_year

UNITS: €/truck/year

DOCUMENT: HT Fuel Cost per year calculates how much hydrogen fuel for one truck costs each year based on hydrogen fuel price estimates and how much fuel **is estimated to be consumed by a hydrogen truck each year.**

HT_Fuel_use_per_year = Average_km_per_truck_per_year*(MM_kg_H2_per_100km/km_per_100_km)

UNITS: kg/truck/year

DOCUMENT: HT fuel use per year calculates how many kilograms of hydrogen a truck uses in a year based on the average kilometers driven.

HT_Ordered = New_Trucks_requested_per_year*Purchase_decision:_Fraction_of_total_purchases_to_be_HT

UNITS: Truck/year

DOCUMENT: HT Ordered calculates how many hydrogen trucks are ordered by procurement each year based on how many trucks are requested by the drivers and any other conditions decided by the company.

HT_Purchase = HT_Ordered

UNITS: Truck/year

DOCUMENT: This flow represents the number of hydrogen trucks purchased and added to Mammoet's fleet in the Netherlands each year.

Hydrogen_Cost = IF Hydrogen_Scenario_Switch=1 THEN S1:_Hydrogen_Cost ELSE IF Hydrogen_Scenario_Switch=2 THEN S2:_Hydrogen_Cost ELSE S3:_Hydrogen_Cost

UNITS: €/kg

DOCUMENT: The hydrogen cost is a parameter that represents different cost of hydrogen per kilogram depending on the scenario that is selected.

The hydrogen cost is calculated in euro per kilogram of hydrogen fuel.

Hydrogen_Scenario_Switch = 1

UNITS: dmnl

DOCUMENT: This switch can be adjusted to show different hydrogen fuel price scenarios.

Initial_DT_Fleet = 40

UNITS: Truck

DOCUMENT: This is the number of diesel trucks that were in the fleet in the year of 2010.

Source: personal contact with the Head of Sustainability at Mammoet, 2022

km_per_100_km = 100

UNITS: km/hundred km

DOCUMENT: This parameter denotes how many kilometers are in a hundred kilometers.

Lifetime_Fuel_Cost_DT = DT_Fuel_Cost_per_year*DT_Fleet_Lifetime

UNITS: €/truck

DOCUMENT: This variable calculates the fuel cost of a diesel truck for the duration of their time in the fleet of Mammoet, based on the number of years a truck is kept in the fleet and the fuel prices available at the time of calculation.

Lifetime_Fuel_Cost_HT = HT_Fleet_Lifetime*HT_Fuel_Cost_per_year

UNITS: €/truck

DOCUMENT: This variable calculates the fuel cost of a hydrogen truck for the duration of their time in the fleet of Mammoet, based on the number of years a truck is kept in the fleet and the fuel prices available at the time of calculation.

Liter_Diesel_to_Tonne_C02_Converter = Gram_CO2_per_liter_diesel/Grams_per_tonne

UNITS: tonne/liter

DOCUMENT: This converter denotes how many tonnes CO2 is emitted by a liter of diesel.

Maintenance_and_Toll_Costs = 200000

UNITS: €/truck

DOCUMENT: Estimated from graphs

Mammoet_Fleet_History = GRAPH(TIME)

Points: (2010.00, 40.0), (2011.00, 40.0), (2012.00, 40.0), (2013.00, 40.0), (2014.00, 40.0), (2015.00, 40.0), (2016.00, 40.0), (2017.00, 40.0), (2018.00, 45.0), (2019.00, 48.0), (2020.00, 52.0), (2021.00, 60.0), (2022.00, 60.0)

UNITS: Trucks

DOCUMENT: From 2010-2017 the fleet was kept stable at 40. This confirms that the company policy that trucks are only purchased to replace and old truck is true.

Then due to acquisitions the fleet grew between 2018 and 2020, and then stayed constant at 60.

Source: personal contact with the Head of Sustainability at Mammoet, 2022

MM_kg_H2_per_100km = Conversion_Reference_usage_to_MM_usage*Reference_kg_H2_per_100km

UNITS: kg/hundred km

DOCUMENT: This variable denotes how many kilos of hydrogen fuel is likely to be used by a hydrogen truck that is equivalent to their diesel truck range.

MM_km_per_year = 1100000

UNITS: km/year

DOCUMENT: This is the total amount of kilometers driven by the studied trucks in a year at Mammoet.

Source: personal contact with the Head of Sustainability at Mammoet, 2022

MM_liter_diesel_per_100_km = 47.59

UNITS: liter/hundred km

DOCUMENT: This parameter denotes how many liters of diesel a diesel truck in Mammoet's fleet uses on average per 100km driven.

"MM_Truck_(Type_2)_Cost" = 160000

UNITS: €/truck

DOCUMENT: This is the average cost of a truck in the fleet of Mammoet in the Netherlands.

Type 2 is used here to symbolize a type of truck that is used by Mammoet.

Source: personal contact with the Head of Sustainability at Mammoet, 2022

MM_Trucks_tracked = 39

UNITS: truck

DOCUMENT: Mammoet tracked 39 trucks in their analysis of how many kilometers their fleet drives in a year.

Source: personal contact with the Head of Sustainability at Mammoet, 2022

Net_change_desired_DT_fleet:_CO2_Goal = CO2_Change_desired_per_year:_CO2_Goal/CO2_per_truck_per_year

UNITS: Truck/year

DOCUMENT: Each year this variable calculates the number of diesel trucks that must be removed from the fleet to reduce the desired amount of CO2.

The equation is negative since it represents a number that should be taken away from the total.

Since the diesel fleet is the only source of emissions the desired reduction divided by the average CO2 per truck to calculate the number of trucks that are responsible for the undesired emissions. The equation is negative because a negative growth is required to reach the CO2 goal.

-(CO2_Reduction_per_year_desired_for_goal/Average_CO2_per_truck)

New_Trucks_requested_per_year = HT_Discarded+DT_Sold

UNITS: Truck/year

DOCUMENT: This variable calculates the number of new trucks that are requested by truck drivers each year based on how many are discarded.

This request is sent to the procurement department who processes the order and decides the conditions of the truck purchased to replace the old truck.

Following company policy, new trucks can only be purchased as a result of a 10 year old truck being discarded from the fleet, therefore the total number of discarded trucks also represents the total number of new trucks that are requested.

Percent_CO2_Reduction_Goal = 30

UNITS: dmnl

DOCUMENT: Mammoet has set a goal to reduce their carbon emissions by 30% by 2030.

Source: personal contact with the Head of Sustainability at Mammoet, 2022

Policy_adj_time = MAX(1, (Policy_deadline-TIME))

UNITS: Years

DOCUMENT: This variable indicates to the company for how many more years the policy will be active.

Policy_deadline = 2030

UNITS: Years

DOCUMENT: This variable indicates by what year the company aims to reach the goal.

The company has set 2030 as their CO2 reduction goal

Source: personal contact with the Head of Sustainability at Mammoet, 2022

Policy_start_time = 2023

UNITS: Years

DOCUMENT: This variable indicates in what year the company implements the chosen policy

Policy_status = IF(Policy_switch=1)AND(Policy_start_time<TIME)THEN(1)ELSE(0)

UNITS: dmnl

DOCUMENT: The policy status denotes whether the policy is active or dormant.

Policy_switch = 1

UNITS: dmnl

DOCUMENT: This is a parameter that is used to allow the model to run with and without the policy active.

Policy_time_period = Policy_deadline-Policy_start_time

UNITS: years

DOCUMENT: This parameter shows how many year the policy would be active if the policy is decided to be used.

"Price_Factor_to_MM_Truck_(Type_2)" = "MM_Truck_(Type_2)_Cost"/Type_1_Truck_Cost

UNITS: dmnl

DOCUMENT: This is a price factor made to estimate what an equivalent hydrogen truck would cost.

This factor indicates the factor of difference that a type 1 truck should be multiplied by to get the price equivalent of a type 2 truck.

"Purchase_Cost_HT_(Type_1)" = GRAPH(TIME)

Points: (2022.000, 360000), (2023.000, 340000), (2024.000, 310000), (2025.000, 290000), (2026.000, 265000), (2027.000, 250000), (2028.000, 240000), (2029.000, 228000), (2030.000, 215000)

UNITS: €/truck

DOCUMENT: This parameter represents the development of the cost of a type 1 hydrogen truck in Europe.

Type 1 is used to describe a slightly less heavy duty type truck than what Mammoet needs, but this is the only cost reference for a hydrogen truck that was available.

The graph is estimated based on the data provided in this paper: https://theicct.org/wp-content/uploads/2022/09/eu-hvs-fuels-evs-fuel-cell-hdvs-europe-sep22.pdf

Purchase_Cost_HT_Type_2 = "Purchase_Cost_HT_(Type_1)"*"Price_Factor_to_MM_Truck_(Type_2)"

UNITS: €/truck

DOCUMENT: This is the estimates cost of a hydrogen truck based on price comparisons made of trucks by IPCC and the factor difference between the prices used by the IPCC and the price of trucks in the fleet of Mammoet.

Type 2 is used to symbolize a type of truck that is used by Mammoet.

Purchase_decision:_Fraction_of_total_purchases_to_be_HT = IF Policy_status>0 THEN

(Fraction_of_total_purchases_to_be_HT:_CO2_Goal*Goal_focus_vs_cost_focus)+(Cost_benefit_Purchase_Decision*(1-Goal_focus_vs_cost_focus)) ELSE 0

UNITS: dmnl

DOCUMENT: This variable calculates what fraction of new purchases will be hydrogen trucks based on the priority given to the CO2 goal over Cost Benefit.

Ratio_of_HT_to_DT = HT_Fleet/DT_Fleet

UNITS: dmnl

Reference_kg_H2_per_100km = 33

UNITS: kg/hundred km

DOCUMENT: In a study that compares diesel trucks to hydrogen ICE trucks the hydrogen truck comparable to the diesel truck tested used 9 kg H2 per hundred kilometers.

This parameter is used to estimate how many kg H2 a truck equivalent to the trucks used by Mammoet would use per 100km.

Joshi, A. (2022, July 8). *H2 Ice Truck cost of ownership vs Diesel and fuel cell vehicles*. Mobility Notes. Retrieved December 10, 2022, from https://mobilitynotes.com/h2-ice-truck-cost-of-ownership-vs-diesel-and-fuel-cell-vehicles/

Reference_liter_diesel_per_100km = 33

UNITS: liter/hundred km

DOCUMENT: In a study that compares diesel trucks to hydrogen ICE trucks the diesel truck comparable to the hydrogen truck tested used 33 liters per hundred kilometers.

Joshi, A. (2022, July 8). *H2 Ice Truck cost of ownership vs Diesel and fuel cell vehicles*. Mobility Notes. Retrieved December 10, 2022, from https://mobilitynotes.com/h2-ice-truck-cost-of-ownership-vs-diesel-and-fuel-cell-vehicles/

Reporting_time = 1

UNITS: year

DOCUMENT: This parameter denotes how many years it takes Mammoet to process and report the yearly emissions.

Source: personal contact with the Head of Sustainability at Mammoet, 2022

S1:_Diesel_Cost = GRAPH(TIME)

Points: (2022.000, 1.7800), (2022.800, 1.7080), (2023.600, 1.6420), (2024.400, 1.5830), (2025.200, 1.5300), (2026.000, 1.4810), (2026.800, 1.4370), (2027.600, 1.3980), (2028.400, 1.3620), (2029.200, 1.3290), (2030.000, 1.3000)

UNITS: €/liter

DOCUMENT: The average diesel price of all 2021 and January-November 2022 according to Shell's historical diesel price in the Netherlands is 1.72 euro per liter.

Scenario 1 (S1) is that the diesel price decreases decreasingly from it's average price to 1.30 euro per liter between 2022 and 2030.

The price 1.30 euro per liter was chosen as it is a significant price decrease from the current diesel price, and would signify the diesel price returning to diesel prices before crises like Covid-19 and the war between Russia and Ukraine causing an energy crisis.

Shell Brandstofprijzen. Benzineprijs en dieselprijs bij Shell-tankstations | Shell Nederland. (n.d.). Retrieved December 13, 2022, from https://www.shell.nl/consumenten/shell-fuels/historisch-prijzenoverzicht.html

S1:_Hydrogen_Cost = GRAPH(TIME)

Points: (2022.000, 9.970), (2022.57142857, 9.91771428571), (2023.14285714, 9.86553846154), (2023.71428571, 9.81120604396), (2024.28571429, 9.75007292707), (2024.85714286, 9.65487612388), (2025.42857143, 9.49164635365), (2026.000, 9.2389291958), (2026.57142857, 8.88991117973), (2027.14285714, 8.44119621288), (2027.71428571, 7.88269984561), (2028.28571429, 7.19532817183), (2028.85714286, 6.35172727272), (2029.42857143, 5.33540909091), (2030.000, 4.3)

UNITS: €/kg

DOCUMENT: Based on Delft (2022) the low price scenario (S1) for 2030 is 4.30 euro per kilogram hydrogen fuel.

The current price of a kilogram hydrogen fuel is 10 euro according to Shell.

The price development is estimated to decrease very little between 2022 and 2025 while hydrogen production and infrastructure is scaled up, and as a result of this scaling up the price is estimated to drop rapidly between 2025 and 2030

Leguijt, C., Rooijers, F., van den Toorn, E., van der Veen, R., van Cappellen, L. & Kampman, B. (2022) 50% green hydrogen for Dutch industry. CE Delft.

Refuelling Hydrogen with Shell. Shell Nederland. (n.d.). Retrieved December 18, 2022, from https://www.shell.nl/consumenten/shell-fuels/alternatieve-brandstoffen/waterstof.html#

S2:_Diesel_Cost = 1.78

UNITS: €/liter

DOCUMENT: The average diesel price of all 2021 and January-November 2022 according to Shell's historical diesel price in the Netherlands is 1.72 euro per liter.

Scenario 2 (S2) is that the diesel price does not change between 2022 and 2030.

Shell Brandstofprijzen. Benzineprijs en dieselprijs bij Shell-tankstations | Shell Nederland. (n.d.). Retrieved December 13, 2022, from https://www.shell.nl/consumenten/shell-fuels/historisch-prijzenoverzicht.html

S2:_Hydrogen_Cost = GRAPH(TIME)

Points: (2022.000, 9.955), (2022.320, 9.9495778976), (2022.640, 9.92655352186), (2022.960, 9.901728441), (2023.280, 9.87746442402), (2023.600, 9.85560473759), (2023.920, 9.83491030109), (2024.240, 9.80969023465), (2024.560, 9.77513240833), (2024.880, 9.72858391538), (2025.200, 9.66803229627), (2025.520, 9.59610790389), (2025.840, 9.51740564325), (2026.160, 9.42686738063), (2026.480, 9.30228863181), (2026.800, 9.120216805), (2027.120, 8.87726205356), (2027.440, 8.5765469111), (2027.760, 8.23079727933), (2028.080, 7.87066967602), (2028.400, 7.51739862607), (2028.720, 7.16863257407), (2029.040, 6.81122453165), (2029.360, 6.45233711586), (2029.680, 6.04501900818), (2030.000, 5.75)

UNITS: €/kg

DOCUMENT: Based on Delft (2022) the medium price scenario (S2) for 2030 is (7.2+4.3)/2 = 5.75 euro per kilogram hydrogen fuel.

The current price of a kilogram hydrogen fuel is 10 euro according to Shell.

The price development is estimated to decrease very little between 2022 and 2025 while hydrogen production and infrastructure is scaled up, and as a result of this scaling up the price is estimated to drop rapidly between 2025 and 2030

Leguijt, C., Rooijers, F., van den Toorn, E., van der Veen, R., van Cappellen, L. & Kampman, B. (2022) 50% green hydrogen for Dutch industry. CE Delft.

Refuelling Hydrogen with Shell. Shell Nederland. (n.d.). Retrieved December 18, 2022, from https://www.shell.nl/consumenten/shell-fuels/alternatieve-brandstoffen/waterstof.html#

S3:_Diesel_Cost = GRAPH(TIME)

Points: (2022.000, 1.7800), (2022.800, 1.8000), (2023.600, 1.8210), (2024.400, 1.8450), (2025.200, 1.8720), (2026.000, 1.9010), (2026.800, 1.9330), (2027.600, 1.9690), (2028.400, 2.0080), (2029.200, 2.0520), (2030.000, 2.1000)

UNITS: €/liter

DOCUMENT: The average diesel price of all 2021 and January-November 2022 according to Shell's historical diesel price in the Netherlands is 1.72 euro per liter.

Scenario 3 (S3) is that the diesel price increases increasingly from it's average price to 2.10 euro per liter between 2022 and 2030.

The price 2.10 was chosen as it reveals what would happen if there was to be a significant increase from current prices in this period.

Shell Brandstofprijzen. Benzineprijs en dieselprijs bij Shell-tankstations | Shell Nederland. (n.d.). Retrieved December 13, 2022, from https://www.shell.nl/consumenten/shell-fuels/historisch-prijzenoverzicht.html

S3:_Hydrogen_Cost = GRAPH(TIME)

Points: (2022.000, 9.970), (2022.30769231, 9.96237539571), (2022.61538462, 9.94880251951), (2022.92307692, 9.93208250566), (2023.23076923, 9.91351768707), (2023.53846154, 9.89372825017), (2023.84615385, 9.87272429453), (2024.15384615, 9.84980246726), (2024.46153846, 9.82352172541), (2024.76923077, 9.79182409954), (2025.07692308, 9.75227434265), (2025.38461538, 9.70236095264), (2025.69230769, 9.63980024522), (2026.000, 9.56279531519), (2026.30769231, 9.47021323295), (2026.61538462, 9.36165449547), (2026.92307692, 9.23740068664), (2027.23076923, 9.09824286834), (2027.53846154, 8.94521641834), (2027.84615385, 8.77929621244), (2028.15384615, 8.60113192835), (2028.46153846, 8.41091226286), (2028.76923077, 8.20841627392), (2029.07692308, 7.9932097966), (2029.38461538, 7.76474148113), (2029.69230769, 7.52175916011), (2030.000, 7.26000000003)

UNITS: €/kg

DOCUMENT: Based on Delft (2022) the high price scenario (S3) for 2030 is 7.20 euro per kilogram hydrogen fuel.

The current price of a kilogram hydrogen fuel is 10 euro according to Shell.

The price development is estimated to decrease very little between 2022 and 2025 while hydrogen production and infrastructure is scaled up, and as a result of this scaling up the price is estimated to drop rapidly between 2025 and 2030

Leguijt, C., Rooijers, F., van den Toorn, E., van der Veen, R., van Cappellen, L. & Kampman, B. (2022) 50% green hydrogen for Dutch industry. CE Delft.

Refuelling Hydrogen with Shell. Shell Nederland. (n.d.). Retrieved December 18, 2022, from https://www.shell.nl/consumenten/shell-fuels/alternatieve-brandstoffen/waterstof.html#

Sale_value_DT = 40000

UNITS: €/truck

DOCUMENT: This parameter is the average sale price of a diesel truck after 10 years.

Source: personal contact with the Head of Sustainability at Mammoet, 2022

Sale_value_factor = Sale_value_DT/"MM_Truck_(Type_2)_Cost"

UNITS: dmnl

DOCUMENT: The Sale value factor is the factor of the purchase price that the trucks are worth after 10 years.

This value makes the assumption that the value of all trucks reduce the same over a 10 year period.

Sale_value_HT = Purchase_Cost_HT_Type_2*Sale_value_factor

UNITS: €/truck

DOCUMENT: This is the estimated sale value of a hydrogen truck after 10 years based on the sale value factor based on the sales value factor of diesel trucks.

TCO_Estimation_Diesel = Lifetime_Fuel_Cost_DT+"MM_Truck_(Type_2)_Cost"-Sale_value_DT+Maintenance_and_Toll_Costs

UNITS: €/truck

DOCUMENT: This variable calculates the total cost of ownership of a diesel truck for Mammoet, considering the purchase price, maintenance and operation cost and fuel cost over their lifetime based on fuel prices at the time of calculation.

TCO_Estimation_Hydrogen = Lifetime_Fuel_Cost_HT+Purchase_Cost_HT_Type_2-Sale_value_HT+Maintenance_and_Toll_Costs

UNITS: €/truck

DOCUMENT: This variable calculates the total cost of ownership of a hydrogen truck for Mammoet, considering the purchase price, maintenance and operation cost and fuel cost over their lifetime based on fuel prices at the time of calculation.

Tonnes_to_Reduce = Baseline_CO2_emissions*(Percent_CO2_Reduction_Goal/100)

UNITS: Tonne/year

DOCUMENT: Tonnes to reduce calculates how many tonnes of CO2 from the fleet of trucks must be reduced to reach their 2030 goal based on their chosen baseline year.

Total_Reduction_needed_2030 = CO2_Emission_Goal_2030-Baseline_CO2_emissions

UNITS: Tonne/year

DOCUMENT: This variable calculates how many tonnes per year the company would emit if they reach their 2030 goal.

Trucks_in_Fleet_2021 = 60

UNITS: Truck

DOCUMENT: This is the number of trucks in the fleet in the Netherlands as of 2021.

Source: Personal contact with the Head of Sustainability at Mammoet, 2022.

Type_1_Truck_Cost = 150000

UNITS: €/truck

DOCUMENT: This parameter indicates the price of a type 1 diesel truck.

Type 1 is used to describe a slightly less heavy duty type truck than what Mammoet needs, but this is the only cost reference for a diesel truck that was compared to a hydrogen truck that was available.

Yearly_C02_Report = SMTH1(Yearly_CO2_Emissions,Reporting_time, 1) {DELAY CONVERTER}

UNITS: Tonne/year

DOCUMENT: The yearly CO2 report is a stock of information which is updated yearly.

This process is translated in the form of a first order information delay since the information takes time to acquire and process within the company.

Yearly_CO2_Emissions = DT_Fleet*CO2_per_truck_per_year

UNITS: Tonnes/Years

DOCUMENT: This variable calculates how many tonnes of CO2 is emitted by the fleet of diesel trucks each year.

This is done by using the average amount of tonnes CO2 that is emitted by a truck in the fleet of Mammoet in the Netherlands each year and multiplying this by the number of diesel trucks in the fleet of Mammoet in that year.