In the 2015 Paris agreement, countries committed to implementing measures to reduce greenhouse gas emissions to limit global warming. For the maritime industry specifically, the International Maritime Organization (IMO) has proposed measures for energy efficiency of vessels and candidate measures regarding fuel choice and speed optimisation. This article aims to contribute to the latter by showing how logistical simulations can be used to optimise fleet operations. We will illustrate this in the form of a conceptual case using one cutter and a range of barge fleets. Running simulations with all possible fleets, we will demonstrate the value of extra energy-based alternatives to challenge the fastest, cheapest and most flexible alternatives.

SIMULATING FOR SUSTAINABILITY: ALTERNATIVE OPERATING STRATEGIES FOR ENERGY EFFICIENCY

This article demonstrates how to use an open-source logistical simulation package for the optimisation and planning of a fleet of dredging or offshore installation vessels. For a conceptual use case, we simulate all possible barge fleets that can be composed of a range of barges. Per simulation, we extract Key Performance Indicators (KPIs) along a number of dimensions. These include the classic fastest, cheapest, and most flexible scenario. We extend it here with the most energy-efficient scenario. Note that in real dredging projects, other KPIs can also be dominant: in some harbours, noise restriction windows are imposed and often there are restrictions to prevent dredging plumes or spill of fine material from settling basins (Van Eekelen et al., 2015). We use these KPIs to rank the simulations along these dimensions, allowing the contractor to properly weigh the options and consider an energy-efficient compromise. The weighing of different scenarios has always been in the scope of a dredging project. However, the anticipated focus in our sector on fuel efficiency serves as a trigger to revisit this classical challenge. Fuel efficiency will increase the solution space by at least an order of magnitude. We believe simulations can contribute to getting most value out of the extra options.
For the simulations, we use the OpenCLSim package introduced by De Boer et al. (2022) and Baart et al. (2022). In their work, they showed its applicability for the dredging sector with the example of one dredging cycle and a number of coupled dredging cycles with one cutter and a number of barges. In this article, we extend their case by running a range of simulations for a real-world project. Further, OpenCLSim was lacking two features that were needed in the context of energy reduction. In this article, we add a critical path analyzer to OpenCLSim to consider what extent barges are on the critical path. Secondly, we add a routing component for sailing to take the fleet mobilisation phase into consideration.

After running all scenarios and choosing an energy-efficient compromise, we export a handful of scenarios to generic purpose, industry-standard planning and Business Intelligence (BI) tools. This enables a range of stakeholders to analyze the optimal scenarios and assess in the context of the available options. We believe these tools will democratise the traditional planning process beyond experts. Adding an energy-efficient scenario alongside the cheapest and fastest scenarios may result in a compromise scenario that has the best overall score but does not necessarily have the best score in terms of cost, time or fuel efficiency alone.

The most energy-efficient scenario may entail additional costs, fuel saving options or delays that will have to be borne by one of the parties involved. Simple data analysis tools will allow each stakeholder to understand and compare the concessions required from them to accept the energy-efficient compromise scenario, rather than just the cheapest, fastest or most expensive scenario. We foresee that BI tools will support conversations and facilitate reaching a mutual agreement among the different parties involved, such as the financiers, contractors and stakeholders.

We shall first explain the use case central in this article: a range of scenarios for a fleet of one cutter and a number of barges to dredge material for a land reclamation from a trench. Illustration use case

De Boer et al. (2022) presented the ‘one cutter, many barges’ problem. This case, illustrated in Figure 1, provides a representative vessel mix for a dredging cycle. The basic setup resembles the dredging works for the Fehmarnbelt tunnel. An overall activity is executed until all material has been added to a reclamation from a trench. This activity determines when the simulation is finished. The while activity repeats a predefined sequence activity that is composed of four activities: first a barge moves towards the trench, then a cutter fills the barge, the barge then moves to the reclamation and finally the barge offloads the material to the reclamation, after which the activity is executed for a next cycle. In Figure 2, the results are shown as the cumulative location of material in all sites and vessels, while Figure 3 shows the sequencing of activities by alleys versus time. In this example with four barges, the cutter is always on the critical path, as well as the barges when they are being loaded by the cutter. The trench where the cutter is located is also always on the critical path. For the final load, the unloading at the reclamation is not the critical path.

OpenCLSim

OpenCLSim is based on the generic discrete-event simulation package SimPy programmed in Python. OpenCLSim has been created as a separate layer on top of SimPy (Matloff, 2009) to mimic concepts from the IADC database would be required. In the IADC database, there are 501 vessel types that have been identified. For more realistic values, we take energy efficiency into account using OpenCLSim. Hence our input values are take energy efficiency into account using OpenCLSim. Hence our input values are OpenCLSim. Hence our input values are...
Finally, the energy consumption has reached almost a minimum at five barges. The energy use keeps a variation for all fleet sizes. With the three KPIs in mind, the optimal choice is a fleet of three, four or five barges. This reduces the options to 336. We can conclude that the choice for the number of barges is not the most important one due to the variations in fleet composition, but the exact fleet composition is in a more realistic use case, the mobilisation of each barge also must be taken into account.

Due to the variation in barge properties, a small fleet might sometimes lead to better results for project duration than a large fleet.

Hence, the right fleet composition is important for the options of three or four barges, but hardly at five barges. We therefore aim to narrow the search window for the contractor to a manageable number of optimal choices. From our experience with project operations, we define a useful days list that fits on one page. For each of the choices of three, four or five barges, we identify the optimal result for each of the KPIs. This approach yields nine options, as shown in Table 1.

Table 1 with the optimal choices, shows that four barges lead to the lowest overall cost (scenario c). For optimal project duration, four or five barges can be optimal (c, d, f, g). For energy use, five barges are best (g), but a scenario with four barges is close (b). This means that four barges will be the most likely choice. However, the cheapest fleet of four barges (c) is different from the most energy-efficient fleet of four barges (d). In this case, fleet (d) might be a good compromise as it is close to the cheapest fleet (c) and the most energy-efficient fleet of five barges (g).

Without our simulations, including the calculation of energy efficiency, probably fleet (c) would have been chosen. Due to our simulations, an extra fleet option (d) appeared that saves 5.9% fuel with only 17% increase in cost compared to (c). Choosing the most fuel efficient option (d) would have saved 2.9% energy but increased by 12.3% compared to (c).

Note that Table 1 only shows the best choice per KPI. A larger number of alternative fleets might be available, which are a similar compromise as fleet (d). The scatter plot in Figure 5 shows all scenarios with four and more barges. Many options are available that are close to the cheaper and close to the most energy efficient one. There is no option that is both the cheapest and the most energy efficient. If we define alternative fleets, these could be considered in case the availability or mobilisation position of barges changes.

An extra consideration is that with four barges, the single cutter will have 100% occupancy.

As there is only one cutter, the cutter will become the critical component of the entire project. Small repairs will immediately result in delays, extra cost and extra fuel. The choice for four barges only fits a setting with an experienced crew and equipment that has just had a dock job. A more flexible scenario would be three barges, with only order 80% cutter occupancy. Three barges are sufficient to provide flexibility regarding the capacity to barge handling issues. However project duration and cost increase rapidly when one barge fails and only two are left. This means that four barges provide partial insurance against barge delays, especially when the project has liquidated damages or strict deadlines.

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The most expensive asset in the example case is the cutter. What will five use five or more barges, the cutter will continuously be on the critical path, with less barges, there will be some waiting time until an empty barge arrives. Tasks that are not on the critical path allow for a delay without impact on the delivery time. When the moving activity of a barge is not critical, it cannot be delayed, but might be delayed by the speed or waiting for barge availability. This will further reduce the duration and cost of the simulation, but we have a different result if we simply add a delay without impact on the critical path.

To detect activities on the critical path of an OpenCLSim simulation, we need to analyse the dependencies between activities. As it is not the critical path which is our main interest, we analyse the activities as indicator of a dependency. We implement two methods to determine the critical path because it has to sail to the branch where the Cutter T1 is waiting. Once the Cutter T2 has started, this critical path is on the critical path. In contrast, Barges I and II are on the critical path because it has to sail to the mobilisation site.

A vessel that is not on the critical path can save fuel with green or slow steaming.

The KPI per scenario, binned per fleets with equal number of barges.

<table>
<thead>
<tr>
<th>Scenario</th>
<th># Barges</th>
<th>Cutter occupancy</th>
<th>Duration and % difference with base</th>
<th>Cost and % difference with base</th>
<th>Energy and % difference with base</th>
<th>Best for</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>3</td>
<td>81.8</td>
<td>0.80</td>
<td>23914</td>
<td>+13.6</td>
<td>210</td>
</tr>
<tr>
<td>b</td>
<td>3</td>
<td>74.1</td>
<td>0.85</td>
<td>31529</td>
<td>+20.1</td>
<td>203</td>
</tr>
<tr>
<td>c</td>
<td>4</td>
<td>99.7</td>
<td>0.65</td>
<td>26825</td>
<td>0</td>
<td>187</td>
</tr>
<tr>
<td>d</td>
<td>4</td>
<td>100</td>
<td>0.65</td>
<td>26825</td>
<td>0</td>
<td>176</td>
</tr>
<tr>
<td>e</td>
<td>5</td>
<td>100</td>
<td>0.67</td>
<td>27970</td>
<td>+6.3</td>
<td>188</td>
</tr>
<tr>
<td>f</td>
<td>5</td>
<td>100</td>
<td>0.65</td>
<td>30297</td>
<td>+18.4</td>
<td>183</td>
</tr>
<tr>
<td>g</td>
<td>5</td>
<td>100</td>
<td>0.65</td>
<td>29473</td>
<td>+12.3</td>
<td>172</td>
</tr>
</tbody>
</table>

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fuel use optimisation and increasing comfort and safety. An optimal path can thereby be found by considering tidal windows (Balkier and VanKoningsveld, 2023), currents (van Halen, 2019) and weather events (see e.g., Ortsid, 2022).

To implement the concept of route-bounded sailing, we have implemented an OpenCLSim ‘routable’ mixin that allows a ship to find its way over a graph. This component can be used to analyze traffic interference (e.g., in case of capacity restrictions or speed limitations). If sailing graphs are extended with information on width, depth, currents and sailing limits (e.g., tidal windows), it can also be used to compute more accurate durations and for energy consumptions and emissions.

Integrating simulation results into project planning and BI tools

For further analysis, we take fleet (d) with four barges that has been chosen as the compromise considering all criteria. The choice for a compromise implies that different stakeholders have to be handled that did not get their optimal choice. A detailed analysis of this chosen fleet is required to assess the pros and cons of this fleet. First, we enable this by extending OpenCLSim with a critical path analyzer. The results are shown in Figure 3.

The second option is to make it easy for all stakeholders to analyze the simulation in their own context. For this purpose, we present the output results of the simulation as the concepts used by project planners: the Planning and the Schedule (Hailey and Walker, 1959). This is illustrated by the data model of the planners in Figure 7. They define the planning as what must occur and in what order, while the schedule follows the planning and adds timetables to the planned activities. The schedule can be created manually or automatically with scheduling software like CPM (Critical Path Method).

An OpenCLSim model definition as in Figure 1 is a representation of what must occur and can thus be regarded as the planning. An OpenCLSim simulation subsequently adds timetables to the input, and thus replaces the role of scheduling software like CPM. We extract the schedule afterwards from the OpenCLSim log. The OpenCLSim core of Simpy generates a log of all events. For example, each ‘Move’ by a ‘ShiftAmount’ activity generates an event when it starts and when it ends. The other IMO’s candidate measures have received less attention but are also needed to meet the IMO targets. This article shows how simulations can add to the mix required for the dredging sector to meet these targets. Simulations are one aspect of the digitisation of processes in ship operation that have a great potential (KPMG, 2021). We believe optimisation can contribute to the energy transition, especially in the short term, while awaiting developments in equipment and fuel types that will have a longer time horizon due to the capital investments involved.

Conclusion

Most of the attention in the energy transition goes to equipment-based developments for new vessels, retrofitting and different fuel types (Juong et al., 2020). These measures will need to provide a major part of the IMO targets to reduce the carbon intensity of international shipping in 2030 at least 40% compared to 2008 levels (IMO, 2022).

We used the existing software framework OpenCLSim to simulate how fleet composition can lead to better choices for energy use, with minimal impact on cost and project duration. The optimisation software is one way to shape the IMO candidate measures that focus on lowering energy use via fleet composition, speed optimisation and speed reduction. IMO indicates that fleet management, logistics and incentives have a GHG reduction potential of 5-50% voyage optimisation a potential of 11-13% and extensive speed optimisation up to 75% (IMO, 2023). We applied the simulation of vessels to a typical dredging project where one cutter and a fleet of barges carry out the work.
The IMO has created targets for the maritime industry to lower emissions of greenhouse gasses (GHG). Currently, these are focused on maritime equipment via the Energy Efficiency Design Index (EEDI) of new vessels and Ship Energy Efficiency Management Plans (SEEMP) for all ships. The IMO has further proposed candidate measures for the short, mid and long term that relate to the context in which the maritime equipment operates. Fuel types and composition, as well as speed, optimisation and reduction. This article contributes to that latter by running an example logistical simulation of a conceptual use case of one cutter with a fleet of barges. We show how simulations facilitate the qualitative comparison of alternative operating strategies to transport goods and materials with varying loading rates, speeds and fleet composition. Currently, dredging and offshore construction contractors already need to make decisions, weighing fleet schedules that favour the fastest, cheapest or most flexible alternative. Energy and emission footprints need to be considered. The OpenCLSim software we present here will allow to quantify that extra alternative.

Gerben J. de Boer

Gerben is an R&D and innovation manager at Van Oord engineering and estimating department. After graduating as a civil engineer, he obtained this doctorate in coastal oceanography from Delft University of Technology in the Netherlands. For over 10 years he worked at Deltares as a consultant on remote sensing, numerical modeling and data management. During that time, he was a member of the IMCO/MEPC marine data expert group to the IMO. In 2016, Gerben joined Van Oord around the Netherlands, where he managed until 2023.

Pieter van Halem

In 2019, Pieter obtained his Master’s degree in hydraulic engineering from Delft University of Technology and joined Van Oord as a data engineer. His work focuses on logistical simulations of the execution processes, optimizing resources and equipment.

Simulations can yield extra fleet options that save fuel with only a small increase in cost. We generated hundreds of possible fleets from a predefined range of vessels. We analysed, ranked and sorted the simulations until – for a small range of fleet sizes – the fastest, cheapest and most fuel-efficient scenarios remained. Although we realised that the benefits from optimisation via simulation are different from case to case, our expert judgement based on these simulations is that contractors may be able to choose a compromise that saves a small percent of fuel, with only a small increase in cost, by considering different fleet compositions.

This already realises the lower reduction potential as mentioned by IMO (2023). Further fuel reduction is possible, but that will yield a more proportional increase in cost. We propose to extend the classic optimisation between the fastest and the cheapest option, with the most energy-efficient option.

The simulations we performed are just an illustration of what could be possible with a minimal impact on cost. To achieve realistic numbers on potential energy savings, this work will have to be repeated with actual data. The actual data required for a simulation like this consists of at least 10 numbers per vessel: energy use and production for each of the four dredging phases, the daily cost and the capacity. The typical fleet of a large marine contractor is in the order of 100 vessels. Hence, for realistic simulations, gathering the actual input data can be a significant effort.

Moreover, in our example, we used simple bulk numbers to represent loading and sailing. However, for realistic energy simulations, simple bulk numbers are typically not enough to assess production (hence cost and duration) and energy use. Depending on the required accuracy, various subprocesses often need to be modelled in more detail. For example, the potential of reducing energy demands, such as the usage of auxiliary equipment, is significant. Further fleet reduction is possible, but that will yield a more proportional increase in cost.

The OpenCLSim software we present here will allow to quantify that extra alternative. Reaching the climate goals set by the 2015 Paris agreement is a big endeavour. For the dredging sector, this will require collaboration and joint research, as stated by Verhoeven (2022). OpenCLSim was started with the collaboration of the departments in the Netherlands: Van Oord, Delft University of Technology (TU Delft) and Deltares. For this article, Verhoeven-Bias joins the collaboration. OpenCLSim is a fully open source and the setup with invites allows anyone to use and co-develop OpenCLSim, while having the option (by design) to allow to keep sensitive details proprietary. TU Delft could lead in aligning these efforts in our industry. We invite everyone to join at https://github.com/TU-Delft-CITG/OpenCLSim.

As shown in this article, logistical simulation software can make a project more energy efficient from a contractor’s perspective. Energy and emission footprints are gaining importance as project design criteria. Anticipating developments to monetise greenhouse gas (GHG) emissions via legislation, project execution strategies that give the smallest fuel consumption and emission footprints need to be considered. By making such alternatives an optional part of the value offering already, marine contractors can stimulate a conversation with the client and government on the merits of an optimal GHG alternative and on funding in a level playing field. The same simulations could be initiated by governments and clients to explore the range of possible ways to execute a work. The OpenCLSim software we present here will allow to quantify that extra alternative.
Mark van Koningsveld

Throughout his 25-year career, Mark has worked at the interface between research and practice. He obtained his PhD from Delft University of Technology in the Netherlands and went on to work as a Deltares fellow at Delft University of Technology in 2013. He was appointed as research manager of the Dutch Deep Ocean Technology (DDOT) program and became a professor at Delft University of Technology. Mark has held several positions at the University of New South Wales and the Australian National University. He has supervised over 30 PhD students and has authored or co-authored over 100 peer-reviewed articles. His research interests include coastal and marine engineering, oceanography, and environmental modelling. Mark is a member of the editorial board of the journal Ocean Engineering.

Fedor Baart

Fedor is a specialist in data science and digital twin technology and software development. He has worked on various projects related to data-driven decision-making and artificial intelligence. His expertise includes machine learning, data analytics, and software development. He has a background in applied mathematics and has published several papers and reports on his research. In his day-to-day work, Fedor develops software tools for data analysis and visualisation, as well as designing and developing complex software systems for controlling and monitoring processes in ocean engineering. He is currently working on projects related to data-driven decision-making, such as the development of new algorithms for predictive maintenance and the design of software for data analysis and visualisation.

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Frank Klein Schaarsberg is a data analyst at Witteveen+Bos. Frank has a Master’s degree in applied mathematics with a specialisation in system and control theory. His expertise is in mathematical optimisation and applied mathematics. Frank applies his skills to software development, as well as designing and developing complex software tools to support real-time decision-making. In his day-to-day work, Frank applies version control and DevOps principles when developing software tools.

Arash Sepehri

Arash is an MSc student at Delft University of Technology. His expertise is in logistics management and he is currently working on optimising the port traffic efficiency, specifically when each port is a part of a larger network. Arash’s previous research has focused on the development and validation of models for marine and coastal engineering applications. He is currently developing software tools for port traffic optimisation.

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