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Marine Units Performance Simulation under Changing Environment in the Caspian Sea

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ABSTRACT

Simulation was performed with Genetic Algorithm (GA) which is a heuristic algorithm for path search optimization as reanalysis using historical observations of ice conditions as input. Several transportation modes (conventional shallow water fleet, Air Cushion Vehicles (ACV) and Amphibious All-Terrain Vehicles (ATV)) were considered with their limiting conditions to understand the effects of changing environment and possibility to access ice covered shallow areas in the Northeastern Caspian. Downtime and travel time variation were used to illustrate joint action of reducing water level and depleting ice cover on logistical chain in the region.

KEY WORDS Caspian Sea; Numeric simulation; Vessel performance; Travel time estimate; Downtime estimate.

NOMENCLATURE
ACV (Air Cushion Vehicle), ATV (Amphibious All-Terrain Vehicle), EER (Emergency Escape Route), GA (Genetic Algorithm), IBSV (Ice Breaking Supply Vessel), OW (Open Water)

INTRODUCTION

Changing environment affects the Caspian Sea in a lot of ways. The most obvious consequence is continuously falling water level because of depleting rivers flow feeding the reservoir and more effective evaporation with increasing regional air temperature among other factors controlling the process. Shallowing waters promote investigations to build resilience of supply chains by operators of extensive economic activities in the Northeastern part of the sea. Depleting ice cover, projected ice regime and new scenarios of impact on operations remain unknown factors due to general unavailability of data driven impact assessments targeted to project the effects of changing environment into the future years.

This article expands generic investigation of declining trends observed in Caspian seasonal ice coverage and volume by Vernyayev et al. (2023b) focusing on support and emergency response fleet for a developed oil & gas field in the Northeastern part of the sea. Simulations of normal operational routines where transit from point A to B is a requirement was performed for variety of crafts that are different from conventional ice breaking fleet used to the date. Resulting travel time and downtime by type of vehicle can further be economically assessed for feasibility with consideration of deck space, tonnage and other operational parameters and requirements.

Transit simulations are performed using genetic algorithm (Holland, 1992) with altered Caspian Sea classification dataset (Vernyayev et al., 2023a) to model shallower waters and compiled as input for operating conditions. Scenarios of operations are imagined for illustration purposes but close to realistic based on authors' experience. Actual vehicle models were selected randomly with google search by type of crafts. Their performance data was extracted from publicly available sources provided by manufacturers or regulators. Resulting travel time and downtime statistics presented in the article are, thus, for illustration only, and should be considered with caution, if referred to in operations.

MARINE TRANSPORT MODES

Study considers three transport modes with corresponding adverse ice and metocean conditions limiting their maneuvers in the area:

- Air cushion type.
- Conventional ice breaking shallow draft vessels.
- Amphibious. ARKTOS and light Sherp ATV.

Objective function that evaluates transit speed for a transportation normally depends on combination of documented vessel performance in ice and navigation safety with experience in an area. This study considers only specifications by manufacturers. Similarly, the list of limiting conditions is based on their recommendations. The latter were summarized into a mask grid identical to simulation grid described below in resolution. The mask was used in simulation to identify areas that were observed unpassable or requiring preliminary time-consuming active mitigation measures with ice and metocean conditions fed into simulation.

Table 1 Transportation modes summary by vehicle or vessel type.

Vessel	Purpose	Operating and Limiting Conditions
ACV	Passengers, Light Cargo, possibly EER	Wind Speed 30 knots, Ice Accretion, Ice Ridge Sail Height 1.5m
Shallow Draft IBSV	Large Cargo and Fluids, Limited Passengers, Barge Operations	Draft 2.8m Level Ice 1 m at 2 knots Cross-drift in channel
ARKTOS	EER, possibly infield passengers and light cargo	Cross drift when disembarking Ice Thickness up to 15 cm 2 knots 15 to 30 (35) cm 0.5 knots Above 30 (35) cm 10 knots
Sherp	EER, infield passengers and light cargo	Ice Thickness OW 3 knots up to 15 cm 0.5 knots, above 15 cm 15 knots

The actual crafts and corresponding findings of their resilience to changing conditions from simulations are presented with results below.

SIMULATION METHOD

Algorithm is targeted to identify paths between two points with maximum transit speed across the grid (and thus shortest transit time) for each day of available observations in the period from 2014 to 2022. In case the destination point is within limiting conditions and is not accessible by transport during the day of simulation the nearest point of grid outside the limiting conditions is chosen for simulations during the day. This way availability of points is described with limiting conditions statistics and transit time estimates in other accessible points is assessed based on a homogeneous and regular dataset.

Input ice and metocean conditions were aggregated into two grids around Kashagan structures that were selected for this experiment due to available information on developed infrastructure. Island locations and completed navigation channels layout were digitized from Sentinel-2 images and were extracted from regularly updated internal dataset of obstacles affecting drift in the region. Fine grid with cell size of 200m was set around the well-developed Eastern part of the field while coarser grid with cell size of 1 km covers the whole license block.

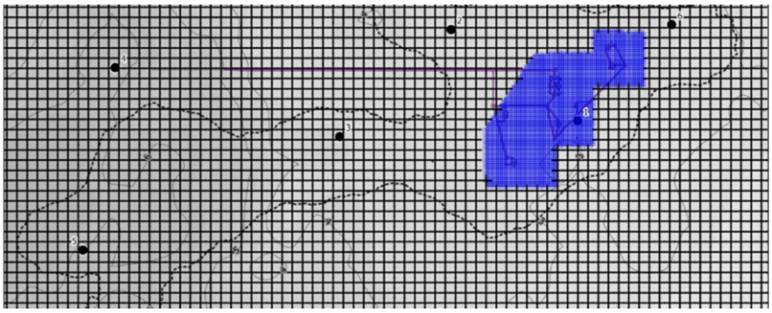


Figure 1 Illustration of the simulation grid points used to assess marine operations.

Each run of simulation was performed with the following steps for each day during the period of available data:

1. Limiting conditions mask identifies unpassable ice and metocean conditions for the day where transport mode cannot be used to access grid points was performed for winter seasons starting November 01st to March 30th.
2. The fastest route simulation is performed to identify time to get to grid points in the navigable zones only outside of limiting conditions.

When looped for each transportation mode with daily iteration over the period of observations this process generates time series for daily travel time between point 1 and each point from 2 to 6 and downtime for limiting conditions is compiled for further statistical analysis of transport mode usability.

Genetic Algorithm

The fastest route simulation is performed with Genetic Algorithm (GA) which is a heuristic algorithm for path search optimization. GA algorithm was applied to develop ship route optimization system by Choi et al. (2013) and verified its performance. The use of GA algorithm allows avoiding graphic analysis of all possible combinations of nodes between points which is time and computing power consuming.

The algorithm is targeted to identify paths between two points with maximum transit speed across the grid (and thus shortest transit time). In case the destination point is within limiting conditions and is not accessible by transport during the day of simulation the nearest point of grid outside the limiting conditions is chosen for simulations during the day. This way availability of points is described with limiting conditions statistics and transit time estimates in other accessible points is assessed based on a homogeneous and regular dataset.

Simulation is accomplished following the steps:

1. Algorithm is initialized with generating 100 random routes between two points outside of limiting conditions defined above.
2. Generated routes are evaluated with conditions described in Table 1, targeted for definition of maximum speed for the whole transit.
3. Best routes (parents) are selected for crossover to generate more optimal child routes.
4. During crossover parts of parent routes are mixed into a child route.
5. Child route is passed to the new generation. Several routes from previous generation of parents are also added to new generation. New generation is also populated with more randomly generated routes.
6. Random mutation is introduced to the route and if the mutation is beneficial the mutated route is passed to the next generation.

Figure 2 illustrates the effect of route optimization with ten generations of evolution performed with algorithm. Note that mutated route is the same as a child route in the tenth generation because it is less likely to introduce beneficial changes to the route for the later generations.

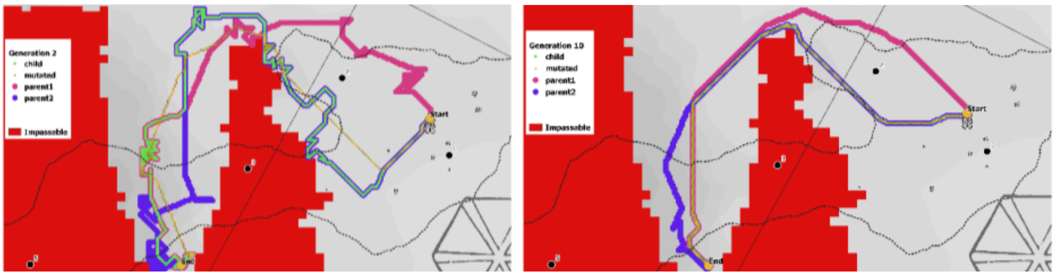


Figure 2 Example of routes generated for light ATV Sherp on 7 January 2018 from point 1 to a randomly selected point from second generation (left) and from tenth generation (right).

RESULTING OBSERVATIONS AND DISCUSSION

This section present results of simulations and discussion on each transportation mode for specific crafts that were considered in the scope of this study. Figure 3 shows photos of considered ACV Caspian Falcon, Ice Breaking Tug Mangystau-2, Amphibious ARKTOS and Sherp with their known description in the caption.

Figure 3 Top left: ACV Caspian Falcon (Length - 29.3-33.7m; Beam - 15m; Passengers - 130-180; Payload - 18-21 Tons.), Top right: IBSV Mangytau-2. Bottom left: ARKTOS utility

craft. Bottom right: ATV Sherp.

ACV Caspian Falcon is the largest hovercraft currently in operation from Griffon's range with 18-21 tons of payload over three separate models according to information published on their website (Griffon Hoverwork 2023). Ice Accretion resulting from interaction of overcooled metal surface with spray traversing open water at freezing point and creating excess weight on the vehicle was considered as the key limiting condition among others:

- Daily average air temperature is below -2°C deemed sufficient to cause spray freezing on the deck.
- Total concentration of ice cover is below 9/10 and weighted average ice thickness is below 10 cm indicate exposure to open water and supply of spray.
- Vertical obstacles in form of rubble fields exceeding 1.5 m rubble height. 75% coverage data of deformed ice from Kadranov et al. (2023) was assumed to condition this limit.

Assumption on rubble fields in terms of rubble height using dataset with an unknown vertical component is compensated with the logic to avoid deformed ice cover regardless of the height at any available opportunity. Thus, more effective fuel consumption without increased hovering elevation and reduction of potential for extended maintenance because of skirts damage due to interaction with rough surface of deformed ice are considered for optimal performance and exploitation of the craft.

IBSV Mangystau-2 is a conventional shallow draft marine vessel with ice breaking capability and limiting condition to support operations being water depth. For simplicity of simulations draft was assumed 2.8 m versus combination of bathymetry with 0.5 m vertical resolution and reduced water level record from KazHydroMet (KazHydroMet 2023) by 1 m for assumed conditions in 10-20 years. In case navigation is considered within channel simplistic cross drift assessment is considered as a limiting condition. Cross-drift conditions with impact of grounding transiting vessel in the shallow waters next to channel were defined following findings of Vernyayev et al. (2019):

- Not semi-stable or stable state of ice cover when only small displacements are possible on local scale.
- Total concentration is above and including 7/10 with weighted average ice thickness above 20 cm
- Wind Direction within 90° sector perpendicular to channel heading and daily scalar average wind speed above 15 knots when ice is stationary and 10 knots when mobile.

ARKTOS Crafts are proven to have the highest level of all-round amphibious mobility; particularly while crossing the transition between ice and water according to manufacturer's description on their website. Due to their unique design, ARKTOS Craft have an unsurpassed ability to climb vertical steps from deep water (multi-year ice floes), operate in mixed ice/water conditions, and maneuver through ice-rubble fields, significant side slopes, steep grades, deep mud, muskeg, quicksand, shallow water and other water transition zones. Limiting conditions for the craft were compiled following the logic of placing heavy object on ice sheet:

ice is compacting, or mobile with total concentrations above 6/10, or other immobile states with total concentration above and including 8/10 and weighted average ice thickness is in the range from 15 cm to 30 cm in combination with 70% relative flexural strength or 35 for below 70%.

It is assumed that ARKTOS will advance in ramming mode within this range at speed comparable with drift speed making transit uncontrollable whereas at lower thicknesses the progress is in milling mode for thin ice (low speed) or on ice surface (high speed).

Usage of Sherps (SHERP 2022) in support of oil and gas operations was confirmed with GazPromNeft that has successfully tested an amphibious all-terrain vehicle to support its operations at the remote Vostochno-Messoyakhskoye oil-gas field on the Gydan Peninsula, West Siberian Arctic according to the news on their website. In case of light amphibious vehicles, it is assumed that they are not used in conditions when they may break through the ice and there is any possibility impact on the sides of the vehicle. Thus, limiting conditions will be:

- Open water, mobile and compacting ice cover state
- When ice is immobile and weighted average ice thickness should be above 15 cm

The ice thickness lower limit is needed to ensure the vehicle does not break through ice cover regularly decreasing the speed of transit to the unacceptable level.

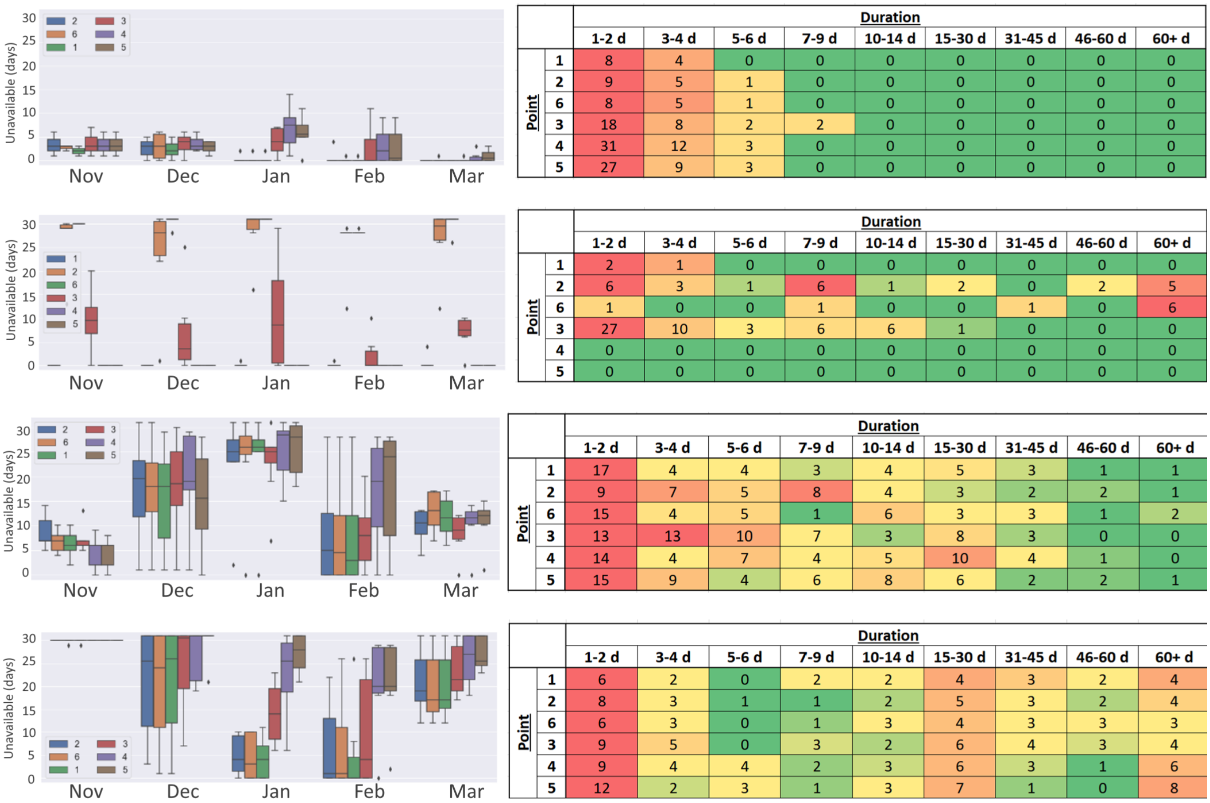
Objective functions used to assess the optimal routing for each mode of transportation are summarized in the list below. Vessel performance parameters are simplified for the purpose of this study and can be further enhanced based on craft performance records and operational experience in the field to increase accuracy of simulations. Approximation at this stage is sufficient to understand how various operations can be carried out in the field with considered options of transportation.

- ACV speed recorded by marinetrafic.com (MarineTraffic) is 41.1 knots / 39.5 knots (Max/Average). Considering there is significant number of high freeboard obstacles in the field this study assumes the speed of craft to be 15 knots. This is also deemed sufficient to account for speed loss during maneuvering.
- IBSV was assumed 1 knot if water depth was less than sum of the thickest ice observation in the grid point of assessment and draft (2.8 m). 5 knots speed was used for other water level conditions outside the limiting conditions from the same source.
- ARKTOS speed of 5 knots was assumed in open water and ice concentrations below 6/10th with weighted average thickness below 15 cm when water propulsion and milling with tracks is an efficient combination to ensure steady progress. Speed of 10 knots was assumed for the ice conditions with weighted average ice thickness above 30-35 cm depending on ice bearing capacity. The intermediate ice conditions were considered limiting as progress would be in ramming mode being too slow to cover significant distances.
- Sherp speed of 10 knots on ice surface was considered for immobile ice outside limiting conditions discussed above for this type of transportation.

Note the objective functions above have sufficient conservatism to account for pilot experience. This is achieved with implementing significantly lower craft speeds than indicated in the known crafts performance reports or technical sheets. Depending on the pilot mastering the craft the speeds may increase to the level when navigation safety becomes a limiting factor.

Downtime Estimates

Figure 4 presents resulting monthly distribution of days with limiting conditions for each reference point in the field and persistence analysis indicating number of events for each mode of transportation. Visual comparison indicates ACV has shown to be the most resilient to the limiting condition with least persistent of observed ice conditions and significantly lower occurrence of limiting conditions at the reference points. Persistence values of accessibility downtime at each location can be used for data driven decision on choice between investment into more autonomous operations or into the suitable means of transportation.



		Duration								
		1-2 d	3-4 d	5-6 d	7-9 d	10-14 d	15-30 d	31-45 d	46-60 d	60+ d
Point	1	8	4	0	0	0	0	0	0	0
	2	9	5	1	0	0	0	0	0	0
	6	8	5	1	0	0	0	0	0	0
	3	18	8	2	2	0	0	0	0	0
	4	31	12	3	0	0	0	0	0	0
	5	27	9	3	0	0	0	0	0	0

		Duration								
		1-2 d	3-4 d	5-6 d	7-9 d	10-14 d	15-30 d	31-45 d	46-60 d	60+ d
Point	1	2	1	0	0	0	0	0	0	0
	2	6	3	1	6	1	2	0	2	5
	6	1	0	0	1	0	0	1	0	6
	3	27	10	3	6	6	1	0	0	0
	4	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0

		Duration								
		1-2 d	3-4 d	5-6 d	7-9 d	10-14 d	15-30 d	31-45 d	46-60 d	60+ d
Point	1	17	4	4	3	4	5	3	1	1
	2	9	7	5	8	4	3	2	2	1
	6	15	4	5	1	6	3	3	1	2
	3	13	13	10	7	3	8	3	0	0
	4	14	4	7	4	5	10	4	1	0
	5	15	9	4	6	8	6	2	2	1

		Duration								
		1-2 d	3-4 d	5-6 d	7-9 d	10-14 d	15-30 d	31-45 d	46-60 d	60+ d
Point	1	6	2	0	2	2	4	3	2	4
	2	8	3	1	1	2	5	3	2	4
	6	6	3	0	1	3	4	3	3	3
	3	9	5	0	3	2	6	4	3	4
	4	9	4	4	2	3	6	3	1	6
	5	12	2	3	1	3	7	1	0	8

Figure 4 Monthly distribution of limiting conditions occurrences (left) and persistence of limiting conditions (right) for from top to bottom ACV, IBSV, ARKTOS and Sherp. See Dutoit (2012) for box plot visualization of quartiles.

Figure 5 illustrates spatial distribution of limiting conditions duration as part from season duration as defined from November 1 to March 31 in the scope of this study for considered modes of transportation across the area of interest. Each pixel in the chart illustrates annual probability of occurrence for combination of adverse limiting conditions derived as day observed versus number of years with fixed duration of season as mentioned above. Increasing likelihood in dark red bands indicates limiting conditions nearing the whole season duration as the effects from changing ice environment that supply chain faces in the near future of the project.

ACV charts and derived statistics based on the scenario were designed to pick coincidence of cold air temperature and high areal coverage with open water. Resulting spatial distributions resembling similar type of likely open water occurrence as analyzed by Sigitov et al. (2023). IBSV analysis illustrates dependence of the project on access channels and necessity to continue dredging operations should the operator persist using conventional fleet support of operations for developing infrastructure. ARKTOS downtime scenario is based on ice thickness (Sigitov et al., 2023) and relative strength controlled with air temperature. Considering the combination of extremely mild and moderate winters in the dataset for input into simulations derived statistics illustrate optimistic scenario of expected downtime for the craft. Distribution of downtime for lighter Sherp ATV clearly questions reasonability of its usage in the western part of the operations area.

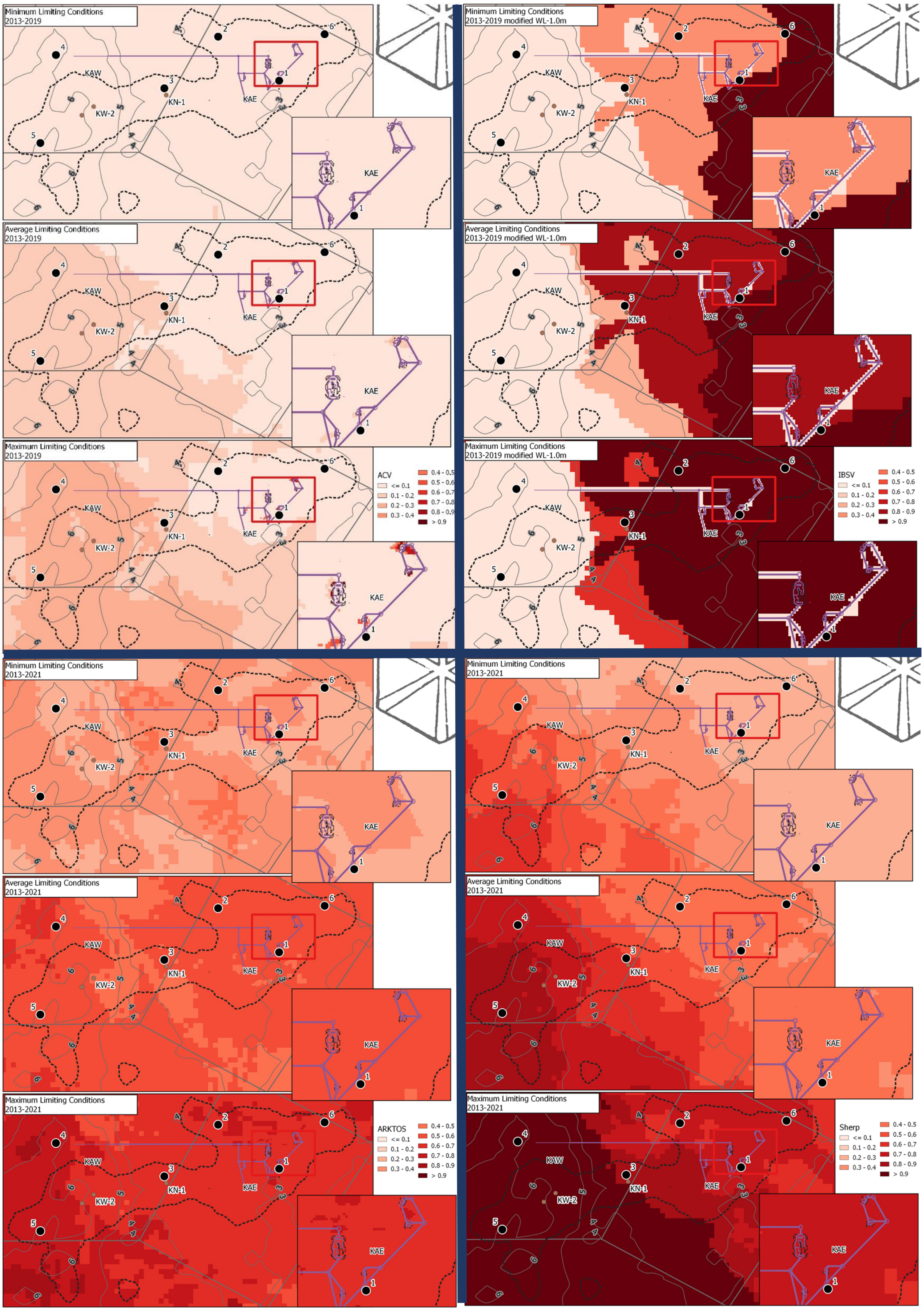


Figure 5 Spatial distribution of Minimum (top) Average (middle) and Maximum (bottom) duration of limiting conditions relative to season duration in parts from one for ACV (top left), IBSV (top right), ARKTOS (bottom left) and Sherp (Bottom Right).

Transit Time Estimates

The biggest island in the Eastern cluster of the artificial islands was assumed to be the logistical and maintenance personnel hub was used as the departure point to simulate in-field transits supporting in-field operations. To limit transit analysis with one-day trip, thus reducing computing time, the second transition hub was assumed in the middle of the field. Cumulative transit time for both estimates can be used as an estimate for transits across the whole field. Note figure below with the transit time estimates that are performed for tracks going around limiting conditions indicated as red zone on the figures below that illustrate a day's run of simulations.

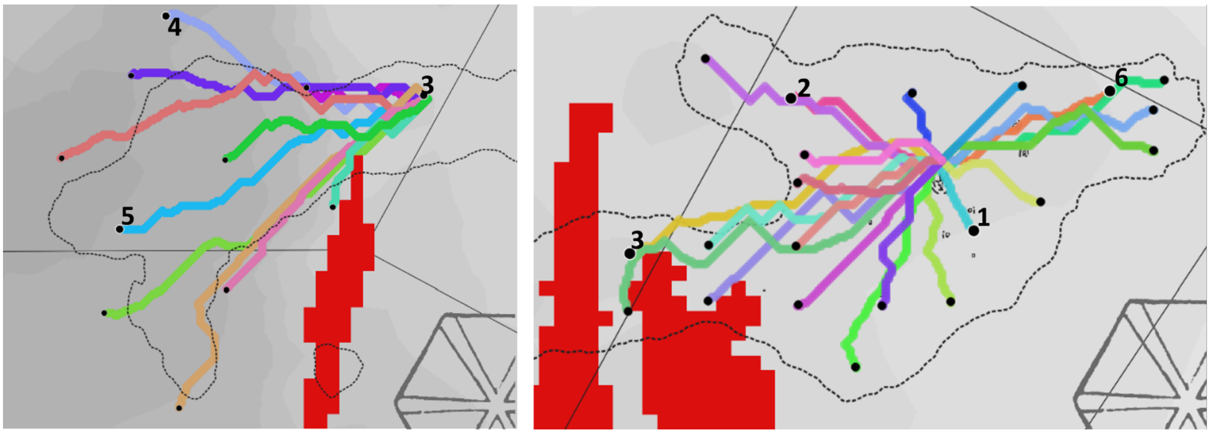


Figure 6 Illustration of departure points to destination reference points along the rim of the field and an example of a day's run.

Transit time was accumulated in grid points along all successive optimized tracks for each day of simulations and for each mode of transportation. These values were used for interpolation to the nearest points in the grid if they were not masked out with limiting conditions. Interpolated times are than aggregated into basic descriptive statistics for each grid point for visualization and further quantitative analysis.

Figure 7 illustrates simulated tracks count and spatial distribution of resulting minimum average and maximum transit times. Statistical output for estimated transit times illustrates complexity of the problem to choose the right mode of transportation for specific operations. Finding the balance between the constraint of limiting conditions above, response time and vessel parameters like payload, deck size and onwards is a challenge.

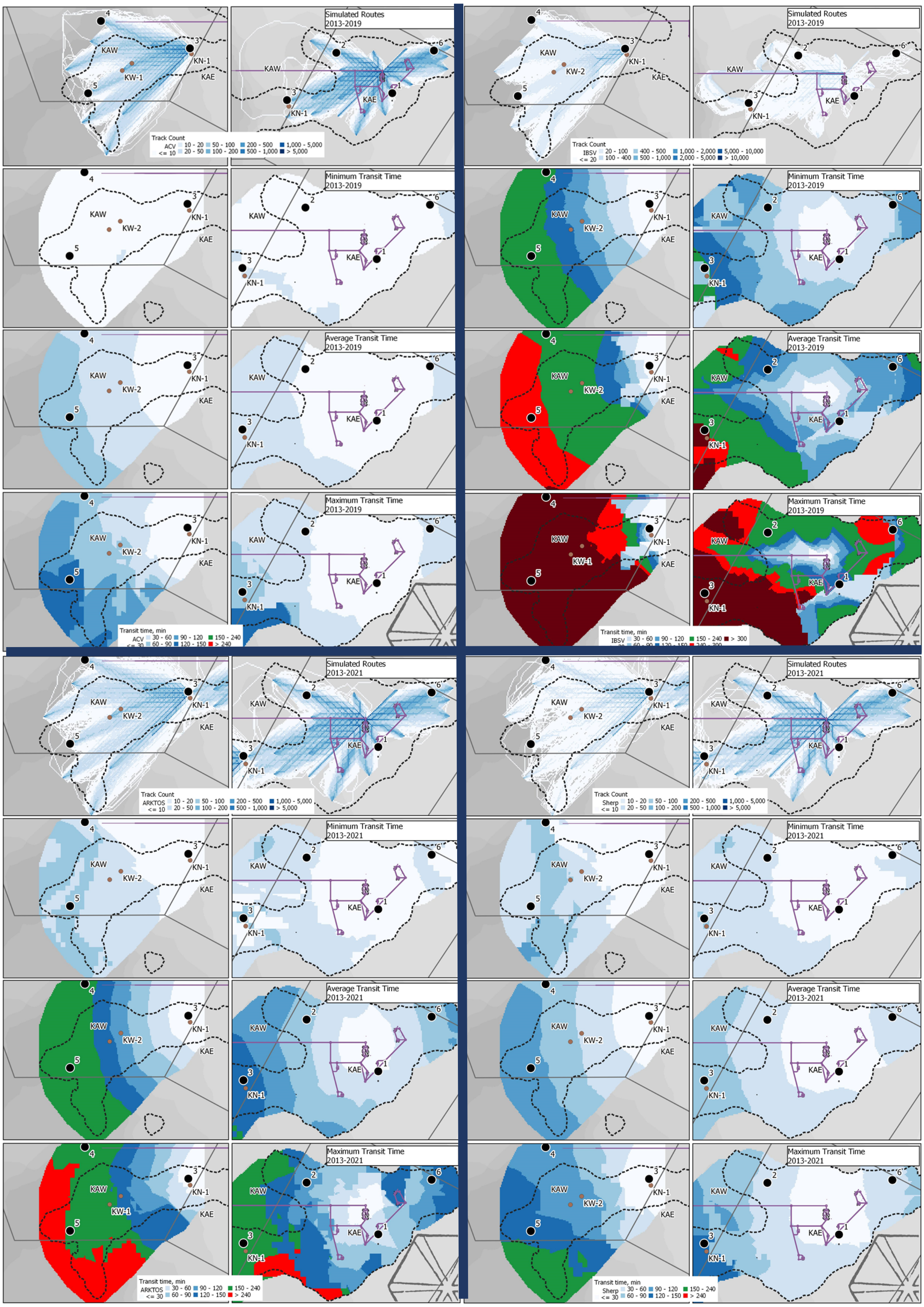


Figure 7 Simulated tracks count and spatial distribution of Minimum (top) Average (middle) and Maximum (bottom) time in route for ACV (top left), IBSV (top right), ARKTOS (bottom left) and Sherp (Bottom Right).

CONCLUSIONS

Presented results of simulations using genetic algorithm to find optimal route illustrate transit time and unavailability time estimates. These operational indices derived from changing environment of the sea can be used for detailed quantified impact assessment and facilitate data driven decision making process. Deployment of a new facility in an area can be used as an example of implementation. Feasibility study will include logistics analysis where downtime statistics for a mode of transport in the deployment location can be fed into operations risk assessment and tolerance versus cost and criticality of operations for EER. Transit time combined with fuel consumption rate, deck size, payload capacity and planned turnover demand at the facility indicates supply chain cost.

Demonstrated capability of applied dataset designed to support this type of numerical simulations can be used with more sophisticated scenarios to answer the most demanding queries. The key advantage of the solution for the Caspian region is availability of detailed data with high spatial and temporal resolution. It enables accurate prediction and data driven justification for introduction of changes to the logistical chains with the highest level of precesion.

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