A Ship Weather Routing Tool to Face the Challenges of an Evolving Maritime Trade

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KEY WORDS

1. Weather routing 2. Human factor 3. Genetic algorithm

A ship route optimization system aimed to face the challenges of a more demanding maritime trade is here presented. The paper highlights the key role of a weather routing system in the current ocean navigation. The steps to follow in the development of an efficient and trustable weather routing tool are explained with special attention to some important features that are sometimes neglected. In particular it is suggested how the ship operators needs should drive the implementation of the code to aim for a tailor-made equipment where the shipmaster can put his confidence. The progresses made in the development of such a tool are also described.

1. INTRODUCTION. Enhancing the competitiveness to maritime trade is fundamental in the global economy where 90% of the international exchanges are carried out by sea (UNCTAD, 2007). The rising fuel price and the increase concern for the environmental impact of marine trades both in the public opinion and in the political eye make this task even tougher. This concern has persisted even in the present trend of lower prices of crude oil. Besides the commitment of considering the ship consumption and emissions since the design phase to build more and more efficient ships (IMO, 2011), the international community stressed the importance of operational management, proving a standard index, the Energy Efficiency Operational Indicator (EEOI; IMO, 2009), to allow a common evaluation of its effect. Indeed it is estimated that the combined effect of fleet management and logistic, voyage optimization and energy management can lead to a reduction in CO_2 emissions between 10% and 50% (IMO, 2009).

This concerns and closer attention to operational life of the ships suggested to promote studies aimed at assessing the energy efficiency in seaways (Prpić-Oršić et al., 2015) and showing the view point of the shipmasters in relation to significant phenomena and their perception of the ocean environment (Prpić-Oršić et al., 2014) to allow a deeper understanding of shipping operations. Both approaches are important in the development of operational tools with the objective of providing a powerful system to aid the ships' masters in the route selection process to lead to safer and more efficient maritime transportation. In fact two different viewpoints are required: the technical and scientific research and progress to be more and more accurate in the results and the human interaction which requires a user friendly, easy to use and complete tool so that the captain can put his trust in.

Weather routing software do exist. They have been studied since the appearance of the first computers (James, 1957; Zoppoli, 1972) when the main objective was to optimize the time of arrival adopting the isochrones method. Thenceforth the international maritime trade underwent many changes, which the researchers tried to follow studying more advanced methods, using the new available technologies, such as the Geographical Information System GIS (e.g. Pacheco and Guedes Soares, 2007), and considering more than one objective by means of a cost function. In this phase Dijkstra’s algorithm (Cormen et al., 2001) revealed to be very powerful in trajectory optimization problems, being easy to implement, very fast and able to find the optimal solution within the grid-defined domain. A significant application of this method can be found for istance in Padhy et al. (2008) and a more advanced one in Skoglund (2012) where the original algorithm was slightly modified to save the sub-optimal solution during the optimization process in the attempt to approximate the Pareto frontier and showing noteworthy improvement in reducing the fuel consumption on respect to the original one.

Dijkstra’s algorithm is in fact adopted in most of the commercial software (Chen, 2011). Nevertheless the confidence of the ships' masters in these equipments is still poor (Faulkner, 1997). This scepticism is mainly due to two factors: the available weather routing systems do not model the ship behaviour in a detailed way, and risk to push the vessel in rough weather compromising the safety of cargo and crew in order to reach the destination in a shorter time and the possibility of control of the captain (who has the legal responsibility of the ship with its cargo) is often limited, the optimal route is given as it is and the captain must either trust it or take a decision autonomously.

In the last decade, although some valuable studies to adapt the classical methods to the new requirements can be found, e.g. Fang and Lin (2015) on respect to the isochrone method, the increase capabilities of the computers encouraged the more and more frequent employment of dynamic programming (as in Avgouleas, 2008; Shao et al. 2012) and genetic algorithms which allows a fully multi-objective optimization. Some of the noteworthy applications can be found in Szłapczynska & Smierzchalski (2007), Hinnenthal (2008), Marie and Courteille (2009), Maki et al. (2011) and Krata & Szłapczynska (2012). In the same time it was clear the importance of taking into account the uncertainties of the entire system (Papatzanakis et al. 2012), already started in Hinnenthal (2008) in relation to the weather with the adoption of ensemble forecast.

The main goal of the present work is to outline the steps towards the development of an advanced ship weather routing system, highlighting the lacks in the available methods (section 2) and the improvements that are expected in the future to provide more and more reliable equipments (section 3). In section 4 the progresses of the work following Vettor and Guedes Soares (2015) to the implementation of an onboard support system for the selection of the most favourable route will be briefly described. Conclusion and last discussions are made in section 5.

2. MOTIVATIONS: THE IMPORTANCE OF HUMAN INTERACTION. In a recent paper (Prpić-Oršić et al., 2014) the point of view of the shipmasters is acquired from questionnaires aimed at understanding how seamen experience the environment and how they act in the trade-off between safety and competitiveness, their awareness on

extremes events and sea-keeping phenomena and also the role of and the confidence in wave forecast and weather routing software is discussed.

Most of the large ships are supported by a commercial weather routing system, but a continuous monitoring of the actual weather condition and a prudent behaviour on uncertain scenario are always essential and an overconfidence on the tool can lead to dangerous situation, in some cases with disastrous consequences (Faulker, 1998).

The reason of this limitation of the weather routing system is mainly a result of two deficiencies: weather condition can be unpredictable or vary during the voyage, in particular in Pacific passages with long-term forecasts, and the modelling of the ship behaviour in seaways often neglects or underestimates dangerous situations, especially when the system is only based on sea-states, not taking account the real effects on the ships and their specific characteristics.

An explanatory example of how the avoidance of harsh wave loads thanks to the master's prudence and experience is also reported. The attempt of an Ultra Large Container Ship (ULCS) to reach the Channel from the Straight of Gibraltar departing on January 4th 2014 is described. Figure 1 shows the prediction of the ship position and sea-surface situation after 20 hours along the Portuguese coast (left) and 56 hours in front of the Breton peninsula (right) from the departure. While the first situation is heavy, with a significant wave height (SWH) of 8.2m, but still sustainable by a very large vessel, in the second case the combination of two factors: the presence of beam sea with a SWH of almost 10m and the vicinity of storm centre with SWH above 13m, suggested to the captain to stop in a port close to Gibraltar waiting for the storm to pass and delaying the schedule.

It is not possible to know whether or not a different decision would have conduct to a disaster, but it is undeniable that it would have be a great and irresponsible hazard that a prudent and expert shipmaster would never take.

What can be learned from this example as researchers and developers of reliable weather routing systems is that giving a prime role to the human factor is unavoidable. Even considering that no container would have been lost following the indication of the software, the result does not change: the shipmaster preferred to ignore it. Such a tool becomes useless if it is not trusted in the most difficult situations. A more and more detailed and precise modelling of the ship behaviour is absolutely necessary, but not sufficient if not combined with an estimation of the uncertainties and the stochastic risk, which tries to reproduce what the reasoning of the master in an unclear scenario.

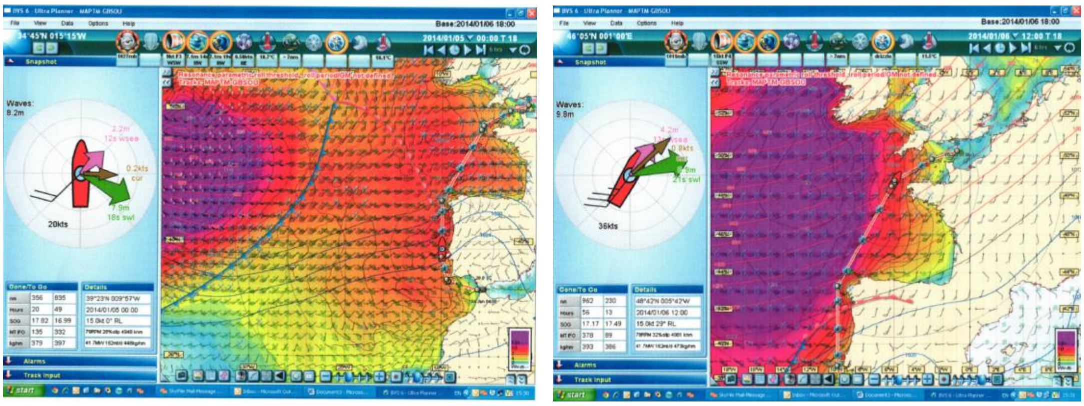

Fig 1. Heavy weather situation in Biskay Bay (from Prpić-Oršić et al., 2014)

3. IMPROVEMENTS ON THE CURRENT SYSTEMS. A weather routing system aggregates tasks, inputs and routines of many different disciplines and is composed by a number of sub-systems, which interact to take into account all the numerous variables in the identification of the most favourable route.

3.1. *Optimization method*. In the choice of the optimization method one should keep in mind that a lot of uncertainties of different extent are embodied in the optimization procedure. Thus to focus the attention on the research of the exact solution is meaningless, indeed it would be exact only in the simulation, but not in the real world. The optimization algorithm should rather allow extensively investigating the solution space, providing a set of favourable solutions and ensure a close approximation to global and local optima. Genetic Algorithms (GAs) demonstrated good performance in the optimization of complex and highly non-linear problems and, thanks to the fast development of the computational resources, they are now suitable to be implemented and processed by PCs. It is not ensured the detection of the exact solution, but of a set of routes approximating the Pareto frontier, among which the most suitable can be found. Another advantage is that a fully multi-objective optimization can be performed, releasing from the constrain of an all-comprehensive cost function, as required by other algorithms (e.g. Dijkstra, often used in path optimization). Successful examples of their application in the weather routing problem can be found in Hinnenthal (2008), Szłapczynska & Smierzchalski (2007), Vettor & Guedes Soares (2015).

3.2. *Weather forecast*. A big effort has been made in the last decades by the international community and the meteorological institutes to enhance the capabilities and the trustworthiness of the numerical weather predictions (NWP) models. With the advent of the third generation wave prediction models, which compute the spatial and temporal evolution of the wave spectra explicitly solving the all the relevant physics, the reliability of wave prediction has considerably increased. Nevertheless the quality is strongly dependent by the forecasted period; long-term predictions are still affected by uncertainties in the inputs for the initialization of the model. The effect of weather prediction errors can be reduced in two ways: feeding the software with updated weather data and repeating the optimization along the voyage and using ensemble forecasts (as in Hinnenthal, 2008), which derives from multiple runs of the same NWP model with slightly different inputs to take into account the stochastic error, and allows an estimation of the confidence interval of the prediction.

3.3. *Ship modelling.* Some of the software currently used are only based on the sea-states, it means that the ship performance is not modelled at all, thus the decisions are taken independently from how the ship will perform in a certain condition. The best available commercial software are ship responses based, that is the specific behaviour of the ship in a given sea-state is assessed by means of performances curves or sea-keeping calculation (through the Response Amplitude Operators). However in most of the case, if not in all of them, the computations are previously performed for a set of pre-defined sea-states defined by standard spectra (usually JONSWAP or Pierson-Moskowitz), mainly to reduce the computational time and the complexity of the code. This is already an acceptable representation, but it means that the forecasted sea-state is represented by some integral parameters, typically the either only the significant wave height (SWH) or together with the wave peak period (T_P), rather then the real frequency distribution of the wave energy density. The first criticism to this method is that the information provided by the weather forecast is not completely exploited. More important is that the lost information can hide the presence of non-standard spectra with multi-modal distribution both in frequency and in direction, spectra which are in fact common especially in the open ocean where a storm can be run over by swell propagating in a different direction. The effect of neglecting the actual spectral shape in the prediction of the ship behaviour can be significant as it is shown in Guedes Soares (1990) and Orlandi and Bruzzone (2012).

Although waves are usually the weather factor that greatly influences the ship performances, even wind (Kwon, 2008; Fujiwara, 2001) and surface currents (Chang, 2013) can be relevant and should be taken into account in an advanced weather routing system.

3.4. *Risk analysis*. As already written in the previous paragraphs, uncertainties are intrinsic both in weather forecast and in the prediction of ship performances. Performing an optimization as for a deterministic system can be not realistic and lead to unexpected hazard. A promising future development of the weather routing is the inclusion of a risk analysis. Adopting the concepts of the risk theory in the weather routing can help to handle in a relatively easy way the uncertainties, but also to include other parameters such as the possible encounter of icebergs or the risk of piracy. In practical applications the parameters to include can comprehend the vicinity from very heavy waves, or the forecast period. However such a tool is not available if not in a trivial way and there is space for a deeper research.

3.5. *User interface options and human interaction*. In the first section the importance of the human factor and especially of the confidence on the tool has been highlighted. Very important in this perspective is the possibility for the user to set the options according to its preferences and the strategy of the ship in a simple and intuitive way. It includes the pre-processing where the objectives and the strategy are defined, but also, even more important, the post-processing when the experience and intuition play an important role. If the selected route is not considered appropriate, the user should be allowed to change the selection and have a comparison with another route that is maybe less favourable according to the computer, but gives more confidence to the captain.

4. DEVELOPMENTS IN THE WEATHER ROUTING CODE. Vettor and Guedes Soares (2015) showed the potentiality and robustness of the SPEA2 (upgraded Strength Pareto Evolutionary Algorithm. Zitzler et al., 2002) in the optimization of the ship route, applied to a simplified case. In the following the further steps to improve both in the software architecture and in the modelling of the ship behaviour in the marine environment are described.

4.1. *Code architecture.* While the optimization algorithm revealed as an appropriate method to be applied to the weather routing problem, the architecture of the code needed to be redesigned. A modular and flexible structure is in fact required in order to allow dealing separately with the many different subsystem, which interact in the optimization process. To work on or modify one part without affecting the other functions is indeed necessary to test new features and to adapt the software to different requests and applications. A new C++ code that integrates SPEA2 algorithm has been developed. It takes care of the description of the sailing area, the weather condition as well as the modelling of the ship behaviour in the seaways, in terms of sea-keeping responses and propulsive performances, and, ultimately, of the optimization of the route. The code consists in six classes: “Ship”, “Journey”, “Route”, “Domain”, “Land” and “Weather”; and five subclasses: “GeoPoint”, “Time”, “Seakeeping”, “Engine” and “Environment”.

4.2. *Ship performance.* Waves are commonly recognized as the major cause of degraded ship performances in seaways. The clearest consequences are the increasing periodic motions (mainly heave, pitch and roll) and an additional component to the resistance. How these factors act in the operational life of the ship are of prime interests in the development of a weather routing code and many studies can be found in the literature to quantify their effects through standard parameters and their relative thresholds (Nordforsk, 1987; Dubrovaskiy, 2000). They influence the work-capability and comfort on board, the safety of the cargo, the efficiency of the propulsion system, that also means the maintainable speed, the consumption and emission.

As a first approach the off-line calculation have been performed offline. Nevertheless the sea-keeping responses and the propulsion performances have been modelled in a very detailed way matching the transfer function computed through sea-keeping codes based on the strip theory (Salvesen et al., 1970) with standard JONSWAP wave spectra (Hasselmann et al. 1973) and considering a wide range of condition, covering sea-states from the still water and a significant wave height (SWH) of 15m with a step of 1m and wave peak periods (T_P) between 0s and 20s, all the relative ship-wave angle with a step of 30° and ship speed from 0kn to 20kn with a step of 1kn. Many different factors can be easily computed and included in the optimization process starting from the spectral moments of the motions (e.g. the motion sickness incidence, the slamming probability, the significant lateral or vertical acceleration, etc.) and the choice depends, case by case, on the type of ship, the strategy of the shipping company and the preferences of the captain. As a reference the following factors have been considered and included in the optimization: the slamming and the green water probabilities and the vertical acceleration on the bridge, while regarding the propulsion system the fuel oil consumption (FOC) per nautical mile computed considering the actual added resistance in waves and the recommendations given by the constructor in the project guide (MAN B&W, 2010).

4.3. *Optimization settings.* As pointed out in the previous sections, an efficient and reliable weather routing tool requires a fully multi-objective optimization process able to be tuned in function of the specific requirements, to indicate the advantages and disadvantages of the proposed solutions in a transparent way, allowing a conscious evaluation and comparison of the merit of each of them by the final user. The method used to achieve this goal is a genetic algorithm (SPEA2), thus it requires the creation of a set of feasible route (initial population) and the iterative recombination of the proposed solution after each cycle (called generation).

The initial population is constitute by random routes which are computed in respect of the constrains. The iterative variation to generate the new generations is performed through three genetic operators: crossover (combination of two routes taken from the previous population), mutation (modification of one of the parameters describing the previous route) and migration (input of a new random route).

Finally the objectives must be set. Although any ship and trip have specific characteristics, we can summarize the typical requirement of any voyage as reaching the destination in a pre-determined or as short as possible time, in safe conditions and at the minimum fuel consumption (and emissions). For this reason the classical objective in route optimization are the fuel oil consumption (FOC), the estimated time of arrival (ETA) and the safety ($SAFETY$).

Instead of using the actual values of the objectives, the following objective functions were introduced:

$$FOC_{obj} = \left(1 - FOC_{\min} / FOC_{journey}\right)^2 \tag{1}$$

$$ETA_{obj} = \left(1 - ETA_{\min} / ETA_{journey}\right)^2 \tag{2}$$

$$SAFETY_{obj} = k \cdot \left(RISK_{coeff}\right)^2 \tag{3}$$

$$k = \left(1 - ETA_{\min} / ETA_{journey}\right) \tag{4}$$

where FOC_{min} is the minimum fuel oil consumption achieved in calm waters at the most efficient optimal engine load, ETA_{min} is the minimum possible duration of the journey if the shortest route is sailed at the design speed and $RISK_{coeff}$ is computed considering the maximum and the average sea-keeping effects along the routes,

These functions help to accelerate the propagation of the initial routes towards the optimal solutions, while the factor k reduces the impact of meaningless routes, which minimize the risk, but imposing odds courses.

4.4. *Test.* To test the code the widely studied S175 containership was considered as a reference. The simulation is performed for a route between the port of Sines in Portugal and the entrance of the entrance of the Gulf of Saint Lawrence. The departure time is set at 8.00pm on August 7th, 2001. The weather conditions are identified analysing the HIPOCAS hindcast database (Pilar et al., 2008).
Relatively to the genetic algorithm, the dimension of the first generation is of 100 individuals, in each generation the mating pool is of 15 individuals and 15 offspring are generated, finally the maximum number of generations is 1000.

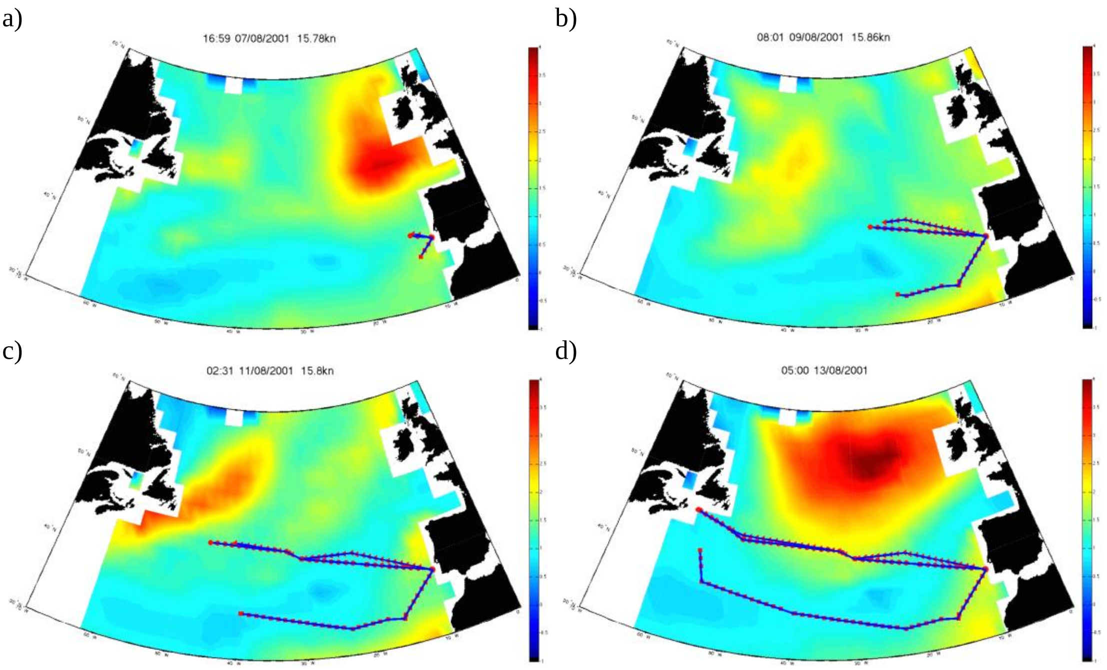

Figure 2. Evolution of three of the routes selected from the Pareto-frontier set, being the best considering the three objective: less fuel oil consumption (red stars), shortest time (red dots) and safest (red triangles).

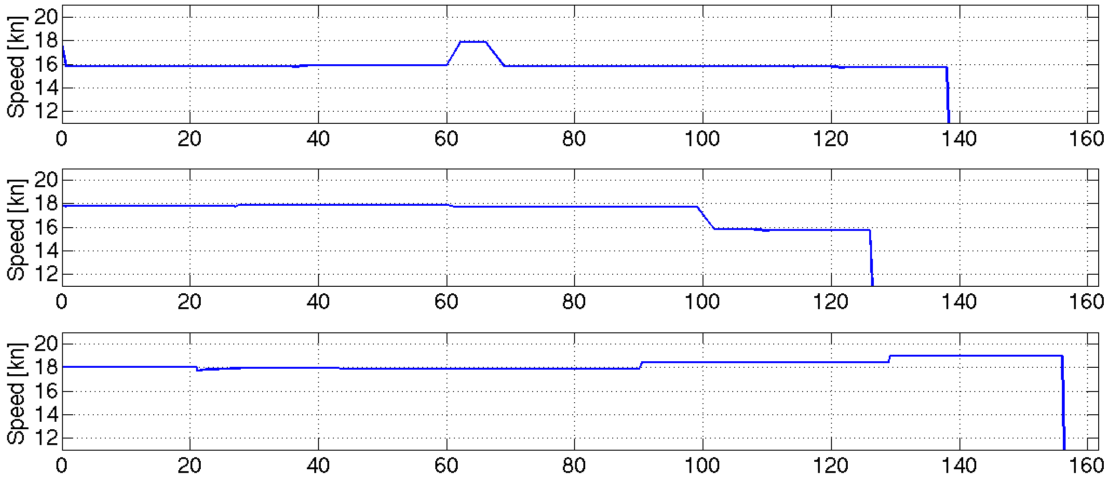

Figure 3. Speed profile of the routes traced in figure 3. From top to bottom: less fuel oil consumption, shortest time and safest.

In figure 2 the evolution of the paths of the best routes among the selected ones in terms of minimum fuel oil consumption, shortest duration of the trip and smallest risk are shown, while the respective speed profiles are plotted in figure 3. The fastest route takes 127 hours, it does not diverge much from the great circle and keeps a speed of 18kn for most of the voyage with a consumption of 241 tonnes of fuel; the maximum encountered wave height is 5.5m. In the cheapest route the path is similar, but the speed of advance is cut and maintained around 16kn for great part of the journey resulting in a reduction of about 20% in the fuel consumption, but at the expanses of the duration, requiring half a day more to reach the destination. The safest is much longer going south up to the domain. It requires more time and fuel and would never be selected, however it is useful in the optimization process, being a reference to ensure a wide spread of the results.
Sailing in summer the weather conditions are not so demanding, but this scenario was chosen because the results show anyway a good variability an possibility of selection among different routes.

5. CONCLUSIONS. Weather routing is a great opportunity for the maritime trade, but also a great challenge for the researchers and developers. A well-designed system involves several different subjects which have to be integrated to consider all the variables that influence the decision, to analyze the solution space and to provide the elaborated information to the user, suggesting the most favourable paths, but also offering a complete and clear view of the scenario that the ship will encounter during the journey. It must be taken into consideration that he captain is the final responsible of the ship, the people and the cargo that carries. Thus, beyond the accuracy of the calculations, the faith that the final product manages to benefit from the shipmasters is crucial to the success of the entire system. Time is changed from the dawn of the weather routing. Safety and environmental impact gained an increasing importance: rarely the shipping company would push the master to run the risk to save time cause the lost or damage of part of the cargo means downgrading of the company and higher insurance rates.

The code here presented takes on this challenge and sets the basis for the development of a more comprehensive software thought to meet the request of the market, to point towards safer and more efficient maritime trades. Nevertheless it requires further work aimed at taking into account other factors that might be important, such as for instance wind and currents, and designing an user-friendly interface. Moreover the possibility of integrating the sea-keeping calculation and the forecasted wave spectra in the code must be tested especially in relation to its computational demand.

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