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Towards Automated Nautical Chart Compilation and Verification of Output Topology and Safety

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Abstract:

The compilation of Electronic Navigational Charts (ENCs) requires significant amount of time, labor-intensive efforts, and cost. Despite the advancements in technology and the various research efforts, generalization tasks are still performed manually or semi-manually with expected human errors. The dramatic increase in the amount of data that is collected by modern acquisition systems, in addition to the increasing timeline expected by the end-users, are constantly driving Hydrographic Offices (HOs) toward the investigation and adoption of more advanced and effective ways for automating the generalization tasks to speed up the process, minimize the cost, and improve productivity. Full automation of the nautical chart compilation process has been unreachable due to the strict nautical cartographic constraints (and particularly those of safety and topology) that pose a challenge for most of the available generalization tools, while it remains questionable whether automation can replace human thought processes. In this paper, we discuss a research effort for an Automated Nautical-chart Generalization (ANG) model in the Esri environment. The ANG model builds upon the nautical chart generalization guidelines and practice and utilizes available tools in the Esri environment to perform the generalization of selected ENC features to the target scale. Safety constraints in the marine domain is of utmost importance, however, since most of the readily available tools do not respect safety, the main goal of this effort has been an output with no topological violations. In the current phase of the project, we evaluate safety of soundings and contour for user fixing and while the validation of bathymetry is a well-researched topic, there was the need for an automated process to identify the sections of the generalized contours that have been displaced toward the shallow water side Therefore, this work also presents a safety validation tool that detects the contours' safety violations in the output. The tool is composed of three main stages that run individually after the ANG model is complete with the aim to highlight the safety violations for fixing by cartographers.

Keywords: Automated, Nautical chart Generalization, ENCs, Safety of Navigation, Nautical chart constraints

1. Introduction

The Electronic Navigational Chart (ENC) is a Digital Landscape Model which is converted to a Digital Cartographic Model when rendered on the Electronic Chart Display Systems (ECDISs) (Dyer et al., 2022). It is a database that comprises numerous point feature objects (e.g., soundings, navigational aids), line objects (e.g., depth contours, coastlines) and polygons (e.g., depth areas, land areas) which are encoded using the chain-node topology and are important for the safety of ship navigation (IHO, 2020). ECDIS integrates ENCs, navigating related system and sensors aboard ships to give mariners complete picture of the instantaneous situation of the vessel and charted dangers in the area (Alexander, 2003). In many Hydrographic Offices (HOs) ENC features were compiled for years directly from the existing paper charts with digitization. Consequently, nowadays, most of the available ENCs are based on the footprints of the paper charts from which they were derived (Kastrisios and Calder, 2018). This is the main reason for the existing horizontal and vertical inconsistencies between adjacent cells, which may confuse mariners and reduce their confidence in the nautical chart. In addition, inconsistencies can affect the performance of ECDIS that uses the data for analysing the safety of the vessels underway, either by triggering false alarms that might contribute to the situation called "mariner's deafness". i.e., the situation where the mariner disregard important alarms because of a considerable number of irrelevant ones (Kastrisios, Calder and Bartlett, 2020), or, even worse, may lead to a system crash. Furthermore, as per the IHO standards for nautical charting (IHO, 2020), six usage bands exist, each associated with the intended navigational

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use (i.e., overview, general, coastal, approach, harbour, and berthing) and the radar range. Therefore, HOs are required to produce, maintain, update, and deliver a large portfolio of ENC bands in support of safety of navigation in a timely and consistent manner, which is considered a tedious and time-consuming process.

On the other hand, the International Hydrographic Organization (IHO) is encouraging HOs to update their current coverage schema (IHO, 2021) from the puzzle-piece layout resulted from the paper-chart-first concept, (e.g., Figure 1a) to a rectangular gridded system (e.g., Figure 1b). In 2019, the Office of Coast Survey (OCS) of the USA National Oceanic and Atmospheric Administration (NOAA), started rescheming their ENC suite by creating a gridded system with standardized scales and cell sizes. The standard scales follow a dyadic system in which each successively smaller scale is half of the preceding scale, and cell boundaries follow lines of longitude and latitude to appear as rectangular on a Mercator projection (e.g., Figure 1b). (NOAA, 2019)

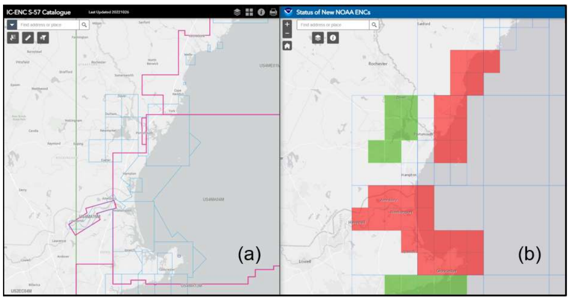

Figure 1. Current and planned gridded scheme for different usage bands, US East-Coast Newburyport (a) IC-ENC S-57 Catalogue (IC-ENC, 2022) (b) Status of New NOAA ENCs (NOAA, 2022)

The new gridded NOAA ENC coverage approach aims to significantly reduce the number of current chart scales, produce larger and standard scale coverage, facilitate metrification for NOAAs' charts and resolve vertical and horizontal inconsistency (NOAA, 2019). The project, which is expected to take years to complete, would benefit greatly from automation of individual generalization tasks, or, should this be possible, the entire process.

A fully automated solution for generating nautical charts from the highest level of detail data, to the appropriate scale, can streamline and minimize the time and effort needed for chart production. Respecting the nautical charts constraints, i.e., legibility, morphology, topology, and safety and especially the latter, is the main reason why current generalization processes and algorithms developed for land mapping are not directly applicable to the maritime domain and safety of navigation related products.

In this paper, we present an Automated Nautical-chart Generalization (ANG) model in the Esri environment that builds upon a set of constrains, extracted from the available nautical cartographic specifications, categorized and translated into rules to be defined in a template as conditions to be respected during the generalization process. The model aims to describe and implement the generalization steps from the highest level of detail ENC data to the target scale with no topological errors. However, since safety is of utmost importance and there are no readily available algorithms that fully respect its relevant constraints, a validation tool is developed and presented that detects all safety violation in the ANG model output and highlight it for user fixing. This tool can be used to validate safety even when new fully safe generalization algorithms are available.

2. Background

Generalization process and algorithms developed for topographic maps are different than those for nautical charts. In other words, it is mostly not applicable to the marine domain due to safety of navigation. For instance, in nautical charts generalization, depth contours are only allowed to move to the deep side during generalization (see Figure 3), this is to guarantee that a ship never runs aground because of miss representation (Peters et al., 2014). There are four types of constraints that need to be respected for the generalization of a nautical chart:

- *Topology* (e.g., no gaps or overlaps between skin of the earth features).
- *Safety* (e.g., Shallow depths need to be maintained and at every location, the indicated depth must not be deeper than the depth that was originally measured at that location). (Figure 2)
- *Legibility* (e.g., only essential information should be shown in a clear and efficient way).
- *Morphology* (e.g., slope and roughness of the seafloor must be maintained as much as possible). (Peters et al., 2014)

Those four constraints are sometimes incompatible with each other. Some are absolute, while others have a degree of flexibility. The first two are considered more strict (i.e., hard constraints) and should be mostly satisfied and hardly violated for the chart to be valid. In other words, constraints do not have the same degree of importance, thus, during the generalization process, compromises must be made. For example, the morphology constraint indicates to maintain the morphology of the sea floor and stay close to its measured shape as much as possible, whereas the legibility constraint deviates from this by disregarding details (Zhang & Guilbert, 2011).

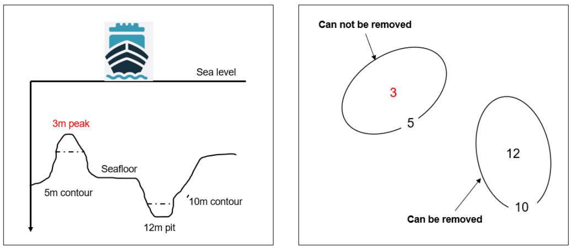

Figure 2. Illustration of Safety constraint, modified from Zhang and Guilbert (2011)

3. Related work

Various research efforts have tried to automate individual nautical chart generalization tasks. For instance, in sounding selection the works by Zoraster and Bayer (1992), Tsoulos and Stefanakis (1997), Sui et al. (2005), Owens and Brennan (2012), Yu (2018), Lovrinčević (2019), Skopeliti et al. (2020), and Dyer, et al. (2022). In Depth contours generalization, those by Guilbert and Lin (2006), Guilbert and Zhang (2012), Miao and Calder (2013), Peters et al. (2014), Yan et al. (2017), Skopeliti et al. (2021). Other works have focused on validating the safety (e.g., Wilson et al. (2017), Kastrisios and Calder (2018), Kastrisios et al. (2019a) and Dias et al. (2022)), and topology of depth information on charts, (e.g., Kastrisios et al. (2020) and Huo et al. (2022)). In addition, a number of available software applications perform S-58 validation checks and provide reports on Group 1 and Group 2 objects (e.g., Esri ArcGIS Maritime, Teledyne CARIS S-57 composer, SevenCs Analyzer and C-Map dKart Inspector) (Kastrisios and Calder, 2020). In 2013, Socha and Stoter introduced a research effort for automating nautical chart production. The research main goal was defining computer translatable rules for creating small scale ENCs (i.e., coastal) from higher scale (i.e., approach) with minimal human intervention. The study focused on nine ENC feature classes (Socha and Stoter, 2013).

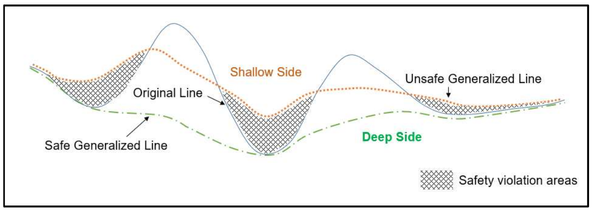

Figure 3. Illustration of the depth curve generalization safety constraint, modified from Guilbert and Lin (2006)

4. The Automated Nautical-chart Generalization model (ANG)

The Automated Nautical Generalization model is developed in the Esri environment. As shown in Figure 4, it utilizes the generalization rules spreadsheet, which is generated from the input database schema and the nautical constraint template (see section 4.1 & 4.2), as the input that drives the data generalization for any desired output scale, using the ArcGIS Pro available generalization algorithms and tools. (Nada et al., 2022)

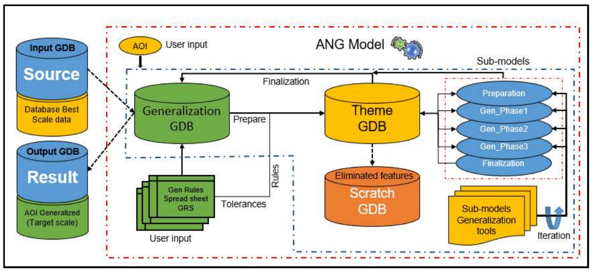

Figure 4. schematic description of the Automated Nautical Generalization Model (Nada et al., 2022)

There are more than 170 geo-features defined for ENCs as per the IHO standards S-57/101 (IHO, 2018). These features are categorized under the three geometric primitives (i.e., points, lines and polygons). In this research work, a number of features were selected for the proof of concept. As shown in Figure 5, the selected features are the seven polygonal feature classes representing the Skin of the Earth (Group1), and six related group of features that belong to S-57 features classes (i.e., natural coastline "COALNE", artificial coastline "SLCONS", depth contour "DEPCNT", sounding "SOUNDG") and NOAA Nautical Information System (NIS) feature class group (i.e., aids to navigation "ATONS", danger to navigation "DTONS"). The NIS is a multi-scale attributed geospatial database, primarily used for NOAA ENC maintenance and publication utilizing Esri ArcGIS (Ence, 2018).

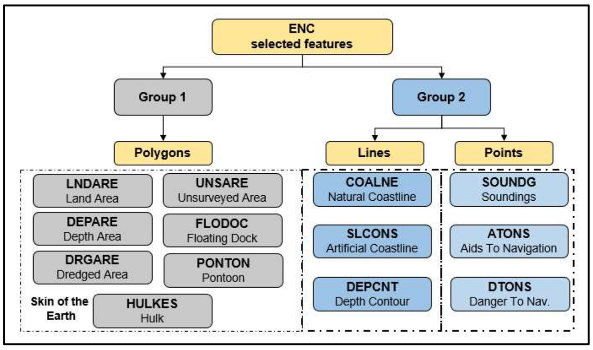

Figure 5. ENC selected S-57/101 features and associated NIS Feature class

4.1 The Generalization Constraint Template

From the available nautical cartographic standards, e.g., S-4 Regulations of the IHO for International Charts and Chart Specifications (IHO, 2020), and NOAA Nautical Chart Manual, Polices and Procedures (NOAA, 2019), a template was developed to categorize and define the properties of the nautical constraints as conditions to be respected during the generalization process. The template includes the geometry type, feature class and value for each condition. This value does not represent sequence but rather the hierarchy, i.e., the degree of importance, of those conditions (Nada et al., 2023b).

4.2 The Generalization Rules Spreadsheet

The generalization rules spreadsheet (GRS) is an excel spreadsheet that is used to configure the ANG model. It is developed from the nautical constraints template to match the input database schema. The GRS is composed of several tabs that contain all the required information about the selected feature classes, e.g., the geometric and generalization relationship between features, the tolerances to be used for the target scale, hierarchy levels

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and operations that needs to be implemented on each feature (Nada et al., 2023).

4.3 The ANG model Generalization Phases

The ANG model is organized in five main phases or sub-models (Figure 6); each phase consists of various generalization tools that are used to automate the process. The GRS drives the data generalization for the desired output scale.

4.3.1 *Preparation phase*

A series of steps are taken before running the ANG model to prepare the input geo-database GDB as follows:

(1) An empty GDB is created in ArcGIS Pro.

(2) The GDB schema is developed using a pre-configured ENC schema in a workspace xml format that contains all the required feature classes, tables, spatial attributes used to capture ENC information in a GDB schema (Esri, 2022).

(3) The Generalization Rules template is then created based on the configured GDB schema to build the GRS rule file.

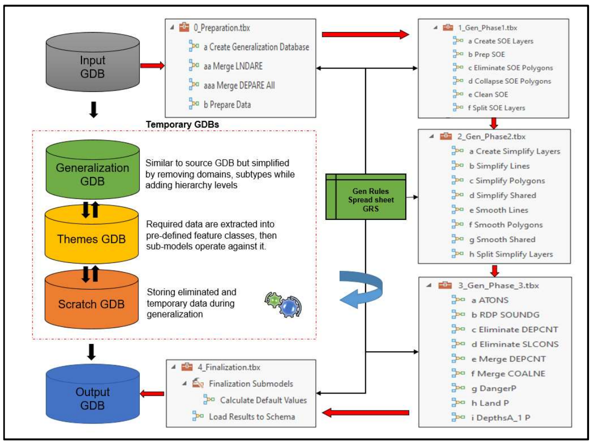

Figure 6. The Generalization Phases in ArcGIS Pro

(4) The area of interest (AOI) highest level of detail available ENCs are loaded to the configured GDB.

(5) The research selected feature classes (Figure 5) are imported from the loaded ENCs to the configured input GDB.

(6) The GRS is validated using the Generalization Rule Validation tools in ArcGIS Pro (Esri, 2021) to confirm that all tolerances and rules have been defined for the target scale.

Once the previous steps are taken by the user, the ANG model runs creating a number of GDBs that will be used throughout the generalization process, each has a specific role as follows:

- A Generalization GDB that has a similar schema to the input GDB but simplified and optimized for generalization within the AOI by removing domains, subtypes, and topologies not being used by the model. This GDB is used to backup the data after each generalization phase.
- A Theme GDB which is used to extract the required and pre-defined feature classes from the generalization GDB and apply the assigned generalization operations on it.
- A Scratch GDB which is used for storing temporary and eliminated data during the generalization process.
- The Result GDB will be created by the Finalization sub-model to match the input GDB schema. After all the sub-models have run, the generalized data are extracted from the generalization GDB and copied to this GDB adding all the attributes that have been simplified in the generalization GDB.

4.3.2 *Generalization first phase P1G*

In the first generalization phase, Group 1 polygons (see Figure 5) that fall under the area tolerance defined in the GRS are either collapsed to points or eliminated. Those features are extracted from the generalization GDB, converted to the theme-based schema and exported to the Theme GDB. As illustrated in Table 1, the generalization and geometric relationship between features are extracted from the GRS and assigned to the selected features. This pre-defined relationship between selected features is a key to the whole process. Each feature is assigned a geometric (e.g., SOE) and a generalization relation (e.g., Shared) that control how features interact during the generalization phases. The final stage in P1G is to clean and split features by dissolving and filling gaps, as well as removing any SOE edge lines where polygons were dissolved. The output of P1G is polygons without topological violations which are stored in the Theme GDB and backed up in the Generalization GDB.

Class Relation	Description	Valid Geometry
	Geometric	
SOE	Skin of the Earth features	**Polygon**
Interior	Features contained within a SOE polygon.	**Line**
Edge	Features that share a coincident edge within an SOE polygon (e.g., Coastline features	**Line**
	Generalization	
Individual	Features generalized individually..	**Line - Polygon**
Shared	Features that contain shared edges that should be generalized together.	**Line - Polygon**
Barrier	Features used as barriers to maintain topological relationships when Individual and Shared features are processed.	**Point - Line - Polygon**

Table 1. The Geometric & Generalization relationship defined in the GRS

4.3.3 *Generalization Second phase P2G*

The second generalization phase is responsible for simplifying and smoothing the selected features. Based on the rules defined in the GRS, shared features are loaded to the Theme GDB and generalized by the assigned tool. For

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instance, the *Simplify Shared tool* extracts the shared simplification tolerances from the GRS, iterate through the selected features and runs *Simplify Shared Edges* on the specified features, using other features as barriers (Nada et al., 2023b).

4.3.4 *Generalization third phase P3G*

The third generalization phase is responsible for generalizing interior, individual and barrier lines and points (see Table 1). For example, dissolving and merging of DEPCNTs, selection of SOUNDGs and ATONS. Barrier features' positions are respected during the generalization process by higher agents (i.e., Polygons - Lines). For instance, a DEPCNT will not cross any SOUNDGs or ATONS on both sides of the contour when being processed, this might restrict the amount of simplification, or be judged as under generalization, but will prevent having a deep SOUNDG on a shallow side and vice versa.

4.3.5 *Finalization phase*

In the finalization phase, an output GDB is created and the generalized features will be loaded to it from the Generalization GDB matching the input GDB schema. This would include adding the domains, subtypes and default values that were simplified in the Preparation Phase.

5. Implementation

The ANG model was tested in a number of locations, with different real world scenarios (e.g., with and without edge matching inconsistency - mix of scale bands), to generalize band 5 (i.e., 20k) to band 4 (i.e., 80k) data. The model output GDBs in all scenarios showed no topological violations (see Nada et al., 2023b).

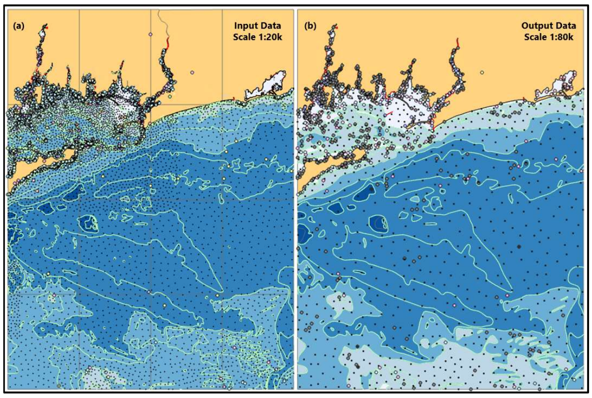


Figure 7. The study area - Block Island, NY-USA (a) Before generalization (b) After generalization

Figure 7 illustrates the model results in the case with no edge matching inconsistency (i.e., New York – Block Island Sound area). The model was able to generalize the selected features from 16 band 5 ENCs (Figure 7a) at scale 1:20k to scale 1:80k (Figure 7b) with no topological errors.

Figure 8 illustrates the model results in the case with a couple of edge matching inconsistent cells (i.e., New York, Long Island Sound area). In this case, selected features (see figure 5) from 16 band 5 ENCs (Figure 8a) were used as the input GDB. The model was able to generalize the selected features, as per the tolerances defined in the GRS, with no topological violations (Figure 8b). However, there were a few instances of edge matching inconsistencies in two of the 16 cells (highlighted in Figure 8a & 8b) that did not share end point topology and where the model was unable to merge or dissolve the respective line and polygonal features. These features were treated and generalized separately from the ANG Model (Figure 8c & 8d).

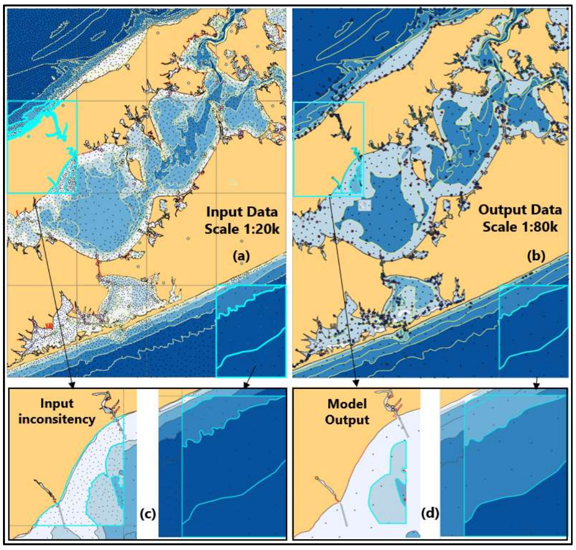


Figure 8. The study area - Long Island Sound, NY-USA (a) Pre-generalization data (b) Post-generalization data (c) Input inconsistency cells (d) Inconsistency model output

6. Validation tools

As explained in Section 2, the two hard constraints of topology and safety must be respected. To validate that the output is free of topological errors, the ArcGIS Pro *validate topology* tool, is used . The tool runs a set of integrity checks to identify any topology violations (e.g., overlaps, gaps, self- crossing) as they are defined in the ENC xml file (Nada et al., 2023b).

Regarding safety, the surface-test developed by Kastrisios et al. (2019b) may be used to identify discrepancies between the charted information (i.e., soundings, depth contours, and other features such as rocks and wrecks). However, regarding the requirement that depth contours may only be generalized toward the deep-water side and that small shallows may not be eliminated, no automated validation process exists. Considering that, generally, the readily available generalization tools in ArcGIS Pro are not intended to respect the nautical safety constraints, a validation tool was developed in the Model-builder. The tool detects the safety violations in the output GDB (meaning the sections of the generalized contour/depth area that have been moved on the shallow water side of the source contour/depth area), sort them by the area of the violation (i.e., the size of the polygon formed by the pre and post-generalized contour/depth area), with the aim to highlight the errors for user fixing. The tool is composed of three main stages as shown in Figure 9.

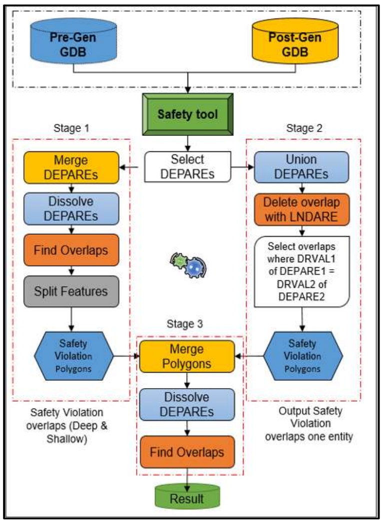


Figure 9. Safety Validation tool flowchart with the three main stages

6.1.1 *Calculate Difference Polygons*

After running the ANG model, the pre-generalization GDB (input GDB) and the post-generalization (output GDB) are loaded to the safety validation tool, then the tool runs a series of operations as follows:

1) Select depth areas DEPAREs from both GDBs using the NIS FC Subtype (i.e., DepthA).
2) Merge Pre & Post generalization DEPAREs into a new single output dataset. All features remain intact even if they overlap (Esri, 2022).
3) Dissolve Pre & Post generalization DEPARE polygons based on specified attributes, for instance Depth Range Value 1 (DRVAL1).
4) Find overlapping areas in the dissolved polygons
5) Split overlapping polygons using the pre-generalized DEPCNT as the cutting features.

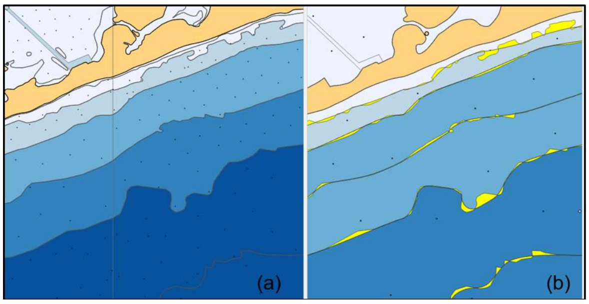


Figure 10. Safety Validation first stage results – Pre and Post generalization differences

The result of this step is a set of polygons that represent the differences between the pre and post-generalized DEPAREs including both the shallow and deep sides (see Figure 10).

6.1.2 *Separate Deep vs Shallow Side Polygons*

The second stage in the safety validation tool is to separate the results from stage-1 into shallow and deep generalized polygons, in other words safe and unsafe generalization.

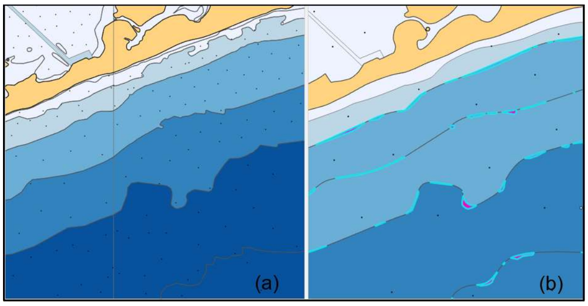


Figure 11. Safety Validation second stage results – safety violations (one feature)

As illustrated in Figure 9, after selecting DEPAREs from both pre- and post-generalization GDBs, stage-2 runs as follows:

1) Union pre and post generalization DEPAREs.
2) Delete the overlapping polygons with land areas resulted from generalization.
3) Select Overlaps where DRVAL1 of DEPARE1 = DRVAL2 of DEPARE2.

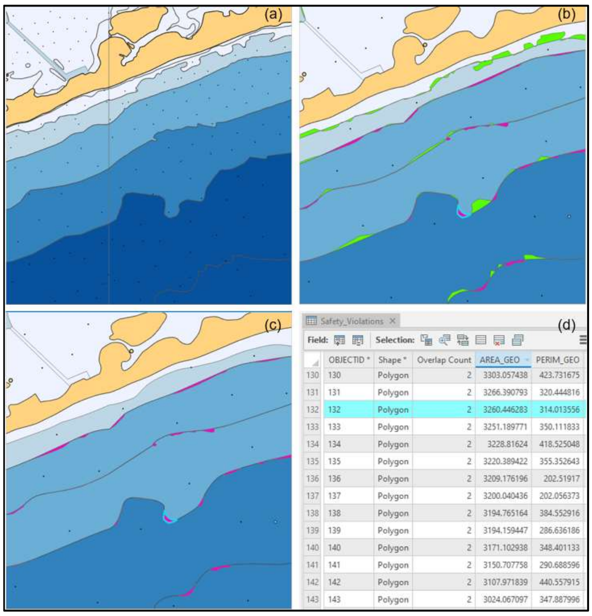
The result of this stage is all the safety violation polygons but as one feature (Figure 11).

6.1.3 *Detect Safety Violation Polygons*

As illustrated in Figure 12, the final stage in the validation tool is simply to split the safety violation polygons from stage-2 then sort them by area as follows:

1) Merge polygons from stage-1 and stage-2.
2) Dissolve polygons.
3) Find Overlaps.
4) Sort by area.

The output of this stage (Figure 12 c, d) is the safety violation polygons sorted in a geo-table by area and perimeter. Accordingly, as a user perception, small and irrelevant violation polygons can be accepted according to scale requirements, this is mainly due to the fact that the highest level of detail information is available in the larger scale chart below. In other words, when the mariner zooms in, all the needed information will be available in the larger scale ENC.



	OBJECTID *	Shape *	Overlap Count	AREA_GEO	PERIM_GEO
130	130	Polygon	2	3303.057438	423.731675
131	131	Polygon	2	3266.390793	320.444816
132	132	Polygon	2	3260.446283	314.013556
133	133	Polygon	2	3251.189771	350.111833
134	134	Polygon	2	3228.81624	418.525048
135	135	Polygon	2	3220.389422	355.352643
136	136	Polygon	2	3209.176196	202.51917
137	137	Polygon	2	3200.040436	202.056373
138	138	Polygon	2	3194.765164	384.552916
139	139	Polygon	2	3194.159447	286.636186
140	140	Polygon	2	3171.102938	348.401133
141	141	Polygon	2	3150.707758	290.688596
142	142	Polygon	2	3107.971839	440.557915
143	143	Polygon	2	3024.067097	347.887996

Figure 12. Safety Validation tool results (a) Input GDB (b) Output GDB with safe generalization-green and unsafe-red (c) Safety violations polygons (separated) (d) Geo-table with safety violations area and perimeter

7. Conclusion

This paper presented an Automated Nautical-chart Generalization (ANG) model as well as a contours' safety validation tool. The ANG model, aims to describe and implement the steps for generalizing large scale ENC data to the target smaller scale. The model is developed in ArcGIS Pro and runs in five main automated phases, utilized by a generalization rule spreadsheet GRS. The spreadsheet is generated from the nautical constraint template, and the input database schema to manage the process and drives data generalization for any desired output scale. The model output was tested in different areas, with different scenarios, and validated for the mandatory validation checks and nautical hard constraints of topology and safety. The ArcGIS topology validation tool confirms that the output is free of topology errors. However, since the available with ArcPro tools are not generally designed to respect safety, violations are expected / encountered in terms of both soundings and depth contours/depth areas generalization. Therefore, a safety validation tool was developed and presented that is capable of detecting the safety violations in the model output through three main stages, sort it by area and highlight them for user fixing.

8. Acknowledgements

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