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Assessment of S-101 Electronic Navigational Chart Accuracy and Reliability through Validation

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Developed in the early 2010s, the S-100 Universal Hydrographic Data Model (S-100 standard) was created to address the limitations of the existing S-57 standard and to support the efficient exchange and integration of maritime safety and traffic data globally. The S-57 standard was last updated in 2000 with version 3.1, while the S-100 standard saw its most recent publication in 2024 with version 5.2.0. The S-101 Electronic Navigational Chart (ENC) mainly serves as a conversion or extension of S-57 ENC-based data, although the direct production of S-101 is also under consideration. The conversion technique involves using a converter provided by the International Hydrographic Organization (IHO), but it requires validation to ensure the converted data's conformity, accuracy, and reliability. In this study, we focus on enhancing the accuracy and reliability of data by incorporating ENC validation into the ENC production process. The S-100 standard processes real-time hydrographic data collected from various shipborne sensors and presents it through ENC ensuring the precise application of navigational information. However, if the standard lacks precision, the reliability of sensor-derived data may decrease necessitating verification and refinement to maintain data quality and operational effectiveness. Implementing this will enhance data quality in producing S-101 ENC and contribute to maritime safety and traffic efficiency. Additionally, standardizing the S-101 ENC production process is expected to maintain consistency and reliability in global maritime data management.

1. Introduction

The International Hydrographic Organization (IHO) has developed the S-100 standard for next-generation hydrographic data exchange based on the ISO 19100 geographic information standard to promote maritime safety and the efficient management of maritime traffic worldwide.[(1)] The S-100 standard facilitates the seamless exchange and integration of maritime data and is poised to surpass the existing S-57 standard as the next-generation standard capable of managing various maritime data not limited to the Electronic Navigational Chart (ENC)

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alone. Moreover, the data's flexibility and scalability are expected to allow a more extensive integration and processing of information significantly, enhancing maritime safety and efficiency.

Currently, there are two methods for developing S-100 standard data. One is using support tools provided by the IHO Standardization Register and the other is converting S-57 data to S-100. However, the validity and accuracy of these methods have not been sufficiently evaluated and maritime data produced without adequate validation procedures may contain errors and inaccuracies that pose serious risks to maritime safety.

Therefore, on the basis of the results of ENC validation check, we aim to explore how to establish S-101 standards for the effective production of ENC data. To this end, we evaluated the accuracy and reliability of S-57 to S-101 ENC conversions using stage 5 ENC data (KR5F2K41) near Incheon, Korea. Initially, the completeness and integrity of S-57 data were verified using the dKart Inspector and the data loss rate during the conversion was analyzed. Additionally, the quality of the converted S-101 ENC was assessed using the S-101 Inspector by categorizing and evaluating key errors. This analysis was conducted to identify improvements in the S-101 ENC production process and ensure data quality.

This will significantly contribute to enhancing the accuracy and reliability of marine data for a secure maritime environment and establish the groundwork for standardizing the S-101 ENC production process. This research is expected to be crucial in enhancing the quality of marine data to improve efficiency and safety throughout the maritime industry.

2. Overview of S-100 Standard and Validation Methods

2.1 S-100 universal hydrographic data model

The S-100 standard is a universal hydrographic data model initially developed in the early 2010s and now updated to version 5.2.0 to meet the rising demands for digital products and services.(2) Currently, the IHO and the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) are the principal developers of product standards such as the S-101 ENC standard, S-102 Bathymetric Surface, and S-103 Sub-surface Navigation, among others. This initiative has provided a system to integrate various data types and operate them efficiently.(3,4)

On the other hand, the United Nations Educational, Scientific and Cultural Organization (UNESCO) Intergovernmental Oceanographic Commission (IOC) and NATO Geospatial Maritime Working Group (GMWG) have not proposed digital standards such as S-300 and S-500, indicating a lack of effort and discussion toward standardization. The S-100-based product specification list is provided in Table 1.

The IHO has published the S-100 Implementation Strategy, under which the IHO and International Maritime Organization (IMO) are collaboratively working to develop and promote the S-100 standard over the decade 2020 to 2030. The "Dual Fuel" concept, which allows the S-100 standard to operate concurrently with the existing S-57 standard until 2029, has been introduced, and new installations of S-100-based Electronic Chart Display and Information

Table 1
S-100-based product specifications.

International Organization	Specification Number	Specification Name
IHO	S-101	ENC
	S-102	Bathymetric Surface
	S-103	Subsurface Navigation
	S-104	Water Level Information for Surface Navigation
	S-111	Surface Currents
	S-112	Open - (See Decision HSSC9/38)
	S-121	Maritime Limits and Boundaries
	S-122	Marine Protected Areas
	S-123	Marine Radio Services
	S-124	Navigational Warnings
	S-125	Marine Aids to Navigation (AtoN)
	S-126	Marine Physical Environment
	S-127	Marine Traffic Management
	S-128	Catalogue of Nautical Products
	S-129	Under Keel Clearance Management (UKCM)
	S-130	Polygonal Demarcations of Global Sea Areas
	S-131	Marine Harbor Infrastructure
	S-164	IHO Test Data Sets for S-100 ECDIS
IALA	S-201	Aids to Navigation Information
	S-210	Inter-VTS Exchange Format
	S-211	Port Call Message Format
	S-212	VTS Digital Service
	S-230	Application Specific Messages
	S-240	DGNSS Station Almanac
	S-245	eLoran ASF Data
	S-246	eLoran Station Almanac
	S-247	Differential eLoran Reference Station Almanac
IEHG	S-401	IEHG Inland ENC
	S-402	IEHG Bathymetric Inland ENC
SERCOM	S-411	Ice Information
	S-412	Weather and Wave Hazards
	S-413	Weather and Wave Conditions
	S-414	Weather and Wave Observations
IEC-TC80	S-421	Route Plan
IOC	S-301 to S-399	None Proposed Yet
NATO GMWG	S-501 to S-525	None Proposed Yet

Systems (ECDIS) will be permitted from 2026. From 2029, the adoption of S-100 standard systems will become mandatory for new installations.

At the 3rd IHO Assembly in 2023, the construction of an infrastructure center to manage the commercialization of the S-100 standard, standard registration system, operational testing, and industrialization support was approved, establishing the institutional groundwork for the systematic development and stable adoption of the S-100 standard.

2.2 Comparison of S-57 and S-101 ENCs

2.2.1 S-57 ENC

Designed on the basis of ISO/IEC 8211 to ensure the global consistency and accuracy of marine data, the S-57 standard was the first international standard for marine data developed by the IHO to represent ENCs digitally. S-57's data processing method, which stores data in a binary format, reduces file size and accelerates data processing.

The main components of the S-57 standard are objects and attributes, which represent various marine information such as marine terrain, routes, and obstacles. Each object signifies a specific marine feature with location information, while attributes provide detailed insights about that object. However, the primary disadvantage of S-57 is that the standard requires updates whenever an object or attribute is added, rendering the process of data expansion and modification inefficient. This considerably limits its flexibility and scalability. Consequently, to incorporate new information, data must be inputted through manual coding, which leads to inconsistencies in data representation across different products, thus impacting data uniformity and consistency. As its rigid format and structure failed to meet the complex requirements for modern marine data management, the IHO officially ended S-57 updates with version 3.1 in 2000.[5]

2.2.2 S-101 ENC

To address the limitations of the S-57 standard, the S-100 next-generation universal hydrographic data model was developed on the basis of the ISO 19100 geographic information standard. Unlike S-57's fixed data structure, the S-100 standard introduces a flexible and extensible structure that accommodates the latest marine data types and technologies. It supports various functions including representing three-dimensional data, processing four-dimensional time series data, and providing web services thus enhancing the interoperability of marine data and its compatibility with diverse applications.[6,7]

The main components of the S-100 standard are the Feature Catalogue and Portrayal Catalogue. These provide rich metadata including the source, quality, and recency of the data thus enabling efficient data management. The Feature Catalogue defines the objects, attributes, and relationships of a product, while the Portrayal Catalogue determines how a product is visualized. Additionally, it includes images that illustrate the data model and presents a UML-defined model of the product standard to ensure consistent authoring experience. It also includes the Product Standard Definition, which describes the background, purpose, and structure of the product, as well as the DCEG guide document for data entry and authoring.

S-101 ENC is a product standard designed to generate ENC data in compliance with the S-100 standard. It integrates with multiple S-100-based product specifications to equip users with comprehensive information including real-time data and reflections of sea conditions. This integration enhances maritime safety and efficiency. This ENC standard is a primary standard in maritime data driving innovations in data management.

2.2.3 S-101 ENC production

Currently, the global production of S-101 ENCs based on the S-100 standard employs two primary approaches. The first approach involves converting existing S-57 ENCs to S-101 ENCs using automatic conversion software, while the second involves directly developing S-101 data using S-100 product standardization tools.

The S-57 to S-101 conversion automatic conversion software programs such as the CARIS S-57 composer(8) and the dKart S-101 converter(9) have been developed and utilized on the basis of detailed guidelines in IHO's S-65 Annex B,(10) which outlines the conversion from S-57 ENC to S-101. The development of such software programs enables the convenient and rapid creation of S-101 ENCs by converting the established S-57 standard. However, the conversion is not flawless as certain data elements do not convert perfectly as some S-57 objects differ in interpretation or require additional information in S-101 leading to data loss. Additionally, updates to the S-100 standard can take significant time to integrate into the conversion software leading to data inconsistencies and potential errors. Consequently, manual interventions after conversion can introduce errors such as missing attribute values or other inaccurate corrections made by developers.

Secondly, directly developing an S-101 product standard using the S-100 Product Standard Authoring Assistant is time-intensive because objects and attributes must be approved by IHO staff via a proposal process before they can be registered or modified in the IHO Standardization Registry. Likewise, the use of standards authoring tools may lead to data loss from version inconsistencies. Moreover, incorrect data entry increases the risk of human errors. As discussed above, such data loss and errors during the conversion process can significantly impact maritime safety. Therefore, this study aims to verify the accuracy and reliability of converted data and to propose methodologies to address any identified issues.

2.3 S-101 standard validation check

2.3.1 Existing validation check software

The primary tools currently used for validating S-57 and S-101 datasets are dKart Inspector(11) and 7CS Analyzer.(12) dKart Inspector validates S-57 datasets and ensures their structural integrity and consistency. The tool scrutinizes relationships between objects and attributes, identifies any inconsistencies or errors within the dataset, and reports these findings to the user. It plays a crucial role in maintaining data quality by identifying issues such as incorrect geometry, attribute errors, and other inconsistencies.

The 7CS Analyzer is a tool designed to validate both S-57 and S-101 datasets, enabling marine data developers to ensure compliance with IHO standards. This tool is used to conduct hundreds of individual checks to assess data for completeness, consistency, accuracy and more. It is fully compliant with the latest S-58 ENC Validation Checks Edition 6.1 and offers functionality for validating S-101 datasets as well.

2.3.2 S-100 product standard guidelines

The IHO provides guidelines for creating S-100 product specifications, designated as S-97,[13] which offer a systematic approach to measuring data quality and ensuring reliability in the development of S-100-based product standards. These standards, including the S-101 ENC, are developed following these guidelines and validated to ensure their compliance. Additionally, the guidelines provide essential advice on data modeling, metadata management, quality control and more, and they delineate specific measures to ensure interoperability among marine information systems. Specifically, Part C of S-97 outlines the integration of data quality elements into the design and validation of product standards and describes methods to verify the reliability of these standards to guarantee their effectiveness in the intended use environment.

Furthermore, an analysis of the validation groups defined in the S-101 Annex C_Validation Checks Ed 1.2.0[14] shows that data quality in S-101 is divided into 10 major groups with subcheck items in each group addressing the completeness, consistency and accuracy of the data. Validation check activities include ensuring data completeness such as the detection of missing files and required objects, verifying the consistency of six items and confirming the integrity and accuracy of the data through assessments of temporal quality, thematic accuracy and topological validation.

Specifically, the items reviewed are Completeness, Conceptual Consistency, Domain Consistency, Format Consistency, Geometric Consistency, Logical Consistency, Metadata Consistency, Temporal Quality, Thematic Accuracy, and Topological Consistency. Table 2 categorizes the data quality measures provided by the IHO under S-101 Annex C_Validation Checks Ed 1.2.0.

Next, the S-100 standard data validation categorization step is divided into three levels on the basis of data error severity,[15] such as Critical Error, Error, and Warning. A Critical Error is defined as a grave issue that renders the dataset unusable in ECDIS, such as data loading failures, ECDIS data conflicts, or the provision of unsafe maritime navigation data. An Error indicates a reduction in data quality that, while impairing usability or appearance, does not significantly jeopardize dataset usability. A Warning pertains to errors like data duplication or inconsistencies that minimally impact usage. Table 3 illustrates the classification scheme developed by the IHO S-100 Working groups for dataset validation.

This guidance acknowledges the critical role of data quality management in developing and validating product standards, while offering specific methods for developers to evaluate and enhance data quality systematically. This approach guarantees that the developed product standards comply with the S-100 standard and exhibit high reliability and usability.

Table 2
S-100 standard classification of data quality.

Number	Classification	Number	Classification
1	Completeness	6	Logical Consistency
2	Conceptual Consistency	7	Metadata Consistency
3	Domain Consistency	8	Temporal Quality
4	Format Consistency	9	Thematic Accuracy
5	Geometric Consistency	10	Topological Consistency

Table 3
S-100 standard classification of checks.

Classification	Detail
Critical Error	An error that would render a dataset unusable in ECDIS by either failing to load or causing an ECDIS to crash or by presenting data that is unsafe for navigation.
Error	An error that may impair the dataset's quality in terms of appearance or usability but does not pose a significant risk when used for navigation.
Warning	An error that could be due to duplication or inconsistency, which will not significantly diminish the usability of a dataset in ECDIS.

However, beginning in 2023, the IHO will more thoroughly scrutinize the S-100 standard's validity by establishing the S-100 validation subgroup. There remain unresolved questions regarding the accuracy of currently produced data, its reliability in products, and maritime safety.

2.3.3 S-57 vs S-101 validation check structures

S-57 ENC encapsulates data in a linked structure featuring Meta, Carto, Geo, and Collection elements, adhering to a chain node spatial model using points (Node) and lines (Edge). Catalog files are encoded following ISO/IEC 8211, similar to 000 files, and are stored in the sequence of dataset common information records, dataset georeference records, vector records and feature records. The S-57 data model configuration is shown in Fig. 1.

Conversely, S-101 ENC is structured into feature types, property types, and attribute types in accordance with the common feature model based on S-100, with the addition of Aggregated and Theme features representing set relationships and thematic information as alternatives to Carto and Collection in S-57. The spatial schema incorporates Point, MultiPoint, Surface, Curve, and CompositeCurve models based on ISOTC211 series standards. Furthermore, the catalog file employs an XML data format and is stored in the sequence of dataset file, information record, vector record and feature record.

Owing to the structural differences between S-57 and S-101 ENC, existing validation check tools based on S-57 struggle to accurately check the complex data structure and consistency of S-101. Consequently, there is a need to develop a validation check tool tailored to the unique characteristics and requirements of the S-101 ENC standard.

2.4 S-101 Inspector

2.4.1 S-101 Inspector characteristics

Developed to verify the accuracy and reliability of S-100 ENC, the S-101 ENC validation check software (S-101 Inspector) has been newly designed to comply with the S-100 international standard and ensures data accuracy.

The existing S-101 validation check software developed from the foundational S-57 validation check software had limitations such as missing data validation check and an inability to cover all

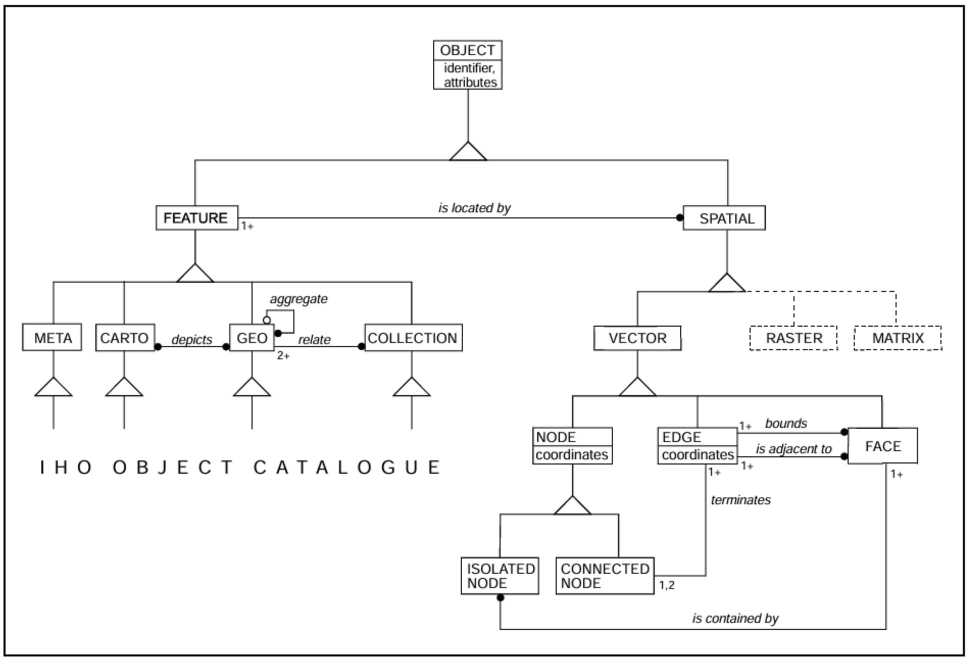

Fig. 1. S-57 data model configuration.(16)

test items due to structural differences between S-57 and S-101, including objects and attribute information exclusive to S-101. However, the S-101 Inspector was specifically developed to incorporate all test item definitions of the S-101 International Standard, thereby ensuring high accuracy and reliability compared with previous versions of validation software that only partially integrated these features.

The S-101 Inspector is designed to validate data using Local DB, .000 file and SDK. It also detects error detection items found during the validation process, which can be checked in a Docx file format. These functions enable users to efficiently conduct ENC validations. The structure of the S-101 Inspector is shown in Fig. 2.

Furthermore, unlike traditional validation check tools, all check algorithms and source codes are open, allowing users to modify items according to their needs during the validation process. This flexibility and responsiveness accommodate the latest S-101 versions.

2.4.2 S-101 Inspector process

(1) ENC loading and display function

The validation process of the S-101 Inspector is shown in Fig. 3. The ENC loading and display function allows users to load ENC data from a selected file path and visually displays it through the object tree list and spatial object map for intuitive understanding and analysis. Notably, the object tree list and spatial object map provide a quick overview of the loaded data. These visual display features importantly aid users in understanding and utilizing the data effectively.

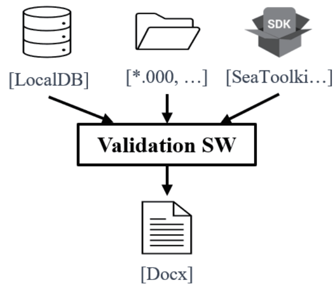

Fig. 2. S-101 inspector structure.

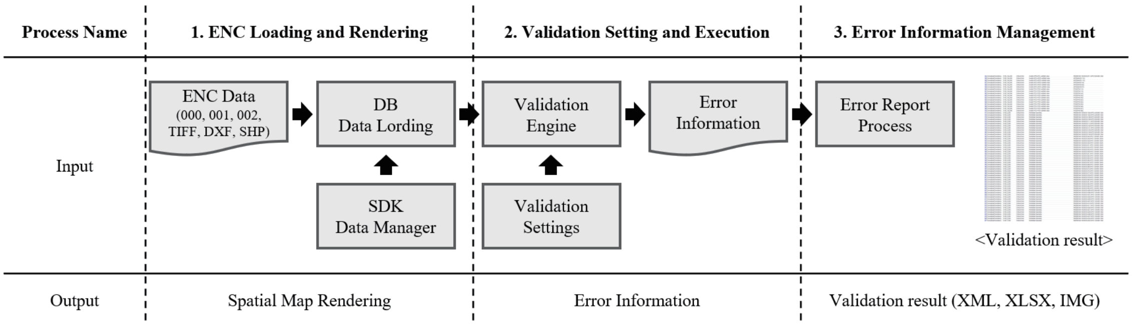

Fig. 3. S-101 Inspector validation process.

(2) Validation setup and execution process

The validation process is divided into Group Tests and Common Tests, which are organized through the CustomizeTestSetting, SetGroupTests, SetCommonTests, and TestOptionSetting classes, and executed via the TestRun class. Specifically, the CustomizeTestSetting class enables the customization of validation check items, allowing the selection of only necessary check items for efficient testing. The validation check engine process is shown in Fig. 4.

As shown in Fig. 5, Group Tests are configured using the SetGroupTests class and currently involve 10 items from the data quality taxonomy including Completeness, Conceptual Consistency, Domain Consistency, Format Consistency, Geometric Consistency, Metadata Consistency, and Geometric Consistency again.

Checking these elements for errors in consistency, conformance and formatting enables the effective detection and remediation of issues that may arise during the data conversion process. Furthermore, Global Tests are conducted using the GlobalTestRun class and Unit Tests via the UnitTestRun class to inspect small data units like individual features or tables, ensuring that each object is accurately defined.

Finally, the SetCommonTests class configures Common Tests, which check for missing, duplicated, or erroneous required objects through CommonTestRun ensuring that the fundamental structure of the data remains intact and free from duplicates.

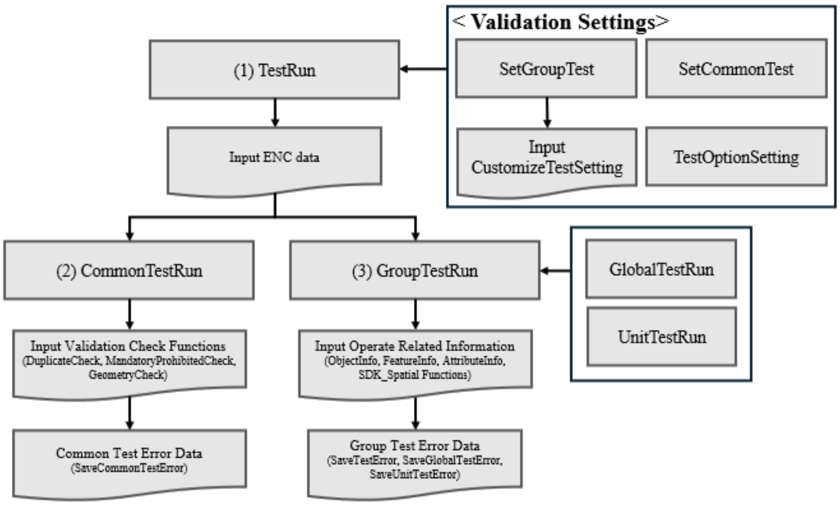

Fig. 4. Validation check engine process.

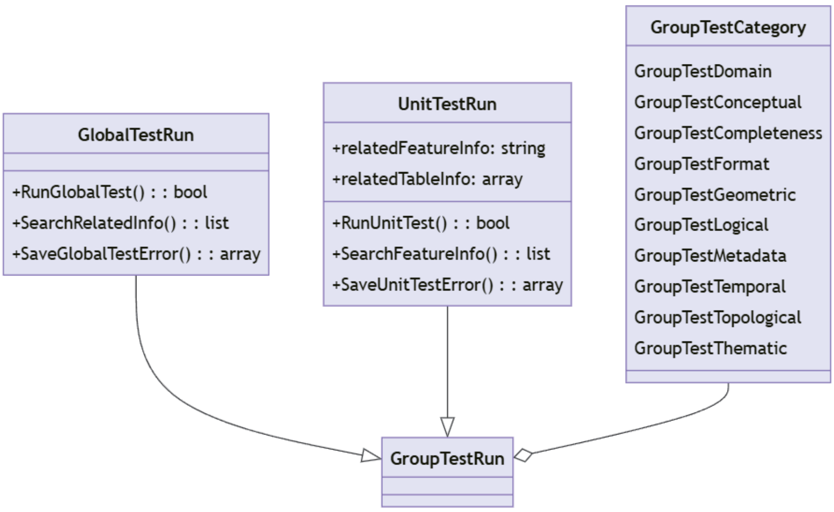

Fig. 5. (Color online) Group test class diagram.

(3) Error detection information management function

Figure 6 presents the Error Report Manager workflow. The S-101 Inspector displays a list of errors sorted by group, test item ID, severity, error message, and so forth, and visualizes them in a tree, attribute, geometry and relationship structure, aiding users in comprehending the details of the errors clearly.

The S-101 Inspector also facilitates the export of detected errors in XML, XLSX and image formats enabling the management and analysis of error data across various formats. This function allows the generation and documentation of error reports and outputs of error analysis results for sharing and reviewing, helping users to identify and systematically address detected errors.

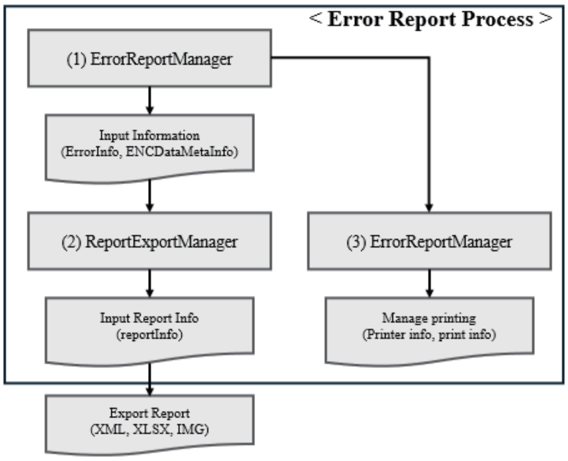

Fig. 6. Error report manager workflow.

3. Discussion

3.1 S-57 to S-101 conversion validation analysis

We assessed the appropriateness of the conversion method by confirming the data accuracy and reliability of ENCs converted from S-57 to S-101 using automatic conversion software, and the data used in this study was the stage 5 ENC dataset KR5F2K41 from Incheon, Korea. Released on January 1, 2024, this dataset follows the S-57 Edition 3.1 specifications standard, the scale is 1:5000, and it contains 4731 geographic records for spatial features, three collection records for feature grouping, and 2313 connected node records.

The data completeness and integrity of S-57 ENC were first evaluated using the dKart Inspector, and the loss rate during the conversion to the S-101 standard was analyzed. Finally, the converted S-101 standard was validated using the S-101 Inspector, and the results were assessed to verify data accuracy and reliability, thus evaluating the conversion method appropriateness and exploring ways to effectively produce ENC data based on the S-101 standard.

3.1.1 S-57 validation results

To verify the data completeness and integrity of S-57 ENC, KR5F2K41 S-57 ENC data were validated through the dKart Inspector, and the results were categorized by major error types by attribute as illustrated in Fig. 7. Geometry validation revealed three warnings for duplicate boundaries, and Encoding Rules validation identified 14 errors in the ‘litchr’ attribute value within the route marker object. In Geo Objects validation, 20 Critical Errors, 1 Error, and 20 Warnings were discovered. Notably, the absence of the KRCAU07N.TXT and KRCAU07E.TXT reference files caused duplicate errors in multiple objects.

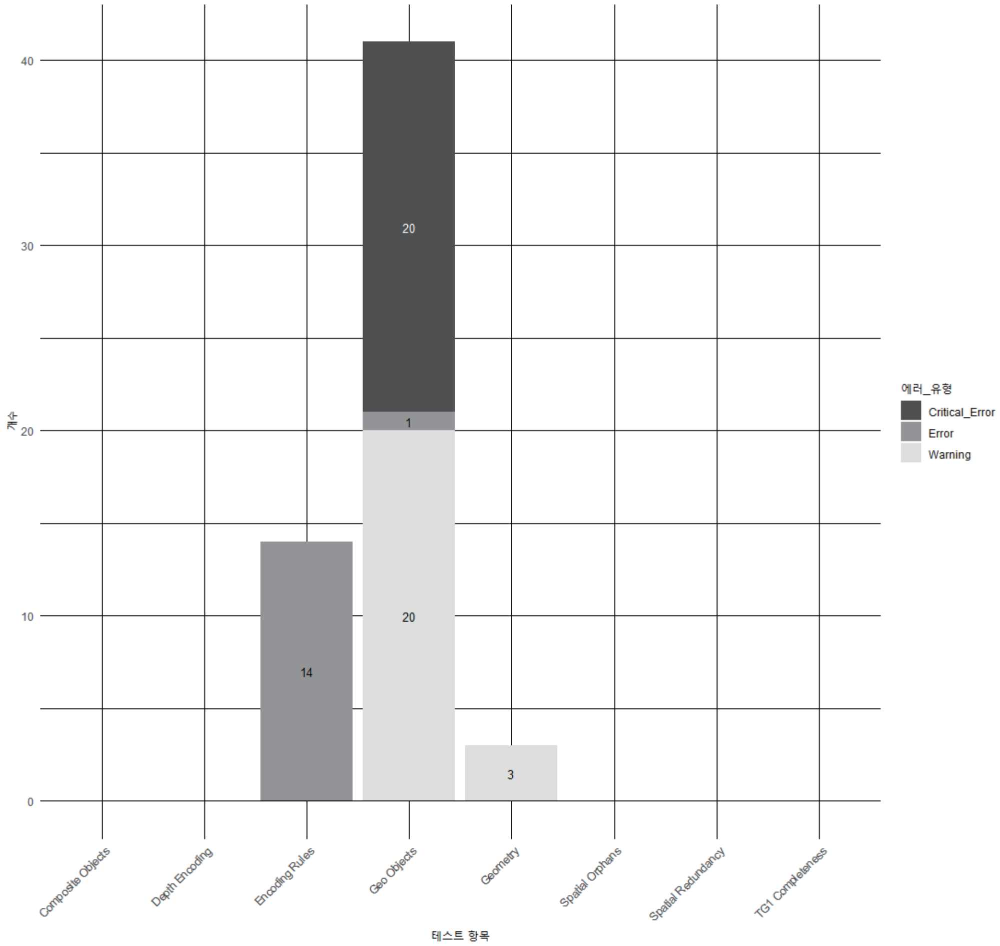

Fig. 7. S-57 validation result.

3.1.2 Analyzing S-101 loss rates during conversion

We analyzed the data loss rate during the conversion of KR5F2K41 S-57 ENC to the S-101 standard, focusing on changes such as the loss or addition of required attribute data. As depicted in Table 4, out of a total of 12853 items, 12840 items were converted, with 13 items lost, yielding an overall loss rate of about 0.1%. Consequently, it was confirmed that not all data elements were perfectly converted, and some attributes were missing during the conversion process. These missing attributes will need to be manually entered by developers, raising the potential for human error.

Noteworthy exceptions include the addition of 15 new entries to the BRIDGE property, increasing from 170 to 185, and the addition of 66 new entries to the M_SDAT property. These changes likely resulted from the incorporation of new data or modifications to the data structure.

Table 4
S-57 to S-101 conversion loss rate.

Attributes	Source	Target	Delta
CTRPNT	12	11	−1
RDOSTA	8	1	−7
M_COVR	3	0	−3
Edge	3449	3447	−2
		…	
Total	12853	12840	−13
BRIDGE	170	185	+15
M_SDAT	0	66	+66

3.1.3 Validation results of S-101 produced by the conversion method

Finally, to validate the data accuracy and reliability of the ENC converted from S-57 to S-101 using the automatic conversion software, we analyzed the results of six checks with the S-101 Inspector and categorized them as shown in Fig. 8. In the Completeness category, 152 errors occurred owing to the omission of required attribute values, while in Conceptual Consistency, 252 critical errors resulted from the use of prohibited geometry and attributes. The Domain Consistency category had 2687 critical errors due to the use of prohibited objects and incorrect property bindings. Format Consistency recorded four critical errors from referencing more than the permissible number of records, and Geometric Consistency and Metadata Consistency reported 1596 and one critical error, respectively.

Upon validation through the S-101 Inspector, the ENC conversion from S-57 to S-101 using automatic software revealed significant errors. This indicates that the automatic conversion method is neither accurate nor reliable for ENC production, and its indiscriminate use could compromise maritime safety.

3.2 Proposed solutions

ENCs converted from S-57 to S-101 using automated software displayed several missing attribute values resulting in a total of 4688 errors in the produced S-101 ENC underscoring the inaccuracy and unreliability of the data. The need for frequent manual correction postconversion increases the likelihood of human error and is time-consuming, thereby hindering timely updates to the S-100 standard. Consequently, this method of producing ENCs from S-57 to S-101 is unsuitable for long-term standard development.

Therefore, we propose the development of an ENC production automation system that integrates CI/CD pipelines and automation tools as shown in Fig. 9 to minimize human errors and enhance efficiency during the S-101 standard development process. This system will automate the entire workflow from standard production and conversion to validation and distribution, streamlining the detection and rectification of errors in real-time S-101 data production. This approach is expected to significantly enhance data accuracy and reliability by reducing complex manual tasks and minimizing conversion errors.

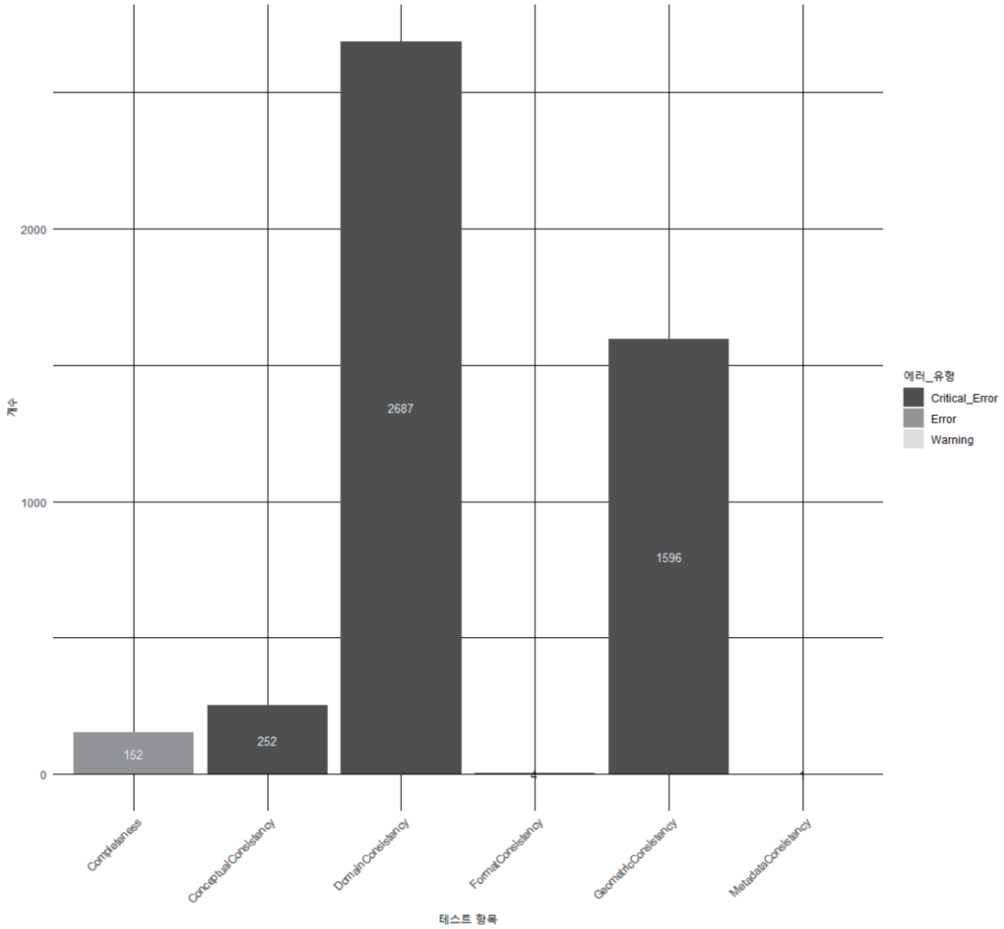

Fig. 8. S-101 validation results.

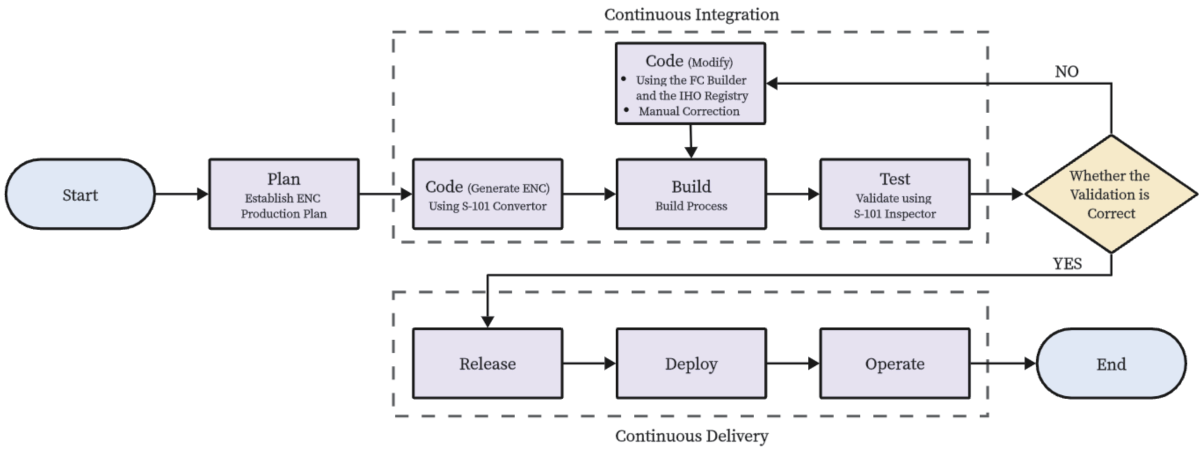

Fig. 9. (Color online) Proposed automation solutions for S-101 ENCs.

Additionally, validation and versioning capabilities facilitate developers in confirming incorrect attribute values and seamlessly integrating objects and attribute information registered in the IHO Standardization Registry for swift data correction. CI/CD pipelines complement this automation tool by merging corrected data into the repository and conducting automatic builds and validations. This enables developers to instantly view the validation results of their modified data and receive automated feedback for rapid adjustments. The deployment process can also be automated to ensure a quick and reliable implementation of S-101 standard data, even with the application of new S-101 standards or amendments. These systems will play a crucial role in ensuring that the updates to the S-100 standard are promptly and efficiently reflected to maintain data accuracy and currency.

In conclusion, a system that includes CI/CD pipelines and automation tools will streamline the S-101 ENC development and deployment process. It minimizes errors in the production and conversion of S-101 standards and ensures data accuracy and reliability, ultimately enhancing the quality of offshore data and significantly improving data management efficiency.

4. Conclusions

In this study, we analyzed the loss rates and error types that occur when converting next-generation ENC data from S-57 to S-101 under the S-100 standard to evaluate the data conversion method's adequacy and identify its limitations. The findings indicate that data loss and errors during the conversion can severely impact maritime safety and are unsuitable as a method for developing ENC standards.

Therefore, development through the conversion method has limitations and automated tools should be developed to minimize human error. We proposed developing an ENC production automation tool that integrates the S-101 standard conversion tool, validation check tool, and standard automation production support tool. This tool is expected to play a vital role in quickly correcting errors and enhancing the accuracy and reliability of data. Additionally, we suggested a CI/CD pipeline that promptly reflects and deploys updates to the S-100 standard, ensuring that the most recent standards are continuously maintained. This approach is anticipated to uphold the quality of maritime data and significantly boost efficiency and safety across the maritime sector.

This research is expected to enhance the accuracy and reliability of marine data by standardizing and automating the ENC data production and validation processes based on the S-100 standard and to lay the groundwork for standardizing the S-101 ENC production process. Through this, the accurate application of real-time hydrographic data collected from shipborne sensors based on hydrographic standards can be ensured. This will help maintain data quality and operational efficiency, ultimately enhancing maritime safety and traffic management.

Acknowledgments

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