



An Approach to Drawing Automation of Ship Stiffeners in the Shipbuilding Industry

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Abstract. Building a large ship structure involves the design of thousands of stiffeners, which add strength to the hull so it can withstand the weight of the cargo as well as any external loads that may act on the bottom of the hull. These ship stiffeners must be 3D modeled and then converted to 2D engineering drawings for manufacturing. Manually generating, dimensioning, and documenting these structural members can be costly, time-consuming, and error-prone. In this paper, we propose an approach to auto-generating engineering drawings for ship stiffeners that includes fully automated dimensioning, complete view selection, production information output, and drawing management. Our solution has been proven to increase productivity and improve the quality of the drawings of ship structures.

Keywords: CAD, ship drawing, automatic drawing, automatic dimensioning, shipbuilding.

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1 INTRODUCTION

With the advent of Industry 4.0, traditional design and manufacturing practices are drastically being transformed. Numerous sectors have increased their efforts to digitize and improve their Computer-Aided Design (CAD) systems, which leverage computational power to explore design spaces in search of optimal, effective, and innovative designs. Despite these advances, the shipbuilding industry relies heavily on traditional and passive computational design techniques [12].

Despite the exploration and integration of advanced technologies like Model Based Definition (MBD) and immersive visualization across various industrial sectors, their applications in replacing traditional drawings in shipbuilding remains a significant challenge, necessitating substantial ongoing development [3,6,10,33]. In a traditional design environment, the primary function of a CAD system is still to generate production drawings that communicate the geometry of the product and the manufacturing processes required to make it to the different stakeholders. The early stages of ship design are mainly completed in two dimensions (2D) and then translated to three dimensions (3D)

during the detailed design stages. This transition from 2D to 3D requires a significant investment of time and labor [20].

Most modern shipyards use specialized CAD packages with advanced functionalities such as ship drawing and procurement data capabilities and factory automation data in the ship and in offshore manufacturing environments [29]. Shipyards utilize 3D product models for various purposes, including automation, data reproduction, and detailed production information [24]. While various academic contributions have focused on the modernization of traditional ship design methodologies, their use in industry remains limited [12].

In shipbuilding, design and automation processes are uniquely challenged by the need for intricate, large-scale configurations and a high degree of customization, which complicates the standardization of automated drawing systems. Some studies have explored the modeling of preliminary ship structures and the generation of 3D models from 2D drawings [11,15,16,21,22,26]. In the commercial space, many software packages such as AutoCAD, Pro/ENGINEER, FastShip, TRIBON, FORAN, and NUPAS CADMATIC, are used in ship design to create engineering drawings [14,28]. Nevertheless, the automatic generation and dimensioning of ship stiffener drawings still rely heavily on manual input and the designer's experience. The process is time-consuming and can lead to inconsistencies in formatting and presentation. In this regard, few studies have examined the automatic generation of production-ready engineering drawings from 3D models of stiffeners, specifically in the context of shipbuilding.

In this paper, we examine the current state of ship design and the shipbuilding industry as a whole. Next, we present a fully automated approach for the creation of production-ready engineering drawings for ship stiffeners, a critical component of hull design, and describe the architecture and implementation details of a software prototype built on Siemens NX to demonstrate our solution. We validate our prototype in terms of functionality, performance, and reliability. Finally, we conclude by discussing the findings and limitations of our study as well as related future work.

2 BACKGROUND

Over the last four decades, CAD tools for ship design have evolved from general applications executed in mainframe computers to sophisticated systems for all shipyard sizes that can run on personal computers [19]. The shipbuilding industry has been leveraging computer technologies since the early 1950s, initially as an accounting tool and later to assist with specialized design and production tasks [14]. The notion of Computer-Aided Ship Design (CASD) soon emerged, quickly becoming a critical tool for companies to maintain a competitive advantage in the global shipbuilding market [4,18].

Establishing a digitized lifecycle-oriented product model has been a goal in many industries, including ship design, for years [32]. The ship design process is a long-articulated path, which begins with the results obtained from the planning stages and finishes when the new product is delivered [13]. Ship design is generally divided into five phases: (1) conceptual design; (2) preliminary design; (3) functional design; (4) transitional design; and (5) detailed design [2]. During the early stages of ship design, functions, configurations, and rough arrangements are identified, and various analysis procedures are executed to find an optimal design [11]. In these stages, most design information is provided in the form of 2D drawings, which are subsequently analyzed and modeled in 3D for downstream processes such as simulation and numerical control (NC) [11]. Disconnections in this information flow often result in inefficiencies, delays, and design errors [11,21].

The design phase represents the transition from the requirements identified in the planning stage to the development of a configuration shape, dimensions, layout, and other characteristics [13]. The integration of ship design and production is a critical aspect of an efficient shipbuilding process. However, it is often challenging due to the complicated documentation required in terms of level of detail and completion schedule [23].

Engineering drawings remain at the core of most shipyards as a primary tool for communication [11,17,28,29]. Indeed, many early designs are transferred to detailed design stages in the form of 2D drawings (e.g., structural drawings, ventilation installation and manufacturing drawings, and gas

pipe installation drawings [29]. In the design stage, engineering drawings and/or 3D CAD models, specifications, and other related information for production must be created [21]. It has been shown that many errors and problems are caused by incorrect or inaccurate ship drawings and insufficient preparation and processing of the information needed for ship production [7]. Unreliable ship drawings often result in costly repairs and/or rework activities that significantly increase manufacturing costs [5,23].

The design and production of a ship's structure require hundreds or even thousands of ship stiffeners. These components not only vary in size but also in shape. Stiffener shapes can be classified into two main categories according to their complexity: conventional (e.g., flat bar, T-section, and angle section) and non-conventional (e.g., rectangular box section, trapezoidal box section, sharp n-section, and M-section) [1]. The corresponding output of 2D drawings during the design of a ship is therefore significant and drafting errors, ambiguities, and inaccuracies can result from the drawing practices adopted [8]. The example shown in Figure 1 illustrates part of the detailed design of an initial hull structure. The large number of stiffeners on the ship plates (called panels in Figure 1) and the challenges related to their layout and orientations relative to a free-form surface make the overall design difficult [30].

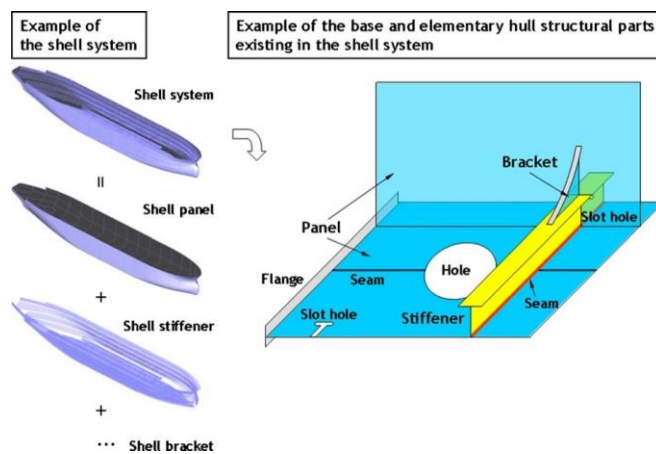


Figure 1: Example of the base and elementary hull structural parts of the shell system in the initial hull structure [21].

Despite their pervasiveness, the role of stiffeners in ship design is often neglected [9], and much of the process of generating dimensioned drawings for ship stiffeners is performed manually or in a semi-automatic manner. Compared to other industrial applications in shipbuilding, the automatic creation of drawings for ship stiffeners has received less attention and has not been reported extensively in the literature. Some notable work in ship assembly drawing applications, for example, include Ruy and Yang's [25], who investigated an overlap avoidance algorithm using genetic algorithms, simulated annealing, and heuristic methods to improve the readability of ship assembly drawings. However, the study did not eliminate the manual intervention during the assembly drawing generation process, which could introduce human errors to the results. Similarly, Woo et al. [31] developed an automatic pipe isometric drawing and Bill of Material (BOM) generation system for ship piping design. The system locates the views of the pipes on the drawings and associates them with the relevant product information. However, the resulting pipe installation drawings often require additional manual adjustments by designers to ensure accuracy and proper alignment. This extra touch-up work might involve correcting misaligned elements or adding missing details, tasks that often require considerable effort and can be time-consuming. In hull and outfitting design, Ruy et al. [25] developed a hole-plan system to accelerate the design process for outfitting holes on hull

structures, achieving greater efficiency through automation. Despite the system's benefits, however, it still involves multiple manual operations within the user interface to create the required drawings. This reliance on manual tasks means that professional experience is essential to navigate the system effectively, introducing the potential for errors or inconsistencies. In this paper, we propose an automated approach to efficiently create ship stiffener drawings to convey accurate and reliable detailed geometry and production information.

3 AN APPROACH TO AUTOMATION

Although CAD technology for shipbuilding is relatively mature and many commercial systems provide the functionality to automatically convert 3D models into annotated 2D drawings, many elements of the drawing, such as fully annotated views, borders, zones, and title blocks depend largely on manual input. Furthermore, the well-known auto dimension functionality available in modern CAD systems often fails to produce production-ready drawings. Some common errors include dimensions that are placed in incorrect views or incorrect locations, missing dimensions, redundant dimensions in multiple views, non-standardized dimensions for standard features and parts, overlapping dimensions, and dimension lines intersecting each other or other lines in the drawing. The extra manual arrangement of these elements required to ensure the correctness and readability of the drawing often involves significant amounts of time, effort, and cost.

To develop a practical solution to automatically generate ship stiffener drawings, four typical ship stiffener profile characteristics are analyzed, as listed below.

- (1) Left and right end cuts carry essential information about the stiffener's shape. The ends of a stiffener may have specific cuts or shapes to fit into the ship's framework. These end cuts help define the stiffener's geometry and how it integrates with other structural elements. Relative to the middle section, the detailed shape and dimensions of the left and right end cuts convey critical design information about the stiffener. For example, the type and the angle of end cut shown in Figure 2-A are essential for manufacturing.
- (2) Detailed features (e.g., ventilation holes, cutouts, etc.) in the middle section of a stiffener are generally distributed evenly across the surface, as shown in Figure 2-B. Depending on the stiffener's function, design requirements, and structural integrity considerations, some stiffeners may have specific features concentrated in certain areas rather than evenly distributed. Although detailed features on stiffeners may not always be evenly distributed, engineering drawings can scale down while preserving the distribution ratio, and this unevenness should not pose a significant issue. A well-scaled drawing ensures that all detailed features are accurately represented in proportion, allowing designers and engineers to understand the actual distribution of features like ventilation holes, cutouts, or other detailed elements. The manufacturer only needs to know the hole size, shape, and overall distribution of these details for production.



Figure 2: A left-end cut on a 3D model of a stiffener (A) and ventilation holes in the stiffener's middle section (B).

- (3) Relative to its length, a stiffener has a small height. Stiffeners are designed to provide rigidity and structural support to ship components, and their height is usually small relative to their length to allow them to fit within the ship’s framework without obstructing other elements. For example, the height of a T-type stiffener is 103.33mm, but its length can reach 5m or even 20m. The height-to-length ratio can be as high as 1:200. Therefore, traditional projection views are not practical for representing a stiffener in an engineering drawing, as the end cut details and features on the stiffener body would be too small to lose the critical information. Instead, detailed views or broken views are required.
- (4) Stiffeners can be categorized according to their form into straight and curved. Stiffeners in shipbuilding can be either straight or curved, depending on the ship’s design and where the stiffeners are located. Straight stiffeners are more common, but curved stiffeners are used when following a specific contour or shape is necessary. Unlike other parts, the front view and a section view are sufficient to represent a stiffener in an engineering drawing. For curved stiffeners, inverse bending lines can be drawn on the curved stiffener profiles to help mark the curves on the unformed stiffeners (as indicated by the two arrows in Figure 3). The inverse bending lines help manufacturers to form the stiffeners until the lines are straight. Therefore, curved stiffeners do not have to be represented in their actual curved forms. Instead, a rectangular profile in the front view can represent a curved stiffener through the inverse bending line (Figure 3).

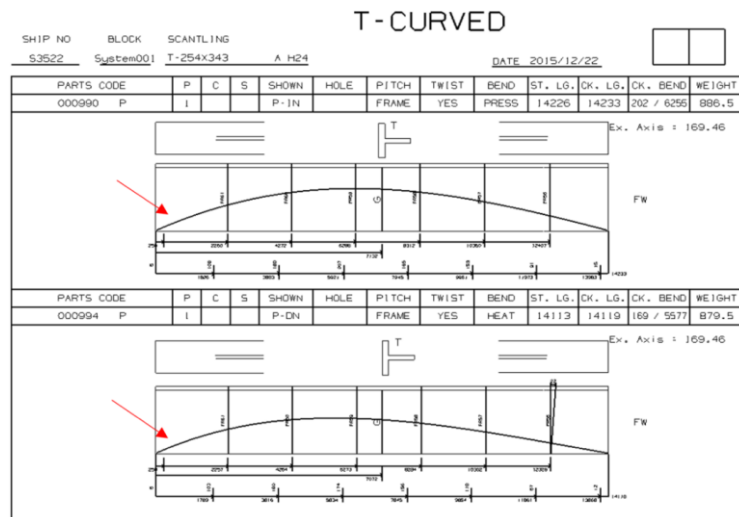


Figure 3: 2D drawings of a curved stiffener.

In order to represent the front view of a stiffener, we propose dividing the ship stiffener into two parts: exterior profile and interior detailed features. The exterior profile can be divided into left, middle, and right sections. The left and right sections contain the stiffener’s end cut details, whereas the middle section is represented by a set of straight lines that convey the shape of the main body. Two sets of predefined lines are used to represent the left and right end cut details, and two straight lines describe the middle part. For example, in Figure 4, the combination of A, B, and C can be used to represent a flat stiffener. Precise placement of the predefined left and right end cut lines with respect to the middle stiffener body lines can represent any stiffener geometry in the drawing. A similar approach can be applied to the interior detailed features (e.g., ventilation holes, cutouts) using a predefined set of lines.



Figure 4: Left (A) and right (C) end cut representation lines and middle body lines (B).

From an auto-dimensioning perspective, stiffener drawings should be complete, clear, and uncluttered (e.g., no overlapping dimensions or intersecting dimension lines). The process includes the dimensioning of the stiffener length, the details on the stiffener body, and the left and right end cut details. To this end, we defined a calibration line that can serve as a reference line to import the length value from the 3D model of the stiffener into the drawing (Figure 5). The ratio between the length of the calibration line and the length of the 3D stiffener was used for dimensioning and positioning the interior detailed features on the drawings.



Figure 5: Calibration line (in red) in a drawing of a stiffener.

Next, for the dimensioning of the end cuts, we defined four main drawing elements (extension lines, dimension lines, gap, and values) in the left and right sections, similar to the corresponding traditional dimensioning elements. The dimension values are linked to the 3D model of the stiffener to complete the automatic dimensioning of the end cuts. For example, the dimension values 32, 35, and 15 on the right end cut shown in Figure 6-A are driven by the 3D model of the stiffener (B), thus variable, whereas other elements cannot be changed.

The same set of predefined lines can be reused for other end cut details if the end cut is of the same type. In other words, the right-end cut profile shown in Figure 6-A can be reused to represent other right-end cuts (of the same type) with different dimensions (e.g., 30, 30, 10). There is no need to redraw any geometric elements to reflect the update in a stiffener drawing.

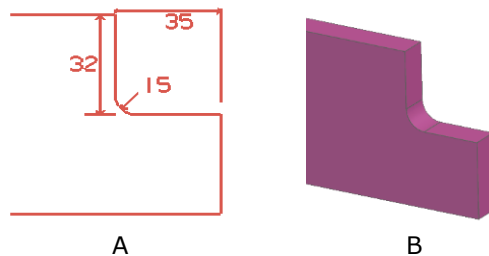


Figure 6: Example of a dimensioned right-end cut profile in a 2D drawing (A) and corresponding 3D model (B).

4 IMPLEMENTATION

To demonstrate and validate our approach, we developed a software prototype using Siemens NX technology, specifically the Siemens NX Drafting module and NX Open Application Programming Interface (API). We utilized the Custom Symbol Library in the NX Reuse Library module and the NX Drafting module to create LEFT and RIGHT end cut symbols for the 2D stiffener representation, a MIDDLE symbol for the middle section of the stiffener, and other symbols for other interior features. The example shown in Figure 7 illustrates the creation of a left-end cut symbol where fourteen objects (twelve lines and two linked text notes) were defined to represent one type of left-end cut shape with dimensions. To drive automated dimensioning for the end cuts, the “arbitrary” text type must be selected to link the initial angular and height dimensions with the dimensions in the 3D stiffener model, as shown in Figure 7. The process can be applied to other symbols to represent additional design features of any stiffener needed in a shipyard. With support from the calibration line and symbols, the front view of a fully dimensioned stiffener using our method is illustrated in Figure 8.

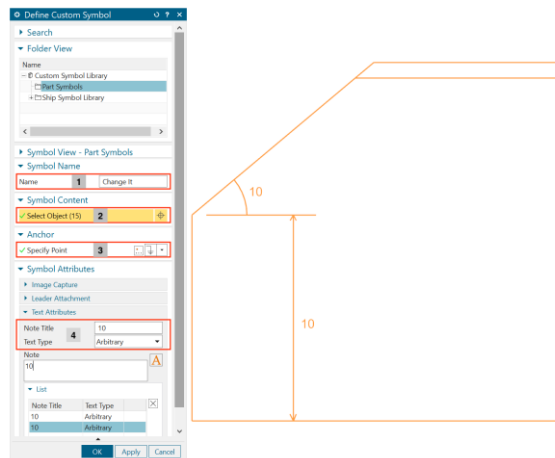


Figure 7: Definition of a left end cut symbol: (1) symbol name, (2) selection of the relevant end cut lines and text notes, (3) anchor point to locate the end cut symbol in the template file, and (4) text type to support the end cut auto dimensioning.

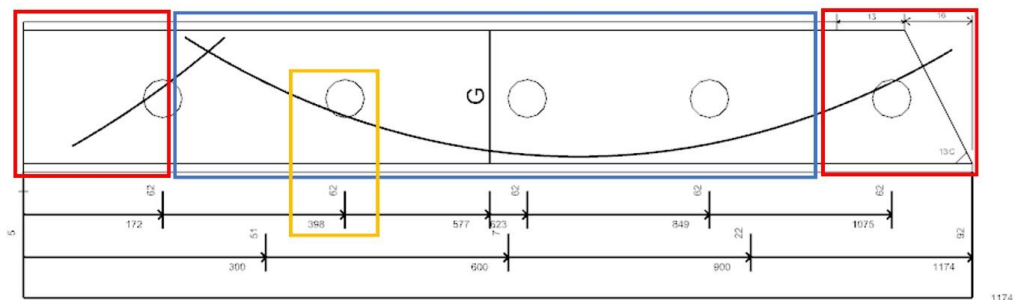


Figure 8: Front view of a stiffener represented by two end cuts (in red), middle section (in blue), and ventilation hole symbols with dimensions (in yellow).

Next, we implemented an alternative method to generate drawing templates and layouts for stiffener drawings which avoids manual selection. The ship designer can define the drawing sheet size according to a particular standard and configure the desired information at the specific location (e.g., part number, ship number, weight, and how many stiffeners will be displayed in one sheet). Drawing multiple stiffeners of the same type on the same sheet can reduce the number of drawings, maximize the use of space, and improve the efficiency of reading the same type of stiffeners. The example shown in Figure 9 illustrates three stiffeners in one drawing sheet and the corresponding production information (e.g., stiffener weight, grade, ventilation hole type) as predefined in a template file. The data embedded in the geometry is also loaded and updated in the drawing to communicate the complete production information related to the stiffener.

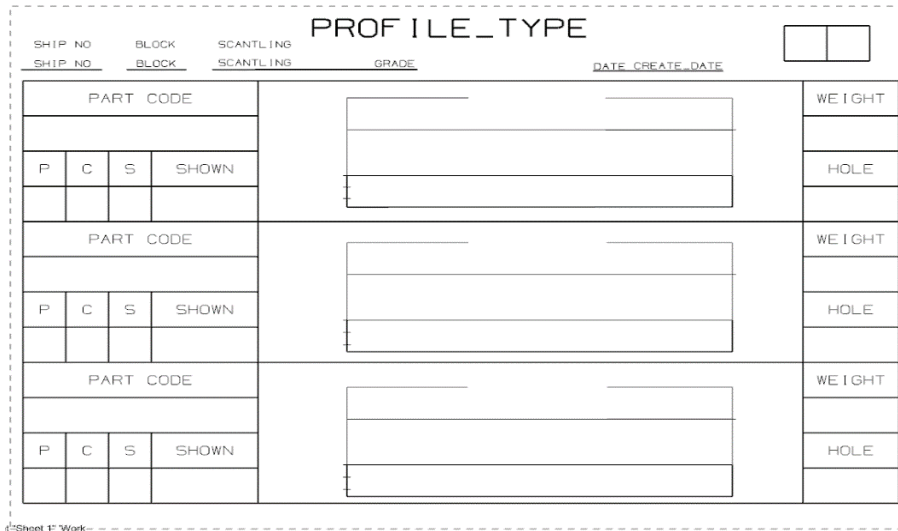
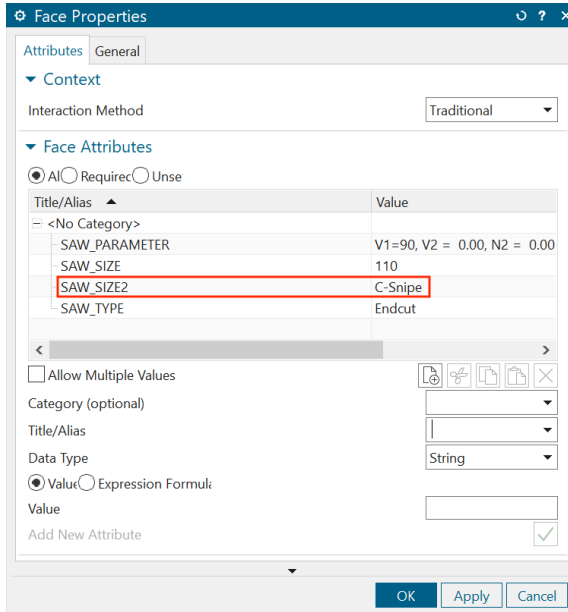


Figure 9: Example of a drawing template for a stiffener.

The selection of the 2D symbol for the 3D stiffeners is performed automatically via a comma-separated values (CSV) file where the symbol subtype (Symbol Sub Type) is mapped to the stiffener face property (SAW_SIZE2). The target LEFT, MIDDLE, RIGHT, and interior detailed symbols can be loaded and updated in the template file to represent any stiffener in the drawing. For example, in Figure 10, the "C-Snipe 1" on row 41 in the CSV file is mapped to the value of "C-Snipe" from the stiffener face properties. As a result, the left symbol part file "ibl_dwg_sym_endcut_left_cs1" will be loaded and updated (including dimensions) in the template file to represent the "C-Snipe" end cut details in the drawing of the stiffener.

	A	B	C	D	E	F
1	Symbol Type	Symbol Sub Type	Symbol Part File	Associated Values		
41	LEFT_ENDCUT_SYMBOL	C-Snipe 1	ibl_dwg_sym_endcut_left_cs1	ENDCUT_SNIPE_ANGLE	ENDCUT_WEB_HEIGHT	
42	RIGHT_ENDCUT_SYMBOL	C-Snipe 1	ibl_dwg_sym_endcut_right_cs1	ENDCUT_SNIPE_ANGLE	ENDCUT_WEB_HEIGHT	
43	LEFT_ENDCUT_SYMBOL	C-Snipe 1(+T)	ibl_dwg_sym_endcut_left_cs1_pT	ENDCUT_TILT_ANGLE	ENDCUT_SNIPE_ANGLE	ENDCUT_WEB_HEIGHT
44	RIGHT_ENDCUT_SYMBOL	C-Snipe 1(+T)	ibl_dwg_sym_endcut_right_cs1_pT	ENDCUT_TILT_ANGLE	ENDCUT_SNIPE_ANGLE	ENDCUT_WEB_HEIGHT
45	LEFT_ENDCUT_SYMBOL	C-Snipe 1(-T)	ibl_dwg_sym_endcut_left_cs1_nT	ENDCUT_TILT_ANGLE	ENDCUT_SNIPE_ANGLE	ENDCUT_WEB_HEIGHT
46	RIGHT_ENDCUT_SYMBOL	C-Snipe 1(-T)	ibl_dwg_sym_endcut_right_cs1_nT	ENDCUT_TILT_ANGLE	ENDCUT_SNIPE_ANGLE	ENDCUT_WEB_HEIGHT
47	LEFT_ENDCUT_SYMBOL	C-Snipe 2	ibl_dwg_sym_endcut_left_cs1	ENDCUT_SNIPE_ANGLE	ENDCUT_WEB_HEIGHT	
48	RIGHT_ENDCUT_SYMBOL	C-Snipe 2	ibl_dwg_sym_endcut_right_cs1	ENDCUT_SNIPE_ANGLE	ENDCUT_WEB_HEIGHT	
49	LEFT_ENDCUT_SYMBOL	C-Snipe 2(+T)	ibl_dwg_sym_endcut_left_cs1_pT	ENDCUT_TILT_ANGLE	ENDCUT_SNIPE_ANGLE	ENDCUT_WEB_HEIGHT
50	RIGHT_ENDCUT_SYMBOL	C-Snipe 2(+T)	ibl_dwg_sym_endcut_right_cs1_pT	ENDCUT_TILT_ANGLE	ENDCUT_SNIPE_ANGLE	ENDCUT_WEB_HEIGHT
51	LEFT_ENDCUT_SYMBOL	C-Snipe 2(-T)	ibl_dwg_sym_endcut_left_cs1_nT	ENDCUT_TILT_ANGLE	ENDCUT_SNIPE_ANGLE	ENDCUT_WEB_HEIGHT
52	RIGHT_ENDCUT_SYMBOL	C-Snipe 2(-T)	ibl_dwg_sym_endcut_right_cs1_nT	ENDCUT_TILT_ANGLE	ENDCUT_SNIPE_ANGLE	ENDCUT_WEB_HEIGHT

A



B

Figure 10: Selected row in CSV configuration file (A) and the corresponding value in the stiffener face properties (B).

An XML file is used to map the target template files with the stiffener types, thus eliminating manual selection errors and ensuring that stiffeners are drawn on the correct drawing sheet with the proper projection views. A sample XML configuration file is shown in Figure 11. In Figure 11, the “tabnote name” section was designed to load the properties from the 3D models of the stiffeners (e.g., DB_PART_NO, PORTSIDE_NUM) and update the specific cell contents in the corresponding table from the template file.

```
<templates>
<template profile_type="HP" flange_type="S-FLANGE" profile_form="NonPlanar">
<part_file name="HP NonPlanar (Metric)" units="Metric"/>
<note name="PROFILE_TYPE" attribute_title="SAW_PARAMETER"/>
<note name="PART_NAME" program_func="SHIP_NO"/>
<note name="BLOCK" program_func="BLOCK"/>
<note name="SCANTLING" attribute_title="SAW_SIZE"/>
<note name="GRADE" attribute_title="SAW_MATERIAL_GRADE"/>
<note name="CREATE_DATE" program_func="CREATE_DATE"/>
<note name="EXAXIS" program_func="EXAXIS" precision_metric="1"/>
-
<tabnote name="PROFILE_MFG_INFO_TABNOT">
<cell row="2" column="1" attribute_title="DB_PART_NO"/>
<cell row="2" column="2" program_func="PORTSIDE_NUM"/>
<cell row="2" column="3" program_func="CENTER_LINE_NUM"/>
<cell row="2" column="4" program_func="STARBOARD_SIDE_NUM"/>
<cell row="2" column="6" program_func="VENTHOLE_STAT"/>
<cell row="2" column="7" program_func="FRAME"/>
<cell row="2" column="8" program_func="TWIST"/>
<cell row="2" column="10" program_func="ST_LEN"/>
<cell row="2" column="11" program_func="CHECK_LEN"/>
<cell row="2" column="12" program_func="CHECK_BEND"/>
<cell row="2" column="13" attribute_title="SAW_MASS" precision_metric="1"/>
</tabnote>
-
<custom_symbols>
<symbol name="SAW_PARAMETER"/>
<symbol name="LEFT_ENDCUT_SYMBOL"/>
<symbol name="RIGHT_ENDCUT_SYMBOL"/>
</custom_symbols>
-
<annotations>
<CALIBRATION_LINE name="CALIBRATION_LINE"/>
<IBL_START_POINT name="IBL_ANCHOR_POINT" interval_metric="11.5" interval_inch="0.45"/>
<VH_START_POINT name="VH_ANCHOR_POINT"/>
<GROOVE_WELD_LEG_START_POINT name="VH_ANCHOR_POINT" groove_attr_title="GROOVE DATA TYPE" material_allowance_metric="20"/>
<CUTOUT_START_POINT name="VH_ANCHOR_POINT" symbol_scale="0.7" interval_metric="5.5"/>
<ALONGGUIDECUT_START_POINT name="VH_ANCHOR_POINT" symbol_scale="0.7" interval_metric="5.5"/>
<PROFILECUTOUT_START_POINT name="VH_ANCHOR_POINT" symbol_scale="0.4" interval_metric="5.5"/>
<KNICKLE_START_POINT name="VH_ANCHOR_POINT" symbol_scale="0.7" interval_metric="5.5"/>
<INVERSEBEND_FRAME_LEFTLOWER_ANCHOR_POINT name="FRAME_LEFTLOWER_ANCHOR" vertical_coefficient="1.0"/>
<INVERSEBEND_FRAME_RIGHTUPPER_ANCHOR_POINT name="FRAME_RIGHTUPPER_ANCHOR" profile_margin_metric="25" profile_margin_inch="1.0"/>
</annotations>
</template>
</templates>
```

Figure 11: XML configuration file.

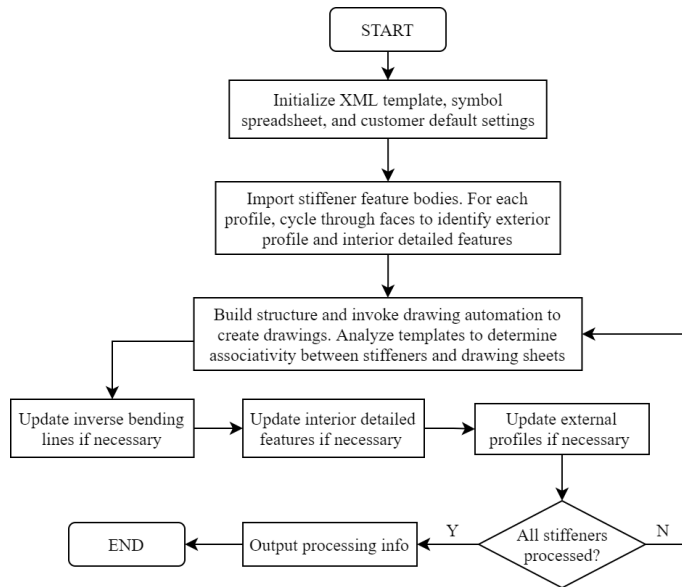


Figure 12: Flowchart of the process for the automatic generation of stiffener drawings.

5 VALIDATION

Our prototype was fully integrated within the NX interface and accessible as a new command in the NX Drafting Module. The prototype was validated in terms of functionality, performance, and reliability.

For the functionality testing, twenty-six test cases were designed and executed. We randomly selected 202 automatically generated drawings and validated the results according to 25 critical validation points, as shown in Figure 13. A description of each validation point and details of one of the 26 test cases are illustrated in Tables 1 and 2, respectively. A total of 198 drawings were generated successfully by our prototype from the test cases, which corresponds to an accuracy of over 98%. The reasons for failure in the four drawings that were not generated successfully include (1) incorrect drawing and dimensioning definition in the symbol preparation stage, (2) incorrect configuration in the template preparation stage, and (3) incorrect configuration in the CSV and XML files preparation stage. These problems could be avoided if the related files were configured correctly during the preparation stages.

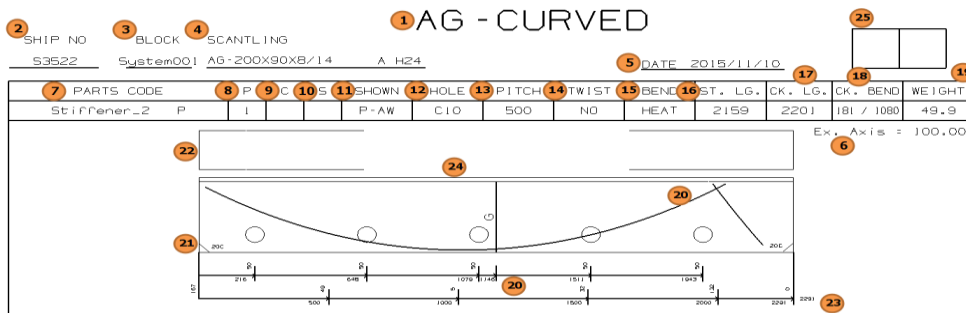


Figure 13: Validation points selected for functionality testing.

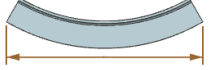
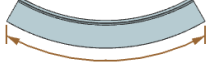
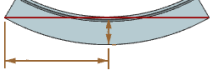
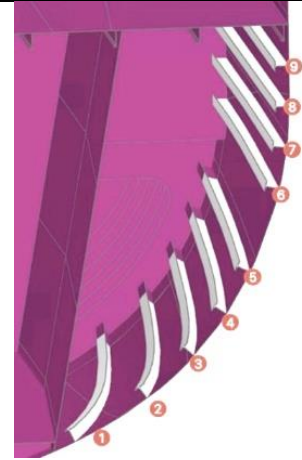
<i>Item</i>	<i>Name</i>	<i>Description</i>	
1	STIFFENER_TYPE	The type of stiffener represented by the drawings on the current sheet	
2	SHIP NO	Name or number of the current project	
3	BLOCK	Name of the assembly or worksheet containing the stiffener parts	
4	SCANTLING	Basic size and material grade of the stiffener are represented by the drawings in the current sheet	
5	DATE	Date the drawing sheet was created	
6	Ex. Axis	Height of neutral axis	
7	PARTS CODE	Name of the part	
8	P	Number of times the part is located on the port side	
9	C	Number of times the part is located in the center	
10	S	Number of times the part is located on the starboard side	
11	SHOWN	Location of the stiffener (port side or starboard) and direction of the face containing the inverse bending line (up, down, forward, aft, in, or out)	
12	HOLE	Name of the major drain or air hole in the stiffener	
13	PITCH	Spacing value if the spacing is fixed. FRAME is displayed if the spacing is equal to the spacing of the frames	
14	TWIST	YES is displayed if the stiffener is twisted, NO if it is not twisted	
15	BEND	Method used to create the bends	
16	ST. LG.	Linear length of the part, rounded to the nearest integer	
17	CK. LG.	Arc length of the part, rounded to the nearest integer	
18	CK. BEND	Maximum length and height of the bend	
19	WEIGHT	Weight of the stiffener	
20	Inverse Bending Line(s)	Drawing and dimensioning of inverse bending line(s)	
21	End Cuts	Drawing and dimensioning of end cuts	
22	Flange	Drawing of stiffener flange	
23	Stiffener Length	Dimensioning of stiffener length	
24	Stiffener Profile	Drawing of stiffener profile	
25	Signature	Signature blocks	

Table 1: Stiffener drawing validation points (adapted from Siemens Documentation: Profile Sketch Drawing Templates).

Test Case Name: Drawings for T-type stiffeners	
Test Instructions:	
1. Open the top ship assembly	

2. Run the developed prototype for the nine annotated stiffeners



Pass/Fail Criteria:

Pass if:

- SHIP NO: S3522
- BLOCK: System001
- SCANTLING: T-254X343 A H24
- Date: Representing the correct drawing creation date
- Signature Blocks: No content should be added.
- PARTS CODE: Representing the corresponding name of the stiffener
- P, C, S: Representing the corresponding locations of the stiffeners
- SHOWN: Representing the corresponding location of the stiffener (port side or starboard) and the direction of the face containing the inverse bending line
- HOLE: No value should be added.
- WEIGHT: Representing the corresponding weight of the stiffener
- The stiffener front and flange views match the 3D models.
- The stiffener length should represent the correct length of the 3D models.
- Two stiffener drawing results should be as follows:

SHIP NO	BLOCK	SCANTLING	T				DATE	WEIGHT
S3522	System001	T-254X343	A	H24			2021/10/25	
PARTS CODE	P	C	S	SHOWN	HOLE	WEIGHT		
Stiffener_174	P	A	A	P-OT		401.9		
UP							427	
PARTS CODE	P	C	S	SHOWN	HOLE	WEIGHT		
Stiffener_167	S	IO	IO	S-OT		295.4		
UP							367	

SHIP NO	BLOCK	SCANTLING	T				DATE	WEIGHT
S3522	System001	T-254X343	A	H24			2021/10/25	
PARTS CODE	P	C	S	SHOWN	HOLE	WEIGHT		
Stiffener_122	P	Z		P-IN		286.4		
UP							337	
PARTS CODE	P	C	S	SHOWN	HOLE	WEIGHT		
Stiffener_121	P	S		P-IN		336.5		
UP							357	

Table 2: Sample test case used during functionality testing.

We designed three test cases using a 3D model of a ship to test the performance of our software prototype, as shown in Figure 14. The results of the tests are shown in Table 3. Our prototype has the fastest performance rate when generating drawings for curved stiffeners (3.81/s), the medium

rate for straight and curved stiffeners (6.56/s), and the slowest rate for straight stiffeners (11.18/s). Finally, no critical errors were identified during reliability testing. Only two software bugs were identified in 215 hours of runtime (total bug rate = 0.009/h).

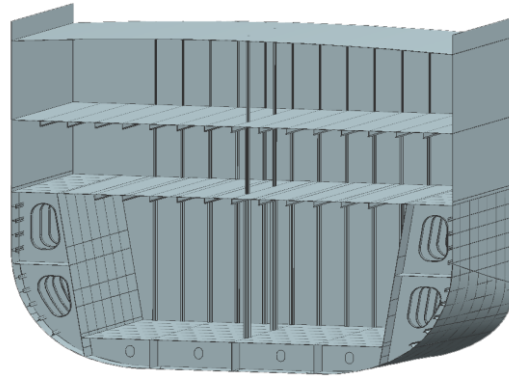


Figure 14: A section of a 3D model of a ship used for performance testing.

<i>Test case</i>	<i>No. of curved stiffeners (n1)</i>	<i>No. of straight stiffeners (n2)</i>	<i>Completion time (t) (in seconds)</i>	<i>Rate t / (n1+n2)</i>
1	0	11	123 s	11.18
2	16	0	61 s	3.81
3	16	11	177 s	6.56

Table 3: Performance testing results.

Our solution allows designers to complete the drawing process in one click without any manual steps. Compared to standard shipbuilding software systems (the exact procedures may vary slightly between systems), our approach eliminates the manual selection of drawing views, manual input for the title and detail blocks, and dimensioning, as shown in Figure 15.

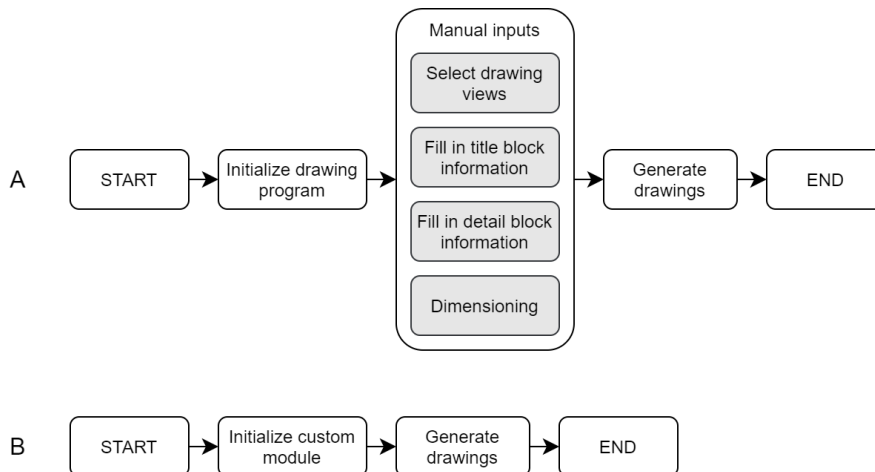


Figure 15: Typical drawing process in shipbuilding software (A) vs. drawing process in our developed prototype (B).

6 CONCLUSIONS AND FUTURE WORK

In this paper, we discussed an approach to auto-generating complete production-ready engineering drawings for ship stiffeners and presented a software prototype that was implemented as a software module for a commercial CAD system. Our strategy consists of dividing the geometry of a stiffener into an exterior profile (left, middle, and right sections) and a set of interior detailed features (e.g., ventilation holes, cutouts) which enables the automated creation of fully dimensioned drawings. Our approach eliminates manual operations that are commonly required by CAD software for the creation of drawings of stiffeners, including the selection of drawing views, manual inputs for title and detail blocks, and dimensioning during the drawing process.

To evaluate the functionality, performance, and reliability of our prototype, we ran 26 functional test cases, three performance test cases, and 215 hours of reliability testing. Our results showed that the approach eliminated errors during typical manual and automated drawing processes, such as incorrect dimension placements, missing dimensions, redundant dimensions in multiple views, overlapping dimensions, and dimension lines intersecting each other or other lines in the drawing.

Our strategy leverages a data-driven and fully associative approach in which the preparation of the symbol library, templates, and neutral files is fundamental but also time-consuming. Furthermore, any error that occurs during the preparation of these elements can result in an inaccurate drawing outcome. In this regard, the implementation of our approach requires a careful preparation stage to ensure the correctness of the configuration files involved. Nevertheless, when an error is found during production, designers can update the symbols, templates, and content of the CSV and XML files, as necessary.

For future work, it would be interesting to improve the preparation process of the symbols for the drawings. For example, by utilizing the projected views of the 3D shape of the stiffener to generate the corresponding end cut symbols, we can avoid manual drawing and improve symbol accuracy. Also, a summary report containing an estimate of the module's run time, as well as information on pass/fail cases for the drawings, can be beneficial for ship designers to analyze the results, if necessary. Lastly, we are exploring methods to adapt our approach to generate drawings of other common mechanical parts and structures automatically.

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