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Quality Management Approach of Product Data Models for Shipbuilding

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List of Abbreviations

2D Two Dimensions
3D Three Dimensions
AIAG Automotive Industry Action Group
API Application Programming Interface
APP Assembly Process Planning
AutoCAD Computer Aided Design System
AVEVA Integrated Design, Production and Life-cycle Management Solutions for Marine Industry
ASCII American Standard Code for Information Interchange
BOB Business Object Builder
BOM Bill Of Materials
B-Rep Boundary Representation
CAA Computer Aided Approval
CAD Computer Aided Design
CAE Computer Aided Engineering
CAIP Computer Aided Inspection Planning
CAM Computer Aided Manufacturing
CAPA Corrective And Preventive Actions
CAPP Computer Aided Process Planning
CAQ Computer Aided Quality Assurance
CATIA Dessault Systemeś, Computer Aided Design System
CAX computer-aided (design, manufacturing, engineering, etc.) system
CE Concurrent Engineering
CS Classification Society
CSG Constructive Solid Geometry
CFD Computational Fluid Dynamics
CIM Computer Integrated Manufacturing
CMM Coordinate Measuring Machines
CNs Customer Needs
COQ Cost of Quality
CRs Common Rules
CSR Common Structural Rules
DBMS Data Base Management System
DFA Design For Assembly
DFM Design For Manufacture
DFSS Design For 6-Sigma
DFX Design For X
DMADV Define Measure Analyze Design Verify

DMAIC Define Measure Analyze Improve Control
DMIS Dimensional Measuring Interface Standard
DML Dimensional Markup Language
DMU Digital Mock Up
ERP Enterprise Resource Planning
ES Electroslag Welding
EW Electrogas Welding
FCAI Federal Chamber of Automotive Industries
FEA Finite Element Analysis
FEM Finite Element Modeling
FSW Friction-Stir Welding
GD&T Geometric Dimensioning and Tolerancing
GMAW Gas Metal Arc Welding
GPS Geometrical Product Specifications
IACS International Association of Classification Societies
ice.NET Information management and collaboration platform & Graphical UML modeler
IGES Initial Graphics Exchange Specification
ILO International Labour Organization
IMO International Maritime Organization
ISO International Organisation for Standardisation
IT Information Technology
JAMA Japan Automotive Manufacturers Association
JAPIA Japan Automobile Parts Industry
KCs Key Characteristics
MS SQL Server Relational Database Management System
NAPA Naval Architecture Package, Computer-Aided Design System
NC Numerical Control
NIST National Institute of Standards and Technology
ODETTE Organisation for Data Exchange by Tele Transmission in Europe
OEM Original Equipment Manufacturer
ORM Object-Relational Mapping
PDM Product Data Management
PDQ Product Data Quality
PDQMS Product Data Quality Management System
PLM Product Lifecycle Management
PMDD Product Model Driven Development
PML Programmable Macro Language
PODAC Product-Oriented Design and Construction
POSEIDON Design and analysis system for the development of hull structures
PRs Procedural Requirements
Pro/Engineer Product model system
PSL Process Specification Language
QC Quality Criteria

QFD Quality Function Deployment
SAE Society of Automotive Engineers
SASIG Strategic Automotive Product Data Standards Industry Group
SAW Submerged Arc Welding
SOLAS International Convention for Safety of Life at Sea
SMAW Shielded Metal Arc Welding
SOVA Stream-of-Variation
SPC Statistical Process Control
SQC Statistical quality control
SQL Structured Query Language
STEP Standard for the Exchange of Product Model Data
STL STereo Lithography
TQC Total Quality Control
TQM Total Quality Management
UI Unified Interpretations
UML Unified Modeling Language
UR Unified Requirements
VDA Verband Der Automobilindustrie/ German Association of Automotive Industry
XML Extended Markup Language

1. Introduction

One of the most challenging tasks in the engineering profession is to develop new products that have the shortest lead-time, highest quality and lowest cost with optimal lifecycle consideration [93]. Product data models and digital representations have replaced the physical drawings in many places in ship design process and have become the main form in which the product data are stored, analysed, and communicated among the teams and individuals involved in the design process. Data exchange and a high degree of complexity have elevated the importance of the quality of the product model data. Published reports revealed that almost 60-80% of physical parts or components, together with digital product data are outsourced by the original equipment manufacturers (OEMs) in the automotive industry [161]. To improve the quality and productivity of constructive processes in marine engineering design, it is helpful to develop tools for monitoring quality criteria. These tools must be adopted at an early stage to detect quality defects by checking the product data model. A ship is a product assembled from individual parts. The description of these parts is stored in a product data model. The quality of the data plays an important role in order to avoid errors later in the production phase, as these can only be solved through substantial efforts [70]. Poor product data model quality can have a severe impact on the overall effectiveness and productivity of shipyards. At this time, there are no automated checks adopted at shipyards that allow to check the ship product data models for compliance with relevant quality criteria. For large data sets in particular, only an automated control can increase productivity and effectivity of ship design processes. In this thesis an approach to manage the quality of ship product data model is introduced. On one hand, product-related information models have to be developed, and on the other hand, complex algorithms have to be implemented to check the compliance of the product data model with the quality requirements to ensure a smooth flow of data throughout the design process, thus preserving time and costs. Both aspects are taken into account for the first time in a laboratory prototype implementation based on a modularly designed, integrated approach in heterogeneous CAD system environments.

1.1. Problem Statement and Motivation of the Work

Design is the process of defining of the materials, shapes, and tolerance of the particular parts of a product. It starts with simple drawings of parts and assemblies; and then processes on the computer-aided design (CAD) systems, where assembly and detailed part drawings are derived. These drawings are then sent to the manufacturing and assembly engineers for seek of optimization of the processes have to be applied to produce the final product [36]. At this phase several manufacturing and assembly problems are frequently encountered and therefore a lot of engineering design changes are required. The large number of engineering changes decreases the quality of manufacturing processes and increases the inconsistency of the product data, which results in the delay of the final product delivery and increases the cost of the final product. Over 70% of the final product costs are determined during design, therefore, it is necessary to take the manufacturing and production requirements in consideration in the early design phases.

The global competition between shipyards and the diversity of owners' requirements lead to very short lifecycles in ship production. The requirements of high accuracy, rapid product changes, and the increased labor costs have forced the industry to utilize computers to improve their productivity [46]. Because of the characteristics of the shipbuilding process, subsection 3.2.3, building a ship prototype for quality requirements is principally impossible. Many CAX systems are usually used in the design and manufacturing processes to manage the product data. The information flow and format conversion between these systems lead to errors and data redundancy. On average, the big companies spend about 100,000 hours per year in order to correct problems associated with CAD data quality [74]. Annually, interoperability problems cost the automotive supply chain about US$1 billion in the US automotive industry [42]. Almost, US$67 million are the yearly average costs to solve product data problems for nearly 250.000 cases, each case needs 1.5 days to be solved [161]. Of 200,000 exchanges of product data, at least 10,000 included quality problems and had to be adjusted or repaired by design teams at DaimlerChrysler [161]. Interoperability problems have been estimated by Hyundai Motors to cost yearly about US$6.8 million. About 45% of change orders are due to quality issues of shape data. Furthermore, about 20-70% of the design time is spent to correct and redesign product data due to late-detected errors [161]. An industry executive report noted that more than 60% of surveyed firms had problems with data quality, which lead to failure of most engineering processes [156].

The applied computer aided systems to build a ship product data model for the ship's structural components offer different functions to define large numbers of structural elements. The ship product data model is voluminous, complex, and distributed across many diverse systems. The systems applied are generally not capable to fully ensure the correctness of the product model data with respect to the numerous quality criteria to be observed and only few of them are truly integrated, and manual works are needed to maintain and ensure the correctness of data flow between the different systems. Neglecting those criteria has a high impact on ship production as well as in the subsequent operations and the result is unreliable, defected and uncontrollable product data model and therefore inefficient and inflexible design process.

Nowadays, the final inspection of highly complex design data is almost manual and drawings oriented and has not been automated thus far. It is associated with considerable time and personnel expenses. A study [27] has shown that modeled ship structures may have errors that may be discovered and corrected only in later phases of the design process, sometimes with considerable costs. In year 1998, McKenney [108] estimated that around 70% of time for finite element analysis is spent to fix CAD models errors.

1.2. Reasons for Faulty Product Data Model

Different studies [74], [63] and [163] attribute the defective data to a number of factors: Oversight; lack of communication; missing and outdated information; CAX systems bugs and system incompatibility; missing quality control mechanisms in a certain design phase; improper modeling practices; lack of knowledge about the downstream processes; non conformance to generic methodologies; neglecting the enforcement of quality standards; time pressures; big number of data translations; loss of data while exchanging between heterogeneous CAD systems; lack of training. Regarding the CAD models, the main reasons for quality problems are user techniques, CAD applied algorithms, and neglecting manufacturing requirements [108]. The first factor includes that the CAD system users may produce errors accidentally when they do some engineering changes or the lack of the knowledge about the design processes outside their considerations. When the capabilities of the implemented algorithms in CAD system are reached, like round-off errors, quality problems can arise. Sometimes, an allowable inconsistency is used to support the intent of the design like a small face to transit between two other faces, on the other hand the existence of such inconsistency causes problems for downstream processes. Interviews at German shipyards regarding reasons for low product data model quality have been conducted [63]. Three major categories were identified, see Figure 1.1. The first category includes human element aspects which are mainly due to oversight and lack of knowledge about constraints stemming from production requirements. The issues related to communication problems and faulty design planning processes are included in the process category. The tools category includes incompatibility issues and system bugs as well as the lack of control and check mechanisms. A combination of the above mentioned reasons will result in a non-sufficient quality of ship product data models.

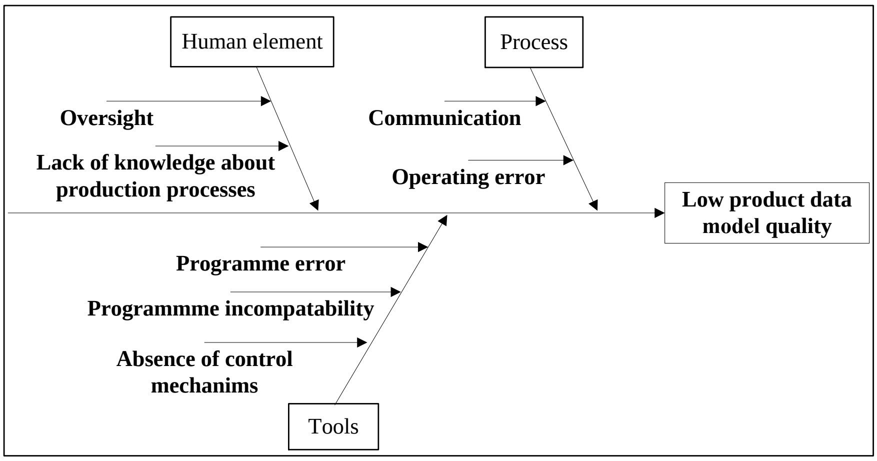


Figure 1.1.: Reasons for low product data quality

1.3. Impact of Product Data Model Quality Problems

MecKenny [108] shows that up to 70% of design time were invested to fix geometry errors in the finite element analysis (FEA), Rapid prototyping, NC tool path generation and product data exchange in the automotive industry. If the corrupted product data model is returned to the upstream process, where the original data is generated, this may lead to production interruption and changing of the design intent as well as over-run in time and cost. With the growing of product data model use and increase in the complexity, error sequences will be more significant. Error sequences lead to inefficiency of design and production processes, delay in lead time, high costs of correction works, low productivity and conclusively inferior product quality [108].

Geitmann et al. [63] have conducted interviews at German shipyards and a design agent and the identified impact of the detected errors in product models data were: own error-correction works, third-party error-correction involvement, increased cost of materials, time delay and in the worst case production interruption. Figure 1.2 shows the costs of error correction along with the progression of the design process. In the implementation phase, an error costs US$50, whereas in the early design phase it is only US$3.5. After the delivery, the cost of error correction increases exponentially by US$170 for each error.

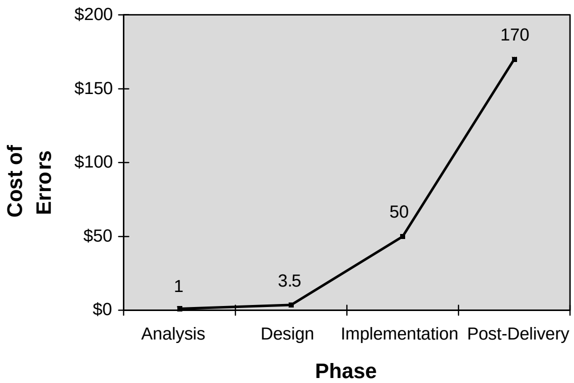


Figure 1.2.: Cost of errors along with the development phase [113]

Figure 1.3 shows the cost of engineering changes and the frequency of changes as a function of time in the product development process. The cost of an engineering change after releasing the product model data to the manufacturing phase is 10 times higher than that in the design phase. Moreover, the cost will be increased to about 100 times in production phase [59].

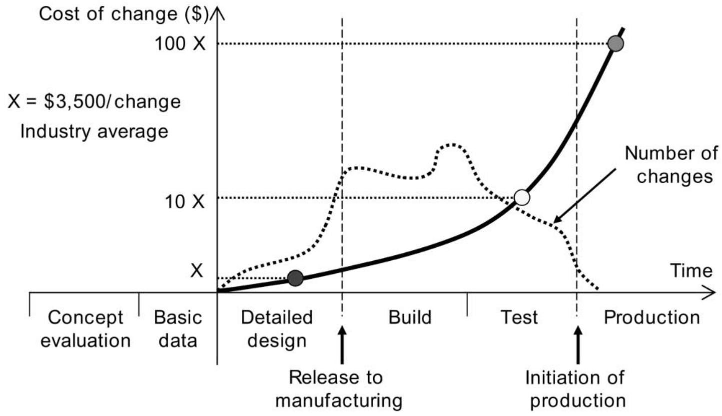


Figure 1.3.: Cost of engineering change (solid) and number of changes (dashed) according to design phase [59]

Detecting deficient designs too late results in time loss and potentially intensive correction works where as much as 20-50% of the time for creating the original CAD model are required. About 10% is needed if the deficient design is detected as early as possible and before the CAD model is released for downstream processes [161]. Table 1.1 shows that the necessary time to correct a detected error rises throughout the ship design process. In basic design the shortest time is needed to correct an error about, 15 minutes, whereas in detail design phase an error-correction costs about 35 minutes. During technical drawing approval and production of manufacturing information, the correction-time may range between 30 minutes and 2.5 hours. The worst case sets in if an error detected too late in the manufacturing phase, where the correction-time can reach two weeks. The estimated average time to solve a quality problem in the OEM industry is about 4.9 h for 453,000 yearly data exchanges with the suppliers [162]. In the Japanese automotive industry, 1.5h has been estimated to correct and replace each detected poor quality item while exchanging the product model data [162].

Process phase	Minimum time	Maximum time
Basic design	10 min	15 min
Detail design	25 min	35 min
Drawing generation	30 min	1.5 h
Generation of manufacturing data	25 min	1.5 h
Production	1.5 h	2 h

Table 1.1.: Correction times according to detection phase [40]

As shown in Figure 1.4 errors are mainly produced in the ship detail design phase, whereas 70% of the errors are detected in the production phase [63] [89].

1.4. Types of Product Data Model Problems

Product data model problems can be categorized from a geometrical and topological correctness point of view into three groups: structure, accuracy and realism. Structure stands for all problems regarding the correctness of the definition and connectivity of the geometrical and topological elements such as points, curves and surfaces. For example, missing geometry, inconsistent edge and curve directions, intersecting loops in face, etc. All of such errors lead to unpredictable behavior of the CAX systems and manufacturing problems. Accuracy stands for problems regarding accuracy information of the connected elements. Such errors rise when approximations are used to compute complex geometric entity. For example, a gap between faces related to an edge. Translation between two different CAX systems can fail if the defined allowable tolerances are not in the same range.

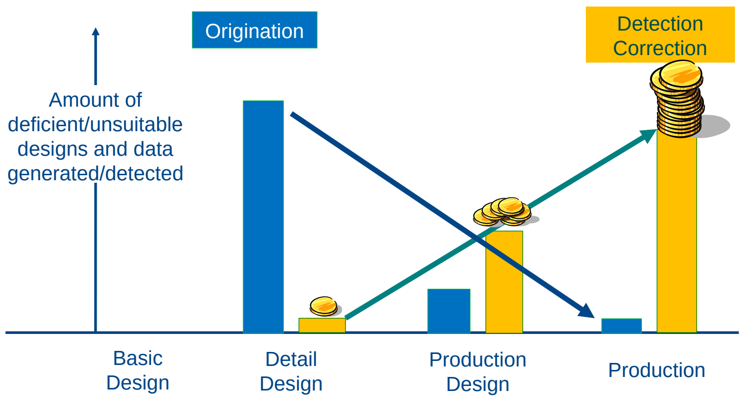


Figure 1.4.: Origination and detection locations of errors [63]

The realism group stands for feasibility of the model elements, like physical cracks in engineering materials. Another approach to categorize the errors in product data model from the invalid shape data point of view is discussed in ISO standards STEP-59 [14] and ISO/TS 8000-311 [22], which include: erroneous topology, erroneous geometry, erroneous topology and geometry relationship, and erroneous manifold solid B-Rep. ISO/PAS 26183 [19] classified the product data problems regarding the application fields. It includes problems regarding Computer-Aided Design (CAD), Computer-Aided Engineering (CAE), Product Data Management (PDM), inspection, Prototyping, and manufacturing data. Problems regarding the CAD data are those associated with various aspects of CAD data such as solid models, assemblies, surface models, tolerance data, and drawing views. Problems related to CAE data are those caused by CAE applications such as finite element analysis, kinematics analysis, and dynamic analysis. PDM data quality issues are those related to the data stored in a PDM system. Inspection data problems are the data created for, used, and stored in an inspection system. Prototyping data problems are the data created, used, and stored in a prototyping system. Finally, manufacturing data problems are the data created, used, and stored in a manufacturing system. Problems in ship product data models fall into six major categories and each one has several subcategories [41] [27]: parts identification attributes problems regarding uniqueness and correct assignment, material logistics problems by disregarding restrictions in raw and stock material, disregarding: manufacturing and welding preparation requirements, design standards, and drawing conventions.

Figure 1.5 shows some examples of inapt designs. Figures 1.5(A) and (D) show notches not provided in correct positions which in both cases are due to profiles which are too long. In Figure 1.5(B), the edge preparation information, which defines the welding joint form, is not provided correctly. Figure 1.5(C) shows an excess material problem and an end-cut problem.

1.5. Definitions

Product data as provided in [35], [51] and [19] include: CAD models (solid, surface, or wireframe); CAE; CAM; PDM e.g. engineering and manufacturing bills of materials, process plans, model revision history, product assembly structure; numerically controlled machine-tool programs; notes; documentation and reports; communication data; analysis/performance data; project planning data; verification and scientific data; digital mock-up data. Product data quality as provided in ISO/PAS 26183 is a measure of the accuracy and appropriateness of product data combined with the timeliness with which those data are provided to all the people who need them. Good product data quality means providing the right data to the right people at the right time [19]. Quality of product, quality of product data and quality of product model are three different kinds of quality, each one of them has to be consider separately as shown in Figure 1.6.

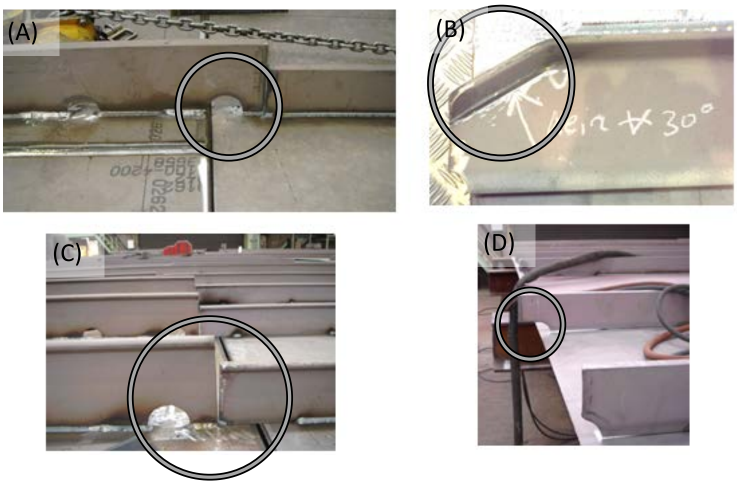


Figure 1.5.: Examples of deficient designs: (A) incorrect notch position (B) missing edge preparation (C) excess material problem (D) incorrect notch position

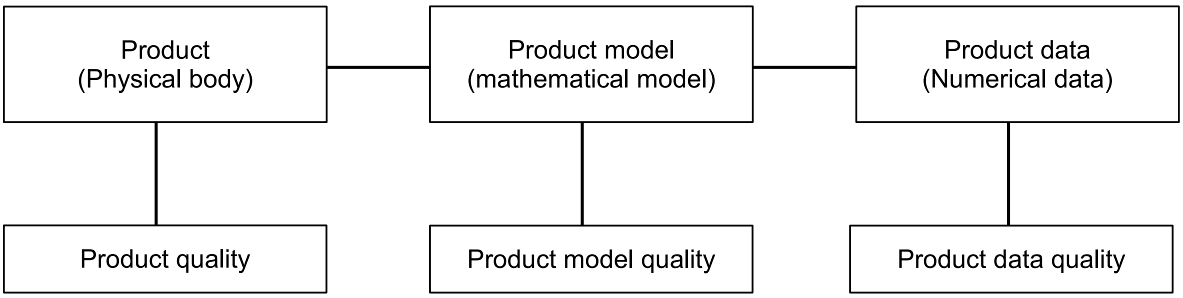


Figure 1.6.: Quality of product, product model and product data, ISO STEP-59 [14]

The following definitions are related to data and quality, as provided in ISO 10303-59 [14], ISO/PAS 26183 [19], [52], [31], and [120].

- *Conformance*: established as correct with reference to a standard, specification or drawing.
- *Error*: a mistake in requirements, design, or implementation.
- *Requirement*: an identifiable element of a function specification that can be validated and against which an implementation can be verified.
- *Specification*: a collection of requirements which, when taken together, constitute the criteria that define the functions and attributes of a system, component or item.
- *Test*: a quantitative procedure to prove performance using stated objective criteria with pass or fail results.
- *Quality*: an indicator depicting to what extent a chosen solution is able to satisfy a given set of requirements.
- *Erroneous data*: data, which breach the logical consistency of the product data structure.
- *Inapt data*: data, which are obviously unfavorable for most applications though they are not mathematically invalid.
- *Product data quality criterion*: requirement for detecting a quality defect in product data, whose presence can be judged by a logical or a numerical test.
- *Measurement requirement*: the requirement corresponding to each quality criterion it defined as a textual description of how the criterion is to be measured and may have additional attributes and rules to control the test and the element or elements to be tested.
- *Thresholds*: user definable, applicable numerical values depend on many factors such as size of a product, design requirements, sensitivity of engineering systems to numerical imprecision, etc.
- *Inspection*: a conformity evaluation by observation and judgment accompanied as appropriate by measurement, testing or gauging.
- *Preventive action*: an action to eliminate a detected nonconformity.

1.6. Objectives of the Thesis

A comprehensive study of the international product and process requirements and standards governing the product lifecycle from the representation of product or manufacturing information, quality and quality control in the design and digital environment for simple and complex products is presented. The major attempts and concepts to enhance the quality of product data including product modelling, CAD-model repair, data exchange and system interoperability, and the product data quality frameworks is addressed. This thesis also provides additional information related to the quality in the technical domains.

Moreover, an extensive review of the requirements and standards which regulate the ship lifecycle is addressed. According to the diversity of the stakeholders involved in ship lifecycle, it is shown how different and complex the requirements can be. In addition, an overview of the whole ship design process is discussed with the focus on the information flows between the different design phases. A short review of the applied CAX systems and the applied welding techniques is discussed. A new error classification approach is introduced based on the analysis of the frequently occurred problems in the design process.

Furthermore, a quality management approach to manage the quality of ship product model data is discussed. It aims to improve and to automate product data model control to make the design and production processes faster and more reliable. This approach is supporting an efficient correction of deficient structural designs under visual guidance towards the identified problems. The correction of the detected problems is performed by applying the same CAD system as used for the product model data generation, where changes can be integrated quickly and at lower cost. The two well known international standards ISO STEP-59 and ISO/PAS 26183:2006 (SASIG) used in the automotive industry are utilized as a background of the quality management approach in this thesis. Based on the identified design problems, a set of quality criteria is developed. The most crucial criteria are those focusing on the structural parts attributes, weld arrangements, and the constructional features.

The development of the data quality assurance approach includes the design of product specific information models and implementing several algorithms to enable processing of product data in a real context. The required information models for ship structure based on ISO STEP-218, quality of product data based on ISO STEP-59, and different support resources based on ISO STEP-41, -42, -43, and -45 are introduced. In addition, the main steps of quality assurance process of product model data as well as the application scenarios are discussed. The representation of the inspection data and the applied tolerances and thresholds are discussed. Furthermore, it is shown how the choice of the applied tolerances and thresholds is dependent on the shipyard and project standards as well as on the classification societies requirements. The developed algorithms for the inspection of product data model according to the quality criteria are introduced. Some sophisticated algorithms, originated from different scientific fields, are applied in this thesis. A new approach for the assessment of inspection results is introduced. Different values such as quality score, cost score in addition to the visual correction guidance of deficient structural parts are the elements of this assessment.

Finally, three real test cases are introduced to check the visibility of the quality management approach. Furthermore, the inspection results are evaluated and assessed. Enhancement and development suggestions are addressed for the future works.

2. Quality Concept in Technical Domains

2.1. Introduction

In this chapter, some information about quality concepts, quality parameters, dimensions, and cost of quality will be discussed. In section 2.4, principles of quality management systems and their characteristics will be addressed. A comprehensive review of the available international standards and approaches in the lifecycle perspective related to product and process, quality standards related to product and product data, quality control of product design in early product design phases, quality control in digital environment, quality control of complex products is provided. At the end of this chapter, all practical quality control attempts in the technical domains including product modelling, CAD-model repair, data exchange and system interoperability, applied product data and data quality frameworks are comprehensively reviewed.

Data quality is a multi-dimensional concept. A dimension of data quality refers to an attribute of data by which the data can be measured or assessed to give an indicator about the degree of quality. The frequently used quality dimensions are [1]: completeness, integrity, timeliness, validity, and consistency. The completeness of data means there is sufficient data provided for the current task, whereas integrity refers to the degree to which data conform to data relationship rules, as defined by the data model. The uniqueness of data ensures that the data are not recorded more than needed. If the data is up-to-date for the current task, it will be referred to as “timeliness”. Conformity to the syntax (format, type) make the data valid for the applied task. Finally, consistency means that the data are the same over multi-representations.

2.2. Cost of Quality

Cost of quality (COQ) is the difference between the actual costs of the final product or service and the costs that will result if the product or service has been built exactly right the first time. The quality costs according to the American Society for Quality include costs for [121]: prevention, appraisal, and failure. The costs of procedures to prevent poor quality in a product or service are called prevention costs and they can be, for example, costs for quality planning. All costs related to measuring, evaluation or auditing of a product or a service are referred to as the appraisal costs. The procedures associated with appraisal aim at ensuring that a product or service conforms to the defined standards and requirements. Failure costs are the summation of the internal and the external failure costs, which applied to a product or service but do not conform to the user’s requirements. The internal costs are produced prior to delivery to the market, such as cost of rework. The external failure costs result after the delivery and include, for example, the cost of warranty claims.

2.3. Product vs. Process Quality

Quality of product and process are two different fields of quality [113]:

Product quality targets the properties and attributes of the product. The finished product is usually inspected against quality criteria to check the conformance with the design standards and the owner’s requirements. Product quality focuses on appraising and enhancing the quality of the product data model in the context of data modelling to keep the product data model free of error and in conformance with the design standards.

Process quality targets the process applied to produce the product. It aims to integrate the quality assurance activities with the design and production processes through technical reviews and inspections. The objective is to prevent the nonconformities instead of detecting them. It focuses on enhancing the data analysis of the production process. Figure 2.1 shows the structure of a process-based quality management system.

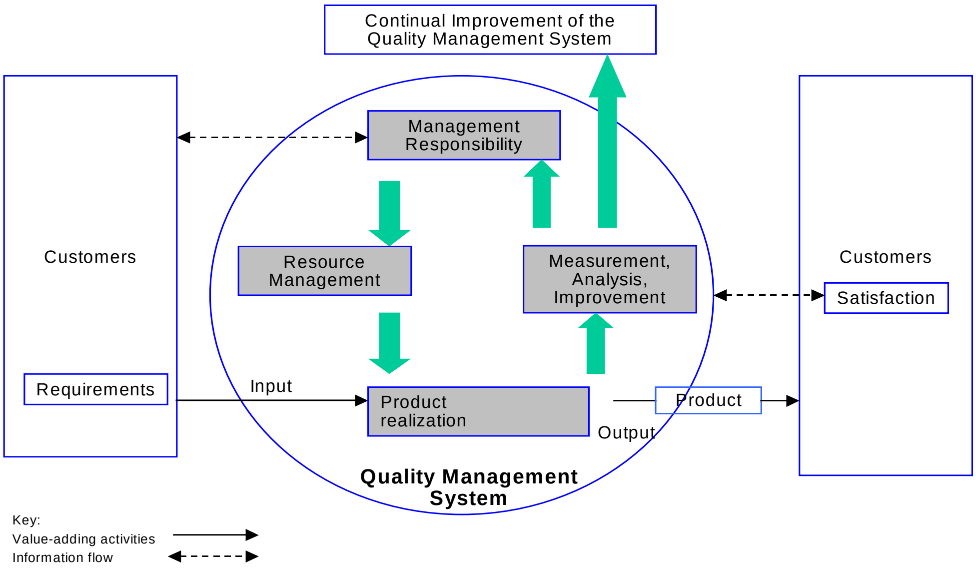


Figure 2.1.: Model of a process-based quality management system ISO/TS 16949:2002 [17]

2.4. Quality Management Systems

A quality management system focuses on planning, organizing, controlling, and human resources processes associated with quality initiatives. In the following, characteristics and principles of a quality management system are addressed.

The characteristics of a quality management system are usually defined by a quality team. Any quality system must fulfill the required characteristics to achieve the intended performance. In the first place, a quality system must be robust against any variation in the way an operation is performed. The degree of complexity, maintainability, and ease of use are important characteristics for the quality team. The implemented quality system must prove flexibility, reliability, compliance to quality standards, and traceability for any quality scenario [76].

To achieve the objectives of any quality management system within an organization, eight main principles must be considered during the design of the system, as provided in ISO 9000 [25]. In the first place, the needs and requirements of the customers must be understood to produce a product or service over and above their expectations. In addition, the leadership concept must be considered to maintain the internal environment of the organization through maximizing the personnel involvement to achieve the planned objectives. By managing the organization activities as processes, effective and efficient results can be achieved. The interrelated processes must then be analyzed and understood within a system approach. Depending on the gathered experience, a prevention of additional costs can be achieved by a continuous improvement of the overall performance. A factual decision making depending on data analysis must be also considered during the development of a quality management system. Finally, a mutually beneficial relationship between an organization and its suppliers must be maintained to add value for both of them.

2.5. International Product and Process Design Related Standards in the Lifecycle Perspective

The most relevant standards to product and process are discussed herein. These standards cover the international product and process requirements, the product lifecycle, quality and quality control in the design and digital environment for simple and complex products.

2.5.1. Standards for Representing Product Information

A range of standards is available for representing product information within different CAX tools. Most of these standards deal with the geometrical data and expand to a wider spectrum of information such as tolerances, kinematics, dynamics and manufacturing processes. One of these standards is: Geometrical Product Specification (GPS), which defines the global guidelines along with the fundamental principles for capturing designer's intent and expressing design requirements. GPS allows the unification and standardization of approaches' practices by industry through the guidelines illustrated in the GPS master plan [15]. Another is Geometric Dimensioning and Tolerancing (GD&T), which is a symbolic language for engineering drawings and computer-generated three-dimensional solid models that explicitly describes nominal geometry and its allowable variation in the product design and the verification phase. It brings significant benefits in design and inspection activities because a correct GD&T representation captures design intent and shows the functional requirements of the part as well as the method for its inspection. The GD&T approach ensures that parts or components will assemble into the real product and function as designed [49]. ISO 10303 (STEP) is a standard for the computer-interpretable representation and exchange of product manufacturing information [7]. It provides a mechanism to describe product data independent from any specific CAX system throughout the product lifecycle. STEP is not only developed for neutral file exchange, but also as a basis for implementing and sharing product databases and archiving to build bridges between different CAX domains. The essential reason for the development of STEP is the need to overcome interoperability issues between the different CAX systems. This standard addresses the product data including mechanical and electrical design, geometric dimensioning and tolerancing, analysis and manufacturing, with additional information specific to various industries such as automotive, aerospace, and building construction, as well as shipbuilding.

2.5.2. Standards for Representing Manufacturing Processes

To represent manufacturing processes, several standards exist. Process Specification Language (PSL) is developed by the National Institute of Standards and Technology (NIST) [18]. PSL can be used for the representation of manufacturing, engineering and business processes, process planning, project management, and etc. It uses the ontology based Knowledge Interchange Format which provides a formal description to specify terminology, concepts, components and their relationships that make up a process. Dimensional Measuring Interface Standard (DMIS) communication protocol was created as standard to allow the communication of inspection data between computer systems and inspection equipment regardless of the vendor [110]. Dimensional Markup Language (DML) is an XML based language for representing measurement results for the purpose of transmitting data between systems [122]. I++DME specification was created to enable the exchange of dimensional measuring equipment commands and results between measurement execution software and a Coordinate Measuring Machine (CMM) [117]. ISO 8062-1 establishes a vocabulary of terms and definitions used to describe the features, form and tolerance types when assigning dimensional and geometrical tolerances to moulded parts in GPS [23]. ISO 8062-2 gives the rules for geometrical dimensioning and tolerancing of final moulded parts. It also gives rules and conventions for the indications of these requirements in technical product documentation and specifies the proportions and dimensions of the graphical symbols to be used [24]. ISO 8062-3 specifies general dimensional and geometrical tolerances, as well as machining allowance grades, for castings. ISO 10135:2007 specifies rules and conventions for the indications of requirements for moulded parts on technical product documentation [6]. ISO 14649 series provides an introduction of a data model for Computerized Numerical Controllers based on the concepts of Product Data. It specifies the process data needed for NC-machining, the technology-specific data elements needed for milling, manufacturing and machine characteristics, cutting tool data etc [16].

2.6. International Quality Standards Related to Product and Product Data in Lifecycle Perspective

The quality standards related to product quality concentrate on fixing quality system defects and product/service nonconformities. This organized approach to managing elements of a business it fosters continual improvement and customer satisfaction. The quality standards related to product data quality specify a set of structured representations of quality criteria together with measurement requirements, and inspection results.

2.6.1. Standards for Product Quality

Several standards are available for ensuring the quality of a product such as the ISO 9000 series which describes the fundamentals of a quality management system. It specifies requirements for a quality management system and provides guidance to organizations for sustained success by a quality management approach. It is applicable to any organization, regardless of size, type and activity [25]. ISO series 10001 to 10007 provide guidance on the process for complaints handling related to products within an organization, in defining and implementing processes to monitor and measure customer satisfaction, in the application of quality management in projects, and in the use of configuration management within an organization [2][3]. ISO 10014:2006 provides guidelines for realizing financial and economic benefits from the application of the ISO 9000 quality management principles [4]. ISO 10019:2005 provides guidance for the selection of quality management system consultants and the use of their services [5].

2.6.2. Standards for Product Data Quality

Due to the importance of the quality of the product model data, several international and regional organizations have dedicated reasonable resources to develop some standards regarding the quality of the product data model to be applied for a specific field. These standards are: ISO/TS 8000-1 series, which specifies fundamental principles of master data quality management, and requirements for implementation, data exchange and provenance. It contains an informative framework that identifies processes for data quality management [20]. ISO 10303-59:2014 specifies the integrated resource constructs for quality of product shape data. It provides structured representation of criteria together with measurement requirements, and inspection results of the data quality of product shape and related data. It is designed for use in quality declaration, quality assurance and for representing quality inspection result of product shape data and related data, thus enabling quality of product data exchange [14]. ISO/TS 10303-1520 series provides representation of high level data elements for managing quality related data such as general quality criteria for product data, general quality criteria for product data associated with the corresponding measurement requirements, general quality criteria for product data associated with the corresponding assessment specifications, and representation of quality inspection results of given product data. A specialization for three dimensional product shape data is also provided [8]. The Strategic Automotive Product Data Standards Industry Group (SASIG) has developed a set of guidelines ISO/PAS 26183:2006 with respect to Product Data Quality (PDQ). Specific data quality criteria primarily on CAD geometry have been addressed as well as suggestions to evaluate measure and correct them [19]. This standard is based on research activities done by different Automotive bodies like Verband der Automobilindustrie (VDA) [130][131], Japan Automobile Manufacturers Association/Japan Auto Parts Industry Association (JAMA/JAPIA) [82], the US Automotive Industry Action Group (AIAG), ODETTE (Sweden), and the Australia's Federal Chamber of Automotive Industries (FCAI). Both guidelines ISO 10303-59 and ISO/PAS 26183:2006 provide a classification for quality criteria which are partially relevant for the quality management approach developed in this thesis. The quality criteria representation, the quality measurement requirements and quality inspection result schemes developed in ISO 10303-59 will be applied along with the quality criteria described in chapter 3.

2.7. Quality Control of Product Design in Early Stages of Product Design

The industrial and lifecycle demands on a product are generally caught in the early design phases according to proper interpretation of the market requirements. Validation and verification in early design stages include product idea validation, which includes the analysis of the costumer needs. These needs then will be changed into a set of appropriate product properties. Quality function deployment (QFD) is customer-driven method for efficient product design and production processes. The aggregated ratings of the customer needs are converted into relative importance scores of design requirements [129]. Originally, QFD was developed in 1972 at Mitsubishi's Kobe shipyard site [65] to translate the Customer Needs (CNs) into technical and design requirements during the design and manufacture of products and services, as well as manufacturing plans and controls in order to achieve higher customer satisfaction. A general QFD process consists of four phases to transform the voice of customers to product design requirements (phase 1), translate these requirements into parts characteristics (phase 2), manufacturing operations (phase 3), and production requirements (phase 4), [48]. Functional decomposition and flow analysis is used to verify and validate a functionas will as the final sub-functions [152]. Adoption of key characteristics (KCs) is also important. Even for the most robust products, it is rarely possible to shift a product into production without encountering any variation-related problems [150]. KCs are usually applied to find and reduce variation in a design process [45] and they indicate where excess variation will affect product quality and what product features and tolerances require special attention from the manufacturing perspective [150]. Prioritizing KCs for manufacturing planning during the early design stages can boost the process capability to ensure that a product meets the yield specifications [147]. Design for X (DFX) is usually used to refer to the design methodologies and product characteristics. DFX pays attention to all design goals and the related constraints in the early design stage which lead to the simplification of products, reduction of process costs, improvement of quality, and reduction of time to market [96]. Each DFX represents a body of knowledge, procedures, analyses, metrics, and design recommendations intended to improve the product in the domain "X". DFX methods provide the most benefit when they are applied early in the design process when changes are relatively easy to make [157]. X can stand for Design for Manufacture (DFM), which is the method of design for ease of manufacturing of the collection of parts that will form the product after assembly. DFM includes the selection of appropriate processes for improving the manufacturability of parts based on the required attributes and the different process capabilities. These processes include raw material selection, process selection, standard component usage, etc. [96]. Design for Assembly (DFA) is the method of product design for ease of assembly. DFA affects the product design verification directly. It is used to minimize product assembly cost through design and process improvement, optimize the assembly process steps, and identify part relevance [157]. Design for Ergonomics is important in labour intensive industries and has a marked and positive effect on process verification, as controls and displays are re-designed so that readings cannot be misinterpreted [127]. Another is Design for 6-Sigma (DFSS) is also referred to as Define-Analyse-Design-Verify. More information about DFSS can be found in section 2.10.

2.8. Quality Control of Product Design in Digital Environment

Usually, physical prototypes are built to identify problems in the initial design. They are generally exposed to several design changes and iterations to optimize the design. Reiterating of the physical prototypes can be extremely costly in the sense of the additional time, money, and materials needed for the next iteration [140]. In some industry branches such as aerospace, automotive and naval industries, digital prototyping is vital to help manufacturers to check product performance, functionality and assemblability before the physical release of the product. Digital prototyping uses a computer model that can be processed and manipulated in exactly the same way as a physical model [135]. In this model, the manufacturers have the opportunity to predict and verify the performance of the end product. Based on the experimental results, the digital test can be validated. The validated digital design is then the base for the verification of the physical performance of the product. For digital design verification and validation, Digital Mock-Up (DMU) is usually utilized. DMU includes a 3D model which integrates the mechanical structure of a system. DMU tools are generally used to check the assemblability, layout and interference, because of the many mismatches and interferences due to designers' faults as well as several kinds of CAD systems being applied [146]. The benefits of the virtual prototyping include a better cooperation between stakeholders spread worldwide and a cut in the time delay between the new ideas and feedback. DMU provides the opportunity to use the concurrent engineering approach during the design process [140].

Utilizing DMU can reduce the automobile development cycle by half, and resolves more than 1,200 issues prior to building the first physical mock-up [135]. Applying DMU has essentially reduced time-to-decision from weeks to one day for General Dynamics Electric Boat, builders of submarines for the US government [135]. Utilization of DMU tools by Boeing led to reduced design errors and engineering changes by 70-90 per cent, which enabled the company to save more than 100,000 hours of design time and millions of US dollars [135]. Recently, DMU integration was approved as one of Airbus' core competencies for successful aircraft development to satisfy individual disciplines' requirements for work methods [62]. Loss of data during the application of the DMU when transferring the data from one CAD format to another one has to be controlled.

Tolerance analysis and optimisation through design of tolerance is also applied for quality control of product design in digital environment. It is essentially affected by two key factors, namely, product functionality and economic concepts. A very high tolerance quality leads to high manufacturing cost because of the complexity added to the applied manufacturing techniques. In contrast, a loose tolerance leads to reduction in manufacturing costs but with low level of product quality and malfunctioning of the product assembly. The optimal tolerance has to balance the two factors [64]. A tolerance design encompasses the tolerance analysis and tolerance synthesis. The former considers the effects of the individual tolerances on the assembly dimensions and the latter considers the relevant individual dimensions to ensure assemblability and functionality [141].

The feature-based design has become very popular for product modelling, where the feature definitions are stored in a feature library [106]. The control of quality is performed by the verification of stored features. This approach has positively affected the design verification by standardising the manufacturing processes and their inspection methods [106]. To verify the assemblability of a product, virtual assembly modelling is applied before the delivery to the market. It is an effective technique to verify the assemblies in the digital design stage. The core element of this technique is the assembly process planning (APP), which considers the assembly constraint identification [168]. The data generated during the assembly tolerance analysis can be utilised to specify the convenient tooling tolerances.

Stream-of-Variation (SOVA) is usually utilised to define the relation between the final product quality and process parameters of complex multistage assembly [78] and to predict and diagnose variation in that system [77]. SOVA predicts the problems that may arise in the downstream assembly phase. The predicted misalignments can be compared with actual measurements to determine the degree of mismatch and to specify the source of the errors [78].

The computer aided inspection planning (CAIP) method is categorized in the tolerance-driven and geometry-based inspection process planning. The former focuses on inspections of features with predefined tolerance requirements and the latter considers the whole geometry [167]. This tool is vital to carry out the measurement planning work from the feature recognition through specification of the measured points and finally simulation and verification. This process includes global and local inspection planning [50]. The former includes the analysis of the features and their nested relations in a part and in the latter considers the detailed inspection operations which must be carried out to determine the suitable number of measuring points [50]. The local inspection planning aims at reducing errors and time during the measurement task. The quality control through process modelling has become a vital technique to evaluate a design and process planning by means of reusing the engineering design knowledge [34]. Functional product verification by means of computational methods are applied in order to reduce the dependency on the costly laboratory experiment. To check the functional behaviour of a new product, several computational methods are utilized. Such methods are the finite element analysis (FEA) and the computational fluid dynamics (CFD).

2.9. Quality Control of Complex Products through Product's Lifecycle

Product lifecycle management (PLM) has been proposed in recent years as a business approach integrating people, processes, business systems and information to manage the complete lifecycle of a product across enterprises [98].

The verification and validation stages for complex engineering products like automobiles and aircrafts have to fulfill the strict requirements for their use and to meet the customer demands within reasonable costs. These products are generally designed in a unique environment with various engineering teams and organizations. The practiced approach for verification and validation in the aerospace industry is the V model in accordance with the ARP4754a standard [31], see Figure 2.2. The left side represents the top-down requirements evolution along the design development. The validation process starts from the product and goes down to check systems and individual items. The design of each stage is represented on the very bottom line of the V model. The bottom-up verification processes on the right side begins from the individual component testing through the system and ends up with the prototype verification [31]. The verification of a new aircraft according to the V model takes several years with an integration between different design systems and the process being managed using PLM systems [106]. A similar approach is used in the development of products in the automotive industry. The functional requirements are captured by means of QFD method and then later verified as described for the aerospace industry.

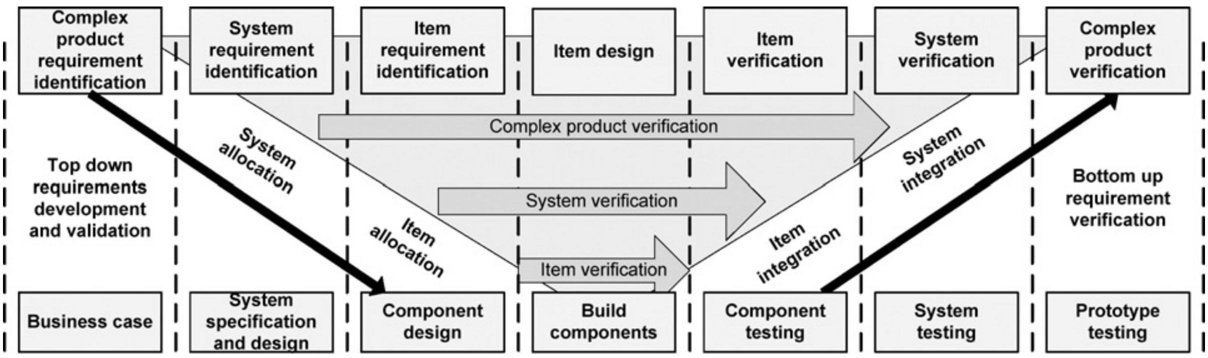


Figure 2.2.: V model for the verification of complex engineering products, a subset from SAE Aerospace ARP4754a [31]

2.10. Approaches for Quality Control

Quality control is a part of quality management with a focus on fulfilling quality requirements [25]. Several approaches for quality control have been developed by the individual organizations and then ended up in a widespread use. Some of these approaches include KAIZEN, a Japanese business practice of continuous improvement in performance and productivity. This philosophy aims at optimizing processes and products by a comprehensive quality management and customer orientation. In Kaizen, every process is standardized after the improvement and before the release. Kaizen is not an integrative management concept because a closed system-oriented approach is not given [92]. This management philosophy focuses on the innovation and standardization of processes in small steps.

By way of contrast, the Statistical Quality Control (SQC) approach is used to describe the set of statistical tools used by quality professionals. SQC can be divided into the following categories:

- Descriptive statistics, which are usually used to express the quality characteristics and relationships. Statistics, such as the mean, standard deviation, etc. are usually used [112].
- Acceptance sampling is the process of randomly inspecting a sample of goods and deciding whether the goods should be accepted or rejected.

The Total Quality Control (TQC) approach includes the application of quality management principles to all areas of business from design to delivery instead of restricting them only to production activities. Statistical Process Control (SPC) is a method of quality control which uses statistical methods. It comprises the test of a random sample of a process output. Application of SPC includes monitoring and controlling of a process in order to ensure that the output conforms as much as possible with minimum of waste (rework or scrap). An evaluation process to check if the output conforms with product characteristics has to be performed and upon that it will be decided if the process is functioning as defined. This method is applied in manufacturing lines using tools like control charts, the design of experiments, and continuous improvement. These charts are used to monitor key product variables in order to detect the occurrence of any event having a special or assignable cause [103]. Application of this method focuses on early detection and prevention of problems, rather than on the correction of problems after they have occurred.

Total Quality Management (TQM) is a very important tool for continuous improvement of long-term competitiveness of a sustainable business through continuous improvement of quality of products, services, people, processes, and environment. It is a cost effective system for integrating the continuous improvement efforts of people at all levels in an organization to deliver products, services and solutions, which ensure customer satisfaction [54]. TQM approaches focus on the early progress phases of a product in order to make the development processes faster [113] and it encompasses the following aspects:

- Customer orientation in consideration of all stakeholders;
- Use of all knowledge resources and link to individual and organisational learning;
- Continuous improvement by little as well as by radical steps;
- Quality responsibility by each single person and by all the teams;
- Working in processes.

Six Sigma (6σ) is a statistical quality control applied to business strategy and consists of a set of techniques and tools for process improvement. Six Sigma focuses on product/service quality measurement, reduction of variation, and reduction of cost. The application of Six Sigma is expanded from the elimination of assembly-line defects into almost every corporate operation [54]. Six Sigma seeks to improve the quality of process outputs by identifying and removing the causes of defects (errors) and minimizing variability in manufacturing and business processes. Each Six Sigma project that is realized within an organization follows a defined sequence of steps with quantified value targets. The maturity of a manufacturing process can be described by a sigma rating indicating its yield or the percentage of defect-free products it creates. Six Sigma projects follow two project methodologies, DMAIC and DMADV:

- Define-Measure-Analyze-Improve-Control (DMAIC) is used for projects aimed at improving an existing business process.
- Define-Measure-Analyze-Design-Verify (DMADV) is used for projects aimed at creating new product or process designs.

A Six Sigma concept for engineering data quality has been proposed in [59]. Tests on 1562 product data models have shown that quality problems are more frequent than the number of errors that may be accepted and desired in the manufacturing process.

Design verification and validation framework is a lifecycle based framework and captures the development of engineering design in four key stages [106]:

- Preliminary design stage, where the requirements are being set.
- Digital design phase.
- The physical, product and process progression and prototyping phase.
- The design of the production system and network for the realisation of complex products and processes such as in aerospace, marine and automotive industries.

For the purpose of validation of requirements and verification of the design implementation for certification and product assurance in the aerospace industry, recommended practices are provided in SAE [31], where the overall process for integrated digital and physical prototype verification and validation is exemplified. Corrective and preventive actions (CAPA) are known principles of quality management. According to identified problems, improvements to an organization's processes can be made to eliminate the causes of nonconformities [114].

2.11. Quality Control of Product Data (Literature Review)

Product modeling is at the center of various new product development paradigms designed to shorten the lead-time, lower the production costs and optimise the lifecycle service. In the following subsections, a review regarding the quality control of product data is introduced. It includes some aspects and approaches for quality control through product modelling, CAD model repair, data exchange and system interoperability, and product and product data frameworks.

2.11.1. Product Modelling

The issue of product modeling is at the center of various new product development paradigms designed to meet this challenge, and, therefore, has received major attentions from application and research communities. Due to the fast developments in computer and information technologies and the increasing demands of competitiveness and productivity, the scope and approaches of product modeling have evolved rapidly in recent years [94]. Approaches regarding the quality of data models from the modelling aspects point of view are detailed [88], [99]. In [88], a framework based on theoretical aspects for the quality of the underlying data model is discussed. For each level of the framework a quality goal is specified. Procedures to achieve this goal are defined. Another level of data quality has been discussed in [139]. The impact of the data quality on the implementation of enterprise resource planning systems has been discussed. The importance of sharing the same understanding and an awareness of bias has been addressed. In [153], the author describes the role of using computer-based product modelling as a reference to support the maintenance and fault diagnosis. The proposed method aims towards functionally robust designs, reduction of preventive maintenance cost and more effective fault diagnosis.

The approach developed in [38] is based on capitalization and on analyzing of the quality problems occurring during the product lifecycle. It deals with the product models to support the views of design engineers as main actors in the whole product development cycle. The improvement of the product design can be achieved by managing the information fed back from the product usage to the engineers and manufacturers. The author suggests capitalization action to increase experience of the designers to learn about errors to guide the next design evolution beside the corrective procedures that have to be carried out to eliminate the errors. The identified quality discrepancies are those regarding the difference between the expected product behavior and the actual product behavior. Those discrepancies described by the actor have to be included in the product model in order to be capitalised for the next design. The suggested basic items to define the quality view are the components, links and relations. The components are the parts that may have quality problems, links are the attributes of a component relevant to quality problem and finally the relations represent the association between two links.

2.11.2. CAD-model Repair

The first attempts to control quality are based on the definitions of a list defining the needed characteristics of a product data model. This simple kind of control helps to understand the aspects regarding the quality and evaluation of product data models. The defined lists are usually disorganized and not precisely defined. Hoffman et al. [73] proposed a system architecture for a product master model. In this architecture, the CAD systems are combined with the downstream application processes to produce different views of features. A call-back mechanism is used in this architecture to correct the geometric tolerance issues. Methods for measuring and improving the CAD data quality have been presented in [67]. 140 parts have been tested using CADIQ software. For reducing the errors generated by the designer, modelling guidelines and error classification were suggested in several groups. Based on the STEP-NC standards, a novel manufacturing chain is proposed in [116]. In this manufacturing chain the CAD data is translated into a neutral geometrical data format like IGES/STEP. The CAM data is extracted from the new data model, therefore the quality of the original data model is significant to ensure a seamless flow of processes downstream the manufacturing chain. A method called "complementary model object tree" is used in [55] to improve the CAD-repair process. A systematic method to repair erroneous STL files for specific downstream applications like pre-processing of CAE systems for injection moulding has been proposed in [100]. Automatic or manual healing methods are developed to fix six major error categories that may occur in the mesh such as dislocation, gaps, holes, overlaps, redundancy and reversed normal. A web-based CAD viewer has been developed in [145] to support collaborative interference inspection of injection mould data over the distributed environment. Another application of the quality of product data is discussed in [137]. A tolerance analysis tool has been applied for tolerance analysis of assemblies. The quality of assemblies is given by calculating the clearance and orientations between parts building up the assembly. Other researchers have developed an approach for error diagnosing and correction of CAD data to fix the topological and geometrical issues based on the design history [162] [161] because of the limitations of the B-Rep which includes only the final shape of the product. The design intention based on a design history scheme has to be extracted from the used CAD system. After conducting the correction works, a reconstructing step is needed to rebuild the design history. An approach based on the feature technology for CAD-CAQ process chain has been proposed in [107]. Different kinds of information can be associated and managed between the design team and inspection engineer during an engineering change using feature mapping i.e. the transition and/or transformation between the different feature classes.

2.11.3. Data Exchange and System Interoperability

Types of frequently exchanged product data in collaborative engineering processes include: project planning data, design data, notes/documentation, communication data, analysis/performance data, verification data and scientific data [35]. Cantero et al. [51] emphasized the importance of the product model data to avoid the problems during data exchange between the different CAD systems, which simplifies the integration with the downstream processes in the design chain. They proposed a linguistic approach to make the present product data quality issues clearer and to accentuate the importance of the modeling methodology based on the quality of the product data model. The approach is divided into three levels: morphological, syntactical and the evaluation of the semantic quality in the quality-checker applications. Modeling methodology and good training for system users are also important factors to increase the productivity and to develop high quality product model data with lower costs and shortened lead-time. Tanaka et al. [148] discussed the problems which hinder the interoperability and concurrent engineering between the different CAD systems regarding the quality of the communicated product model data. Methods to analyze the quality of shape data and a classification of the quality criteria based on criteria published in [19] have been used. The approach is applicable in any phase of the product development process. In this study, the classification of quality criteria is divided into data structure criteria and geometric criteria. The latter group needs geometric calculations to be checked. This approach can be extended to other industry branches and not only to the automotive. Quality criteria have been classified depending on the geometric problems associated with the 3D-shape representation. Product models have also been used to support ship inspection by inspecting the ship in three stages (plan, do and check) depending on a product model and integrated with a shipbuilding computer integrated manufacturing (CIM) system [69].

You et al. [164] engaged with issues faced by industry while communicating and converting the data between the different CAD/CAM-systems. They implemented a prototype CAD data validation system using JAMA and AIAG checking criteria. Some procedures and algorithms were developed to ensure the quality of the data. The addressed quality nonconformities are those encountered in the entities for representing the topology and geometry of the product data structure due to different representation of the topological and mathematical information. A similar study [163] focused on the problems associated with loss of data between different CAD systems or due to technical instability of used neutral CAD formats that are normally used in CAD systems such as STEP and IGES. Methods to verify and identify CAD-model deficiencies regarding topological and geometrical characteristics have been developed in order to check a CAD-model step by step against errors to preserve the system resources. Another approach for integrating the communications among the different engineers teams involved in the design processes and the co-ordination was proposed [151]. This is realized by managing the best sequence of the design work leading to reduction of multiple descriptions of a product, lead time and data exchange errors. A Product Model Driven Development (PMDD) approach is supposed in [133]. It supports the managers and engineers who are responsible for process planning and carrying out of tasks in the design process. The integration of the product models and the design situation plays an essential role in producing a new product with better quality through reducing the inconsistencies and uncertainties in information flow by allowing better process planning with fewer iterations. Various research focuses on the persistent naming problems arising during the exchanging and modification of parametrised feature-based CAD models [43], [95], [115], [160] and [169]. Two approaches, i.e. topological and geometrical, have been utilized to guarantee persistent naming.

2.11.4. Product and Product Data Quality Frameworks

A framework to ensure the quality of product data while collaboratively developing a new product was proposed in [159]. The authors emphasized the impact of different data sources and types on the quality of the product data. This framework is composed of four essential parts: the original data model, the exchange data platform, the product data family, and the function repository. Based on a test case, they applied their approach to a case company with four subsidiary companies using XML format as an alternative to the original data type of the product data model. Despite the advantages of using the approach to rapidly retrieve accurate product data, the engineers were unwilling to use the system because of the additional efforts that had to be made to learn the new system. This approach supplemented the existing ISO 10303 standards by ensuring the product quality of the exchanged data. An approach to allow decision-makers to proactively manage and measure data quality based on information product approach is detailed in [138]. Shankaranarayanan showed the capability of the proposed framework in evaluating data quality using an important data quality dimension i.e. completeness.

The Kaizen “improvement” or “change for the better” approach focuses on the continuous improvement of the processes in the manufacturing, engineering, and business management. Its main objective is to eliminate waste through the integration of all persons involved in design, production and manufacturing processes to continue improve all functions being applied. It has been applied at Toyota within local workstations and each group is supervised by a line supervisor. The main elements of Kaizen are management teamwork, increased labor responsibilities, increased management moral, a quality circle, and management suggestions for labor improvement. Baguio [86] proposed an approach based on a model review. The review process, which can be performed at early phases of design processes consists of two stages. In the first stage, the whole hull construction model has to be checked and in the second stage, the outfitting data as well as the hull construction model must be reviewed. Mismatches or model discrepancies are recorded and reported to the designers. A confirmation report has to be fed back to the review team for confirmation. The main activities in the first stage include checking the alignment of the structural parts, the conformance with plans, drawings, and standards, clashes between the different structural items as well as ensuring safety and accessibility. The main activities in the second stage are the inspection of outfitting data like pipe connection and alignment, control interference of cable and electrical elements, sufficient space for operability and maintenance. The review activities are managed by authorized personnel, where designers, manufacturing supervisors and clients are involved. Implementing such an approach may increase the accuracy of the work’s outcome. Because the 3D model is navigated before it is built, every pipe and every detail will be checked, and clashes will be avoided, which results in higher savings and therefore increases the shipyard’s productivity.

Tang et al. [149] have developed a multi-layered quality data model framework. This framework provides a way to control, analyse and trace the quality data of the product throughout its lifecycle and evolution course. Six major layers build up this framework: general bill of material, quality data carrier, quality processes, quality activities, quality objects and physical data.

A rule-based product data quality validation system has been developed in [144] for fully automated validation and integration of data quality in the product development processes of high-tech industries. The proposed system is applied to check the product data against the geometrical and topological errors (e.g. surface quality, curvature and continuity) with 3D error reports for error correction. The system sends a quality report which can be received by any user. When the data is transferred from the original data creator to the downstream process owner, a quality stamp has to be provided. Another rule-base approach has been proposed in [63] and [39]. The benefit of that approach is the ability to apply it at any phase of the design process even while exchanging the product data between the different partners involved in ship design activities, e.g. shipyard, design agents, and classification societies. Quality criteria have to be formulated in predefined rule sets. The application of the rule-based quality control shows that the formulation of the quality criteria is complex. The definition of these rule sets has to be done by experts which should have enough knowledge of the underlying ship data model. Changing one rule has an impact on the rest of the rule sets, therefore, system dependencies between the different rules must be carefully observed.

3. Requirements in Ship Lifecycle

This chapter is dedicated to describing the requirements and standards that regulate the ship lifecycle starting from the initial planning passing through the design, operation, and ending with the recycling. In the next section, the general requirements requested by the owner or the international and national organizations during the lifecycle will be introduced and then the acquisition process of the new vessel will be described. An overview of the applied systems in the design and production processes is also given. In the last part of this chapter, a classification of the faulty information in the ship detail design will be discussed and finally, the quality criteria to ensure fulfillment of selected product data requirements in shipbuilding industry will be illustrated.

3.1. General Requirements in Shipbuilding

During the ship design, construction and operation until the recycling phase, various requirements, tests, rules and regulations must be strictly observed. These requirements and rules are formulated by different individuals and organizations. The owner's requirements represent top-level performance requirements, such as service speed, cargo capacity, dimensions. Classification society rules represent requirements of ship design. The national and international regulations refer to issues related to environment, safe navigation, and personnel health and safety, which formulate requirements of the ship design and operation. Shipyards also define their own requirements depending on the production and fabrication facilities and based on the long-time gained experience for best practice ship design and production. These requirements and design standards can have a meaningful influence on a new design and on the design process itself. Therefore, it is crucial to consider all applicable requirements as early as possible in the design process to avoid problems arising in downstream processes which result in rework, delays, and added expenses and resources.

3.1.1. Owner Requirements

The owner's requirements are divided into top-level mission requirements and other technical requirements. The former are vital for appropriate contract specifications. These needs depend on the vessel's intended area of work which include: national defense, marine service, and marine transportation. For each service area, specific requirements are applied. The latter group of vessel is the most important because of the important role in the global economy. Therefore, the significant general mission requirements will be discussed in the construction specifications prior to signing the contract, [118]:

1. Cargo Type and Cargo Capacity: They have big impacts on the size, subdivision of the vessel, and on the trade and port requirements.

2. Principal Particulars: Some ports or maritime corridors have constructional or operational restrictions, which impact on one or more principle particulars. These restrictions include: port limitation on maximum draft, which also has influence on other design aspects such as length, breadth, speed, propeller diameter, power, etc. Limits on vessel length due to berth restrictions where the vessel is intended to operate. Beam limitation due to canal width restriction. (e.g. Panama Canal has maximum beam restriction of 32.31 m). Depth of the vessel can be influenced by the loading and offloading facilities at ports of operation. Minimum ballast capacity to meet freeboard requirements of port's cargo loading/unloading facilities. Finally, the maximum height of the vessel above the water line can also be restricted due to bridge clearance. Loading/unloading facilities of the vessel must be compatible with the cargo handling arrangements at the port. Environmental requirements such as air pollutants also have big impact on ship requirements setting.

3. Rules and Regulations: These rules and regulations are formulated by the following organizations: the International Maritime Organization (IMO), the flag state where the ship are registered, port state, and the classification society. See subsections 3.1.3 and 3.1.4 for more information.

4. Service Speed: Service speed must be chosen carefully to decrease the overall cost of marine transportation. When choosing the service speed, four economical effects must be considered: operational gain by increasing the amount of delivered cargo per unit of time, operational savings due to reduced cargo inventory carrying cost, increased operational cost due to increased consumption of fuel, and increased capital cost.

5. Endurance: To ensure the required distance that a vessel can move without refueling or refilling the stores, the design requirements regarding the adequate fuel oil capacity must be taken into consideration as early as possible in the project.

6. Design Environmental Conditions: The consideration of the environmental conditions in the early design stage will ensure the functionality of the vessel in the intended operation routes. Such conditions will affect the choice of the forebody and upper deck design, sea margins for propulsion power and service speed, etc.

7. Vessel Design Life: Some significant specifications that are generally influenced by the vessel's design life are the quality of coating system, structural design standards, outfitting standards, and quality of machinery and equipments. A high quality coating is significant for ballast tanks and can help to reduce the maintenance costs. Structural design standards are important for long life vessels and include the considerations of the fatigue failures, corrosion, and considerable structural analysis. The outfitting standards can result in more durable design and lower maintenance if high quality materials are used. Quality of machinery and equipments can significantly enhance the design life of the vessel due to high quality material and lower maintenance costs.

Technical requirements are based on safety, environmental protection, improved cost effectiveness to reduce the maintenance costs, operational needs for ease of operation, and charter's requirements. They include, [118]:

1. Propulsion Plant: Selecting the propulsion plant includes the determination of the type of main propulsion plant depending on the operation area and experience, auxiliary systems design, and fuel quality.

2. Electrical Plant: The requirements on the electrical plants depends on different factors: level of redundancy, fuel quality, allowance for growth after the construction, and the generators sizes.

3. Electronic Navigational and Radio Equipment: The selection of these devices depends on the requirements such as the level of redundancy, special communications devices, and using automatic steering systems.

4. Automation: The automation depends on the owner needs to increase the safety, reduction in manning, overtime costs, or shoreside maintenance costs.

5. Manning and Accommodations: They include: number and types of cabins, accommodation and outfitting standards, public spaces, etc.

6. Hull Structure: These include additional requirements to identify the structural weakness to increase the design life and to minimize the operational costs. Some examples are finite element, vibration, fatigue, and dynamic load calculations.

7. Quality Standards: The standards are additional to those defined by the shipyard and/or the classification society. They include standards for safe working environment, higher environmental requirements than those required by the rules and regulations, additional construction for highly stressed areas of the ship's hull, etc.

8. Maintenance and Overhaul Strategy: The main maintenance aspects that may be influenced by the ship design are maintenance during the operation e.g. based on number of auxiliary generators, and if riding crews will increase the number of the additional accommodations and maintenance tools like air compressors, spare parts, spare parts stowage.

3.1.2. Shipyard Requirements

Each shipyard develops its own guidelines, design catalog, and production standards to be applied during the whole design process. These guidelines and standards are built upon the acquired experiences and the practice pursued at the present time as well as depending on the specific production facilities and equipment available at the shipyard. The shipyards' requirements are influenced by different constraints such as the shipowner's requirements and constraints for both process and product such as time and cost. An example of the production standard is the developed guidelines by a working group of the member yards of the Verband Für Schiffbau und Meerestechnik E.V. (VSM) [60]. These guidelines are developed to establish uniform principles of evaluation for German ship construction to ensure constant high quality. All processing accuracies and thresholds are the result of long term experience gathered in close cooperation with Germanischer Lloyd and corresponding to the practice applied nowadays at the German yards. Furthermore, comments of various classification societies were widely considered. This standard is divided into nine sections:

1. Surface Errors and Laminations: The first section deals with the limit figures for surface defects. The method is used for the elimination of the defects, by removing the defects by grinding or replacement with a new plate etc. The individual laminations on plate edges is also discussed in correspondence with the allowed stress. The recommended size of the plate areas to be replaced is defined as the greater value between 300 mm, or 10 times of the plate thickness. For some individual cases, the distance between neighboring seams can be decreased to 50 mm plus 4 times the plate thickness.

2. Standard Preparation for Coating: In this section the primary and secondary surface preparations are discussed according to ISO 12944-4, ISO 8501-1, and ISO 8501-2. The exposed thermally cut and saw-cut or shear-cut joint faces are also discussed e.g. by complete removal of cutting slag, burr removal, chamfer edges, etc. The recommended treatments of welding imperfections which reduce the quality of the coating are also specified. Welding imperfections treatments depend on the preparation grade between no treatment, chamfer sharp edges, or complete removal of slag, welding spatters, pores, burr, sharp undercuts, and sharp edges. The execution of the welding for skip welding/ one-sided fillet weld is also advised by closing or full welding of non-welded sections/of opposite weld side, or even no treatment depending on the preparation grade. The inspection of surface features and the condition of the inspection as well as the documentation of the inspection are also specified.

3. Welding: In this section, the allocations of the structural parts and welding joints in accordance with EN 25817 are discussed, where the quality of welding is achieved according to the following criteria: type of vessel/construction; stress requirements (kind/dimensions); welding location to the main stress direction; type of construction of structural parts.

4. Component Part Production: In this section, the permissible tolerances of built-up sections for different component parts such as flanges, Figure 3.1, welded girders, corrugated bulkheads, etc. are defined. This section provides very important requirements for the quality assurance of the produced construction regarding the welding and assembly.

5. Structural Component Production and Assembly: In this section, the permissible distortion of beams, frames, girders and stiffeners, Figure 3.2, are discussed. The treatment of assembly misalignment e.g. non-aligning internal structural members (stiffening), any misalignment between a beam bracket and a frame, or misalignment of seam crossings are discussed.

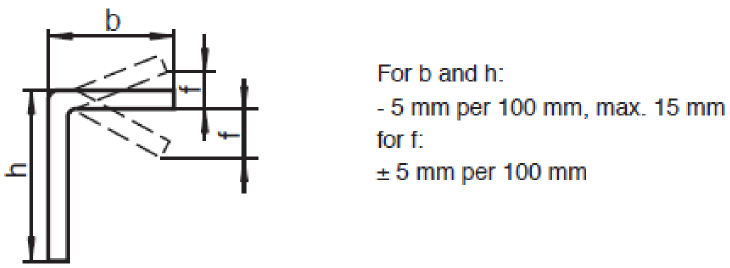


Figure 3.1.: Permissible tolerances for flanges, taken from [60]

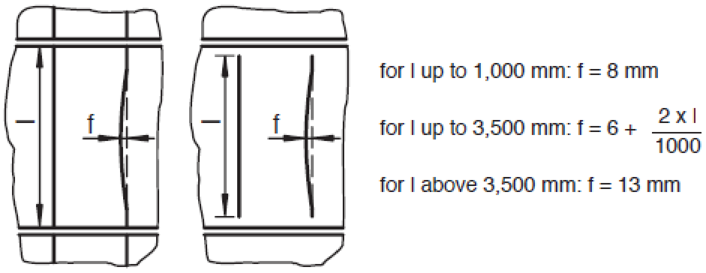


Figure 3.2.: Permissible deviation from the straight line related to the length between two supported points, taken from [60]

Important recommendations for assembly welding including fillet and butt welding are introduced. The different parameters affecting the chosen welding process like plate thickness and the gap between the neighboring plates are discussed. The permissible misalignment of superpositioned plates with intermediate plates of differing thickness according to the angle of crossing are illustrated. Figure 3.3 shows examples for joints crossing at an angle of less than 65°.

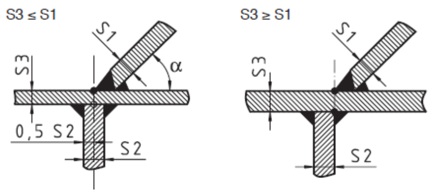


Figure 3.3.: Permissible misalignment of joints crossing at an angle less than 65°, taken from [60]

The requirements regarding the minimum distance from neighboring weld seams for butt weld to butt weld, Figure 3.4-left, as well as butt weld to web connection, Figure 3.4-right, are advised.

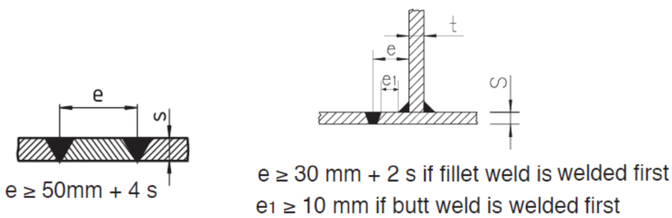


Figure 3.4.: Min. distance butt weld to butt weld (left) butt weld to web connection (right), taken from [60]

6. Fairing Work: This section is dedicated to the fairing works, which include the permissible bulges in the plate panel and seam sag, maximum permissible angle shrinkage, and permissible deformation, see Figure 3.5-a to -c respectively.

7. Final Work: This section deals with the removal of temporary attachments and treatment of erroneously or temporarily flame-cut openings. The treatment of the individual openings depends

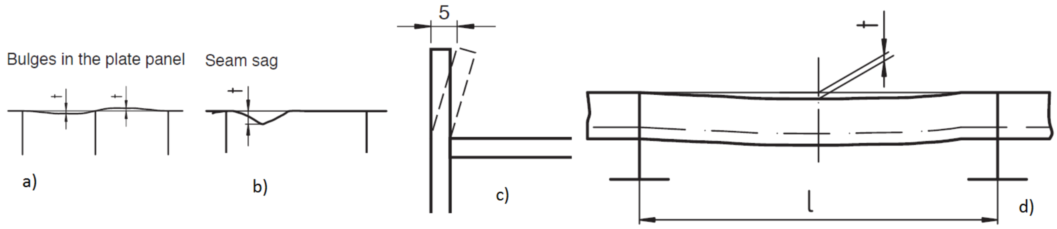


Figure 3.5.: Bulges in plate panel (a) seam sag (b) maximum permissible angle shrinkage (c) permissible deformation(d), taken from [60]

on the opening's diameter and plate's thickness. For example, individual openings of up to 25 mm in diameter in plates of $t \leq 25$ mm thickness will be countersunk and closed by welding. For plates with more than 25 mm in thickness, the treatment must be discussed with the Classification Society. Cut-outs and other openings are recommended to be closed by overlapping plates, treatments of areas with high stress concentration must be consulted with the Classification Society.

8. Tightness Test: This section deals with the way of performing the tightness test and closing devices. The tightness test is performed according to the rules of the Classification Society. The correction of defects during and after pressure testing is also advised in this section depending on the size of the pores or spots.

9. Principal Hull Dimensions: In this section, the permissible deviation from principal dimensions, deformations, and draught marks are defined. Examples of acceptable deviations are ± 100 mm per 100 m length for the length over all, ± 15 mm per 10 m breadth, but max 40 mm for breadth over all, -10 mm per 10 m depth for the depth. Deformations of the ship's bottom approximately cover the range between ± 25 mm per 100 m length. Acceptable hog and/or sag of ship's fore and aft ends must be: f = + 50 to 25 mm, see Figure 3.6.

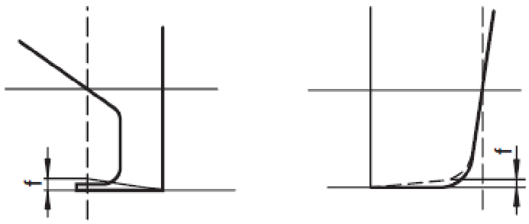


Figure 3.6.: Permissible hog and/or sag of ship's fore and aft ends, taken from [60]

3.1.2.1. Shipyard's Requirements on Design

Shipyards are usually built on riverbanks or the shores of bays and developed to best suit the planned product range and building process. A wide range of shipyard layouts exist worldwide, which has a big impact on the design and the productivity of a new vessel's design. It is wrong to assume that the same design can be built with the same productivity in a number of different shipyards, unless the shipyard facilities and building practices are identical. Therefore, the designers must consider the requirements of the shipyard facilities such as stores, cranes and welding devices at an early design stage. Shipyards adopt several levels of automation, fabrication, assembly, and piping techniques, e.g. welding subsection 3.4, which have influence on the structural parts dimensions, arrangements and storage. Due to a space restriction for storing plates in stockyards or profiles in magazines or due to the applied welding techniques, the dimensions of plates and stiffeners i.e. maximum welding length must not be exceed the allowed values. The crane capacity also plays a key role in the assembly and fabrication method i.e. assembling of small or big blocks build up of small or big parts.

3.1.3. International Statuary Requirements

These are governmental or statutory requirements to protect the interests of the society and the general public regarding the safety and environmental aspects related to the maritime industry. Generally, the international accepted standards are applied for vessels operating between countries. The statuary documents include the requirements issued by the International Maritime Organization (IMO) and International Labour Organization (ILO):

3.1.3.1. International Maritime Organization

IMO established global standards for the construction, operation, and maintenance of vessels. These conventions, resolutions, and guidelines aim at preventing accidents, mitigating damage, and defining liability and compensation.

3.1.3.1.1. International Conventions

The international conventions include:

1. International Convention on the Control of Harmful Anti-Fouling Systems on Ships, 2001 (AFS): This convention prohibits the use of harmful organotins in anti-fouling paints used on ships and establishes a mechanism to prevent the potential future use of other harmful substances in anti-fouling systems. Anti-fouling system means a coating, paint, surface treatment, surface, or device that is used on a ship to control or prevent attachment of unwanted organisms.

2. International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004 (BMW): This convention aims at preventing the spread of harmful aquatic organisms from one region to another, by establishing standards and procedures for the management and control of ships' ballast water and sediments.

3. Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREGs): This gives guidance in determining safe speed, the risk of collision and the conduct of vessels operating in or near traffic separation schemes. The COLREGs include 38 rules divided into five parts: A- General; B- Steering and sailing; C- Lights and shapes; D- Sound and light signals; and Part E- Exemptions. There are also four Annexes containing technical requirements concerning lights and shapes and their positioning; sound signalling appliances; additional signals for fishing vessels when operating in close proximity, and international distress signals.

4. International Convention for Safe Containers, 1972 (CSC): This convention has two goals: the first goal is to maintain a high level of safety of human life in the transport and handling of containers by providing generally acceptable test procedures and related strength requirements. The second goal is to facilitate the international transport of containers by providing uniform international safety regulations, equally applicable to all modes of surface transport.

5. International Convention on Load Lines, 1966: In the 1966 Load Lines convention (adopted by IMO in 1966), provisions are made for determining the freeboard of ships by subdivision and damage stability calculations. It is an extension for the first International Convention, adopted in 1930. The regulations take into account the potential hazards present in different zones and different seasons. The technical annex contains several additional safety measures concerning doors, freeing ports, hatchways and other items.

6. International Convention for the Prevention of Pollution from Ships, 1973 (MARPOL): This convention is the main international convention covering prevention of pollution of the marine environment by ships from operational or accidental causes. It includes regulations aimed at preventing and minimizing pollution from ships - both accidental pollution and that from routine operations. Currently, it includes six technical Annexes.

7. International Convention for the Safety of Fishing Vessels (The Torremolinos Convention), 1977 (SFV): The 1977 Convention contains safety requirements for the construction and equipment of new, decked, seagoing fishing vessels of 24 meters in length and over, including those vessels also processing their catch.

8. International Convention for the Safety of Life at Sea, 1974 (SOLAS): This is generally regarded as the most important of all international treaties concerning the safety of merchant ships. The main objective of the SOLAS Convention is to specify minimum standards for the construction, equipment and operation of ships, compatible with their safety. The current SOLAS Convention includes Articles setting out general obligations, amendment procedure and so on, followed by an Annex divided into 12 Chapters, see [132] for more information.

9. Hong Kong International Convention For The Safe And Environmentally Sound Recycling of Ships, 2009: The Hong Kong Convention is aimed at ensuring that ships, when being recycled after reaching the end of their operational lives, do not pose any unnecessary risk to human health and safety or to the environment. Regulations in the new Convention cover: the design, construction, operation and preparation of ships so as to facilitate safe and environmentally sound recycling, without compromising the safety and operational efficiency of ships; the operation of ship recycling facilities in a safe and environmentally sound manner; and the establishment of an appropriate enforcement mechanism for ship recycling, incorporating certification and reporting requirements.

10. International Convention on Standards of Training, Certification and Watchkeeping for Seafarers, 1978 (STCW): The 1978 STCW was the first convention to establish basic requirements on training, certification and watchkeeping for seafarers on an international level.

11. International Convention on Tonnage Measurement of Ships, 1969: This Convention is provided for gross and net tonnages, both of which are calculated independently. Gross tonnage forms the basis for manning regulations, safety rules and registration fees. Both gross and net tonnages are used to calculate port dues.

12. International Convention on Maritime Search and Rescue, 1979 (SAR): The technical requirements of the SAR Convention are contained in an Annex, which is divided into five chapters.

3.1.3.1.2. International Codes

The international codes include:

1. Code on Alarms and Indicators, 1995: This Code is a recommendatory document for alarms and indicators. It is intended to provide general design guidance and to promote uniformity of type, location and priority for those alarms and indicators which are required by the 1974 SOLAS Convention, as amended, MARPOL 73/78 as amended, and associated instruments.

2. Code on Alerts and Indicators, 2009: This Code is intended to provide a general design guidance and to promote uniformity of type, location and priority for those alerts and indicators which are required by SOLAS Convention 1974, as amended.

3. Code of Practice for the Safe Loading and Unloading of Bulk Carriers, BLU Code: The purpose of the Code is to assist persons responsible for the safe loading or unloading of bulk carriers to carry out their functions and to promote the safety of bulk carriers. The Code primarily covers the safety of ships loading and unloading solid bulk cargoes and reflects current issues, best practices and legislative requirements. The recommendations in this Code provide guidance to shipowners, masters, shippers, operators of bulk carriers, charterers and terminal operators for the safe handling, loading, and unloading of solid bulk cargoes. The recommendations are subject to terminal and port requirements, or national regulations.

4. Code of the International Standards and Recommended Practices for a Safety Investigation into a Marine Casualty or Marine Incident, 1997 Casualty Investigation Code: This Code requires a marine safety investigation to be conducted into every "very serious marine casualty", defined as a marine casualty involving the total loss of the ship or a death or severe damage to the environment.

5. Code of Safe Practice for Cargo Stowage and Securing, 2011 CSS Code: The purpose of this Code is to provide an international standard to promote the safe stowage and securing cargo.

6. Code of Safety for Diving Systems, 1995 DS Code: The purpose of this Code is to recommend design criteria, and construction, equipment and survey standards for diving systems.

7. Code of Safety for Dynamically Supported Craft, DSC Code: This Code represents the recommended requirements for the design and construction of dynamically supported craft, together with the appropriate equipment which should be provided, and the appropriate condition for their operation and maintenance.

8. International Code on the Enhanced Programme of Inspections During Surveys of Bulk Carriers and Oil Tankers, 2011 ESP Code: This Code defines the minimum extent of examination, thickness measurements and tank testing.

9. Fire Safety Systems, FSS Code: It provides international standards of specific engineering specifications for fire safety systems required by SOLAS, 1974.

10. International Code for Application of Fire Test Procedures, FTP Code: It is intended for use by the Administration and the competent authority of the flag State when approving products for installation in ships flying the flag of the flag State in accordance with the fire safety requirements of the SOLAS, 1974, as amended.

11. International Code for the Safe Carriage of Grain in Bulk, Grain Code: This Code is applied to ships regardless of size, including those of less than 500 tons gross tonnage, engaged in the carriage of grain in bulk, to which part C of chapter VI of the 1974 SOLAS Convention, as amended, applies.

12. International Code of Safety for High Speed Craft, 1994 HSC Code: The Code is intended to be a complete set of comprehensive requirements for high-speed craft, including equipment and conditions for operation and maintenance.

13. International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk, IBC Code: The purpose of this Code is to provide an international standard for the safe carriage, in bulk by sea, of dangerous chemicals and noxious liquid substances listed in the Code.

14. International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk, IGC Code: This Code provides an international standard for the safe carriage by sea in bulk of liquefied gases and certain other substances listed in this Code, by prescribing the design and construction standards of ships involved in such carriage and the equipment they should carry.

15. International Maritime Solid Bulk Cargoes Code, IMSBC Code: The aim of the mandatory IMSBC Code is to facilitate the safe stowage and shipment of solid bulk cargoes by providing information on the dangers associated with the shipment of certain types of cargo and instructions on the appropriate procedures to be adopted.

16. International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes on Board Ships, 2001 INF Code: The INF Code sets out how the material covered by the Code should be carried, including specifications for ships.

17. Intact Stability for All Types of Ships Covered by IMO Instruments, 1993 IS Code: IS Code includes fundamental principles such as general precautions against capsizing (criteria regarding metacentric height (GM) and righting lever (GZ)); weather criterion (severe wind and rolling criterion); effect of free surfaces and icing; and watertight integrity.

18. International Management Code and Revised Guidelines on Implementation of the ISM Code: ISM Code aims at ensuring safety at sea, prevention of human injury or loss of life, and avoidance of damage to the environment, in particular, to the marine environment, and to property.

19. International Code for the Security of Ships and of Port Facilities, ISPS Code: This Code aims at establishing an international framework to secure ships and port facilities.

20. International Life-Saving Appliance Code, LSA Code: The purpose of this Code is to provide international standards for life-saving appliances required by the International Convention for the Safety of Life at Sea (SOLAS), 1974.

21. Code for the Construction and Equipment of Mobile Offshore Drilling Units, 1979 MODU: This Code has been developed to provide an international standard for mobile offshore drilling units of new construction so that its application will facilitate international movement and operation of these units and result in a level of safety for such units and for personnel.

22. Code on Noise Levels on Board Ships, Noise Levels: The Code on noise levels on board ships is developed to provide international standards for protection against noise regulated by regulation of SOLAS, 1974, as amended.

23. Technical Code on Control of Emission of Nitrous Oxides from Marine Diesel Engines, NOx Technical Code: The purpose of this Code is to establish mandatory procedures for the testing, survey and certification of marine diesel engines which will enable engine manufacturers, shipowners and administrations to ensure that all applicable marine diesel engines comply with the relevant limiting emission values of NOx.

24. Code of Safe Practice for the Carriage of Cargoes and Persons by Offshore Supply Vessels, OSV Code: OSV aims at providing an international standard to avoid or reduce to a minimum the hazards which affect offshore supply vessels in their daily operation of carrying cargoes and persons to, from and between offshore installations.

25. Code for Recognized Organizations, RO Code: The Code serves as the international standard and consolidated instrument containing minimum criteria against which organizations are assessed towards recognition and authorization and the guidelines for the oversight by flag States.

26. Code of Safety for Small Commercial Vessels Operating in the Caribbean, SCV Code: The aim of this Code is to prescribe standards of construction, and emergency equipment for small commercial vessels operating in the Caribbean Region.

27. Code of Safety for Special Purpose Ships, SPS Code: The purpose of the Code is to recommend design criteria, construction standards and other safety measures for special purpose ships.

28. Seafarers' Training, Certification and Watchkeeping, STCW Code: This part of the STCW Code contains mandatory provisions to which specific reference is made in the annex to the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers, 1978, as amended.

29. Code of Safe Practice for Ships Carrying Timber Deck Cargoes, 2011 TDC Code: The purpose of the Code is to ensure that timber deck cargoes are loaded, stowed and secured to prevent, as far as practicable, throughout the voyage, damage or hazard to the ship and persons on board as well as loss of cargo overboard.

3.1.3.1.3. Guidlines

The guidelines include:

1. Guidelines for the Application of the Revised MARPOL Annex I Requirements to Floating Production, Storage and Offloading Facilities (FPSOs) and Floating Storage Units (FSUs): These Guidelines aim at providing for uniform application of the revised MARPOL to Floating Production, Storage and Offloading facilities (FPSOs) and Floating Storage Units (FSUs) that are used for the offshore production and storage or for offshore storage of produced oil.

2. Guidelines for the Provisional Assessment of Liquids Transported in Bulk: The Guidelines provide step-by-step procedures of ascertaining the carriage requirements for all products offered for carriage in bulk.

3. Guidelines for the Development of Shipboard Oil Pollution Emergency Plans (SOPEP): The main objectives of these Guidelines are: to assist ship owners in preparing shipboard oil pollution emergency plans in conformance with the cited regulations; and to assist Governments in developing and enacting domestic laws which give force to and implement the cited regulations.

4. Guidelines for the Development of Shipboard Marine Pollution Emergency Plans for Oil and/or Noxious Liquid Substances - SMPEP: These Guidelines contain information for the preparation of shipboard oil pollution emergency plans, shipboard marine pollution emergency plans for noxious liquid substances and/or a shipboard marine pollution emergency plan.

In addition to the conventions, codes, and guidelines, there are different specifications and manuals such as for crude oil washing systems, dedicated clean ballast tanks, and inert gas systems. They provide specifications for the design, operation and control of the concerned systems, see [132].

3.1.3.2. ILO Documents

The International Labour Organization (ILO) is a United Nations agency dealing with labor issues, particularly international labour standards, social protection, and work opportunities for all. These conventions are:

- Convention Concerning Food and Catering for Crews on Board Ship, ILO 68
- Convention concerning Crew Accommodation on Board Ship, ILO 92
- Convention Concerning Crew Accommodation on Board Ship, ILO 133
- Convention Concerning Minimum Standards in Merchant Ships, ILO 147
- Convention Concerning Occupational Safety and Health in Dock Work, ILO 152
- Labour Inspection (Seafarers) Convention, ILO 178, 1996
- Maritime Labour Convention, 2006

3.1.4. Classification Requirements

Classification societies establish and maintain technical standards for the construction and operation of ship and offshore structures. The objective of ship classification is to verify the structural strength of the ship's hull and its appendages, and the reliability and function of the propulsion and steering systems, power generation and auxiliary systems which have been built into the ship in order to maintain essential services on board. Classification Societies try to reach these goals through the development and application of their own rules and by verifying compliance with international and/or national statutory regulations on behalf of flag Administrations. Classification process involves, [118]: technical plan review, survey during construction, acceptance by the Classification Committee, subsequent surveys for maintenance of class, and the development of standards, known as rules. The International Association of Classification Societies (IACS), an association of twelve Classification Societies, is an international Non-Governmental Organization that works in co-operation with IMO in order to ensure that regulations developed at IMO are clear, unambiguous and can easily be applied without the need of interpretations. IACS contributes to maritime safety and regulation through technical support, compliance verification. IACS resolutions include:

3.1.4.1. Procedural Requirements

IACS Procedural Requirements (PRs) are resolutions on technical matters of procedure and cover the following procedures: procedure for transfer of class; procedure for adding, maintaining or withdrawing double or dual class; procedure for suspension and reinstatement or withdrawal of class in case of surveys, conditions of class or recommendations going overdue; procedure for class entry of ships not subject to PR1 and PR2; procedure for failure incident reporting and early warning of serious failure incidents - "Early Warning Scheme - EWS"; transparency of classification and statutory information; definition of exclusive surveyor and non-exclusive surveyor and procedure for employment and control of non-exclusive surveyors; procedure for activity monitoring of surveyors, plan approval staff and auditors; procedure for the training and qualification of survey and plan approval staff; procedure for responding to port state control; procedural requirements for ISM code certification; procedure for the selection, training, qualification and authorisation of marine management systems auditors; IACS procedure for assigning date of build; statutory certification at change of class without change of flag; procedure for providing lists of classed ships to equasis; and reporting by surveyors of deficiencies relating to possible safety management system failures.

3.1.4.2. Common Rules

Common Rules (CRs) are IACS rules covering broad areas of classification requirements which shall be applied by all Members without the possibility of reservations. IACS Common Structural Rules (CSR) are a comprehensive set of minimum requirements for the classification of the hull structures of bulk carriers and double-hull oil tankers, where the contract for construction was signed on or after 1 April 2006. There is now a single set of Rules "Common Structural Rules for Bulk Carriers and Oil Tankers" (CSR BC & OT) comprising of two parts; Part one gives requirements common to both bulk carriers and double hull oil tankers and part two provides additional specialised requirements specific to either bulk carriers or double hull oil tankers.

1. Common Structural Rules for Bulk Carriers: The Rules are applied to the hull structures of single side skin and double side skin bulk carriers with unrestricted worldwide navigation, having length L of 90 m or above. The present Rules contain the IACS requirements for hull scantlings, arrangements, welding, structural details, materials and equipment applicable to all types of bulk carriers having specific characteristics. The Rule requirements apply to welded hull structures made of steel having characteristics complying with requirements in these rules. The requirements also apply to welded steel ships in which parts of the hull, such as superstructures or small hatch covers, are built in material other than steel, complying with requirements in these rules. The functional requirements are the relevant set of requirements to the functions of the ship structures to be complied with during design and construction, to meet the following objectives: to remain safe and environmentally-friendly during the expected design life, to be designed based on the assumption of trading in the North Atlantic environment for the entire design life, to be designed for structural safety, to be designed with adequate means of access to all spaces, and to be built in accordance with controlled quality production standards.

2. Common Structural Rules for Double Hull Oil Tankers: These rules apply to double hull oil tankers of 150 m length and upward classed with the Society and contracted for construction on or after 1 April 2006. The Rules are structured in sections giving instructions for detailed application and requirements which are applied in order to satisfy the rule objectives. The objectives of the Rules are to establish requirements to reduce the risks of structural failure in order to help improve the safety of life, environment and property and to provide adequate durability of the hull structure for the design life.

3.1.4.3. Unified Requirements

Unified Requirements (UR) are minimum technical requirements adopted by the IACS Members relevant to matters directly connected to or covered by specific Rule requirements and practices of Classification Societies and the general philosophy on which the Rules and practices of Classification Societies are established. URs define the requirements concerning mooring, anchoring and towing; mobile offshore drilling units; electricity; fire protection; gas tankers; polar class; propellers; subdivision, stability and Load Line; machinery installation; navigation; pipes and pressure vessels; strength of ships; material and welding; survey and certification; and High Speed Craft Code.

In addition to UR, Unified Interpretations (UI) are adopted resolutions on matters arising from implementing the requirements of IMO Conventions or Recommendations. IACS produces recommendations and guidelines related to adopted resolutions that are not necessarily matters of class but which IACS considers would be helpful to offer some advice to the marine industry. Among them are recommendations for: equipment; materials selection guideline for mobile offshore drilling units; guidelines for surface finish of hot rolled steel plates and wide flats; standards for ship equipment for mooring at single point moorings; hatch cover securing and tightness. IACS also produces Guidelines and Recommendations, not necessarily on matters of class, on issues which IACS Members consider advice or guidance may be beneficial to the industry.

3.1.5. National Regulatory Requirements

The national regulatory requirements were established to consider the requirements not covered by the rules and regulations of the international requirements i.e. for vessels operating in the national waters. They serve as a supplement to the international regulations and provision of an adequate level of safety and environmental protection not achieved by the international regulations, [118]. Such regulations include the United States National Standards for marine safety and environmental protection contained in the Code of Federal Regulations (CFR). These standards are pertinent to the designers and builders.

3.1.6. Regional and Local Regulatory Requirements

These additional regulatory requirements have been developed by regional groups of individual nations, such as the European Union and some states within the United States, and have their own requirements for the maritime industry. These requirements cover the environmental aspects.

3.2. Ship Lifecycle

The lifetime of modern vessels is about 25-30 years starting from the initial planning through ordering, design, ship operation, and finally recycling. In the following subsection, each phase of the ship's lifecycle will be discussed.

3.2.1. Initial Planning

Initial planning is the cornerstone of any new big project activity. It starts from the strategic planning through the analysis of the internal (owner) and the external environment (the area, where the vessel will operate). The internal analysis includes the assessment of the technical resources like engineering, the financial resources like assets, human resources e.g. number and types of personnel, and finally, the management resources like project control and communications. The external environment considers the aspects related to the market and logistics and it includes the analysis of: market size like market growth and trend, competitors like market share and strengthens and resources, economics like rate trends, physical environment e.g. distance and weather conditions and channel and port depths, port conditions e.g. cargo loading/unloading facilities, barriers of entry e.g. government restrictions, etc. After finishing the deep assessment of the environment aspects, the strategy development is performed. This includes: profitability, return on investment, market share, growth, stability, product or service stability, customer contentment, fulfillment the market needs, and competition. The environment analysis and strategic planning are then changed to implement business plans such as marketing, competitors, operations, financial, technology, organization, and corporate development plan [118]. All information will be packaged into specifications that are used as basis for a quotation.

3.2.2. Ordering

In this phase, negotiation between the ship owner and shipyard takes place. Once the contract is signed, engine builders and equipment manufacturers become involved. The classification society to certify the vessel will be also chosen in this stage.

3.2.3. Ship Design Process

Ship design process is a specialization of an engineering design process, which is the formulation of a plan to build a product with a specified performance goal, and it aims at modelling a ship and defining and specifying all systems which will be used. Additionally, it defines the strategy of assembling of its sub-systems and components to build the whole ship. This process is characterized through the concurrently modeling with broad internationally distributed groups and integrative teams, integration of conglomerate IT systems, and big number of systems for specific views (e.g. production, system analysis). Continuous engineering changes and material replacement are expected in the production phase since the material procurement and production begins while design phase is taking place. Ship design is not able to be standardized because of the diversity of requirements and the high grade of complexity of the ship structure, [90]. Table 3.1 illustrates the similarities and differences between different industrial sectors regarding their characteristics [68].

Characteristic	Shipbuilding	Aerospace	Automotive
Production facilities	Few simultaneous	Few simultaneous	1000s simultaneous
Development process	Concurrent design production	Design prototype custom manufacture	Design prototype bulk manufacture
Design collaboration	Real time	Pre-production	Pre-production

Table 3.1.: Characteristics of aerospace, automotive, and shipbuilding industries [68]

Two design methods are applied nowadays in shipbuilding i.e. the sequential, Figure 3.7, and concurrent engineering (CE). The traditional ship design is a sequential and iterative process due to the complexity of the design task. In each design phase, a particular synthesis or analysis task is performed. The final result of each design step is analyzed and then modified. The modified result is then reanalyzed until all requirements are met. In practice, the design process is not fully sequential and the designer can move from one step to another one as needed. CE approach is used to design a new product by performing all processes parallel to reduce the lead times and costs. It is a holistic approach to the design process, which affirms the importance of integrative teams to design a product and its processes. With this systematic approach, the designers have to consider all elements of the product lifecycle from the early design phase through disposal, counting quality, cost, and user requirements [155]. The underlying principle of concurrency is that downstream activities start before upstream activities are completed [19]. It enables the designers to observe the requirements of the shipyard, owner and classification society through the product's lifecycle starting from the concept design to the recycling, including the quality, cost and planning aspects. In contrast to CE, the sequential approach is slow and time consuming. Applying the concurrent approach increases the available knowledge at early design stage [97], and allows bi-directional communication of the design related information.

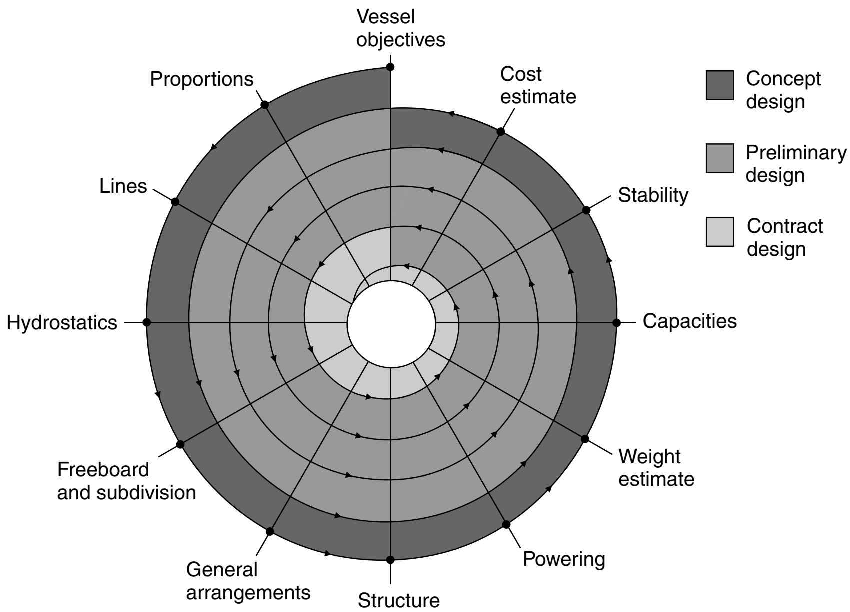


Figure 3.7.: Sequential design method, taken from [58]

The design process is subdivided into several phases due to the different nature of design tasks, required personnel and skills, level of information complexity with the progress of the design development. During the basic design phase, the ship is designed completely on a system-by-system basis. In the detail design phase, ship structure will be designed at the parts level. In the production design and planning phase, detailed plans will be generated. Finally, in the production phase, the real construction will be started.

3.2.3.1. Basic Design

The basic design phase includes three sub design processes i.e. concept, preliminary and contract design. All requirements formulated by the classification societies, owner or according to internal regulations are the main inputs of this phase. Hull form definition, rule-based scantling calculations, vibration calculations, hull steel weight estimation, power prediction, engine concept, internal subdivision, longitudinal strength, stability, manoeuvrability, seakeeping aspects and structure design are the main tasks in this phase. The outline of ship steel structure will be designed also in this phase. For critical details such as hatch corners, more detailed designs are made and their interaction with the global ship structure are validated regarding class regulations [170]. A catalog of shipyard standards is applied in this phase to support the designers in the next ship design phases. Almost 80% of the design solutions for the design of the steel structure are given by the aid of this catalog [83]. The output of this phase are the 3D data model, Material lists and precise weight calculations as shown in Fig. 3.8.

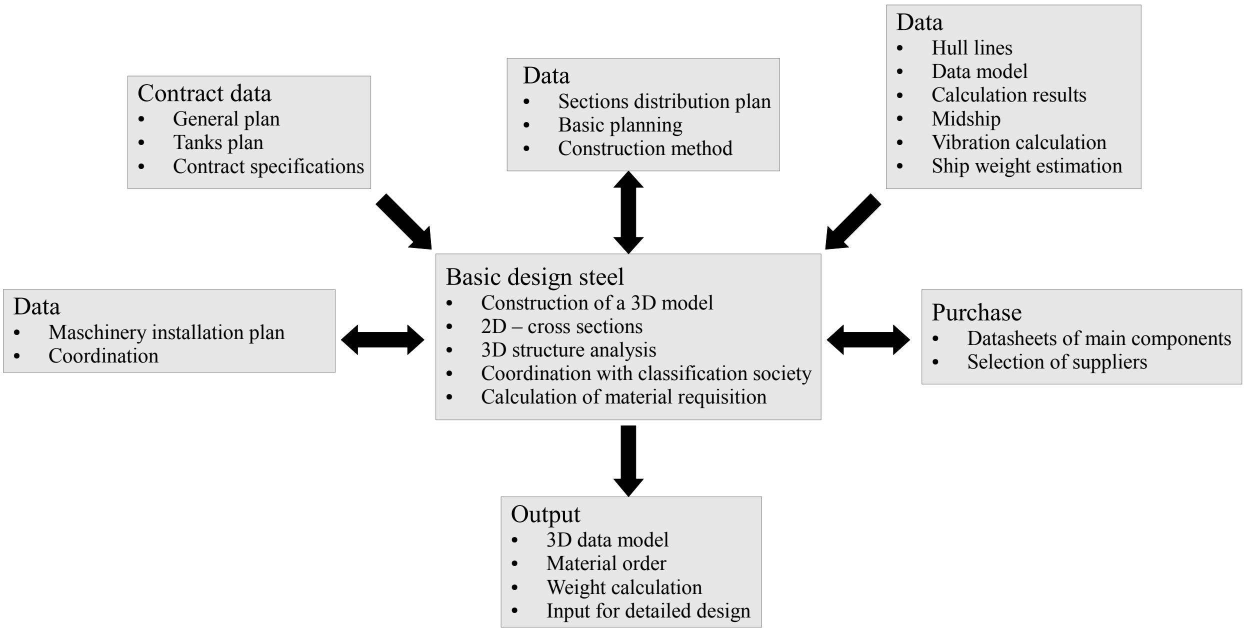


Figure 3.8.: Basic design process

3.2.3.1.1. Concept design

In this phase, the shipowner's requirements will be discussed i.e. required performance to achieve the balance between them and the capabilities of the shipyard. The second goal is to define a concept design solution which meets the requirements [61]. A close working relationship between the shipowner and the design team will exist to define the ship's mission. In this phase, the vessel will start to get its form and dimension. The owner requirements such as main dimensions and power will be transformed in this phase into early design configurations or alternatives. For each configuration, a feasibility study with sufficient information about the cost e.g. capital, performance and risk assessment will be performed. A relatively accurate solution from the alternatives will be chosen within the shipowner's budget. This process is repeated untill the best concept solution with the minimum assessed risk and feasible cost estimation at the best performance requirements is achieved. In addition, fully or partially dimensioned drawing as well as a written documents including performance specifications, body plan and appendage sketch, area/volume summery, concept general arrangement drawings, weight estimation, machinery arrangement sketch, speed-power curve, cost estimation, etc will be created. The designer knowledge is most wanted here to meet the requirements within the available technology and constraints. Normally, a small, creative and innovative design team compares ships, with well known performance characteristics. Those variants will be assessed and optimized to get the most relevant design meeting the main requirements.

3.2.3.1.2. Preliminary Design

The main design work is started at this phase based on the feasibility study performed in the previous phase. Earnest trade-off analyses will be performed to balance between the design configuration, performance and cost and risk assessment. Such analyses are the hull shape, general arrangements, hull proportions (L/B, B/D, etc.). The main objectives of this stage include establishing the ship size configuration, validating the main performance requirements such as speed, seakeeping, cargo on-/off-load rates etc., choosing the main systems, refinement of the cost estimation and risk assessment, developing of draft version of build strategy including the production methods. The output of this phase will be precise performance specification, cost estimation, detailed general arrangements drawings, preliminary scantling drawings, propulsion system analysis, shafting arrangements, electric load analysis, typical space arrangements, stability analysis, endurance fuel analysis, seakeeping and maneuvering analysis, technical risk assessment, delivery date, etc. This will all be handed to the ship owner [44] [119]. The outcome of this stage affects the costs in the next design steps and is considered as the basis for the definition of the contract specifications.

3.2.3.1.3. Contract Design

The main objectives are a confirmation of ship capability, provision of relevant and precise bid package including ship specifications, drawings, and all other data such as weight and cost estimation, and provision of criteria for shipowner acceptance of the ship [119]. In this phase, all systems will be selected in accordance with the future operators and maintainers. Systems specifications and drawings will be developed and ship hull with appendages will be refined. Arrangements drawings for the internal spaces and topside system installations e.g. mooring system will be developed. A refinement of building strategy resulting from the previous phase will be performed i.e. building plan. All technical specifications, ship performance and material ordering will be reviewed and analyzed. The output of this design process is a set of plans, arrangements drawings and specifications which form an integral part of the shipbuilding contract document [91]. Among the outcomes of the contract design phase are: ship specification, lines drawings, appendage drawings, general arrangements, propeller design, navigation system diagram, piping system analysis, ventilation and air conditioning systems analysis, loading conditions, damage stability analysis, hydrodynamic model test results, maintenance plan, cost estimation, production plan etc.

3.2.3.2. Detailed Design

When the design process is shifted to the detail design, the shipyard has the key-role instead of the ship owner. The main input in this phase is the data from the previous phase such as contract data, documentations, purchase data, Fig. 3.9. In the detailed design phase, the standards and catalogs defined in the basic design are the reference documents. Furthermore, detailed calculations are performed such as structural and vibration analyses. Complete definitions of all material and outfitting will be accomplished. All structural design, systems, diagrams, and manufacturing drawings, and all technical specifications will be completed. The design becomes block or zone oriented and the breakdown of each zone and block into small zones will be defined. In addition, the bow, stern, engine room, and superstructure are designed in detail and the corresponding drawings are generated. These plans consider the fitting arrangements and hull block assembly process [124]. Some production information such as weld preparation, identification numbers and assembly structure are also defined. Detailed drawings, a fully defined 3D product model at the piece level and the structural parts take their exact shape, BOMs, and precise weight estimation are the most important outputs of this phase.

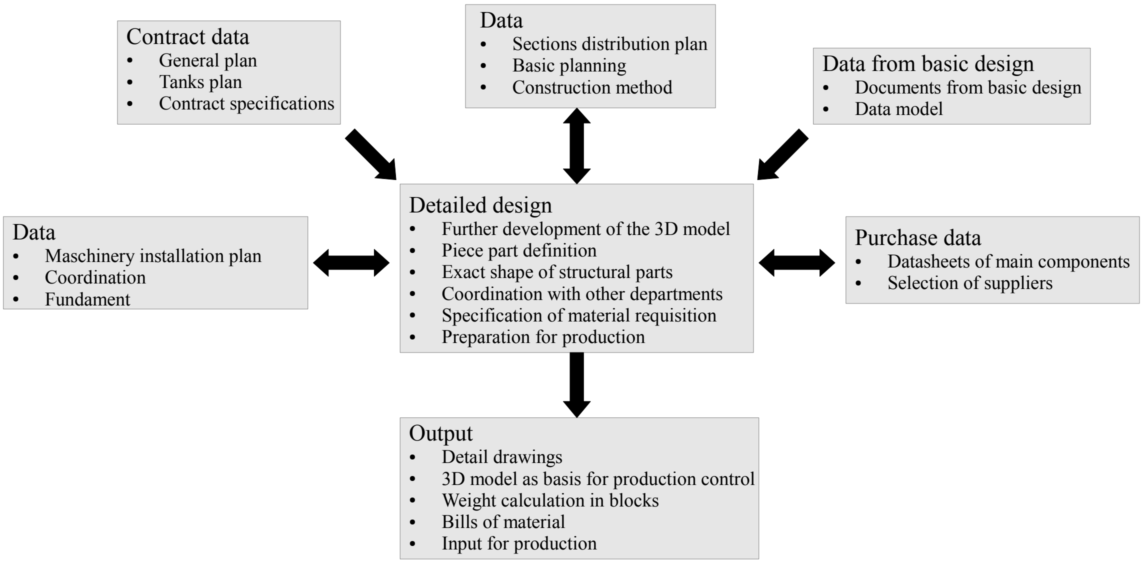


Figure 3.9.: Detailed design process

3.2.3.3. Production Design and Planning

In this phase, the design information is organised in the detailed plans holding the components information. The definition of production process is made in this phase based on the existing detailed data model. The evaluation of the solutions developed from the previous phases regarding the manfacturability is also done here. Construction strategy including assembly structure, resource planning, production simulation and sequence and assembly hierarchy are defined. Resource planning comprises the assignment of workforce, construction area, cranes, equipments, time as a function of product and process as well as of external suppliers and flow of all parts and assemblies. Focusing on optimal manufacturing methods, the welding process and the proper weld preparation are chosen. Solutions for the downstream processes are prepared and validated in this stage such as robot control data (cutting, welding and bending of plates and profiles), nesting of plates and profiles, tool and quality control (bending patterns) as well as workshop information (assembly plans, pipe sketches), see Figure 3.10. Incorrectly implemented specifications formulated in the early design processes or ignored requirements may be checked and reported in this design phase.

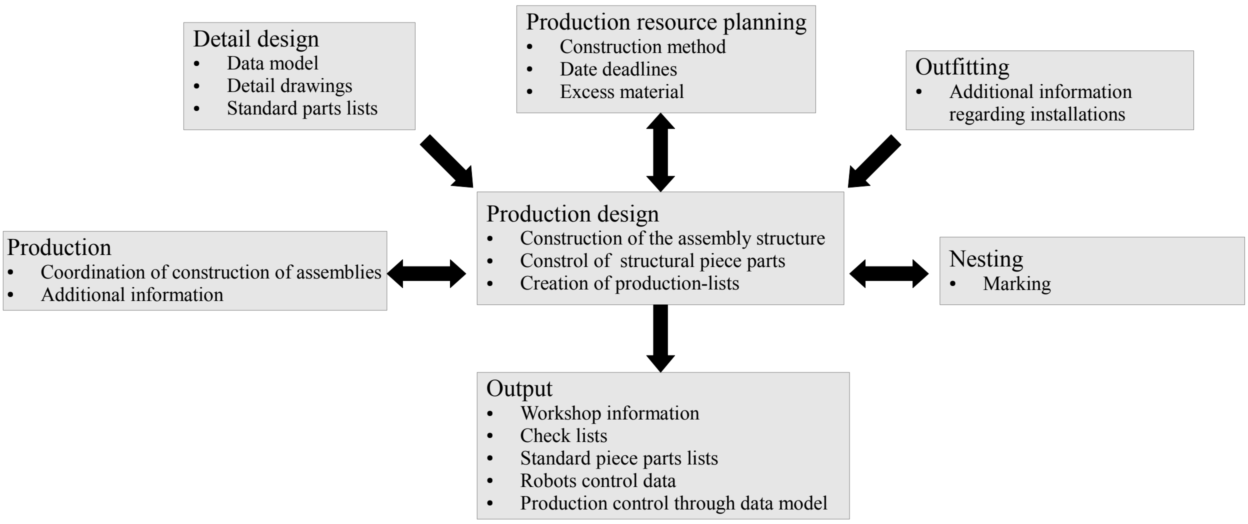


Figure 3.10.: Production design process

3.2.3.4. Production and Fabrication

Nowadays, ships are constructed in units or blocks. Small steel parts are joined together to build sub-assemblies which will then be connected to build assemblies. Commonly, the resulted blocks will be erected block-by-block to build the whole ship. The size, shape and weight of each construction depends on the size of the final ship, the available handling and lifting resources at the shipyard and the extent of outfitting completed within the ship [58]. Building the ship as a set of sub products is known as the concept of Product-Oriented Design and Construction (PODAC) [87].

3.2.4. Sea Trial

Prior to delivery, the shipbuilding contractor has to test if the vessel complies with all contract requirements. Tests of speed, stability, engine performance and quality of the mounted equipments and devices e.g. piping systems, steam generating plant, radio are the main goals of the sea trial. Normally, sea trials are classified in three wide groups: standardization, economy and maneuvering trials and tests [81]. The test result is kept as a performance record of the ship.

3.2.5. Delivery and Acceptance

After finishing all tests the ship will be delivered to the owner. The protocols for delivery and acceptance are usually detailed in the contract. At the time of delivery, the owner obtains a complete set of certificates from the regularity bodies [81].

3.2.6. Ship Operation

Ship operation includes all processes associated with the vessel from the delivery to recycling. All environmental, economical, technical aspects are included. During the ship operating time, the international conventions and regulations guided its life and play a key role.

3.2.7. Ship Recycling

After years of service or when repairs and retrofitting cannot be financially justified, the ship is recycled. For safety, health and environmental issues the IMO has set up new rules for the process [109] [47].

3.3. Systems Used in Design and Production of Ships

Computer aided systems are usually applied for the modelling of ships. These systems offer a lot of functions to increase the production's effectivity and enable the managing of large amount of information flow in a short time. Among the advantages of using computers in ship design and production are [136]:

- quicker response to requests for quotes and shorter design and construction lead times,
- increased accuracy,
- enhancement of concurrent engineering and production planning activities,
- more flexibility in making design modifications,
- a more controlled environment to help support standardization,
- improved cost control,
- elimination of many tedious manual and repetitive calculations,
- less rework in production
- less skilled labor needs in production,
- storage of lifecycle data for the ship, and
- configuration arrangement of changes through design and life of the ship.

The following systems are generally used in shipbuilding industry:

1. Computer aided design (CAD) is developed to replace the traditional drafting of engineering drawings and in designing and/ or modeling of parts, products, or structures. CAD system represents geometry and dimensions on the computer monitor and not directly on paper even though the final output of CAD systems is still paper drawings. The typical capabilities of CAD systems in shipbuilding industry include hull design, decks and bulkheads, compartmentation, profiles and arrangements, distributed system (e.g. HVAC system, piping), drawings, engineering analysis (e.g. calculation of tank areas and volumes, hydrostatic and stability data etc.) [136]. Such CAD systems include AVEVA Marine, NAPA, CATIA, AutoCAD.

2. Computer aided engineering (CAE) automates various ship design calculations in the areas of hull and equipment [136]. The CAE systems have the capabilities to analyze pipe thermal expansion, calculate the hydrostatics and stability, volume and cargo capacity, loading conditions, plate bending, electrical loading, weights and centers, analyze the strength of structure, maneuvering and control, selection of propeller, HVAC calculations, launching calculations, seakeeping prediction and noise analysis. Such systems are POSEIDON and OpenFOAM.

3. Computer aided manufacturing (CAM) helps to bridge the gap between ship design and construction. It is normally used to control and manage the manufacturing processes, such as riveting and welding machines. These systems are mostly used for accounting of weld shrinkage, dimensional control for hull and outfit interfaces, as an interface between product model and robots i.e. transmission of welding, geometry, cutting data into robot path, robotic programming to avoid collisions, to calculate lifting and rigging requirements, to support production management i.e. cutting, welding, fabrication etc, to automate the paint design and monitoring, assignment of part coding, nesting, plate and profile forming and pipe bending.

4. Product model systems are used to analyze and support the design, construction and maintenance of ships. These systems enable the designer to start his work in a 3D environment. The most important capabilities of these systems are to: ensure designers have a single data base shared between all modules, support the topological relationships between the different components, allow the use of specific programming language (Macro) to make the repetitive task in ship design, visualization of geometric model, support assembly strategy, support the parametric definition of structural (e.g. Manhole defined by major and minor diameters), nesting, generation of bill of materials, enabling of part data and support production (for cutting, bending, etc.). An example system is Pro/Engineer.

5. Computer-integrated manufacturing (CIM) is an integration between individual processes that support ship design to control the entire production process. This integration enables the automation of the manufacturing process [66]. The main goals of CIM are to support the full integration between the communication and technical and administrative systems, control the material, support production planning and automation, support material purchasing and enhance the communication between the yard and vendors.

6. Product data management (PDM) is used to manage all data related to a product and to control the access to this data, track the creation, change and archive of all information related to a product [134]. The most important capabilities of PDM systems are to control the access to each element in the product definition data base, supporting standardization through classification and organizing of the components and materials. PDM offers the ability to hold different kinds of relationships such as manufacturing, financial, maintenance beside the physical relationships of a product's parts, support and facilitate engineering changes to be more carefully matured and evaluated to improve the definition of the change impact, support process management by defining process steps related to the development, distribution and use of product data, support collaboration of the design teams through using this system as a base for communication and discussion.

7. Enterprise resource planning (ERP) is a tool that can be integrated across multiple functional areas by focusing on how to perform processes, rather than the individual functions [125]. The capturing and modification of business resources (materials, human, physical, and knowledge factors etc.) can be planned through such systems. The data desired for different business function such as manufacturing, material management, and human resources management etc. can be found in this system [166]. The complexity and large number of human resources in shipbuilding industry make the use of such system very beneficial. It enhances the efficiency of the users, increases the data quality and boosts the information's flow through the project [37].

8. Computer aided process planning (CAPP) utilizes the computer technology to boost the planning of processes to produce a new product or part. Missing the process planning creates a gap in the interface of CAD and CAM systems [46]. CAPP maintains the connection between CAD and CAM systems, which reduces risks and improves productivity [143]. Through tracking of equipment, costs, lead times, etc., CAPP helps in developing a process plan. It converts design data into a set of steps and instructions to perform the process of products manufacturing efficiently and effectively. When the manufacturing process becomes more complex the need for CAPP system will increase [57]. The following applications are included in CAPP: computing weld length as a primary factor structure assembly process, computing of weight and center of gravity, which are very important factors for different activity like stability calculations, and lifting. Interferences may happen during lifting and erection activities but can be avoided by simulating the lifting and erection operations before the building gets started [33].

9. Computer-aided quality assurance (CAQ) is the engineering application of computers and computer controlled machines for the definition and inspection of the quality of products. It includes computer-aided procedures for planning and implementation of quality assurance. CAQ supports and monitors the production process from production planning (CAE) up to and including the production (CAM). CAQ imbeds itself in the model of CIM.

10. Computer-aided approval (CAA) is a web-based service, where the drawings, digital documents and data model files (STEP, XML) are sent from the shipyards, manufacturers and suppliers to the classification society for the approval process. The submitted drawings and models files must fulfill certain minimum quality requirements. It is originally developed to replace the paper based drawings and the documentation of the drawings and data models. The CAA benefits include the faster approval by faster exchange of information, lower costs by reducing paper and their handling costs and better overview by continuous and fast access to approved documents and the status of the project documentation [56].

3.4. Welding Techniques in Shipbuilding

In this section the welding techniques and the related processes will be described. Welding is the dominant technique to join ship structure. This technique underwent a substantial development from the manual to mechanized to automatic and robotic welding. This development is aimed to reduce the production costs including potentially expensive post-processing and correction of unsatisfactory discrepancies and internal stresses by welding distortion and shrinkage for reliable joints in ship structures. The ship designer must observe the quality requirements regarding the welding since 70% of structural man-hours have to be spent for welding [32].

The commonly used welding techniques at shipyards include shielded metal arc welding (SMAW) where the heat generation is produced by an electric arc between a covered metal electrode and to be welded parts. The generated heat melts the metal of the electrode and the droplets across the arc coalesce as a molten pool before solidifying. The gas metal arc welding (GMAW) is also applied where in this process a gas shields the arc and molten weld area from the atmosphere. Tungsten and Metal inert gas welding are the widely applied GMAW techniques. The submerged arc welding (SAW) technique is frequently used for plates welding. It is a semi- or an automatic technique. In this technique, an arc is provided between a continuously fed spool and the work area. In the laser welding techniques, a laser beam is focused by means of mirrors on the surface of the work piece. There is no need for additional weld filler material for small gaps. In shipbuilding industry, two types of laser welding are applied, the CO_2 laser and ND:YAG (neodymium-yttrium-aluminum-garnet) laser. In the electroslag welding (ES) and electrogas welding (EW), the molten weld pool is restricted within two movable copper shoes. Due to the high deposition rates and large molten weld pools, it is only applicable for vertical welding. The friction-stir welding (FSW) technique uses the friction between two metallic parts to produce adequate heat to form the welding joint.

3.4.1. Weld Preparation

To achieve complete penetration of the welded metal piece, it becomes necessary to bevel the edges on thick plates that are to be butted together, see Figure 3.11. This operation may be finalized during profiling or trimming the plate edges, which must be aligned correctly. To achieve the required bevel, most edge preparations are made by plasma or gas heads provided with three nozzles out of phase to form the required angles. Sometimes, edge preparation can be produced by mechanical machining methods using either a planing or milling tool. For thick plates with high accurate welds, mechanical machining is recommended. Plates of varying thickness may be butt welded together at different locations. The thickest plate is chamfered to the thickness of the adjacent thinner plate before the edge preparation is made.

3.4.2. Welding Sequence

To reduce distortion and limit the residual stresses in the structure it is important that a correct welding sequence is applied. Welding of stiffeners to the plate panels is usually performed after completing the welding of the panel plates. For erection, the principles provided for panels are generally followed. In welded ships the lower side plating seams should not be welded before the upper seams, particularly the deck and gunwale seams. If this sequence of welding is applied, the upper portion of the hull structure would tend to be shortened, causing the hull to rise from the blocks at the ends. In modern construction methods this problem does not arise because the side shell and deck plating are erected in blocks and a suitable welding sequence is employed. Repair work procedure follows the general pattern for butts and seams in plate panels, particularly where new material is fitted into the existing relatively rigid structure.

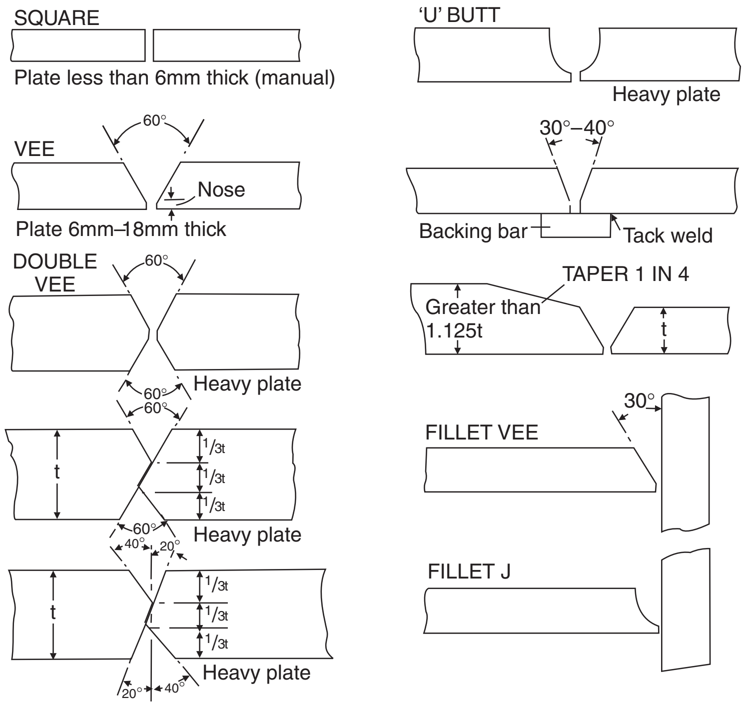


Figure 3.11.: Plate edge preparation [111]

3.5. Classification of Faulty Information in Detail Design Phase

Different requirements and production constraints in the shipbuilding are discussed in section 3.1, among them there are crucial requirements which influence the production process and have a dominant effect on the cost and delivery time. To check the compliance of the ship product data model with the requirements and standards, faulty information in detail design phase must be analyzed and the corresponding criteria must be formulated. Only the requirements and production constraints with the significant influence on the whole design process will be selected and considered. Guided interviews held at shipyards and a design agent in Germany identified 174 typical problems regarding the ship product data model that mostly affect the overall performance [63]. These deficient designs occurred in different design phases and can be classified systematically into three fields: production planning process, manufacturing and non conformance to shipyard standards. Production planning process are problems regarding the identification of attributes of structural parts in a 3D model as well as the problems arising by disregarding the limitation in raw material. Manufacturing issues are inapt designs arising by not observing manufacturing requirements of the structural parts including weld preparation. Non conformance to shipyard standards are problems due to special shipyard dependent design practices and disregarding the drawing conventions. Further analysis yields to four general quality criteria categories in which all identified errors can be categorized:

1. existence: this criterion states that the required information has to be provided;
2. compliance: predefined project and shipyard specific standards have to be fully observed;
3. conclusiveness: object properties have to be consistent in relation to other objects of the same kind;
4. consistency: multiple representations of same object to be without conflict.

3.6. CAD Data Quality Requirements

In general, PDQ problems can be classified into geometric and non-geometric data problems. The classification of welding quality criteria is built upon ISO/PAS 26183 and has been expanded, see

Figure 3.12. The quality criteria (in grey) are outside the scope of this work. Quality criteria are differentiated on the uppermost level into those directly related to CAD-data and to manufacturing. `Non_Geometric_Quality` criteria are further subdivided into features, parts information and weld arrangements. These aspects are related to excess material, welding preparation (bevel) and the existence of notches at positions defined by a specific design context and production sequence, but not being in accordance with a standard. The latter mainly addresses complex requirements in relation to two parts or design features.

The applied coding system is similar to that used in ISO/PAS 26183, see Figure 3.13. Possible values for the domain identifiers are: `G` for `G`eometry-CAD data, `O` for Non-geometric and `M` for `M`anufacturing. The possible values for the concerned elements are: `NO` for `NO`tch, `EX` for `EX`cess, `EP` for `E`dge `P`reparation, `PPDI` for the `DI`stance between two `P`arts, `PSDI` for the `DI`stance between a `P`art and a `S`eam, `SSDI` for the `DI`stance between two `S`eams, `PPAN` for `AN`gle between two `P`arts, `PSAN` for the `AN`gle between a `P`art and a `S`eam, and finally `SSAN` for `AN`gle between two `S`eams. Values for the general quality critera are: `MI` for `M`issing `I`nformation, `NS` for `N`ot `S`tandard information, `NC` for `N`ot `C`onclusive information. In the following, the above mentioned criteria regarding weld preparation etc. are further discussed.

CAD data include solid models, assemblies, surface model, tolerance data, and drawings views and is subdivided into: Geometric, Non-Geometric and Drawing quality criteria [19]. The quality criteria for geometric data can be classified into mathematical (shape) and process quality. Mathematical criteria are criteria necessary for maintaining the correctness of the mathematical definition of the CAD-model concerning the shape of an object (geometry). Process quality criteria ensure the manufacturability of CAD-models for the downstream applications. Poor process quality makes product data also not applicable for the FEM or CFD analysis.

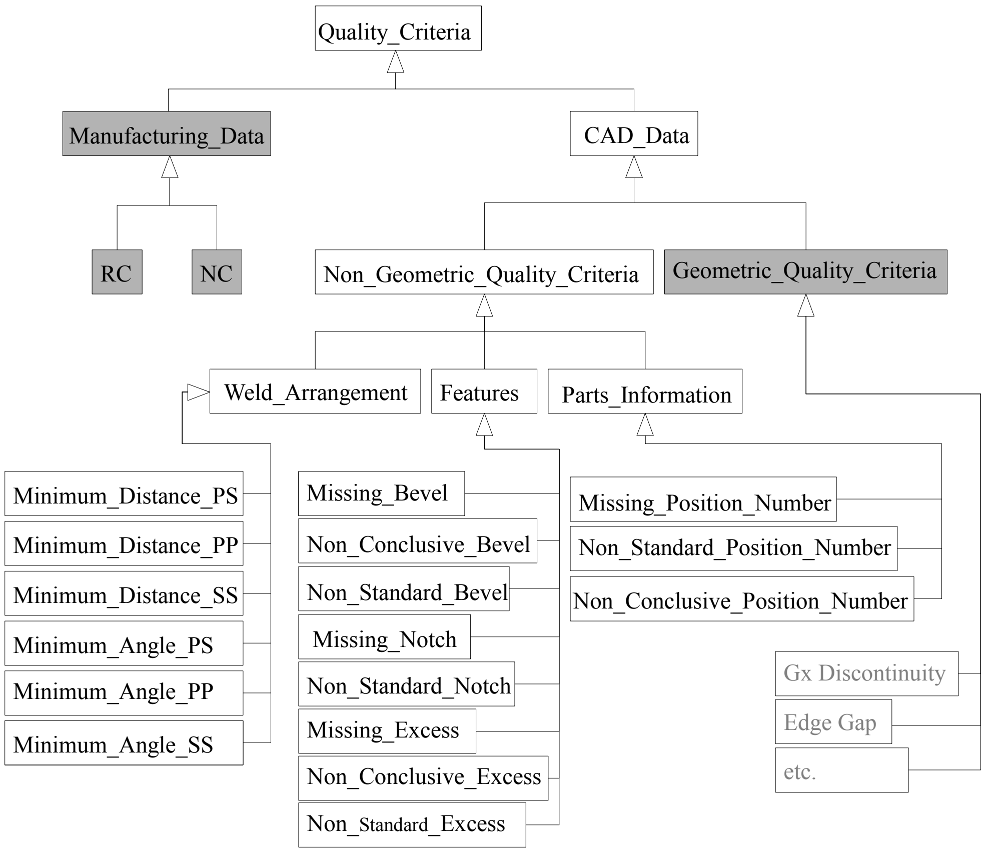


Figure 3.12.: Classification of quality criteria

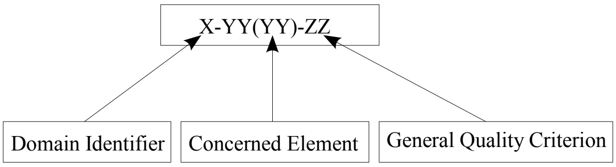


Figure 3.13.: Coding system of quality criteria

3.6.1. Geometric Quality Criteria

The quality criteria of shape data are used to check if data are satisfactory to downstream applications. According to ISO STEP-59, the quality criteria of 3D shape data can be classified into: erroneous and inapt data. Each group is further categorized into sub-groups regarding the type of the inspected entities or objects. These sub-groups are: geometry specific, topology specific, and combined geometry and topology issues. Erroneous data are mathematical invalid product shape data. Inapt data are data which are not relevant for some application, but are not necessarily mathematically incorrect. The shape data quality criteria for B-rep data representation according to ISO STEP-59 include erroneous and inapt data [14]. The erroneous data quality criteria contain erroneous topology e.g. open edge loop, erroneous geometry e.g. erroneous B-spline curve definition, erroneous topology and geometry relationship e.g. inconsistent edge and curve direction and finally, erroneous manifold solid B-rep e.g. intersecting shells in solid. The inapt quality criteria include criteria regarding inapt topology e.g. free edge, inapt geometry e.g. self-intersecting geometry, inapt topology and geometry relationship e.g. topology related to nearly degenerate geometry as short length edge and finally, inapt manifold solid B-rep e.g. small volume solid.

3.6.2. Non-Geometric Quality Criteria

Non-geometric (process) quality criteria are criteria for maintaining a robust and optimal utilization of the product data within a manufacturing environment like tolerances, dimensioning, drawing conventions, model naming rules and bill of material (BOM). The considered quality criteria are:

3.6.2.1. Parts Information

Each structural part must have a position number assigned to it. Position number is usually assigned using one of the following methods [104]:

- Automatic position number assignment. Depending on the settings made new position numbers are assigned or existing numbers reviewed and, if necessary, modified or even totally overwritten.
- Manually assigning of position numbers.
- For bars and sealing plates position numbers can be predefined and in the settings stored. Deviations from the stored settings no position number will be assigned. Then the number will be assigned regarding the first and the second methods.

The correct assignment of position numbers is an important quality criterion regarding the ship's structure. Within a certain scope (blocks or panels), e.g. all plates with an equal shape (within certain tolerances) and equal material properties must have the same position number. The quality criteria regarding this requirement are:

- `Missing_Position_Number O-PN-MI`: This criterion states that every structural part must have a position number assigned to it.
- `Not_Standard_Position_Number O-PN-NS`: This criterion states that regarding the type of the structural part (e.g. plate, profile, bracket etc.) the position number must be assigned to according to the project specific standards, e.g. the position number of plates must be in a certain value range. Normally, number ranges are directly defined.

- `Not_Conclusive_Position_Number O-PS-NC`: This criterion represents the relationship between two position numbers assigned to two different plates. In that case identical parts must have the same position number. Two parts are generally regarded to be identical when they have the same properties concerning material, thickness and shape. Shape in this case includes the outer and the inner contours (holes).

3.6.2.2. Features

1. Excess: Due to possible inaccuracies occurring during the assembly process, excess material is to be added at certain panel boundaries, see Figure 3.14. These boundaries will be connected to other panels at a late production stage, e.g. in block assembly. The reference value of excess to be applied in the detail or production design respectively are defined in the production planning process and documented in a separate excess plan which is generally not a part of the 3D-product data model. The excess value is given as a number in *mm*. All CAD system have their own representation for excess material depending on the structural part type such as plate or stiffener. Normally the standard excess values to be assigned are predefined according to the shipyard and/or project specific standards. The severity of the problem regarding the excess differs from case to case, i.e. for an excess value smaller than the must value is much more severe than for an excess value bigger than the required one; therefore the following three quality criteria have been formulated:

- `Missing_Excess O-EX-MI`: an excess material value has to be assigned to the plate boundary functioning as a section boundary but does not exist;
- `Not_Standard_Excess O-EX-NS`: the actual excess value assigned is not the value according the relevant shipyard or project standards;
- `Not_Conclusive_Excess O-EX-NC`: a reserve of 5 mm is defined for section boundaries when no excess values are predefined. This criterion is not critical.

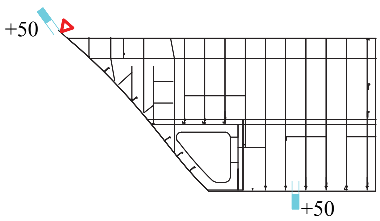


Figure 3.14.: A portion of an excess plan

2. Weld preparation bevel: Quality criteria regarding the edge preparation of plates and profiles represent examples for more complex quality issues to be considered in the product data model quality. The weld preparation representation differs between CAD systems. For example, in the AVEVA Marine system, this information has to be assigned to a seam or plate boundary as a "bevel code" [104]. Bevel codes define the final form of weld joints between two structural parts, namely the root gap, the joint form and the opening angle, see Figure 3.15. The bevel code to be assigned is a function of the plate thickness, steel quality and the welding technique being used at the shipyard. The correct assignment of the weld preparation has a major impact on the production process, on the seam quality and the resulting deformation due to the energy input. Some recommended values can be taken from the international standard like ISO 9692-1 [26].

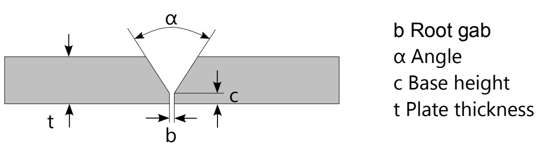


Figure 3.15.: Weld preparation

The three criteria to ensure the correctness of welding arrangements are:

- `Missing_Bevel O-EP-MI`: a bevel has to be assigned to a seam or boundary but does not exist in the product data model;
- `Not_Standard_Bevel O-EP-NS`: the value assigned is not compliant with standard values predefined in the production standard of the shipyard;
- `Not_Conclusive_Bevel O-EP-NC`: edge preparations are assigned for a seam but the two parts to be joined do not have the same bevel information:
  1. adjacent structural parts with the same thickness should have the same weld preparation, yielding to the same bevel assigned to them;
  2. the bevel must exist on the same side of the adjacent plates.

Figure 3.16 shows two examples in which the requirements are not met.

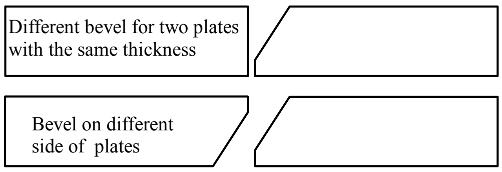


Figure 3.16.: Inadequate weld preparation

3. Notches: A notch is material cut off from a panel or stiffener edge or corner, see Figure 3.17. Notches serve to reduce the restraint of the shrinking along the seam and thus to reduce the welding residual stress. The existence of notches makes it possible to weld a plate on an existing weld joint without the necessity to grind the weld joint. Whether a notch should exist depends on the welding sequence and the function the adjacent compartments serve. In conventional shipyards double bottoms are manufactured as sections in automated production lines. Production starts by welding of all plane panels of the inner bottom to build a plate field. At the next stages of the production line supporting profiles and girders are mounted and welded on the plate field. The individual plates of the inner bottom will be welded by means of butt joints. There is no need for notches for profiles and girders that crossed the butt joints. The situation is different at section boundaries. Butt joints are also usually used to connect the plates between different sections. However, the notches are required here, as these butt joints are applied only after the welding of profiles and beams. The structural parts that cross two connected plane panels must have notches at the cross points. But even at the corners of components such as plates and stiffening profiles, notches may be necessary, especially where fillet welds are found.

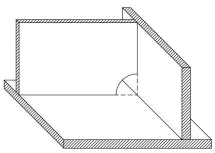


Figure 3.17.: Notch at plate corner

Quality criteria regarding notches can be formulated as follows:

- `Missing_Notch O-NO-MI`: a notch should exist at the corner of a plate bounded by two other structural parts having a different orientation than the concerned plate. This condition is restricted by the function of the plate (non-oiltight or non-watertight);
- `Not_Standard_Notch O-NO-NC`: the size and form of a notch does not match with the standard values.

In the regulations of Germanischer Lloyd GL, the following recommendations for minimum sizes of notches are listed:

- Radius of notches should be more than: $25mm$ or $2 \times$ plate thickness.

- Especially for components with the mainly dynamic loading, notch should be shaped to provide a gentle transition to the adjoining surface and adequately notch-free welding should be carried out around the end faces.

3.6.2.3. Weld Arrangement

1. Minimum distance between structural components: Minimum distances guarantee that the welding zone is freely accessible and prevent too high internal stresses due to the welding process. For this, three part-seam combinations have to be addressed. Due to these combinations, the minimum distance has to be checked by seam-seam O-SSDI-NS, part-part O-PPDI-NS and part-seam O-PSDI-NS criteria, see Figure 3.18. The minimum distance is also a function of the applied welding technique and the plate thickness (t). Recommendations regarding these minimum dimensions can be found in the guidelines and instructions of classification societies [102].

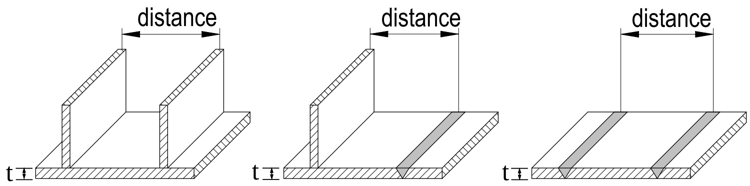


Figure 3.18.: Minimum distances between structural components

The requirements regarding the minimum distances as recommended by Germanischer Lloyd can be listed as follows:

- Minimum distance between components.
- Minimum distance between welding joints.
  - For big welding joint thickness, the minimum distance between butt seams must be not less than $50mm + 4 \times$ plate thickness.
  - Distances between fillet welds as well as between butt and fillet welds must be not less than $30mm + 2 \times$ plate thickness.
- Some other minimum distances
  - Interchangeable plate sections must not be narrower than $300mm, 10 \times$ plate thickness.
  - Minimum diameter of reinforcing, welding flanges, drain unions, mounting or other similar parts socket welded into plating should be of the following minimum size $D_{min} = 170 + 3 \times (t - 10) \geq 170mm$, where D is diameter of round or length of side of angular socket weldments in [mm] and t is platting thickness in [mm].
  - With angular socket weldments, the corner radii should be at least 50 mm or the “longitudinal seams” should be extended beyond the “transverse joints”.

2. Minimum angle between structural components: Like for minimum distances, three criteria, namely seam-seam O-SSAN-NS, part-seam O-PSAN-NS and part-part O-PPAN-NS have to be observed for minimum angles, see Figure 3.19. The recommended values of the minimum angles are based on the welding technique used in the shipyard and the available welding facilities .

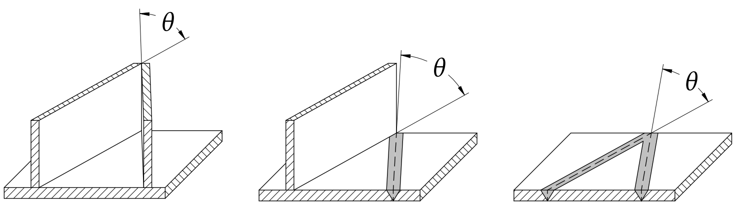


Figure 3.19.: Minimum angles between structural components

3. Maximum weld length: This quality criterion states that the length of a plate edge or a profile to be welded must be as long as the facilities of the shipyard allow. Maximum length depends on the dimensions of the shipyard spaces where the structural part is to be welded and also on the weld devices available at the shipyard. This length can be defined in the project specifications. If the actual length of the plate edge or the profile is more than the value allowed an error must be reported.

4. Quality Management of Ship Product Data

Good quality of design data improves concurrent working which leads to shorter product development time, and eliminates delays in information flow to the downstream applications. In this chapter, the product quality process PDQ will be discussed and a quality management approach to ensure a good quality of ship product data will be described. The proposed approach is based on the ISO standard 10303-59 focusing on quality criteria for an efficient ship structure production process, see section 3.6. The usage scenarios of the introduced framework and the different information models will be discussed.

4.1. Usage Scenarios

Different usage scenarios are expected for the quality management approach among them are:

Quality control between shipyards and external partners: This use case is applied in a collaborative work between shipyards and external partners. Especially in Europe, it is common that a considerable amount of design work is assigned to external design agents. The design agents usually work simultaneously for different shipyards with heterogeneous CAD systems and different shipyard specific standards and requirements. Disregarding or neglecting these standards leads to significantly increased probability of error generation. For this use case, configurable quality criteria must be applied on the received data and before integrating these data in the shipyard's own CAD systems, errors must be excluded as early as possible for a higher reliability of the ship product model data. The same use case can be applied for quality assurance of information flow between the different departments in a shipyard.

Internal quality assurance: This use case represents the integration of the quality management method with the CAD system. In this case the engineers are able to check their job at run-time. To improve the quality of inspected data, information on the nature and severity of any quality defects must be provided. Therefore, the quality defects have to be reported at the instance level.

Declaration of quality: In this use case, the shipyard, according to the applied CAD system, declares some quality information such as selective quality criteria and thresholds for which product data model can be considered as free of defects.

Long-term archiving of product data: In this case and for purpose of archiving, the detailed information about the quality defects is stored together with the inspected data.

4.2. PDQ Process

PDQ process [72] consists of four major steps, namely data inspection, error evaluation, error correction and finally knowledge capturing as a learning process for best design practice and error prevention, see Figure 4.1. In the first inspection step, as indicated by (1) Figure 4.1, product model data will be checked against relevant predefined quality criteria with given thresholds values and tolerances as described in section 3.6. Data checking must be performed using the relevant algorithms to capture various possible errors precisely. In the following evaluation step (2), designers check the candidate inapt designs using the inspection report and the original CAD-model upon a request from the quality inspector/manager. Depending on the design intention, production requirements and error severity, designers are able to judge the detected error prone designs. In the quality assessment process which is a part of the data evaluation step, information about the current quality status of the inspected data like pass/fail decisions or the estimated time and costs for the errors correction can be delivered without any human intervention. After finishing the inspection, the reasons for errors generation can be specified. When the error is due to bugs in the CAD system or to incompatibility problems between the collaborative heterogeneous systems that have been used in the design stage, it is very important to enhance the CAD system performance as soon as possible by a cooperation with the software vendor. In the correction step (3), designers correct the inapt data which have been identified as candidates in the previous step. The correction activities take place in the design phase where the product data is originally generated using the inspection report and a visual guidance of the defected parts. After finishing the correction works, the product data must be checked again and verified before it is delivered to the downstream processes. In the final knowledge capturing step (4), the identified nonconformities are analyzed in order to develop actions to prevent further errors in the early design stage. The acquired knowledge has to be documented for establishing design standards to minimize the required resources for error correction during the design process. Two cycles with the same quality steps can be linked into the ship design process independent of the applied design's tasks: solid line for the detail design process and dashed for the production design process step.

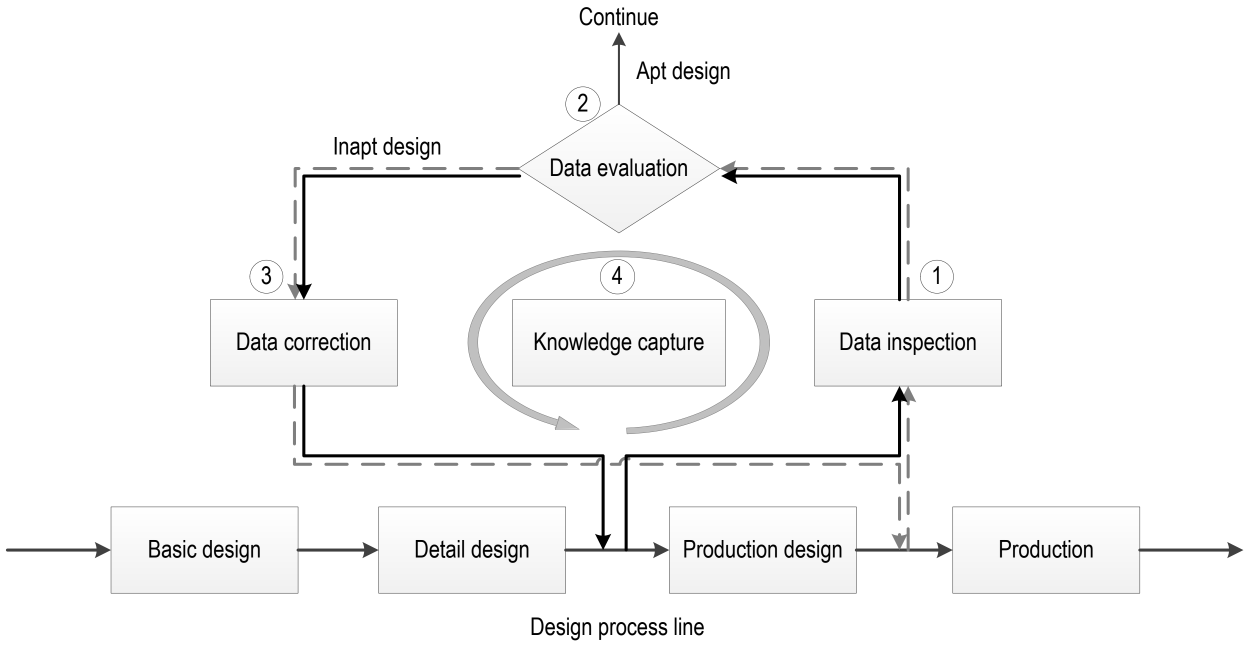


Figure 4.1.: PDQ process linked to ship design process

4.2.1. Roles and Responsibilities in PDQ

For transparently managing PDQ, different individuals with different roles and responsibilities must be involved: the designer(s), the quality inspector and the quality manager, see Figure 4.2. Designers are responsible for modelling the ship structure. By this stage all generated data will be stored in a CAD system database for further usage. The quality manager is in charge of the definition of quality parameters depending on the downstream applications and processes restrictions as described in chapter 2. The result is a set of well-defined criteria which are to be applied in the related quality management process. The quality managers can be any administrators of any department in the downstream processes, and they should be the professional people with the best design experience, who are familiar with the quality requirements of product data in their departments. The quality inspector is responsible for the quality of a certain new project. He/she checks the product data generated by the designer against the formulated quality parameters. The quality inspector's role is to coordinate the integration and maintain the communication between the designers and the quality manager. The quality inspector forwards the inspection result to the designers in charge of the specific ship structure to apply the requested corrections or engineering changes.

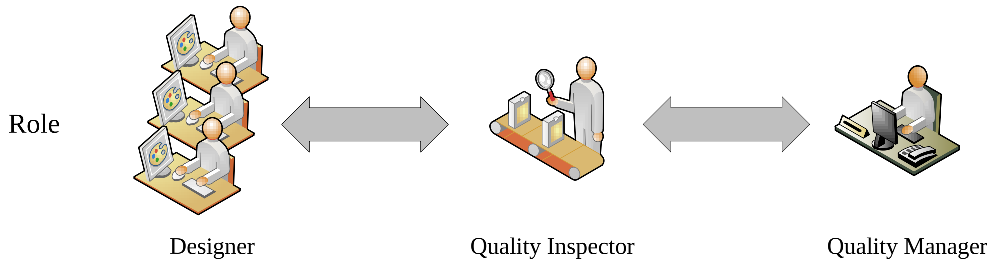


Figure 4.2.: Roles in quality management.

The knowledge can be optimally captured step (4) by effective participation of the mentioned persons in multiple quality cycles. Any suggested and approved enhancements should be submitted to the quality requirements database for application in future tests. Apart from the formal role assignments and for a more effective design process, the designers must be able to perform the inspection themselves at any early design phase. This is especially important in the detail design phase as the majority of all errors are generated there. This PDQ process also is vital for use cases in which a collaborative work is performed between shipyards and external design agents. Partial data models from design agents will be checked against the relevant criteria prior to merging the data into the common ship database. In case of identified problems the quality inspector can decide about further steps to be taken: either corrections will be done locally or the delivered design will be rejected asking the design agent to correct the identified errors.

4.3. Quality Management Framework

4.3.1. System Architecture

Based on ISO standard 10303-59 and ISO/PAS 26183 SASIG, a proposed product data quality management system PDQMS [72] is introduced in this section. To realize the product data quality process as discussed in section 4.2, different tools and resources are provided, see Figure 4.3. The top level represents the roles of the involved partners in the product data quality assurance process as discussed in subsection 4.2.1. Three types of tools are applied regarding their functions and capabilities. The first tool is a CAD system for the modelling of the ship structure used at a shipyard or by a design agent. The tool used by the quality inspector is at the core of this framework. It is basically a database-application along with the required algorithms and functions to inspect the product data against the quality requirements. The tool utilized by the quality manager is used to define the project-specific quality parameters. The parameters are used to evaluate the existence of quality defects against a set of selected quality criteria. Those tools are linked to different resources and databases. The database used for storing the ship structure is provided with the CAD system and it is used only as a source of CAD data and no modifications will be performed to the original data. The middle layer represents a neutral database and includes information built upon different information models as will be discussed in section 4.4 of this chapter. It serves as storage for the imported product data from the CAD system database, therefore it must be provided with interfaces to extract the data from the considered CAD system and map them into the neutral database. Quality control methods are also implemented in this layer. These methods represent the programming form of the predefined quality criteria. The quality criteria parameters i.e. tolerances and values as well as the range of the selected structures are managed by the quality manager and stored into the database utilized by him. Examples for these parameters are the required distances and angles between the structural parts as well as the proper sizes of notches. The inspection results will be stored also in the middle layer to be used later for different purposes. For example, the automatically detected inapt designs and the reason of the error will be documented and reported back to the designer, in order to assess the reported cases, and if necessary, to correct them. The inspection results can be used also for archiving purposes, where preventive actions can be defined in a design catalog for best recommended practices to avoid the errors in the future.

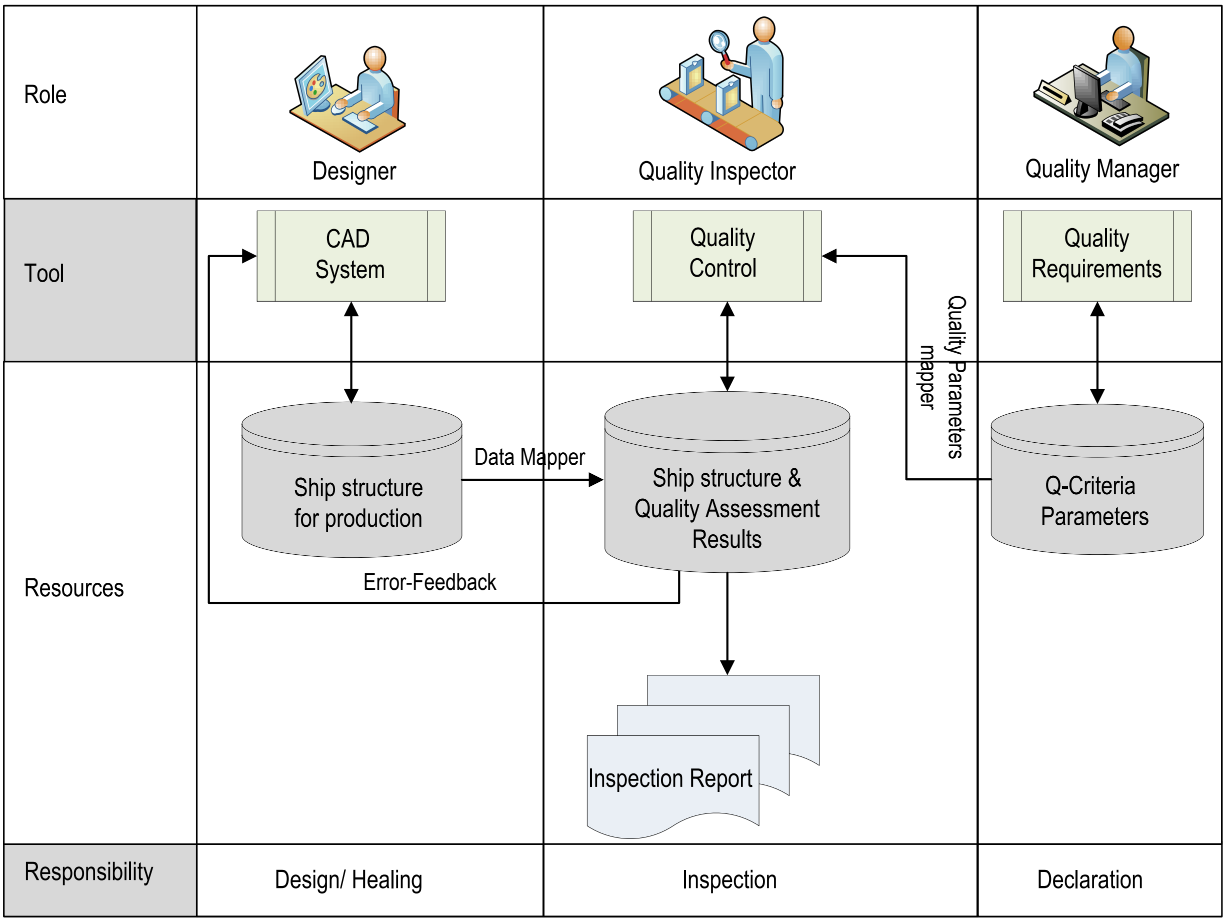


Figure 4.3.: Structure of ship product data quality management system

The advantages of using a neutral database in this framework are:

- Provides customization and extension possibilities for the data model
- Independent of the CAD system specific internal data structure and data access method
- Inspection of non-CAD data or data from different CAD systems via neutral data model is possible
- Complex inspection algorithms can be developed to be applied on the data model

The only disadvantage is that, a data synchronization step is needed before the inspection.

The proposed quality management framework is built upon three main subsets of well known International Standards [72], see Figure 4.4. The first subset represents the ship structure for which relevant objects are selected from ISO 10303-218 [9]. The second subset represents all used objects from STEP resource models: `measure_schema` from ISO 10303-41 [10], `representation_schema` from ISO 10303-43 [12], `qualified_measure_schema` from ISO 10303-45 [13] as well as the geometrical and topological information objects from ISO 10303-42 [11]. The third subset is built upon ISO 10303-59 and consists of three main object types. They include the definition of the product data quality criteria to be inspected, the data quality measurement requirements, and finally the inspection results of the ship data quality. Inspection results include statistical information such as the total number of the inspected objects and the number of quality issues raised as well as detailed information on data instance level where the quality defect has been detected. The detailed description of the information models are provided in section 4.4.

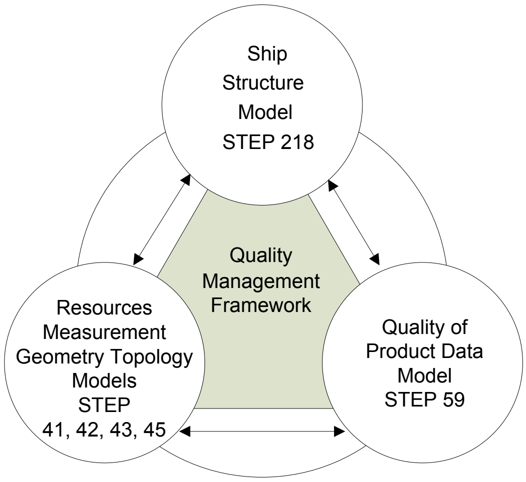


Figure 4.4.: Quality management framework

The motivation for choosing the ISO 10303-59 standard as a basis for the proposed quality management framework is that the product data quality is defined as an information model to support the classification of quality defect, measured values, thresholds, and test results. The differences between ISO-59 and the quality system proposed in this work are: The product quality model introduced in STEP-59 uses the formal specification language, EXPRESS, but UML class diagrams have been used in this work. Entity in EXPRESS language corresponds to a class in an UML class diagram [30]. The second difference is the classification of errors. The classification of quality criteria is based on the same way as applied in the ISO/PAS 26183, see Figure 3.12. The considered quality criteria are those applied to check the conformance of product data with optimized ship design processes such as the welding, manufacturing and production processes as described in section 3.6.

4.3.2. Information Flow

The ship design data are stored in digital form in the CAD system database. These data include important topological, geometrical, and manufacturing information, which will be used in the downstream processes. The data mapper module is responsible for mapping the extracted product data from the CAD system into the neutral database of the product quality management framework in the middle layer. This step enables the application of the same set of inspection algorithms without the need to modify them for each data representation. After completing the inspection job, test results will be registered in the PDQ system database. These results are saved along with the inspected product data and include information about the inspected quality criteria, references to the defective instances of product data, as well as the applied tolerances and thresholds. A notification Email will be sent to the designers, quality inspector, and quality manager after finishing the inspection. An assessment report will be automatically generated to help the quality team to arrange the required resources for data correction process. This report provides graphical representation of the inspected structures. A colour-based representation of ship blocks will be created depending on error rate as discussed in section 4.5. The designers have access to inspection results, where they can put the automatically generated macros into the used CAD system to display the defected structures with visual guidance to accelerate the error correction. If the product data are provided by an external partner, the inspection results can also be forwarded. The quality manager, based on the usage scenario of the inspection, can specify the configuration information with the required quality parameters for a specific inspection process. The defined parameters will be assigned to the proper attributes in the information model, which will be applied by the inspection algorithm.

4.3.3. Application Area of Quality Management Framework

The proposed framework enables the quality control of product data at an early design stage and after the creation of the detailed ship structure information including the manufacturing data, i.e. after the detailed design stage and during the production design phase, see Figure 4.5. The application of the quality control at these phases has a big impact on the needed resources to heal defective data for a seamless production process.

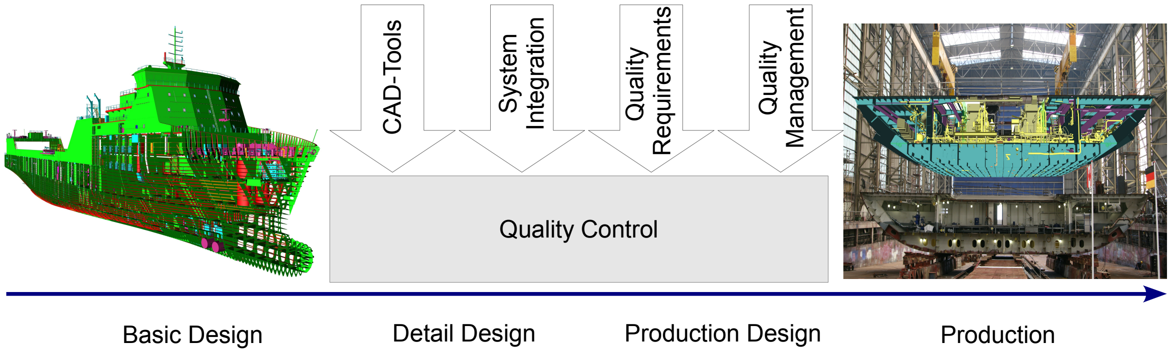


Figure 4.5.: Application area of the proposed quality management system, Figures taken from [104]

4.4. Information Models

Unified modeling language (UML) class diagrams are used as data modeling language. A class diagram is used to depict the classes of an information model. In an object oriented application, classes have attributes (member variables), operations (member functions) and relationships with other classes. The used relationships in the information models are: Inheritance, aggregation, association and dependency, see Figure 4.6.

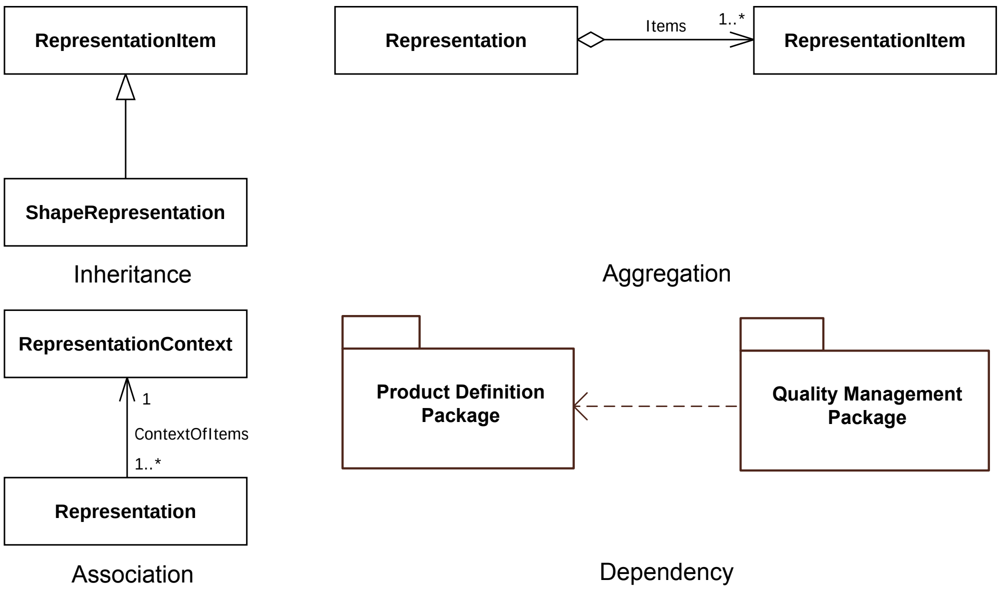


Figure 4.6.: Relationships used in a class diagram

The inheritance relationship in UML is depicted by a triangular arrowhead. This arrowhead points to the base class. One or more lines proceed from the base of the arrowhead connecting it to the derived classes. The aggregation relationship denotes that the aggregate class (the class with the white diamond touching it) is in some way the “whole”, and the other class in the relationship is somehow “part” of that whole. The association relationship is another form of containment that does not have whole-part implications. Finally, the dependency relationship is a relationship in which changes to one model element (the supplier) impact on another model element (the client). This relationship is used to represent precedence, where one model element must precede another. Dependency is displayed in the diagram as a dashed line with an open arrow that points from the client model element to the supplier model element. All used information models (packages) in the quality management framework are depicted in Figure 4.7. These packages are interrelated with each other.

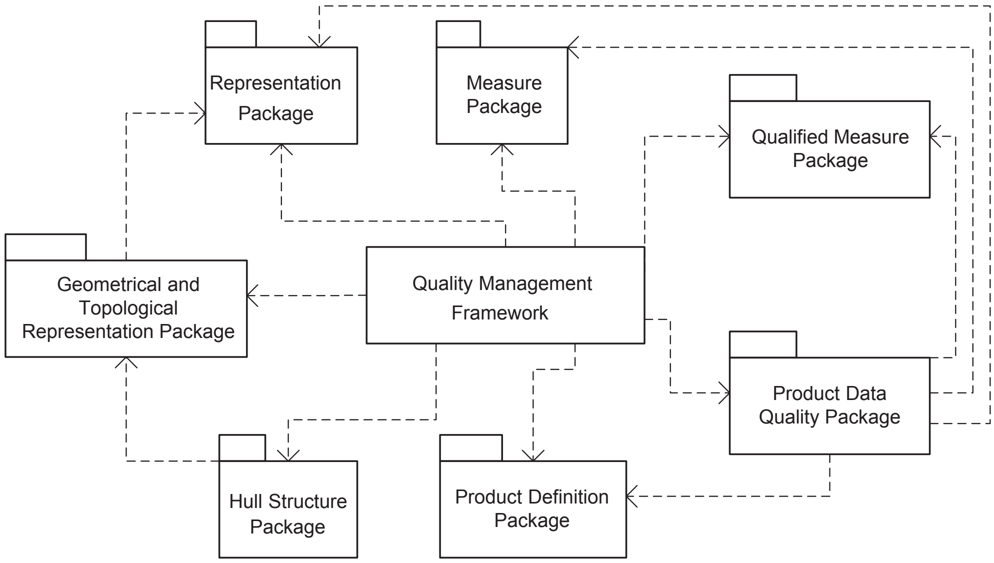


Figure 4.7.: Used information models (packages) in the quality management framework

4.4.1. Product Data Quality Package

This package consists of three sub-packages as shown in Figure 4.8. These packages will be described separately in the next subsections. The main objects of PDQ model are data quality criterion, data quality measurement requirement and data quality inspection result, see Figure 4.9. The quality criterion defines an aspect of a requirement on product data quality. Data quality measurement requirements represent requirements on acceptable measurements for testing whether the criterion on data quality is satisfied or not. The data quality inspection results represent the inspection results for a specific set of product data quality criteria of a specific product data instance.

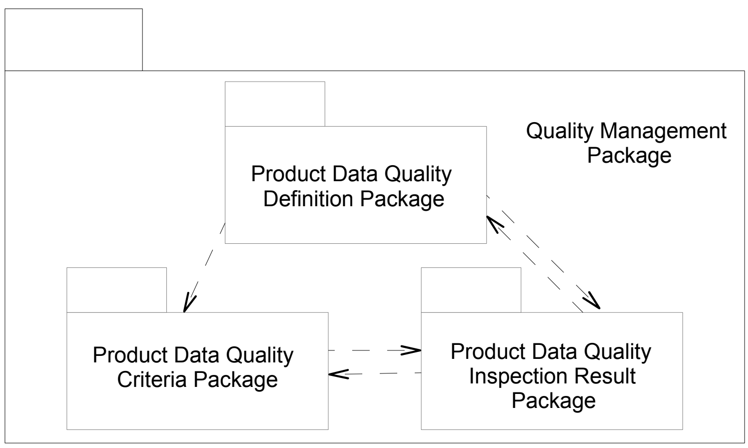


Figure 4.8.: Packages included in the quality management package

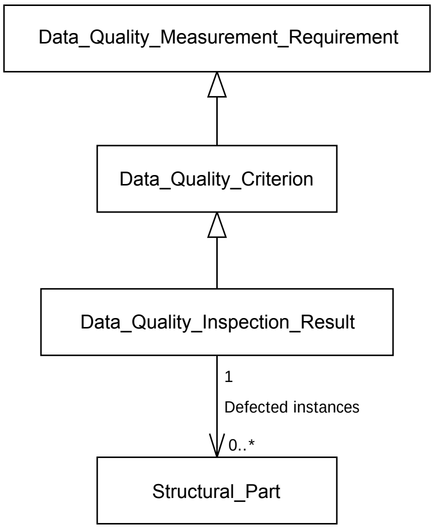


Figure 4.9.: Information model for product data quality (subset of ISO 10303-59 [14]).

4.4.1.1. Product Data Quality Definition Package

The quality information of product data is not a part of the product data. Therefore, this package is used to relate the product data quality with the inspection results. This package must be instantiated for all usage scenarios as described in section 4.1 i.e. to relate the product data model with the inspection result or even only for the declaration of the quality requirements needed to maintain the quality of product data before the product data model is generated. This relationship will be created between a `DataQualityDefinition` class and a `ProductDefinition` of `Product Definition` package. It consists of five classes as shown in Figure 4.10. The first class `DataQualityDefinition` is used to relate the product data with the data quality information. Class `DataQualityDefinitionRepresentationRelationship` is used to connect the data quality definition with the used representation of quality depending on the usage scenario i.e. inspection declaration or quality archiving. Class `ProductDataAndDataQualityRelationship` is used to connect the data quality definition to a product definition. Class `DataQualityDefinitionRelationship` relates two `DataQualityDefinition` when more than one inspection is commenced during the development of the product data model with different/same quality criteria. The last class `UsedQualityRepresentationSelect` is used depending on the usage scenario to select the quality representation i.e. representation of quality criteria only or quality criteria and inspection results. For the selection, classes `DataQualityCriteriaRepresentation` from package `Product Data Quality Criteria` and `DataQualityInspectionResultRepresentation` from package `Product Data Quality Inspection Result` are available.

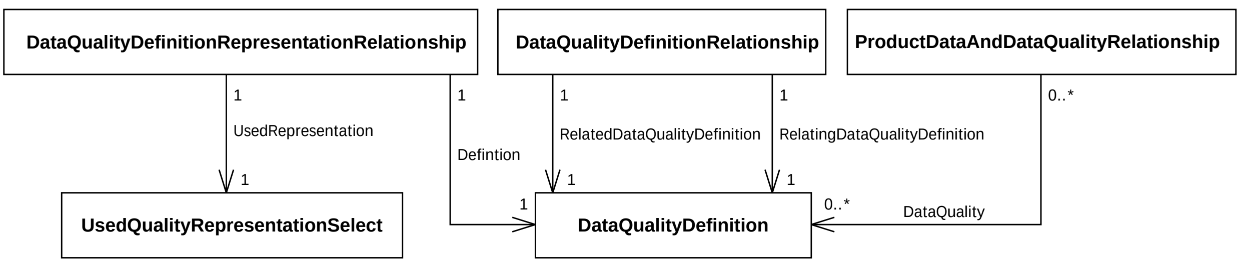


Figure 4.10.: Information model of product data quality definition package

4.4.1.2. Product Data Quality Criteria Package

This package is a part of the product data quality and shape data quality criteria schemes of ISO STEP-59 and has been modified to meet the purpose of this research, see Figure 4.11. It provides information about: the applied data quality criteria, the measurement requirements to check if a quality criterion is met (defects exist) or not as a textual description, and finally assessment information as a textual description to judge if the quality measurements are acceptable or not. For the sake of brevity, only the main objects will be described, more information can be found in [14]. The class `DataQualityCriterion` is an object to represent a requirement on the product data quality. An example of quality criterion is the `Not_Conclusive_Position_Number` criterion, subsection 3.6.2.1. The measurement requirement for this criterion is that two structural parts with the same position number must be inspected for equality. Inspection algorithm can also be specified here. The measurement assessment requires that if the measured distance between both parts is bigger than the threshold, an error must be reported. The class `DataQualityAssessment` describes the requirements or specifications to evaluate and assess the result of the inspection for each quality criterion. The class `DataQualityMeasurementRequirement` defines the acceptable requirements to check if a quality criterion is met (existence of defects) or not. To relate the quality criterion and an assessment specification, the class `DataQualityCriterionAssessmentAssociation` is used. If two or more assessment specifications are needed for a criterion, more instances of this class can be instantiated and in case that a criterion does not need any assessment specification, no instances are required. Criteria can share the specifications when their assessment specifications are the same.

To relate the quality criteria with the corresponding measurement requirement, the class `DataQualityCriterionMeasurementAssociation` is instantiated. The relationship between a measurement requirement and its corresponding assessment specification is maintained by an instance of the class `DataQualityAssessmentMeasurementAssociation`. To represent the specification of an inspection report, an instance of the class `DataQualityReportRequest` has to be instantiated. Two type of requests are available: `SummaryReprotRequest` for summarized inspection information or a `DetailedReportRequest` for more details about the defected data. The class `DataQualityCriteriaRepresentationWithAccuracy` is a subtype of base class `DataQualityCriteriaRepresentation`. It includes a set of instances of class `MeasurementAccuracy`. This information is used as default value of the required general accuracy for the quality criteria. The measurement accuracy is applied when the measurement algorithm calculates an approximate solution. An example for approximation is when a circular curve has to be approximated into a polygonal curve with straight lines. The approximation process is controlled by an accuracy value given by the user to get an approximated polygonal curve instead of dealing with circular segments. The difference between the exact and approximated solutions has to be smaller than this value. This value can be changed for different measurements, therefore there are two types of accuracies. One can be applied generally and the second for a specific measurement.

Quality criteria can be assessed by logical or numerical tests, therefore, two classes `DataQualityAssessmentByLogicalTest` and `DataQualityAssessmentByNumericalTest` can be respectively used. To define the threshold for a numerical test, a relationship to `DataQualityValueLimitTypeSelect` has to be used. From this class, two options are available: `DataQualityValueRange` or `DataQualityValueLimit` for evaluating the measured value. If the measured value is within the specified range or limit, then a quality defect will be detected. The value limit is represented by a `DataQualityUpperValueLimit` (maximum value) and `DataQualityLowerValueLimit` (minimum value). To define the relationship between the `DataQualityCriterion` and the `MeasurementAccuracy`, an instance of the class `DataQualityCriterionAndAccuracyAssociation` can be used. It relates the required specific accuracy (`MeasurementAccuracy`) with the considered quality criterion. When a specific accuracy is applied, the default general required accuracy will be ignored. The class `SummaryReportRequestWithRepresentativeValue` is a subtype of `SummaryReprotRequest` and used to represent a summarized inspection report with representative measured value on the considered criterion. The summarized report is an instance of the class

`DataQualityInspectionCriterionReport` from the `Product Data Quality Inspection Result` package, section 4.4.1.3.

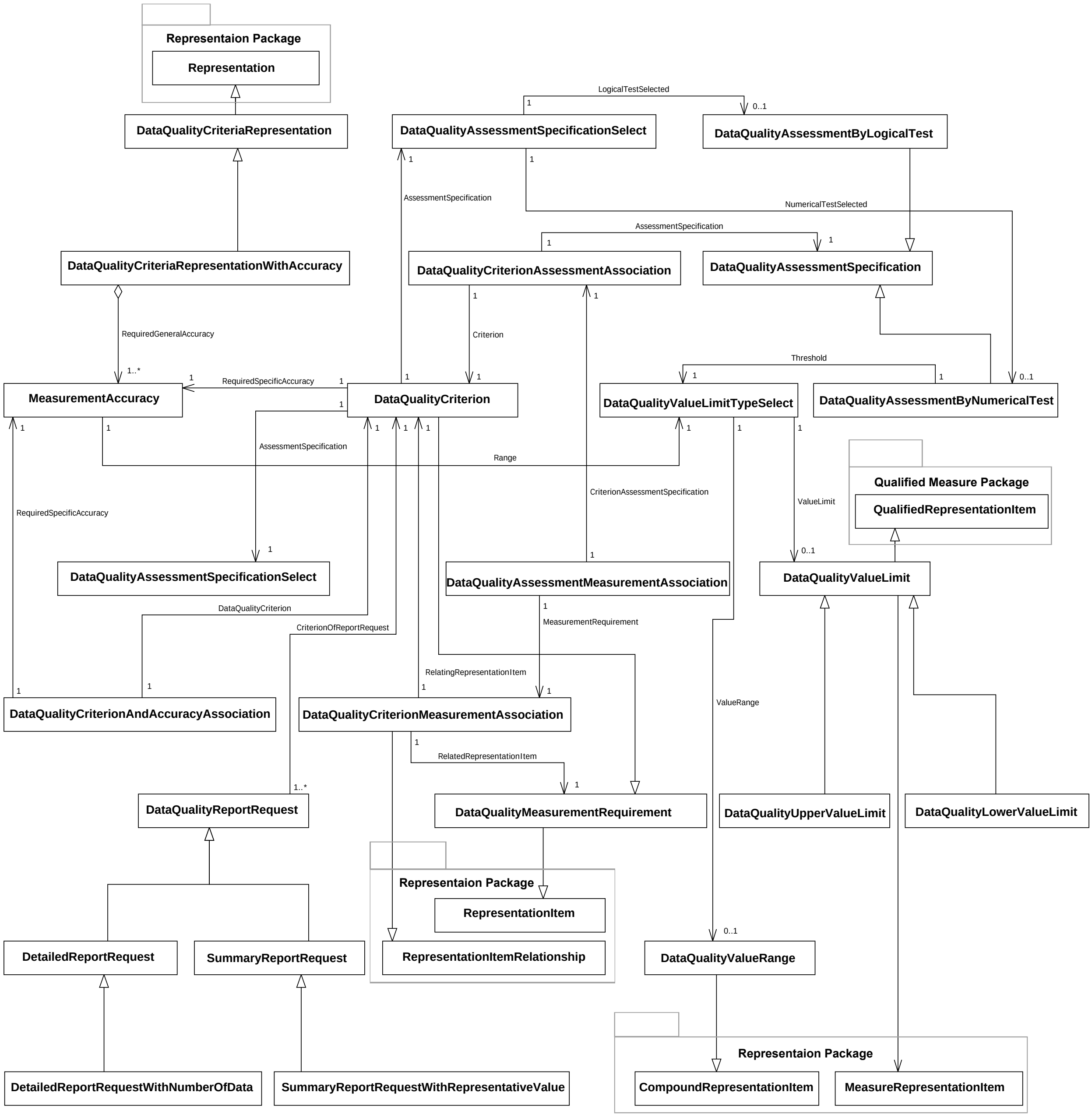


Figure 4.11.: Information model of product data quality criteria package

4.4.1.3. Product Data Quality Inspection Result Package

This package is a part of the product data quality inspection result and shape data quality inspection result schemes of ISO STEP-59 and has been modified to meet the purpose of this research, see Figure 4.12. This package includes the general specifications to represent the result of quality inspection of product data. It is used to relate the product data model with the applied quality criteria. Each usage scenario requires different requirements on the inspection results. For sake of brevity, this package is described briefly. More information can be found in [14].

This package offers two types of inspection result report: the summary report and the detailed report. The summary report gives general information about the inspection results and quality criteria that have been checked. The detailed report provides information about the instances that caused the quality defects. Class `DataQualityInspectionResultRepresentation` represents the results of the inspected quality criteria against specific product data instance. One or more data quality inspection results for each inspected quality criterion are represented by an instance of this class. The inspection result of one specific quality criterion is represented by an instance of the class `DataQualityInpsectionResult`. If a judgment is needed whether the inspected data are defective or not, an instance of the class `DataQualityInspectionResultWithJudgement` has to be created. A boolean attribute is used for this purpose. The inspection report itself is represented by an instance of the class `DataQualityInspectionReport` and has a relationship to the class `DataQualityInspectionResult` for which the report is created. The summary inspection result information for one specific quality criterion is represented by an instance of class `DataQualityInspectionCriterionReport`. An instance of this class must be referenced by at least one instance of class `SummaryReportRequest` from package `Product Data Quality Criteria`. This class has one relationship `StatisticalValues`, which is related to one or two instances of class `DataQualityInspectionCriterionReportItem`. These items show the number of inspected instances of product data and/or the number of the detected quality defects.

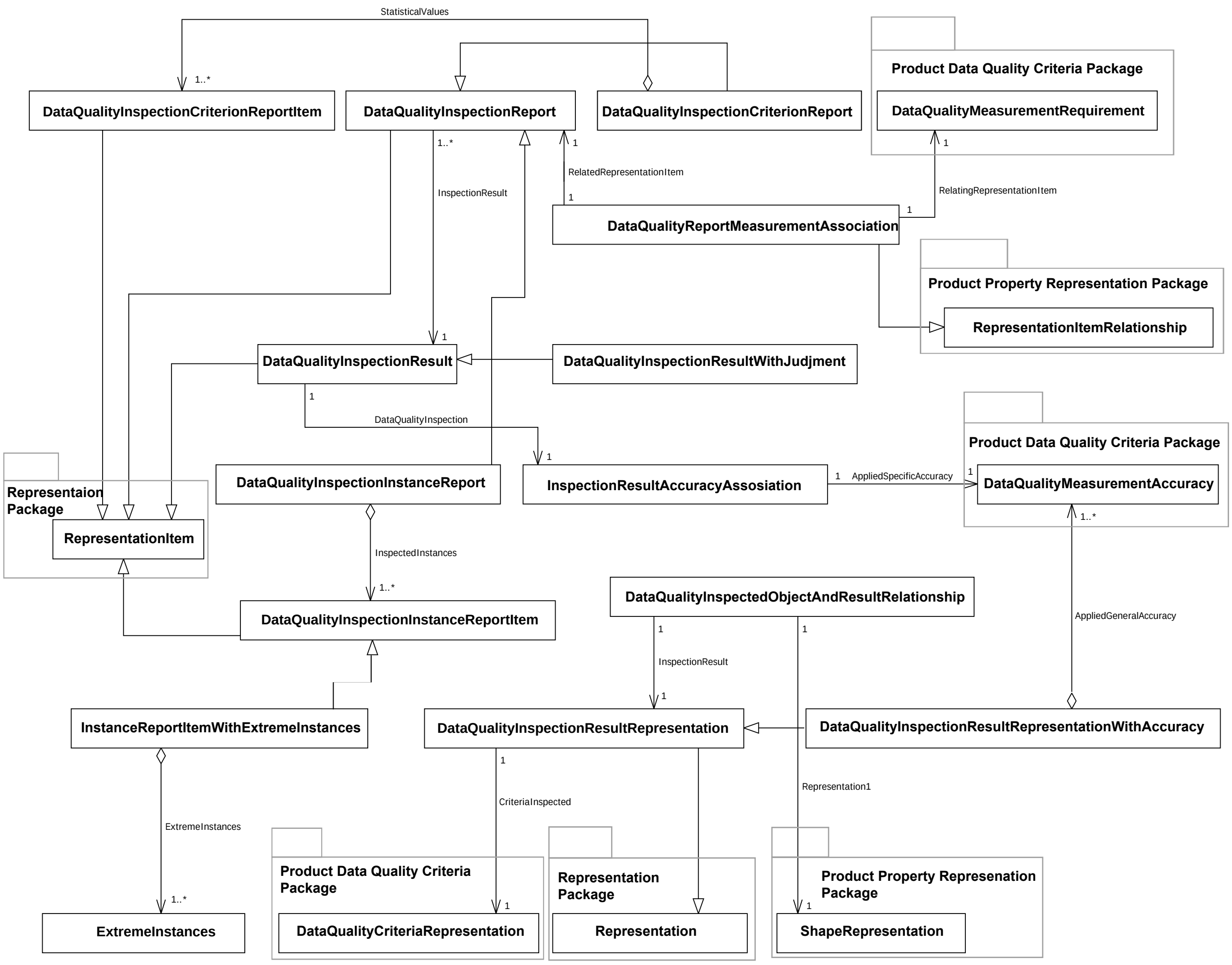


Figure 4.12.: Information model of product data quality inspection result package

The class `DataQualityInspectionInstanceReport` is a subtype of `DataQualityInspectionReport`. An instance of this class represents the inspection result of the inspected instances of the product data for one specific criterion. This class includes a list of the `DataQualityInspectionInstanceReportItems`, each item represents the inspection result for an instance, e.g. `FlatPlate` instance from `Ship Structure` package or a pair of instances, e.g. two instances of class `FlatPlate` of the inspected product data. At least one `DetailedReportRequest` instance has to be referenced by one instance of `DataQualityCriterion`, that is associated with an instance of this class. Class `DataQualityReportMeasurementAssociation` relates the inspection report with the measurement requirement from package Product Data Quality Criteria. A special scheme for shape data quality inspection results is provided in ISO STEP-59. In this work, this scheme is integrated with the scheme Product Data Quality Inspection Result. Therefore, all notations about the shape are omitted. The class DataQualityInspectionResultRepresentationWithAccuracy includes all information of the general accuracies applied to all measurements for inspecting a specified product data against a set of quality criteria. Class DataQualityInspectedObjectAndResultRelationship relates the inspection results and ShapeRepresentation, which represents the shape data of the product data of the ship structure being inspected. To associate the specific MeasurementAccuracy regarding a specific criterion and the DataQualityInspectionResult, an instance of class InspectionResultAccuracyAssociation can be instantiated. Due to the big number of inspected elements and to avoid overload of the storage capacity of the database, the set of the inspected elements will not be instantiated from class DataQualityInspectionInstanceReportItems and only the instances of report items with quality defects will be created. The class InstanceReportItemWithExtremeInstances has information about the elements with quality defects.

4.4.2. Ship Structure Package

Figure 4.13 shows a subset of ISO 10303-218 [9] integrated with the data structure provided by Aveva Marine. The usage has been extended to achieve the research objectives. The model includes all major elements required for analysing of structural parts. The uppermost ship project is represented by an entity of type Project. Each ship consists of several assemblies. These assemblies reflect the actual assembly break down of the ship. Each assembly consists of series of panels to represent the required steel structure. Different panel types can be used such as plane, knuckled, curved panels. The maximum and minimum extents of the particular panel in space can be specified by an entity of type BoundingBox, which is related to two instances of the entity Point of the Geometric and Topological Representation package to define the maximum and minimum points of the box. The class PlanePanel is made up of a number of structural parts such as plate or stiffener or features such as seams and notches. For machinery room, parts of type MachineryPart can be used. Class FlatPlate is a specialization of a StructuralPart entity. This entity has several properties such as the GroupID to which this plate belongs, MaterialGrade, Thickness, DefinitionSide is an enumeration of types PS, BS, CL, NumberOfHoles and Area. To define the simple and detailed outer contours of a plate or the outer contour of a plane panel an instance of type ShapeRepresentationItem from the package Geometric And Topological Representation has to be used. The detailed contour differs from the simple contour, because the level of detail of features like cut-outs and notches are not represented in the simple contour. If a plate includes some holes these have to be represented by an instance with the same name Hole. Parts like panels and plates are also defined topologically based on the neighboring parts, such that an entity of type Boundary can be used to define the limits of the considered part. The Boundary element lists the referred objects Limits, which limits the panel/plate in the intersected plane, such as other panel, hull etc.

Class Limit has two properties defining the welding information i.e. WeldCode and Weldside. WeldCode is of type string and Weldside can be one of the following values: Port, starboard, both or as defined. A Limit can be specified by a start point of type Segment_2D from package Geometrical And Topological Representation and the information about the neighboring structural items specified by an object of type ModelRef. If Limit is a limit of an assembly, an object of type BlockLimit has to be instantiated and related to it. This object defines the excess material information, which has to be checked against the quality criteria regarding the correctness of the assigned excess material as described in subsection 3.6.2.2. A ModelRef element refers to another object or a part within an object and has four attributes: ObjType, ObjId, CompType and CompId. ObjType is the type of object while ObjId is the model object name unique within the database. CompType is the component type while CompId is the component identity unique within the model object. NotchRef is a specialization of class ModelRef and defines the boundary limit on

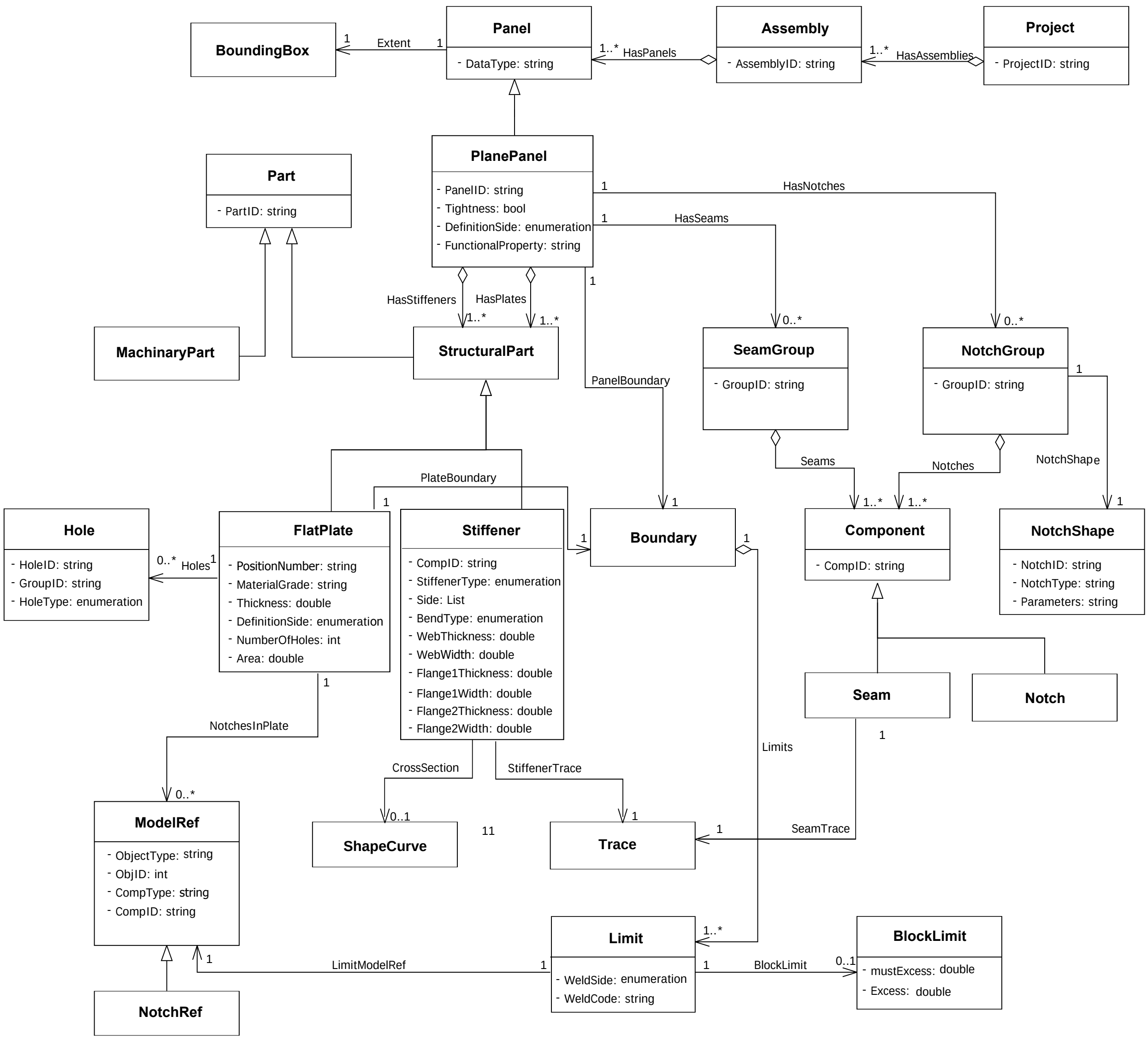


Figure 4.13.: Information model of the ship structure package (subset of ISO 10303-218 [9])

which a notch is defined and this information is provided in `CompType` and `CompId`. A `Stiffener` object has attributes like Id, type, web thickness and flange thickness, side, bending type (straight or curved), etc. The trace line of the stiffener is defined by a separate object of a same name `Trace` in the u-v plane of the local coordinate system by a set of objects of type `Segment_2D` from the `Geometric And Topological Representation` package. The cross section of a stiffener is defined through an object of type `ShapeCurve`, which is related to `ShapeRepresentationItem` from the `Geometric And Topological Representation` package. Each set of notches or seams having the same shapes and types is grouped together within an object of the type `NotchGroup` or `SeamGroup` and each group is distinguished with `GroupID` attribute. The trace of a seam is defined by an object of type `Trace` as used by a stiffener. Notch shape is defined by a `NotchShape` object with the following attributes: `NotchID`, `NotchType` and `Parameters`, for more information see Appendix A.3 Table A.2.

4.4.3. Geometrical And Topological Representation Package

The purpose of this package is to represent the shape and geometry of a ship product model as defined in `Ship Structure` package. This package is a subset of the ISO STEP-42 [11], see Figure 4.14. It can be used for both 2D and 3D geometry. It contains the basic topological classes such as faces, edges and vertices. A geometric shape model provides a comprehensive representation of the shape which in many cases includes both geometric and topological data. For the modelling of product shape, there are classically two types of definition: constructive solid geometry (CSG) and boundary representation (B-Rep). CSG is a type of geometric modelling in which a solid is defined as the result of a sequence of regularised Boolean operations operating on solid models. B-Rep is a type of geometric model in which the size and shape of the solid is defined in terms of the faces, edges and vertices which make up its boundary. In this thesis, B-Rep has been selected, because of its relevance to represent the shape of the structural components defined in the ship structure package, subsection 4.4.2. Geometric and topological representations can be used independently. Within the geometry part, the definition of points, curves and surfaces is provided. Within the topology part, topological entities like vertex, edges, and faces are provided. Faces are bounded by loops and an edge is bounded by vertices. These entities can be associated with geometry classes like point, curve, and surfaces respectively. Transformation information is provided by an object of class type `Local_Coordinate_System`. A local coordinate system can be defined through three objects i.e. the `local coordinate system origin`, `U_Axis`, and `W_Axis`. The `U_Axis` is a unit vector of the orientation matrix which defines along with the origin of the coordinate system, the orientation in the plate's plane. The `W_Axis` is a second unit vector of the orientation matrix which defines the orientation unit perpendicular to the plate's plane. The third unit vector of the orientation matrix can be determined by the cross product of `U_Axis` and `W_Axis`. Class `CartesianPoint` is a subtype of class `point` to define a location by its coordinates in a rectangular coordinate system. The used coordinates are dependent on the used space, namely, one, two or three-dimensional space.

Class `Direction` is used to define a general direction vector in two or three dimensional space. Class `Placement` belongs to the geometrical representation and it is used to locate a geometric item with respect to its geometric context and has two subtypes `Axis2_Placement_2d` and `Axis2_Placement_3d`. Class `Axis2_Placement_2d` defines the location and orientation in two-dimensional space of two mutually perpendicular axes by means of a point from the supertype class `Placement` and an axis. It is used to locate and orientate an object in two-dimensional space and to define a placement coordinate system. The required direction vector is defined by an instance of class `Direction`. An instance of class `Axis2_Placement_3d` is used to locate and orientate a part in three-dimensional space of mutually perpendicular axes. It is defined by means of a point which defines the origin of the placement coordinate system from the `Placement` supertype and two orthogonal axes X and Z. The Y axis can be calculated by cross product. The class `Curve` defines lines, elementary conics, a general parametric polynominal curve, and some referentially or procedurally defined curves. The class `BoundedCurve` is a curve of finite arc length with identifiable end points. Class `PloyLine` is a `BoundedCurve` of n - 1 linear segments, defined by a list of n points. The class `Surface` is used to define a `Face` mathematically. The `TopologicalRepresentationItem` is the supertype for all the representation items in the topology package such as `VertexPoint`, `EdgeLoop`, `Face` and `EdgeCurve`. Each subtype has a geometrical reference i.e. Vertex-Point, Edge-Curve and Face-Surface. Class`Vertex` is the topological object corresponding to a point. Class `EdgeCurve` is a topological object that connects two vertices of type `VertexPoint`: one for the start and the second one for the end of the edge. To locate the edge geometrically in space, a reference to an object of type `Curve` must be created.

In this package, class `PolyLoop` uses a list of ordered coplanar segments of type `Segment_2D` bounding a planar region in space. The planar region represents for example 2D boundaries of structural parts as provided by AVEVA Marine CAD system. The boundary contour of a plate is expressed as contours made up of coplanar circular arc segments `Segment_2D`, which forms a closed contour in a 2D plane. An endpoint and an amplitude vector define a segment. The start point of the segment is the endpoint of the previous segment. The amplitude vector is defined as the vector from the midpoint of the chord between the two points going perpendicular to the top of the arc. A zero-length amplitude vector gives a line segment. A contour has a start point and a number of segments. For a closed contour like a hole, the start and end points in the loop are the same. The direction of the loop is in the direction of the segments. A `Face` is a topological entity of dimensionality 2. The underlying geometry is a surface bounded by loops. A face shall have at least one bound (outer contour) or optionally some inner contours (Holes). The outer bound and inner bounds of a face are defined by instances of type FaceBound. A class FaceBound is a loop, which is used to bound a face. Class ConnectedFaceSet is a set of Faces.

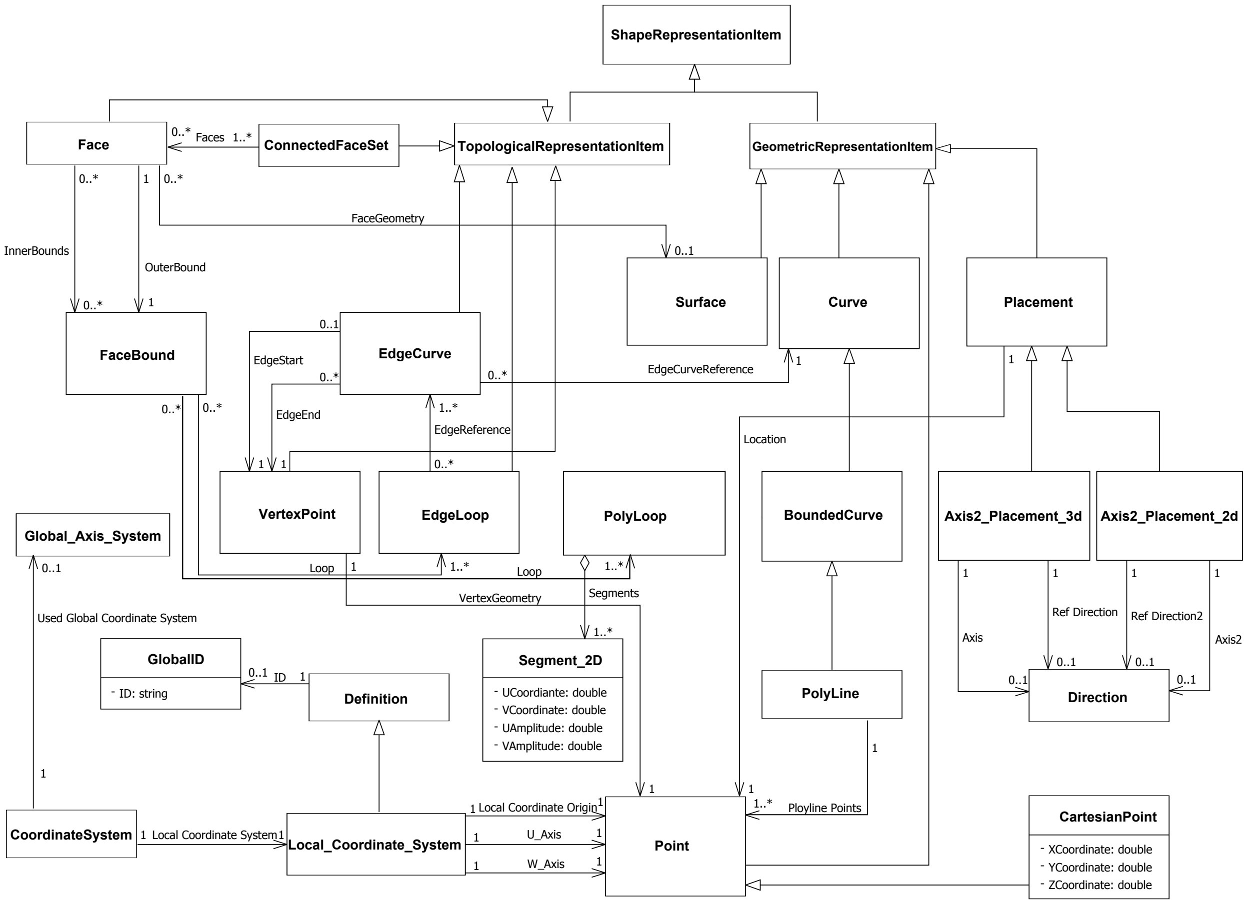


Figure 4.14.: Information model of geometrical and topological representation package (subset of ISO 10303-42 [11])

4.4.4. Support Packages

In this section, all support packages for the quality management framework will be discussed:

4.4.4.1. Product Definition Package

This package is a subset of the product definition scheme as provided in ISO STEP-41. The definitions of products and the different kinds of relationships between products are examples of generic aspects of product definition. More details can be found in ISO STEP-41. A subset of this package is shown in Figure 4.15. Class Product is the identification and description of a physically realizable object by a process like production, manufacturing, fabrication etc. Each product has a unique identification number and name. Class ProductDefinitionFormation defines an identified group of ProductDefinitions for a product and it is used to support the identification of different versions of the same product. Each version is described by a unique group of ProductDefinitions and each group is identified by a ProductDefinitionFormation, which is associated with the same product through a relationship OfProduct. ProductDefinitionFormation has a unique ID such as a part version number. Two ProductDefinitionFormation can be associated by an instance of class ProductDefinitionFormationRelationship. This association can be applied for different Products with different formations with the same product. Class ProductDefinition defines the identification of a product in a particular application context. Different ProductDefinitions of the same Product can be related to the same

ProductDefintionFormation but these definitions can be used in different application contexts. For example physical and functional designs are different ProductDefinition but can refer to the same Product in different contexts. Tow ProductDefinitions can be associated by an instance of class ProductDefinitionRelationship.

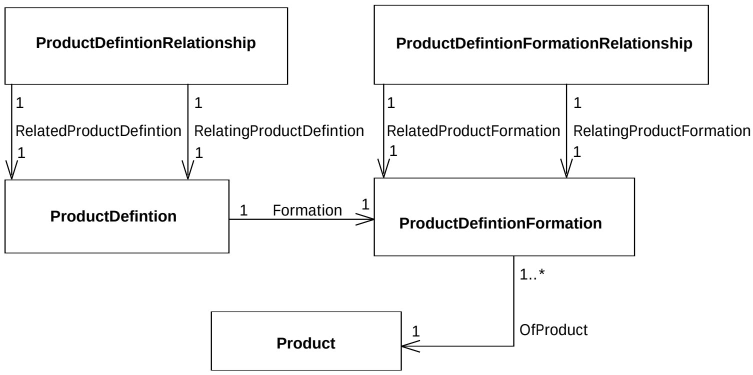


Figure 4.15.: Information model of product definition package

4.4.4.2. Representation Package

This package is a subset of ISO STEP-43. It is used to group elements of product data into collections in order to describe aspects of products, see Figure 4.16. A class Representation is a collection of one or more RepresentationItem instances that are related in a specified RepresentationContext. A RepresentationItem is an element of Representation. One RepresentationItem can be used in one or more instances of Representation. It can also be used in the definition of another RepresentationItem. Class ShapeRepresentationItem is a subtype of RepresentationItem. Examples for RepresentationItem as used in different packages are DataQualityInspectionReport of package Product Data Quality Inspection Result, see Figure 4.12 and classes GeometricRepresentationItem and TopologicalRepresentationItem of package Geometrical And Topological Representation, see Figure 4.14. An association between two instances of RepresentationItem within the same representation or in two different instances of representation can be realized by an instance of a RepresentationItemRelationship.

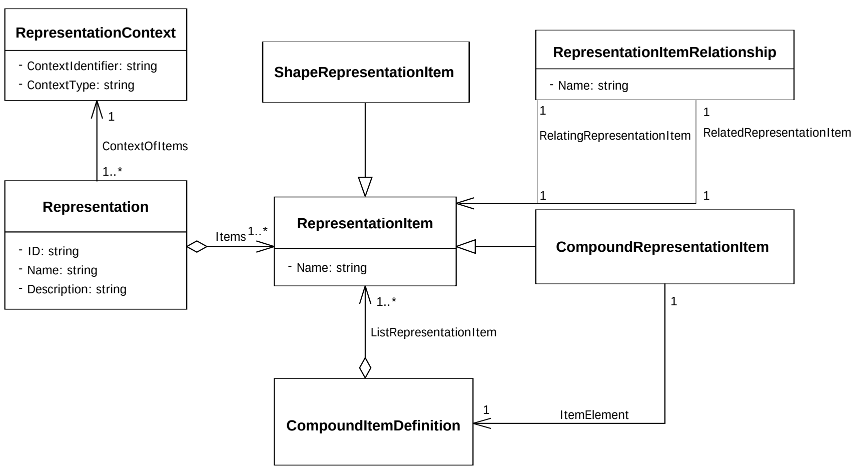


Figure 4.16.: Information model of representation package

4.4.4.3. Measure Package

This package is a subset of ISO STEP-41 and includes resource classes to describe the physical quantities such as time, area, angle, volume and length, see Figure 4.17. Only the used classes will be discussed. More information about this package can be found in ISO STEP-41 [10].

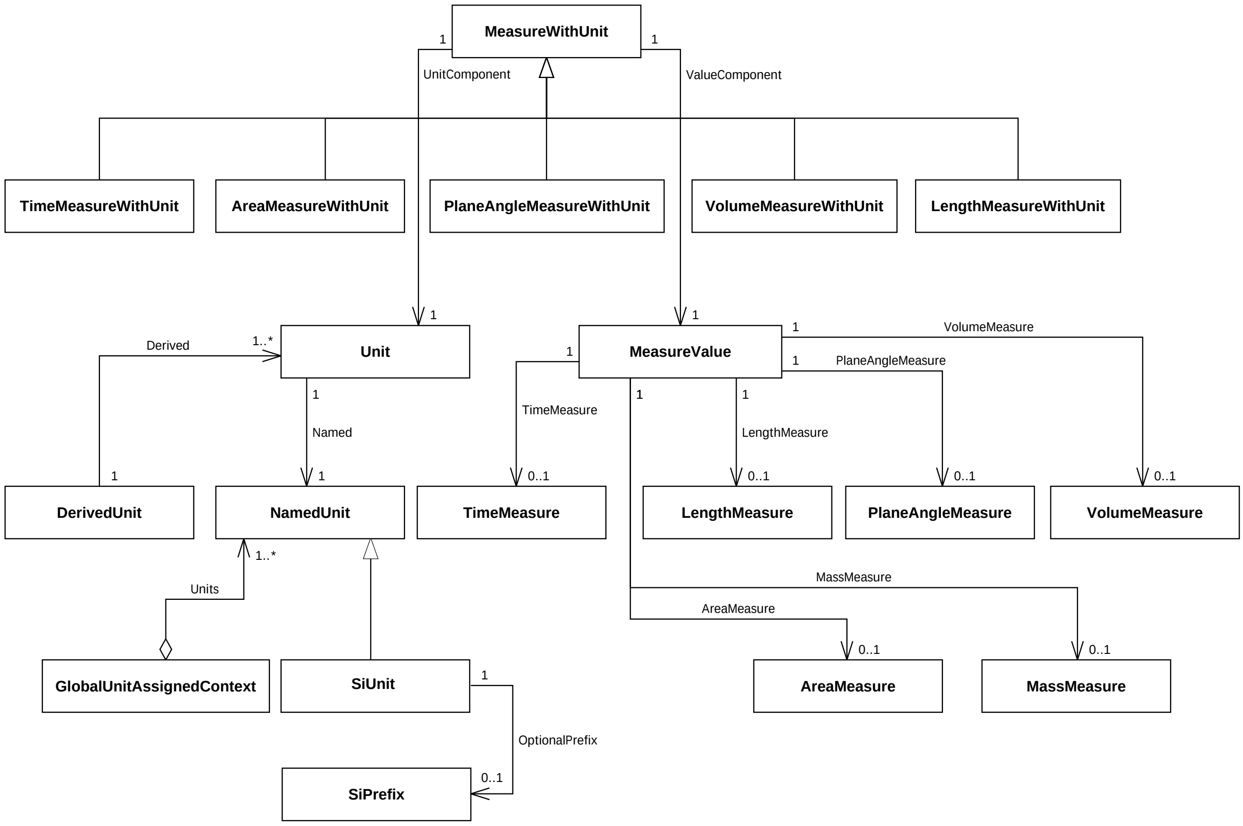


Figure 4.17.: Information model of measure package

Class `MeasureValue` can be one of the following values: `LengthMeasure` for distance, `MassMeasure` for mass, `TimeMeasure` for duration of periods, `PlaneAngleMeasure` for angle in a plane, `AreaMeasure` for extent of a surface, and `VolumeMeasure` for solid content of a body. Class `Unit` defines a physical quantity. The name of the unit is identified by an instance of type `NamedUnit` which can be a word or group of words. This class is the supertype of class `SiUnit`. `SiUnit` is the fixed quantity used as a standard. It may have an optional `SiPrefix` which is the name of a prefix that may be associated with it. The class `DerivedUnit` is an expression of derived units for example kilometer per hour. Class `GlobalUnitAssignedContext` is a subtype of class `RepresentationContext` of `Representation` package and it contains a set of unique units which apply in the `RepresentationContext`. Class `MeasureWithUnit` is the specification of a physical quantity. Classes `TimeMeasureWithUnit`, `AreaMeasureWithUnit`, `PlaneAngleMeasureWithUnit`, `VolumeMeasureWithUnit` and `LengthMeasureWithUnit` are subtypes of class `MeasureWithUnit`. The value of the measured quantity is defined by an association `ValueComponent` to the class `MeasureValue` and the specified unit of the physical quantity is defined by an association `UnitComponent` to class `Unit`.

4.4.4.4. Qualified Package

This package is a subset of the ISO STEP-45 integrated generic resource: Material and other engineering properties. It includes classes to describe the values of the measured data. The class `MeasurementRepresentationItem` is a subtype of classes `MeasureWithUnit` of package `Measure` and class `RepresentationItem` of package `Representation`. Class `MeasuredRepresentationItem` is a subtype of class `RepresentationItem` of package `Representation`. It has a relation to a class `TypeQualifier` which defines the type of the measured value of the following types: maximum, minimum, measured, calculated, nominal, theoretical, reminder, design-allowable, combined, A-basis statistical, B-basis statistical, and arithmetic mean.

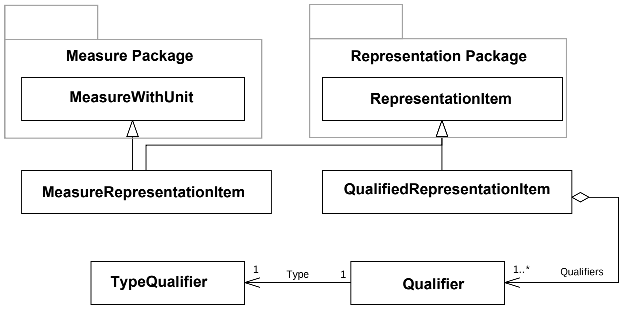


Figure 4.18.: Information model of qualified measure package

4.5. Evaluation and Assessment of Inspection Result

A quality report provides information on the main quality characteristics of a product so that the user should be able to assess product quality. In the optimal case, quality reports are based on quality indicators. As mentioned in section 1.3, if the number of detected product data quality problems is too high, the time needed for production increases and therefore the ship's delivery is delayed. The correction time differs depending on the design phase in which the error has been detected. Depending on the use case of the design data, a quality measure has to be defined in which the grade of the product data quality can be identified. For this purpose and to help the administrators of design departments and quality managers, two related concepts are introduced to assess the maturity of the product data, namely, quality and cost scores.

4.5.1. Quality Score

After finishing the inspection, deficiencies with respect to the predefined production requirements are reported to the engineer while integral quality parameter values allow for an assessment of the overall quality of the design. In order to get a quantified assessment of revealed errors, the quality manager can predefine an individual error weight for the different criteria. For each quality criterion, the number of the revealed errors will be multiplied by an error weight to get the quality score. Each quality criterion is weighted dependent on the severity of the consequences (correction-time) and frequence of occurrence. Quality score indicates how serious an error is from the correction costs point of view. One of five weights can be assigned for each criterion: 5 for KO criterion, 4 for fatal error, 3 major error, 2 for error, and 1 for warning, see Table 4.1.

The degree of product data quality can be obtained by calculating the error rate. Error rate represents the ratio of the summation of all quality scores divided by the total number of errors, Equation 4.1. A value between one and five is expected, with 5 for bad, 4 for faulty, 3 for insufficient, 2 for acceptable, and 1 for free-of-error.

$$Error\,Rate = \frac{\sum Quality\,Score}{\sum Number\,of\,Errors} \tag{4.1}$$

Depending on the error rate, the of CAD data are forwarded to downstream processes or departments. To support an efficient correction of deficient structural designs, an approach is presented which allows the correction of faulty structures under visual guidance towards the identified problems applying the same CAD system as used for the product model data generation. The so-called error-feedback allows the engineers to detect and fix the automatically detected error easily by means of error visualization based on the CAD system being used. This will result in significant time savings in the production phase as the designer can already analyse whether the formulated requirements are met. They concentrate their efforts on the major defective parts and blocks. This method depends on the application program interface (API) provided with the used CAD system. Depending on the API a "macro" is automatically defined to display the faulty structural part(s), e.g. by different colours within the specific design context. An error message will also be displayed on the screen, specifying the type of the identified error related to a specific quality criterion. In addition to displaying the individual defective parts, the inspected blocks will be displayed in different colours according to the error rate. The colours allow recognition at a glance of how many errors are in the block and what their weight is. The display colour varies between green for a block with few errors gradually to yellow for blocks with average error rate and finally to red for blocks with a maximum error rate, see Figure 4.19. For this purpose, the error rate in each block will be calculated as a percentage of the whole of detected quality issues. In the next step, the minimum and maximum error rates will be determined and this range will be divided into ten fields from the minimum to the maximum value.

Criterion	QC-Identifier	Weight
Missing excess	O-EX-MI	5 (KO)
Not standard excess (big)	O-EX-NS	3 (Major Error)
Not standard excess (small)	O-EX-NS	5 (KO)
Not conclusive excess	O-EX-NC	2 (Error)
Missing bevel code	O-EP-MI	5 (KO)
Not standard bevel code	O-EP-NS	5 (KO)
Not conclusive bevel code	O-EP-NC	5 (KO)
Missing notch	O-NO-MI	4 (Fatal Error)
Not standard notch	O-NO-NS	4 (Fatal Error)
Not standard distance between two seams	O-SSDI-NS	4 (Fatal Error)
Not standard distance between two stiffeners	O-PPDI-NS	4 (Fatal Error)
Not standard distance between stiffener/seam	O-PSDI-NS	4 (Fatal Error)
Not standard angle between two seams	O-SSAN-NS	4 (Fatal Error)
Not standard angle between two stiffeners	O-PPAN-NS	4 (Fatal Error)
Not standard angle between stiffener/seam	O-PSAN-NS	4 (Fatal Error)
Missing position number	O-PN-MI	1 (Warning)
Not standard position number	O-PN-NS	5 (KO)
Not conclusive position number	O-PPPN-NC	5 (KO)

Table 4.1.: Weights of quality criteria

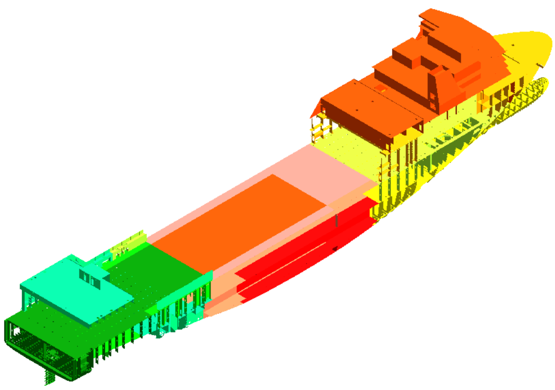


Figure 4.19.: Block-wise representation of ship according to error rate

4.5.2. Cost Score

Cost score can be calculated through estimation of the time needed for error correction as a percentage of the total work time. To calculate the cost score, the durations shown in Table 1.1 can be approximated, [40]. In detail design phase on average 25 to 35% of the work will be spent to correct an error. In the drawing inspection phase, there is a big difference in the estimated times for an error correction. The designers need between 1 minute and a whole working day of 8 hours for an error correction. The error correction during the generation of the manufacturing information averages between 25 minutes and 1.5 hours. In some cases, the error correction may take about 3 days for one single error. Correction time is most difficult to assess for errors detected in the production phase. The expected time to fix an error is estimated at 1.5 to 2 hours for some kinds of inapt design. For some cases, error correction can be done within minutes, while for other cases such as problems with edge preparation it may take up to 80 hours to complete the correction. It is clear that the later an error is discovered, the more time is needed to solve the problem. It may take six times more to correct an error in the production phase than it takes in the detail design phase.

In Appendix A.2 Table A.1, some correction times are listed depending on the error nature and the detection phase, to assist the project manager to assign the required resources for the correction of the product data model. The detected errors will be multiplied by the approximated correction time. Then, a statistical dispersion study will be performed to get some key values to support the quality management team to make the right decision and to assign the appropriate resources.

5. Algorithms

In the previous chapter, the quality management system was introduced, whereby, different quality criteria to assess the relevance of the product data were discussed. To check the compliance of product data with the formulated quality criteria, several algorithms were implemented and developed. The applied algorithms differ in their complexity and their application usage. In the simplest cases, only a comparison of single attribute of product data is needed for the error detection. In other scenarios, complex algorithms for analyzing the geometrical and topological relationships of the structural parts are applied. For some quality criteria, several steps are needed to prepare the data for the analysis such as the pose estimation and approximation of the curved segments. Depending on the nature of the quality aspect, the applied algorithms can be classified in three groups:

- analysis of shape aspects,
- ensuring optimized manufacturing and production processes,
- ensuring the function of the inspected parts

The first group includes algorithms to check the equality of the shapes of structural parts. The shape of structural parts can be represented in the 2D or 3D spaces as described in section 4.4.3. The algorithm presented in this chapter for evaluating the identity of the shape of structural parts, here focusing on plates parts, is based on the Fréchet distance method for the 2D space case. The Fréchet distance is widely used in medical imaging and drug design fields in order to identify similar forms. For the 3D case, three algorithms, namely shape distribution, 2D slice and Monte Carlo algorithms are applied. The 2D slice algorithm is proposed for the first time. These algorithms, to the best of the author's knowledge, have never been used in the context of ship design CAD systems before. The second group includes algorithms to check the product data for ensuring optimized manufacturing and production processes and to preserve the design intention. The last group of algorithms focuses on quality requirements regarding the provided notches.

5.1. Analysis of Parts Information

The position number is one of the most important piece of information which must be assigned to structural parts. The correctness of parts identification numbers is vital for a seamless production phase. The control of the position number quality criteria includes three sub criteria. First, the inspection for missing position numbers, second to check for position numbers which were not assigned according to the standards, and finally, the conclusiveness of the assigned position numbers. The control of the first two criteria is simple, where the only information needed is the position number value, which must be retrieved from the CAD system database. The latter criterion is much more complicated because the conclusiveness of the position number includes the analysis of the shape aspects. The developed algorithms for checking the conclusiveness must consider 2D and 3D shape representation of the structural parts.

5.1.1. Missing Position Number O-PN-MI

This criterion states that all structural parts must have position number assigned to them. The control of position number is simple and performed by checking if the attribute `PosNo` of an object `FlatPlate` is not empty as shown in Listing 5.1. This kind of error is easy to check and can be eliminated by new assignment of position numbers.

Listing 5.1: Test missing position number

```
algorithm ‘‘Missing position number’’
  when
           position number: FlatPlate(PositionNumber == null || PositionNumber == ‘‘’’)
  then
           error: ("Missing position number" , 1 );
end
```

5.1.2. Position Number not Standard O-PN-ST

Position numbers are unique and are assigned according to the shipyard or project guidelines. Depending on the structural parts types, position number are usually falling in number groups as those shown in Table 5.1.

Part type	Number group
Plate	$0 < \text{PosNo} \leq 1000$
Stiffener, Pillar and Flange	$1001 \leq \text{PosNo} \leq 2000$
Bracket	$2001 \leq \text{PosNo} \leq 2500$

Table 5.1.: Groups of position numbers according to part type

The recommended values are assigned to the corresponding `DataQualityValueLimit` discussed in section 4.4.1.3. The upper and lower values represent the number range for the inspected parts. Listing 5.2 gives an example algorithm for testing standard position number criterion for structural parts of type plate.

Listing 5.2: Test standard position number

```
algorithm ‘‘Standard position number’’
  when
           position number: FlatPlate(PositionNumber > 0 && PositionNumber ≤ 1000)
  then
           error: ("Position number not standard" , 5 );
end
```

Detection of an error of this type is critical in the production phase, therefore a weight of 5 is assigned to this error.

5.1.3. Position Number not Conclusive O-PPPN-NC

Identical parts must have the same position number. The identity in this case includes shape equality of parts having the same position number and the equality of the attributes for both parts. Checking the equality of attributes is a simple task compared with checking shape equality. Listing 5.3 shows an example of implementation of attributes inspection.

Listing 5.3: Test attributes equality for conclusive position number

```
algorithm ‘‘Conclusive position number’’
  when
          position number: FlatPlate (Plate1.PosNo == Plate2.PosNo)
          if (Plate1.thickness != Plate2.thickness || Plate1.area != Plate2.area ||
          Plate1.weight != Plate2.weight || Plate1.NumberOfHoles != Plate2.NumberOfHoles)
  then
           error: ("Position number not conclusive" , 5 );
end
```

Errors of this group is also weighted with 5. To check the shape identity, it must be distinguished between the 2D or 3D shape representations of structural parts. In the following subsections, different algorithms will be discussed. Listing 5.4 shows the general scheme for shape comparison:

Listing 5.4: Test shape equality for conclusive position number

```
algorithm ''Conclusive position number''
  when
          position number: FlatPlate (Plate1.PosNo == Plate2.PosNo)
          if (ShapeComparison (Plate1, Plate2) == false)
  then
           error: ("Position number not conclusive" , 5 );
end
```

5.1.3.1. 2D Case

To assess the shape identity, the Fréchet distance algorithm can be applied, [29] [71]. The Fréchet distance is a metric in the space of continuous curves like those describing the outer contours of structural parts. It takes into account the order and position of the points defining the curves. If the outer contours of two structural components are considered, the Fréchet distance describes the maximum deviation of the contours. In order to use the 2D representation of structural parts produced by a CAD system in the mathematical operation it is necessary to convert such representations to polygonal curves, which are loops consisting of straight edges bounding planar regions in space. These loops are represented by a list of coplanar of points forming the vertices of the loops. Doing such approximation allows the curve to be represented by a list of sequenced straight edges. Parametrizing the polygonal curve by using a parameter $b \in R$ enables the user to refer to a position along the curve. For example, two polygonal curves P and Q consist of N and M points respectively. $P(0), Q(0)$ are the first points of the curves and $P(\mathrm{N}), Q(\mathrm{M})$ the last one, as shown in Figure 5.1.

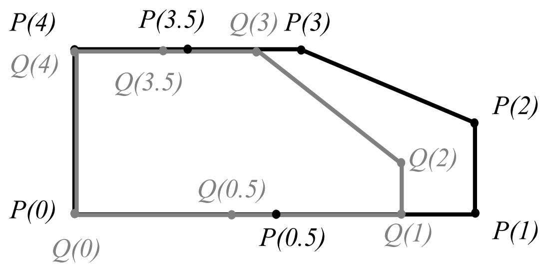


Figure 5.1.: Parameterization of two polygonal curves

By using two continuous and increasing functions $\alpha(t)$,$\beta(t)$ with $t \in [0,1]$, arbitrary positions on the polygonal curves P and Q are defined. The Fréchet distance for two curves P and Q is defined in the following form:

$$\delta_F(P,Q) = \min_{\substack{\alpha[0,1]\longrightarrow[0,N] \\ \beta[0,1]\longrightarrow[0,M]}} \; \max_{t\in[0,1]} \{ d(P(\alpha(t)), Q(\beta(t)))\} \tag{5.1}$$

with $\alpha(0) = 0$, $\alpha(1) = N$, $\beta(0) = 0$ and $\beta(1) = M$. d represents the Euclidian distance between two points. The Fréchet distance in this case is the smallest distance among all distances between points defined by using the functions $\alpha(t)$, $\beta(t)$ along P and Q.

5.1.3.1.1. Computing Fréchet Distance of Two Curves

Through parameterization of the two contours, the parameter space of the points on the two polygonal curves is represented. Firstly, two polygonal curves $P(\mathrm{s})$, $Q(\mathrm{t})$ consisting of one segment each will be considered. It will be tested if the Fréchet distance $\delta_F(P,Q) \leq \delta$, with δ is the predefined tolerance. Thus, the free-space will be defined as follows:

$$F_\delta = \{(s,t) \in [s, s+1] \times [t, t+1] \,|\, d(P(s), Q(t)) \leq \delta\} \tag{5.2}$$

F_δ describes all pairs of points, one on P, one on Q, whose distance is at most δ.

In Figure 5.2, two line segments $P(2)P(3)$, $Q(3)Q(4)$ of the shapes shown in Figure 5.1, with a distance $\delta > 0$, and F_δ the white area within the unit square are depicted.

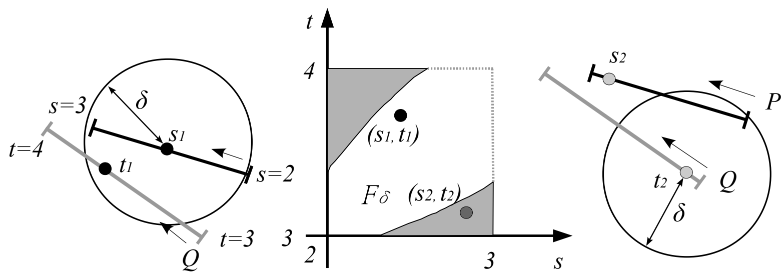


Figure 5.2.: Free space of two segments

As the distance between the two points defined by s_1 and t_1 is smaller than δ, the corresponding parameter pair in the unit square is member of the free space. The two points defined by s_2, t_2 however are not members of the free space as their distance is larger than δ. An important conclusion according to [29] is that the resulting free space of two line segments is always convex.

The effect of δ on the free space F_δ is shown in Figure 5.3. Since the δ_1 value is smaller than the δ value used in the previous example the resulting free space is smaller.

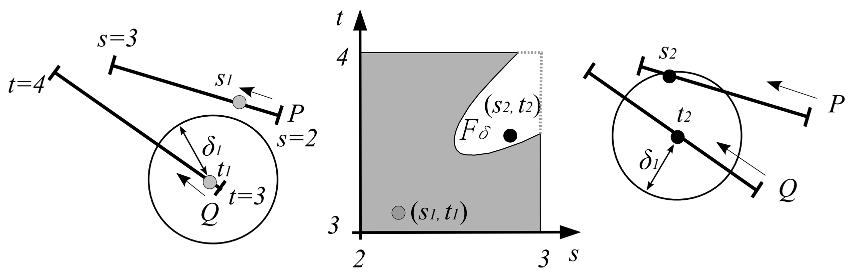


Figure 5.3.: Effect of δ on the free space

5.1.3.1.2. Comparison of Polygonal Curves

Two polygonal curves are identical if a monotone curve within the corresponding free space exists. An example combination of two segments is shown in Figure 5.4. The free cell F_δ (i,j) with i=2, j=3 corresponding to the segments above $P(2)P(3)$, $Q(3)Q(4)$ can be determined by finding the intersection of the free space with the edges of the cell (unit square) F_δ (2,3). After calculating the intersection, the monotone curve passing from (s=2, t=3) to the end point (s=3, t=4) can be determined. In Figure 5.4 for a pair of segments, the values $(a_{ij}, b_{ij}, c_{ij}, d_{ij})$ and $(a_{i+1,j}, b_{i+1,j}, c_{i,j+1}, d_{i,j+1})$ of the free space are shown, which are found by circle-segment intersections. For the calculation of $c_{ij}, d_{ij}, c_{i,j+1}$ and $d_{i,j+1}$, circles of radius δ are defined with the centroid in $P(2)$ and $P(3)$. The intersection is represented on the left c_{ij}, d_{ij} and right side $c_{i+1,j}, d_{i+1,j}$ of the square. The same process is performed for the segment Q and the intersection with P represented on the bottom a_{ij}, b_{ij} and upper side $a_{i,j+1}, b_{i,j+1}$ of the square. As an example, the point represented by a black triangle results from the case depicted on the right side of Figure 5.4.

Equation 5.2 can be extended for polygonal curves each consisting of more than one segment:

$$F_\delta = \{(s,t) \in [0, n] \times [0, m] \,|\, d(P(s), Q(t)) \leq \delta\} \tag{5.3}$$

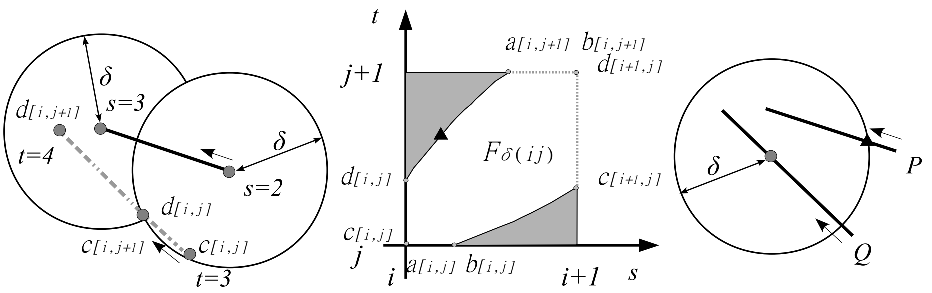


Figure 5.4.: Example for calculating the necessary values

In Figure 5.5, two polygonal curves P and Q and the corresponding free space are depicted. The horizontal axis represents the segments of the polygonal curve P which are in this case six segments. The four segments of polygonal curve Q are represented on the vertical axis. Therefore, each element represents the result from the distance analysis of the two corresponding segments on P and Q forming a $n \times m$ matrix.

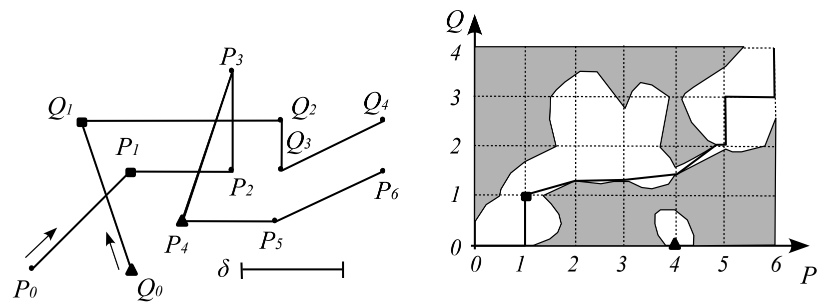


Figure 5.5.: Free space of two polygonal curves (from [29], Fig. 3)

The two polygonal curves are considered to be identical if a monotone curve exists passing through the free space from s=0, t=0 to s=n, t=m, where n and m are the number of segments of the polygonal curves P, Q respectively. If this is the case, the Fréchet distance is smaller than a predefined tolerance value δ. As in this example, if the distance between P_1 and Q_1 (in Figure 5.5 marked by a small black square) is smaller than δ it is part of the free space and considered while checking the existence of the monotone curve. The distance between P_4 and Q_0 (in Figure 5.5 marked by a small black triangle) is also within the defined tolerance δ but the parameter pair s_4=1, t_0=0 does not participate in the monotone curve as it has no connection to the remaining free space.

The Fréchet distance will not be calculated but it will be tested for if for a user defined tolerance δ, a continuous monotone curve exists passing through the free space from (0, 0) to (n, m), where n and m are the number of the segments of the polygonal curves P, Q respectively. To check for the existence of a monotone curve, a graph data structure is applied. The main elements of the graph are the vertices and the edges which connect the vertices. In the context of the shape identity detection the intersections resulting from each pair of segments on both polygonal curves represent the vertices. After calculating all possible intersections and storing in a graph, the Dijkstra's algorithm [21] is used for searching a path (monotone curve) from the start to the end of the free space. In the following discussion some examples are detailed.

In Figure 5.6 two plate parts P, Q represented by their outer contours are depicted, which in this case are evaluated as not being identical. The corresponding free space is shown together with the limiting parameter pairs marked by a star and a triangle. The white small triangle in Figure 5.6-right results from the analysis of segment combinations P_7P_8, Q_1Q_2 and P_7P_8, Q_2Q_3. According to the applied tolerance value δ^*, the resulting intersections are depicted on the cells edges.

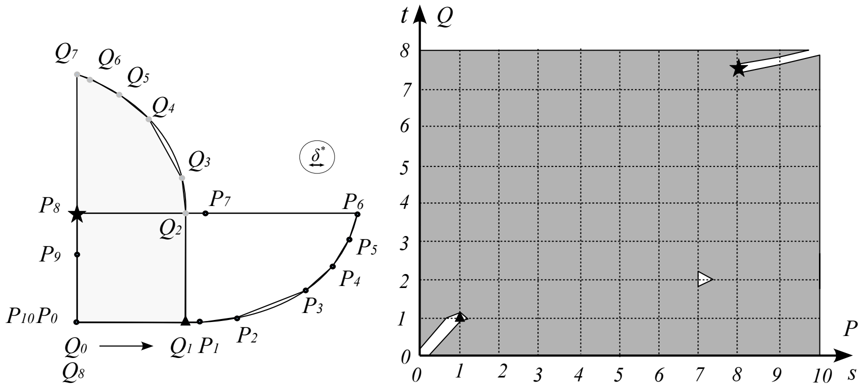


Figure 5.6.: Free space for two parts in an unsuitable position

In Figure 5.7 the same two plate parts are shown. In this case, with the same tolerance δ^*, a monotone curve exists passing continuously through the free space from the beginning to the end. Therefore the two parts are considered to be identical. These two examples show the importance of a well conditioned orientation of the parts being analyzed for identity before the algorithm is applied.

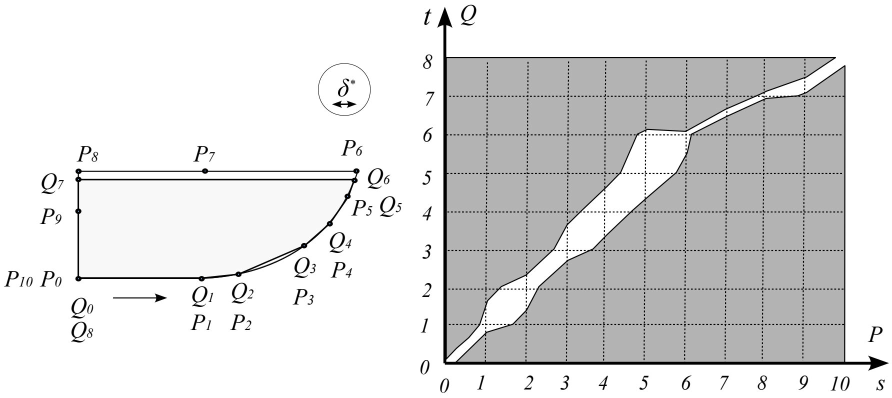


Figure 5.7.: Free space for two identical plates

The effect of tolerance and number of vertices on the comparison result as well as the computation of part orientation are described in detail in [71].

5.1.3.1.3. Implementation

The workflow is shown in Figure 5.8. The process starts with the selection of two plate parts to be evaluated for an identical shape and ends with the result which is expressed by “parts are identical” or “parts are not identical”. The implementation was performed in a such way as to observe the overall runtime efficiency.

1. Two parts are selected; and the thickness, material and the number of inner contours (holes) are compared. If one of these conditions is not satisfied, the process is stopped and another pair of parts will be analyzed.
2. The contours of the boundaries are approximated by polygonal representations driven by e.g. a production tolerance σ.
3. The two parts are compared with respect to their area and the second moments of area $Imax, Imin$.
4. Both contours are translated and oriented so that the principle coordinate systems coincide.

5. The two outer contours are tested for identity based on the Fréchet algorithm with a given tolerance δ.
6. If the two contours are not identical the second contour is reflected about the X axis and checked for identity again.
7. If the two contours are not identical the second contour is reflected this time about the Y axis and checked for identity again.
8. If both parts have the same outer contour observing the given tolerance, the inner contours are checked for identity applying the same algorithm as for the outer contours.
9. If identical hole representations are detected the process stops and new parts will be selected continuing until all possible combinations have been processed.

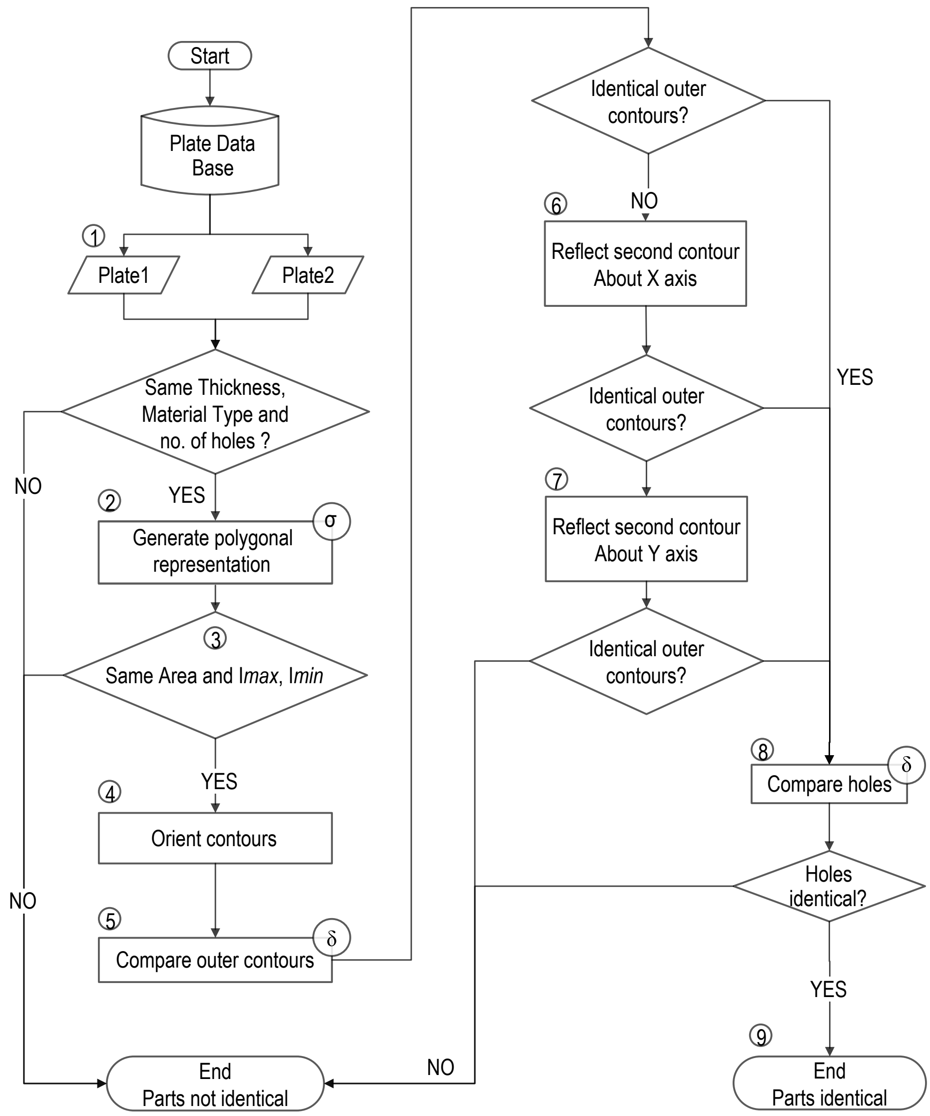


Figure 5.8.: Flow chart for comparing two plane plate parts for identity

5.1.3.2. 3D Case

Shapes can be compared based on their statistical properties as discussed in the subsection 5.1.3.2.1. A novel algorithm based on the Monte Carlo method is also developed to evaluate the similarity of 3D shapes, subsection 5.1.3.4. Finally, a new method called 2D-slice algorithm is developed for shape matching. The key function of this method is to reduce the 3D shape matching problem to a 2D problem through replacing the 3D shape representation by a set of 2D slices along the main principle axes of the structural part as discussed in subsection 5.1.3.3.

5.1.3.2.1. 3D Shape Distribution

The key of the distribution-based shape method is to find an appropriate shape signature that can be created and compared fast with the ability to discriminate the similar and dissimilar shapes [75]. The used signature is called the shape distribution and it is sampled by measuring some geometric distances on the surface of an object. The advantage of this method is its simplicity by reducing the shape matching problem to the comparison of two shape distributions describing the shapes of two objects. In this method, the 3D representation is replaced by a histogram using the shape function which measures the geometric properties of the 3D model [123]. An example of these shape functions is the so-called D2 function, which represents the distribution of Euclidean distances measured between pairs of randomly selected points on the surface of a 3D model. After computing the shape distributions, the dissimilarity value is easily calculated by the application of any metric for measuring the distance between distributions. The following properties of shape distribution are very useful for shape matching, [126]:

- Invariance: shape distribution is invariant against all transformations of a rigid body like translation, rotation, and reflection. Invariance against scaling can be achieved by normalizing the shape distributions before the comparison.
- Robustness: shape distribution is insensitive to small perturbation in the polygonal mesh because of the random sampling. The degree of the changes to the shape distribution is directly related to the degree of the changes to the 3D model.
- Generality: shape distributions are independent of the representation and the topology of the 3D models. It can be applied on a polygonal mesh or constructive solid geometry etc. which are quite common representations in the shipbuilding domain.

The D2 shape function is the preferred function, because it produces the most distinctive invariant shape signature as suggested in [123].

Building Shape Distributions

This process is performed as proposed in [75]: firstly, n points have to be sampled on the tessellated faces. For this purpose, all triangles will be traversed and the number of points in each triangle m is determined by multiplying the ratio of the area of the considered triangle to the whole object's area by the number of the points to be sampled n. If $m < 1$, m is assigned 1, otherwise, m is assigned the least integer greater than m. After computing of m, the points in the target face are generated according to the following equation:

$$P = (1 - t_2)A + t_2(1 - t_1)B + t_1 t_2 C \tag{5.4}$$

with `P` being the sampled point in a triangle with the vertices (`A`, `B`, `C`). t_1, t_2 are random numbers between 0 and 1. To ensure the randomicity of the sampled points, t_1 is computed using the following formula $t_1 = 1/(1{+}m)$ and t_2 is randomly generated. It must be noted that the comparison results depends on the density of the sample points. The larger the sample, the more distinctive and accurate the shape distribution is. But the accuracy has a negative effect on the computing time. The total sampled points may be more than the proposed number, due to the mentioned assumptions. The Euclidean distances between all pairs of points will be computed and stored. To evaluate the shape similarity, a shape distribution from the measured distances must be constructed.

The maximum computed distance is determined and divided into $B = 64$ fixed sized bins. By counting the distances which fall into each bin, a histogram can be constructed.

Some examples for the shape distribution are shown in Figure 5.9. In each plot, the horizontal axis represents the normalized distances and the vertical axis represents the normalized probability of the distances that fall in each bin. The normalization of the distances on the horizontal axis is achieved by dividing each measured distance by the maximum measured distance. The probability of the distances on the vertical axis is normalized by dividing the number of the counted distances in each bin by the total number of the measurements.

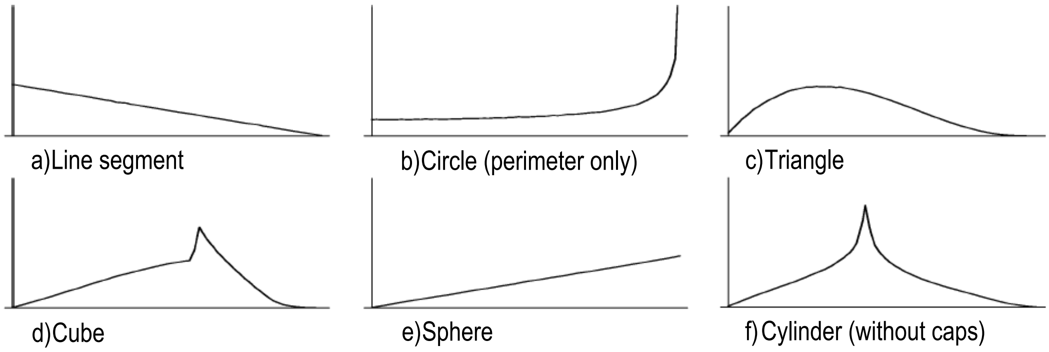


Figure 5.9.: Example for shape distributions using shape function D2 (taken from [79])

Comparing Two Shape Distributions

There are many ways to compare two shape distributions. For instance, Minkowski L_N norms or the Earth Mover's distance [80]. In this thesis, the $L1$ is used to compute the dissimilarity measures. $L1$-norm is also known as the least absolute deviation or least absolute error. It is basically minimizing the sum of the absolute differences (S) between two set of values Y_i and X_i:

$$\mathbf{S} = \sum_{i=1}^{n=64} |Y_i - X_i| \tag{5.5}$$

Implementation

All steps to construct a shape distribution of 3D model represented as a polygonal mesh are depicted in Figure 5.10. Figure 5.11 shows the structure of the shape similarity evaluation using the shape distribution.

Shape matching using the shape function D2 is illustrated in the following steps, see Figure 5.12:

1. A query plate is selected from the plates repository (polygonal mesh).
2. In the next step, shape representation will be extracted (vertices and triangles). Each triangle consists of three vertices and each vertix defined by three coordinates `x`, `y`, and `z`, see Appendix A.4.
3. In the next step, the subareas of each triangle as well as the total area of the of the selected plate will be computed.
4. Depending on the subareas and the total area, the number of points to be generated in each triangle is determined.
5. The number obtained from the previous step is used to generate the random points according to Equation 5.4.
6. The maximum measured distance between the points is determined.
7. Building of shape distribution as mentioned above.
8. A candidate plate is selected from the rest of the plates and steps 1 to 7 will be performed. A second shape distribution is calculated to be compared with the one created for the first plate.
9. Similarity evaluation is performed using equation 5.5. The dis/similarity measurement is a real number. Similarity value is located in the range between zero for two identical plates and 2 for totally different plates. This range results from the fact that the summation of the values

of shape distribution is equal to one because of normalization. According to this, two identical plates have the same shape distributions and thus the similarity value must be equal to zero or very close to zero and that depends on the density of the generated points.

10. The above mentioned steps will be applied on all candidate plates.
11. The comparison result is represented as a matrix, see chapter 7 for more details.

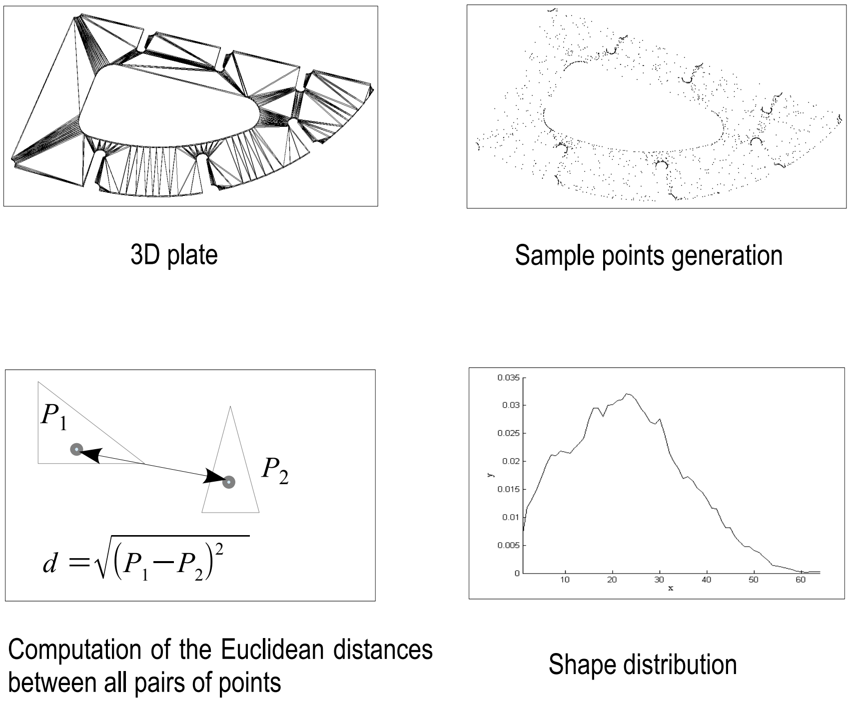


Figure 5.10.: Generation of shape distribution for a plate using the shape function D2

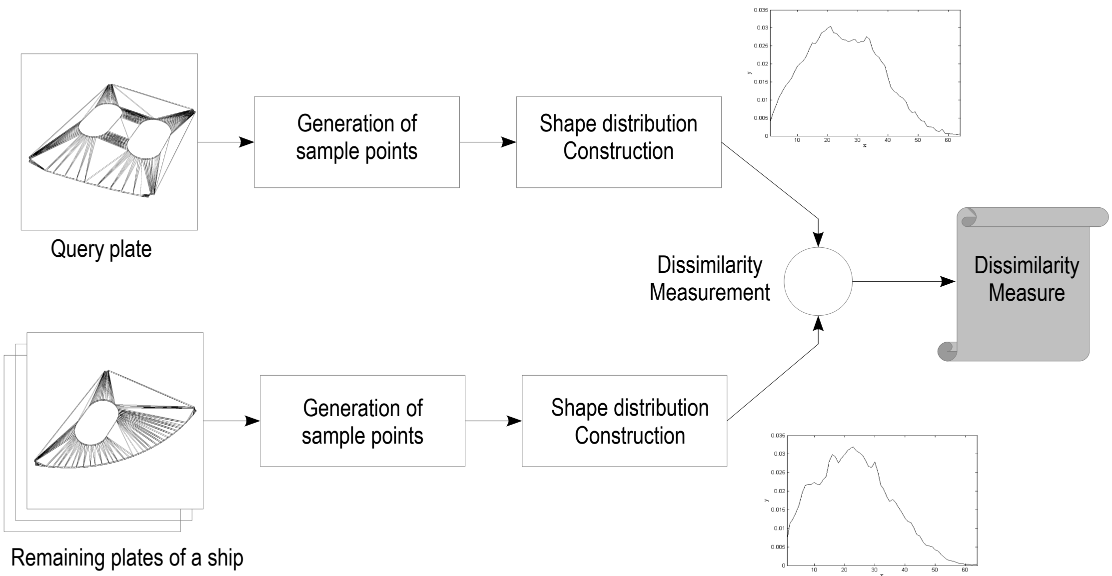


Figure 5.11.: Structure of shape similarity for 3D plates

5.1.3.3. 2D-Slice Algorithm

In this subsection, a novel approach for evaluating the similarity of ship structural parts is introduced. The key idea of this approach is to reduce the evaluation problem from 3D to 2D space. This is achieved by replacing the shape representation of a 3D model by a set of 2D slices along the main principal axes. The evaluation can be then performed by comparing the two sets of slices for the inspected models. This approach needs a pose estimation of the compared objects. This step includes the determination of object's orientation in the 3D space by obtaining the orientation of its main principal axes. After determining the object's orientation, a transformation step is needed to move the object in the global coordinate axes system. This ensures that the principal axes of the object coincide with the global coordinate axes system. After performing the transformation, a set of 2D slices along the global coordinate axes will be constructed. This process will be discussed in detail in subsection 5.1.3.3.2. The comparison of the resulting two sets of slices is performed using the Fréchet distance as described in subsection 5.1.3.1.

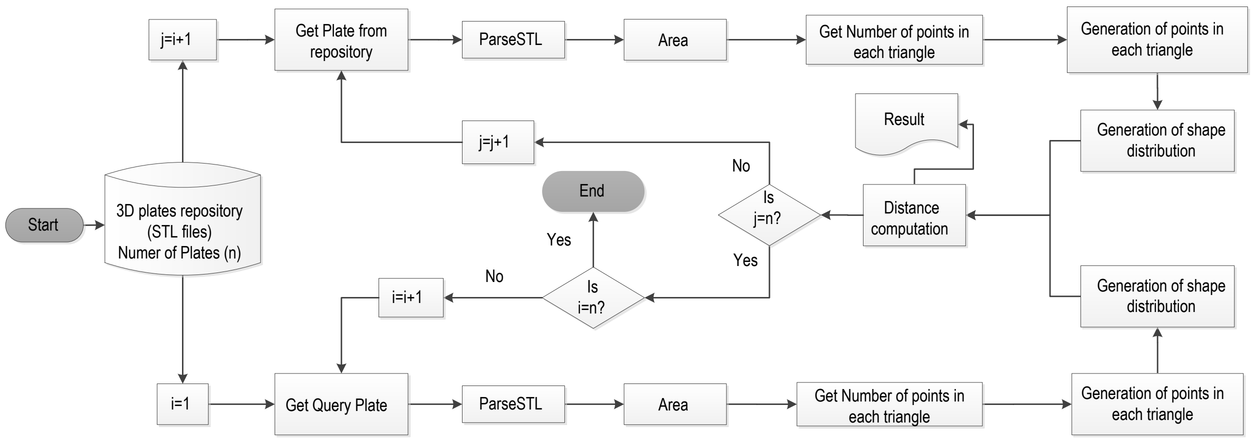


Figure 5.12.: Flow chart of the similarity measurement

5.1.3.3.1. Pose Estimation

Rotation invariance is a very complicated issue for a wide range of object categories. In 3D space $\mathbb{R}^3$, objects represented as polygonal meshes usually have an arbitrary scale, position or even orientation. To compare two objects for identity, invariance regarding scaling, translation, reflection and rotation of the tessellated mesh has to be achieved. The 2D-slice approach is dependent on an accurate pose estimation to get the same sets of slices for two identical 3D objects oriented differently in the space. The widely applied method for pose estimation is the principal components analysis (PCA) or one of its variants [53] [85]. The key idea of the PCA method is to reduce the dimensionality of a large multivariate data set containing a huge number of correlated variables [84] [158] [165]. In the following, three variants of PCA method will be addressed:

1. Principal Axes of Inertia

Principal axes of inertia can be computed using the following covariance matrix C of an object surface vertices, [164]:

$$C_i = \frac{a_i}{24}\left(v_{i,0}^2 + v_{i,1}^2 + v_{i,2}^2 + (v_{i,0} + v_{i,1} + v_{i,2})^2\right) I - a_i \cdot V_i^T \cdot S \cdot V_i \tag{5.6}$$

C_i is the inertia tensor of a triangle i around a given point (the center of gravity of the 3D model). V_i is a vector of a triangle's vertices from the mesh surface and $v_{i,0}, v_{i,1}, v_{i,2}$ are the coordinates of a triangle's vertices in the coordinate system related to the center of gravity of the plate:

$$V_i = \begin{vmatrix} v_{i,0} \\ v_{i,1} \\ v_{i,2} \end{vmatrix}$$

$a_i = 2A_i$ is two times the area of the triangle.

S is the following matrix:

$$S = \begin{vmatrix} 2 & 1 & 1 \\ 1 & 2 & 1 \\ 1 & 1 & 2 \end{vmatrix}$$

Since all tensors C_i are computed around the same center of gravity of the plate, the inertia tensor of the whole surface of the object is

$$C_{object} = \sum_{i=1}^{N_{triangle}} C_i$$

and the principal axes of inertia of the plate are calculated from the eigenvectors of the inertia tensor C_{plate}. Figure 5.13 shows an example for computing the principal axes using this method.

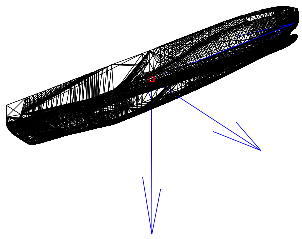


Figure 5.13.: Example of computing principal axes using the PCA method

2. Normal PCA - NPCA

This method is called rotation normalization [128]. An important advantage of this method is the insensitivity to inconsistent directions of the normal vectors of adjacent triangles forming the surface of an object. The computation of the principal components is similar to the previous method. The orthonormal basis for the surface's triangles is computed to transform the input data to an uncorrelated feature space. The principal components can be determined by computing the eigenvectors of the covariance matrix C_{object} of the input data according to equation 5.7:

$$C_{object} = \frac{1}{A} \sum_{i=1}^{N_{triangle}} A_i n_i n_i^T \tag{5.7}$$

where A_i represents the area of the i^{th} triangle of the 3D model's mesh, n_i is the corresponding normal vector, A the total surface area of the model, $N_{triangle}$ the total number of the triangles building the surface of the object and T the transpose operation. The computation and normalization of the orthogonal eigenvectors of the covariance matrix C_{object} provide the corresponding principal axes. The determined axes can be then sorted in an increasing or decreasing way according to the maximum or minimum variance along each eigenvectors. The transformation of the object's vertices to the global coordinate system can then be achieved by multiplying the vertices of the original object by matrix ϕ, which represents the sorted and normalized eigenvectors in each row. Figure 5.14 shows an example of alignment using NPCA.

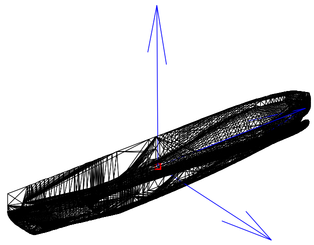


Figure 5.14.: Example of computing principal axes using the NPCA method

3. Continuous PCA - CPCA

Continuous PCA (CPCA) [154] uses the points of the model's surface instead of the normals of the triangles as used in NPCA. The covariance matrix C_{object} is computed as the following:

$$C_{object} = \frac{1}{12A} \sum_{i=1}^{N_{triangle}} A_i \left[f(v_{i1}) + f(v_{i2}) + f(v_{i3}) + 9 \cdot f(\frac{v_{i1} + v_{vi2} + v_{i3}}{3}) \right] \quad (5.8)$$

Where v_{i1}, v_{i2} and v_{i3} are the vertices of the i^{th} triangle, $f(v) = (v - m_c)(v - m_c)^T$ and m_c is the centroid of the model's surface. $N_{triangle}$ the total number of the triangles building the surface of the object and T the transpose operation. Computing and normalizing the correspondent orthonormal eigenvectors of the covariance matrix C_{object} provide the principal axes. The matrix ϕ represents the transformation matrix, its rows are the sorted eigenvectors. Multiplying the original object's vertices by the ϕ rotates the vertices corresponding to the global coordinate system. After the rotation, the object's vertices can be translated to its centroide. Figure 5.15 shows an example for object's alignment using CPCA.

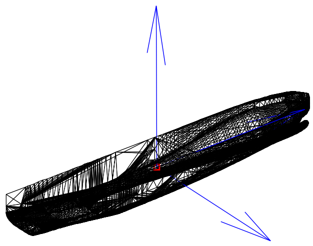


Figure 5.15.: Example of computing principal axes using the CPCA method

5.1.3.3.2. Representation of 3D Model by Set of 2D Slices

This process includes the generation of sets of 2D slices along the computed principal axes as follows:

1. Determination of principal axes, see subsection 5.1.3.3.1.
2. Transformation of the original shape to the global coordinate system.
3. Perform the slicing process.
4. Generation of the set of 2D slices.

5.1.3.3.3. Slicing Process

The slicing process involves the extraction of the intersection points between a cutting plane perpendicular on the cutting direction and the triangles building the surface of the object. After determining all intersection points, 2D closed slices have to be constructed. This is because the intersection points are randomly ordered and have no connection to each other. Since the used 3D models are represented as polygonal meshes, the natural way to describe the resulting slices is as polygons. The flowchart of the slicing process is shown in Figure 5.16.

In the slicing process, each triangle is analyzed. According to the orientation of the triangles in the mesh, there are five cases which must be considered as shown in Figure 5.17:

- Case 1: all the triangle vertices are away from the cutting plane.
- Case 2: one point in the cutting plane and the other two vertices are on different sides of the cutting plane.
- Case 3: one point in the cutting plane and the two other points on one side of the cutting plane.
- Case 4: two points of the triangle are in the cutting plane.
- Case 5: the triangle lies in the cutting plane.

The intersection between a cutting plane and a segment can be computed in different ways. One way is by considering the following three conditions:

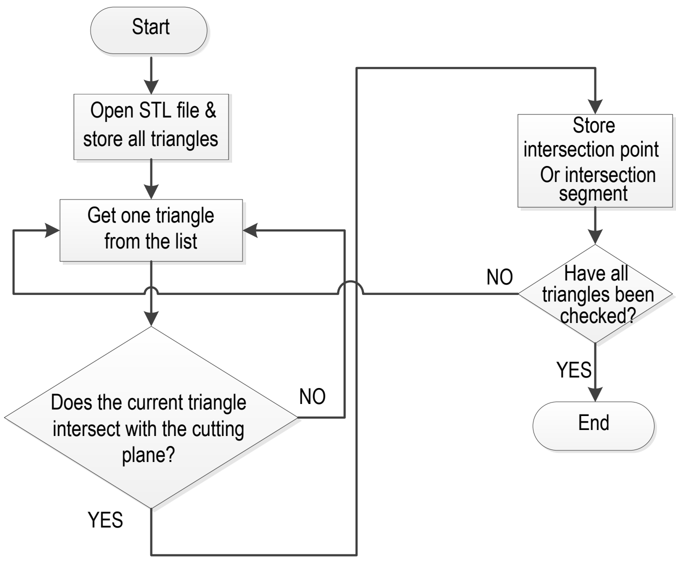


Figure 5.16.: Flowchart of slicing algorithm

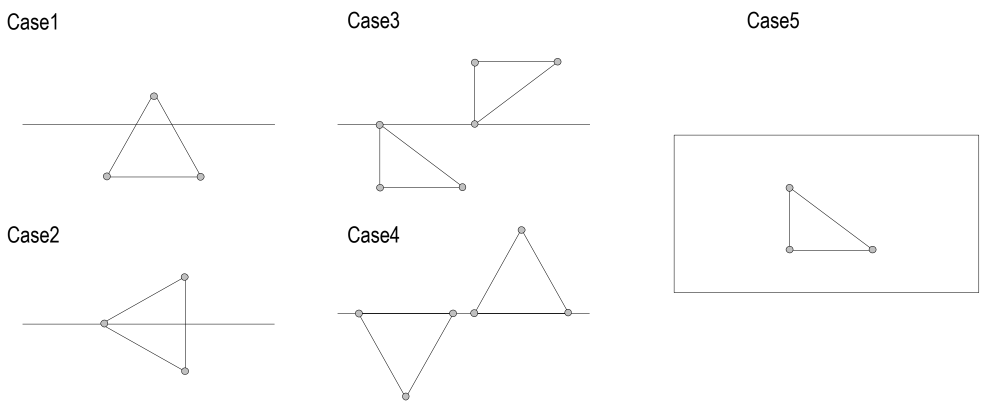


Figure 5.17.: Possible cases of triangle-plane intersection

$$x_1 \leq x_{cut} \leq x_2 || x_2 \leq x_{cut} \leq x_1$$
$$x_1 \leq x_{cut} \leq x_3 || x_3 \leq x_{cut} \leq x_1$$
$$x_2 \leq x_{cut} \leq x_3 || x_3 \leq x_{cut} \leq x_2$$

Where x_{cut} is the current position of cutting plane. x_1, x_2, x_3 are the x coordinates of a triangle's vertices. For each case, if one point lies before the cutting plane and another point lies after the cutting plane, the missing coordinates of the intersection point can be computed according to the following equations:

$$\frac{x_{cut}-x_1}{x_2-x_1} = \frac{y_{cut}-y_1}{y_2-y_1} = \frac{z_{cut}-z_1}{z_2-z_1}$$

Changing to y and z:

$$y = \frac{(x_{cut}-x_1)\cdot(y_2-y_1)}{x_2-x_1} + y_1$$

$$z = \frac{(x_{cut}-x_1)\cdot(z_2-z_1)}{x_2-x_1} + z_1$$

Another way to solve the intersection problem is to find the intersection point between the line segment and a cutting plane. In the 3D space the result of line and plane intersection is either an intersection point or no intersection if the line is parallel to the plane. If L is a given line and its parametric equation between two points P_0 and P_1: $P(s) = P_0 + s(P_1 - P_0) = P_0 + su$, where u is a direction vector along the line from the start point P_0. The cutting plane P_n is defined as a point Q_0 on the plane and a normal vector n.

Firstly, it will be checked if the line L is parallel to the plane by checking if the direction vector of the u is parallel to the normal vector n according to the following dot product $n \cdot u = 0$. To check whether the line coincides or is just parallel to the plane, it is enough to check if any point of the line, say P_0, contained in P_n , that is whether is satisfies the implicit line equation: $n \cdot (P_0 - Q_0) = 0$. If the line and the plane are not parallel, then it exists an intersection point. By solving the dot product condition: $n. \cdot (w + su) = 0$, where $P_s - Q_0 = w + su$, the intersection point can be calculated, that means the line between Q_0 and P_{s_I} perpendicular to n, see Figure 5.18. The line parameter at the intersection point is equal to:

$$s_I = \frac{-n \cdot w}{n \cdot u} = \frac{-n \cdot (Q_0 - P_0)}{n \cdot (P_1 - P_0)} = \frac{-(ax_0 + by_0 + cz_0 + d)}{n \cdot u}$$

with $w = P_0 - Q_0$. If the line L is a constrained segment between P_0 to P_1 it has to be checked if $0 \leq s_I \leq 1$ to verify that there is an intersection between the plane and the segment.

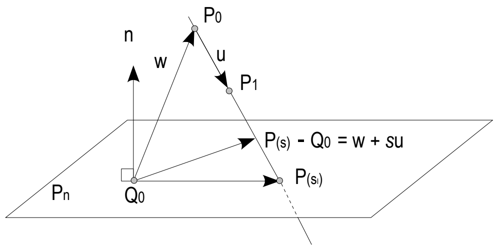


Figure 5.18.: Line segment-plane intersection

5.1.3.3.4. Contour Construction

After computing all intersection points, a method will be started to construct a set of closed slices. This construction process depends on the topological relationships between the resulting points. If a cutting plane intersects a triangle in two points, a line segment with end and start point is defined. When the cutting plane passes through one vertex of the triangle, this point is the start and the end point of a line segment. The construction process of a slice starts with one end point. The next point is a start point of another line segment. This process continues until reaching the first selected point to build a closed polygon. If free points are found, a construction of a new slice will be started, see Figure 5.19. This process is repeated until all points are visited. When no more free points exist, the algorithm ends.

After constructing the slices, a simplification step is needed for the sake of optimization. The optimization includes a deletion of the redundant points (collinear points). This step is needed because of the effect of the number of the points of the resulted polygons on the similarity evaluation

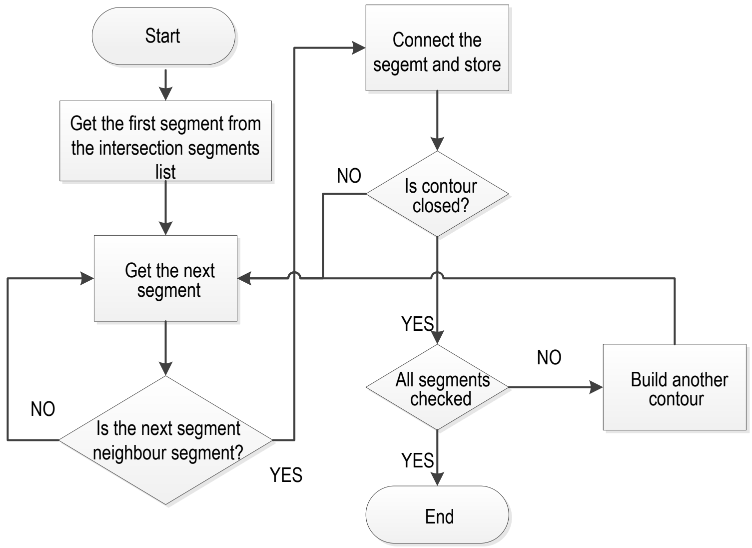


Figure 5.19.: Contour construction algorithm

time using the Fréchet algorithm. An example of collinear point is shown in Figure 5.20, where point B is collinear with point A and C.

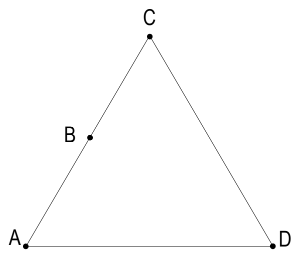


Figure 5.20.: Redundant points

To identify the redundant point B, the curvature of point B is determined. As shown in Figure 5.21, where l is the length of line-segment AC and the vertical distance from point B to line AC is h. The ratio h/l is the curvature of point B. This value will be compared with a user-defined critical value according to the required accuracy. If the curvature of point B is less than the critical value, point B can be recognized as a redundant point and can be removed from the polygon's points.

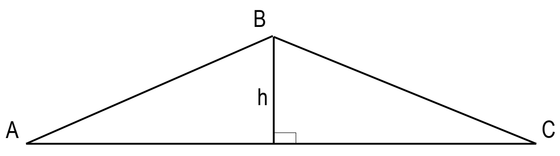


Figure 5.21.: Curvature

5.1.3.3.5. Influence of Slicing Directions on Resulted Slices

Different cutting directions lead to different sets of slices representing the same shape. To check the 3D models for their identity, unique cutting directions should be selected. Otherwise, it makes no sense to measure the similarity between those two slice sets. Figure 5.22 shows examples for holes and notches.

Figure 5.23 shows three sets of slices along three different cut directions. It can be seen that the slices in some directions have better quality than in other directions. For example, the volume

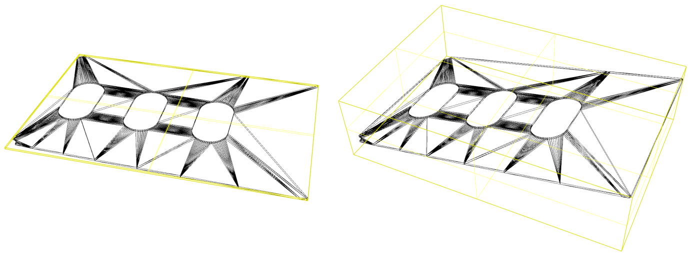


Figure 5.22.: Different bounding boxes for the same model

deviation of the resulted slices in Z direction is the minimum, where the representation of holes and outer contours are more accurate than in the other directions.

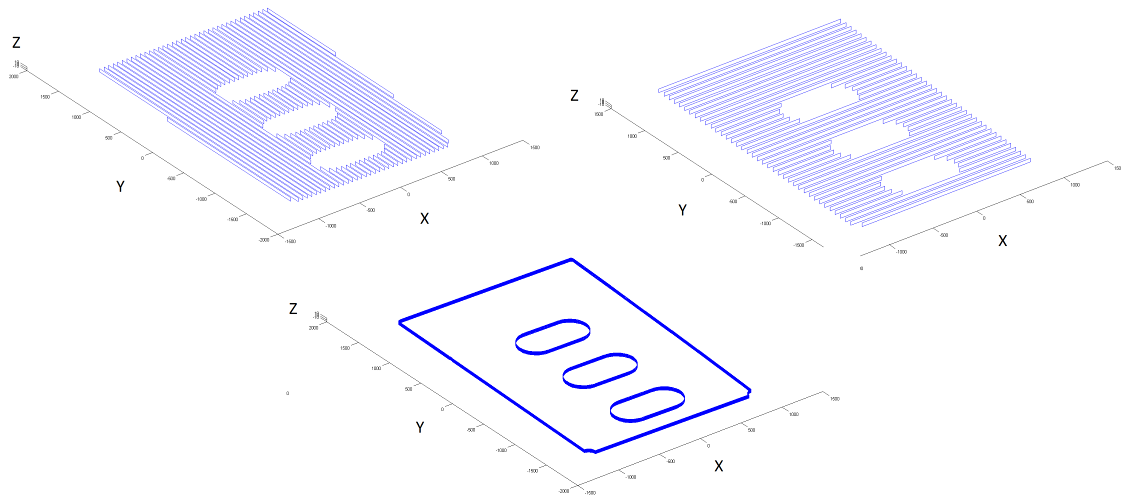


Figure 5.23.: Different sets of slices according to the slicing direction. X direction (top left) Y direction (top right) Z direction (bottom)

5.1.3.3.6. Recommended Cutting Direction and Slicing Distance for Planar Plates

For plane plates, vertical slicing of the plane of the plate will capture all the features in the plate. Such these features are the holes, cut-outs, notches and weld preparation at the edges of the plate, see Figure 5.24.

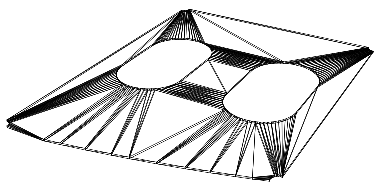


Figure 5.24.: Plate with two holes and four notches

To determine the proper slicing distance, the weld preparation along the edges of the plates being compared must be considered. Weld preparation, which is defined by a bevel code in the ship product data model, is dependent on the thickness of the plate and also on the welding technique which is applied in shipyard where the ship will be built. In Appendix A.6 four kinds of weld preparation normally used for butt joint are considered. Each weld preparation is characterized by some dimensions like the gap between the two plates (b), root height (c) and flank height (h). The dimension of interest for welding a joint of type (I) is the thickness. Therefore, one slice in thickness direction is sufficient for the purpose of shape similarity evaluation. Welding joints of type V and Y are characterized through the root height (c) and thickness (t), therefore, it is enough to choose the distance between the slices to be less than (c/2). With the type (Double-Y) weld joint, the critical distance has to be the smallest one between (c) and (h), where (h) is defined as $h_1 = h_2 = \frac{t-c}{2}$. In general, the slicing distance must be smaller than half of the minimum dimension in thickness direction to capture all changes of the shape in this direction.

5.1.3.3.7. Similarity Measurement

After determining the objects' orientation, transforming the new position, and building the sets of slices, the similarity is calculated by computing the percentage of the number of the identical slices over the number of all slices and multiplying by 100.

$$\text{Similarity ratio} = \frac{\text{Number of identical slices}}{\text{Number of all slices}} \cdot 100 \tag{5.9}$$

Two identical parts have a similarity ratio equal to 100, non identical parts have a similarity ratio equal to 0 and the remaining values are between the two limits.

5.1.3.4. Evaluation of the Similarity Using Monte Carlo Method

Monte Carlo method is a statistical sampling technique and is based on repeated random sampling to compute numerical results. This method is used in physical and mathematical problems and, according to the author's best knowledge, has never been used to solve similarity problem. The Monte Carlo method is mainly applied in three groups of problems i.e. optimization, numerical integration, and generating draws from a probability distribution. Different types of Monte Carlo methods exist. They have a general scheme which includes: The definition of a domain of possible inputs, the generation of input samples randomly over the domain, the carrying out of the required mathematical operations on the inputs samples, and finally, the accumulation of the result. The system structure to evaluate the similarity using the Monte Carlo method will be explained in detail.

5.1.3.4.1. System Structure

The introduced method to evaluate the shape similarity using the Monte Carlo method is applicable for 2D and 3D objects i.e. it can be applied to the set of slices as described in the previous section or directly applied on the polygonal mesh representation of parts. The later is performed according to the following scheme, see Figure 5.25:

1. A first structural part is selected.
2. Pose estimation and transformation into the global coordinate system are performed.
3. Computing of the bounding box (BB) of the new transformed part, which represents the domain in which the random points will be generated.
4. A user-defined number of random points will be generated within the determined bounding box from the previous step.
5. A point-in-polyhedron test will be performed to check which points are in, on or outside the polygonal mesh of the first part.
6. The interior and on surface determined points from the previous step will be applied on the a second part and a point-in-polyhedron test will be performed on the second part.
7. Computation of the similarity ratio through counting the *on* surface and the *interior* points and using the formula 5.10.
8. The steps 1-7 will be repeated for the second part.
9. After computation of the both similarity ratio, the smallest one will be considered.

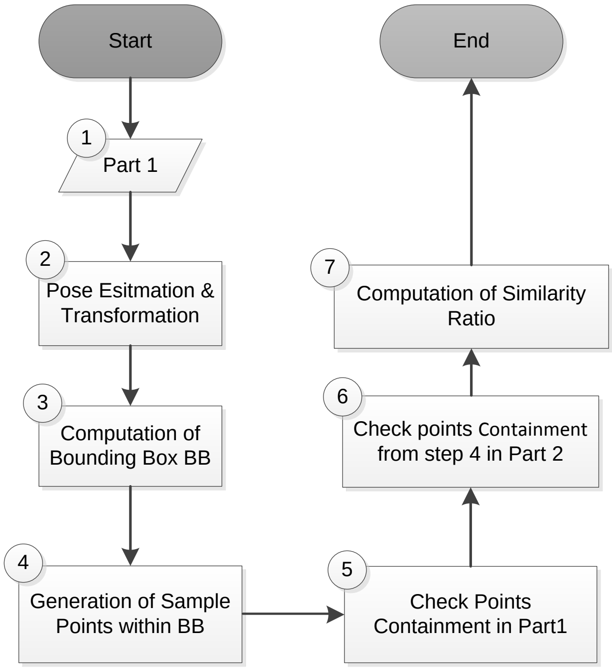


Figure 5.25.: System structure of similarity evaluation using Monte Carlo method

$$\text{Similarity ratio} = \frac{\text{Number of interior and on surface points (second part)}}{\text{Number of interior and on surface points (first part)}} \cdot 100 \tag{5.10}$$

Step 6 is performed using the algorithm based on preprocessing and determining triangles as described in [101]. The evaluation process according to Figure 5.25 is repeated. In the first run, the points of the first part will be used to check the containment in the second part. In the second run, the points of the second part will be checked for the first part. Two similarity ratios will be determined and the smallest one will be considered. Two identical parts have a ratio equals to 100% and two completely different parts have a ratio equal to 0%.

5.1.3.4.2. Algorithm for Testing Point Containment

The applied point containment algorithm is based on preprocessing and determining triangles i.e. a single determining triangle is sufficient to determine whether the point is inside or outside the polyhedron [101]. The concept is to find a visible triangle in the surroundings of a sample point P. A visible triangle T is a visible triangle if a line segment can be drawn from P to T without crossing the polyhedron. Upon the visible triangle, a determining triangle can be defined to find the position of P regarding a polyhedron Q. A determining triangle is a triangle adequate to compute the position of test point P relative to the polyhedron Q based on the Orientation Operation [101]. Obtaining a visible triangle is based on the use of octree data structure. An octree is a data structure in which each internal node has up to eight children and is usually used in 3D graphics. A regular octree recursively subdivides a cube in eight cubes of equal size. The leaves of an octree are called “voxels”. In an adaptive octree, the nodes of the tree can have different lengths so as to sample space in an heterogeneous way, see Figure 5.26. The root of an octree is the bounding box including the whole polyhedron. The correspondence to octree in 2D case is the quadtree, where each internal node has exactly four children instead of eight for an octree. The construction of an octree is performed by inserting the vertices into the tree one-by-one. After inserting the vertices, triangles are also inserted. Each leaf node will contain all vertices and triangles covering it.

Listing 5.13 shows point-in-polyhedron containment methodology developed by Liu et al. [101]. In the first two steps, the octree is constructed with three types of voxles: black, white, and gray. An

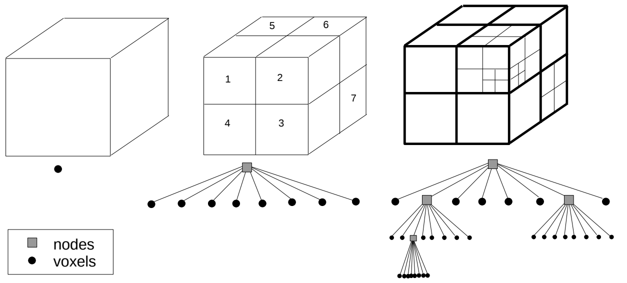


Figure 5.26.: The octree after inserting the vertices (top), hierarchical representation (bottom)

empty voxel with no triangles of the polyhedron Q is marked with black or white based on whether it is inside or outside Q. A gray voxel is a voxel with a record of any triangle overlapping it. A benefit of using octree is that, the position of a test point contained in black or white voxels can be directly computed. If point P is contained in a gray voxel, it is necessary to find of the visible and determining triangles in order to obtain the position of P. The determination of the visible and determining triangles is explained in detail in [101].

Listing 5.5: Inspection of standard notch size

```
//Preprocessing

Construct the octree; each voxel contains at most a predefined number of
vertices k. The voxels marked with black are for those contained
completely in the polyhedron Q. White voxels are those lie totally
outside Q. Gray voxels are cells overlapped with any triangle.

//Begin test

If test point P is out of the bounding box of the octree, then
return 'out'

//Otherwise P will be in a certain voxel
Find the voxel containing P; marked it as voxelP.
If voxelP is black return 'in' and the associated region number
or white then return 'out'.

//Otherwise voxelP is gray
Search for a visible triangle and infer the determining triangle from it.
Depending on the obtained determining triangle find the position of the test
point P.
```

where $voxel_P$ is the voxel containing the test point P.

5.1.3.4.3. Monte Carlo Simulation

To compare the identity of two parts, the Monte Carlo simulation is applied by generating N points inside part 1 and counting how many points are inside part 2; and vice versa. To perform the Monte Carlo simulation, firstly, N random points *inside* and *on* the mesh should be generated. To define the domain where the sample points will be generated, the bounding box of the part must be computed after performing the transformation of the polyhedron into the global coordinate system as described in subsection 5.1.3.3.1. The bounding box is computed by determining the minimum and maximum vertices of the cube surrounding the polyhedron as shown in Figure 5.22. Generally, N random numbers in the interval [a,b] can be generated using the formula $r = a + (b - a) * rand(N, 1)$, where *a, b* are the minimum and maximum limits of an object's bounding box. The number generated by $rand(N, 1)$ is between 0 and 1. An example of the samples generation can be seen in Figure 5.27.

The number of points to be generated N differs from one case to another. To obtain a reliable similarity ratio, a convergence analysis should be performed until reaches an error between two successive runs smaller than a user predefined value i.e. the total number N will be increased

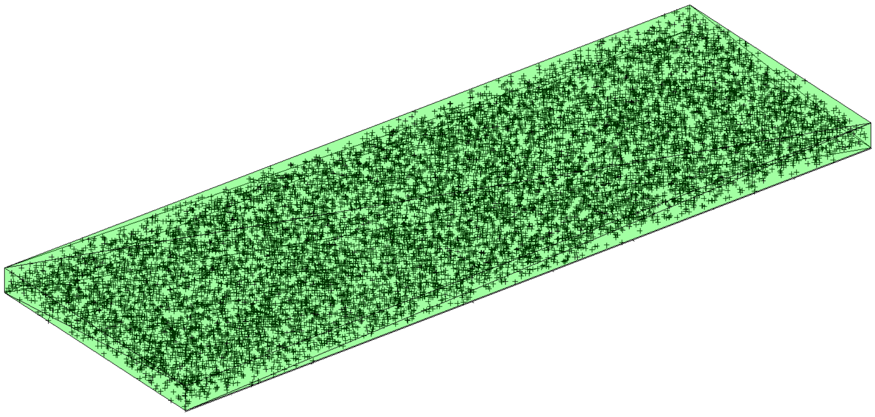


Figure 5.27.: An example for random point generation inside a polyhedron

for each run until it fulfills the condition of convergence. To exclude the case that one plate is completely in the interior of the other one, see Figures 5.29 and 5.28, the points of the polyhedron itself will be analyzed. It is necessary to check if the points of the first polyhedron exactly lie on the surface of the second polyhedron and vise versa. In the right Sub-figure, all the points of the smallest plate (blue) are completely inside the boundaries of the largest one. In this case, a similarity ratio of 100% is to be expected, therefore an inverse containment test and the consideration of the polyhedron points can be used to solve this inconvenient situation.

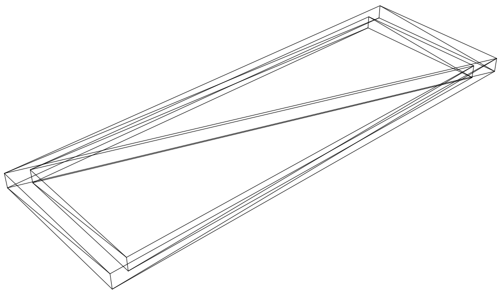


Figure 5.28.: Two different scaled plates

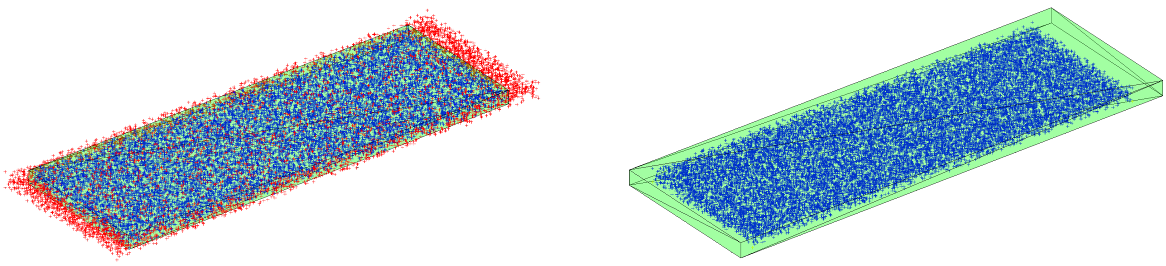


Figure 5.29.: An example of containment test for two different scaled plates

5.2. Ensure Optimized Processes

In this section, the addressed algorithms are those meant to ensure the correctness of ship product data for optimized ship structure production processes like parts management and requirements with respect to weldability in ship assembly processes. According to the American Welding Society [142], weldability is the capacity of a material to be welded under the imposed fabrication conditions into a specific, suitably designed structure and then to perform satisfactorily in the intended service. Among the weldability criteria, there are guidelines which for example demand minimum values for distances and angles as well as the requirements on the weld preparations along the edges to be assembled into structural elements. Three algorithms for controlling the correctness of product data model regarding excess material, allowed welding length, and edge preparation, respectively, are discussed in the following subsections.

5.2.1. Weld Length Inspection

Extension over the welding length permitted by welding machines will result in extra work and material loss. The value of the maximum welding length is a function of the machines and spaces available at a shipyard. To check if the weld length is compliant with the predefined value, a shape analysis has to be performed based on the actual shape representation of the used CAD system. In this subsection, an algorithm will be discussed for an early detection of parts with such problems. Automatic detection of such cases at an early design phase contributes to avoid the additional works required for correction during the production phase. The inspection of plates and stiffeners follows the same scheme, see Listing 5.6. For the inspection of welding length, a the simple contour as discussed in subsection 4.4.3 will be used. The maximum edge length of the considered plate part will be determined and compared with the maximum allowed value. If this value is exceeded, then an error has to be reported for healing purposes.

Listing 5.6: Inspection of standard weld length

```
algorithm "Standard weld length"
  when
        Plate : Simple contour( maximum welding length == x, maxLength == y, x > y)
        Stiffener : Trace( Trace == x, maxLength == y, x > y )
  then
        error("Weld length not standard", 5));
end
```

The inspection of stiffeners is performed in the same way, the only difference being the shape representation of the stiffener. A stiffener is defined by its cross-section and a trace-line defining its extension and represents the description line of the stiffener in the mould plane, which can be straight or inclined. Control over the maximum allowed length is achieved by measuring the trace line and comparing its value with the maximum allowed value. To increase the precision of the calculation, a simplification step is to be performed to reduce the number of the collinear points as described in subsection 5.1.3.3.4.

5.2.2. Ensure Excess Material Requirements

The object `Limit` in Figure 4.13 defines one limit of a plate's or panel's boundaries. If this limit is a boundary of a section of a ship, an object of type `BlockLimit` must be instantiated to hold the excess material information in two attributes i.e. `mustExcess` and `Excess`. The former defines the value which must be assigned according to the shipyard standards and the latter defines the actual assigned value. For the control of the quality criteria regarding the excess material, both attributes will be used.

5.2.2.1. Ensure the Existence of Excess Material O-EX-MI

In this inspection scenario, the existing excess value will be checked. If this value does not exist or the assigned value is equal to zero, an error must be reported. The inspection algorithm will call all objects of type `BlockLimit` and check the value of attribute `Excess`. All instances with no valid values will be reported and sent back to the designer for new excess assignment. Missing excess material is weighted with 5 due to its serious.

Listing 5.7: Inspection of missing excess material

```
algorithm "Missing excess"
  when
        Excess : BlockLimit( Excess == 0,
                             mustExcess > 0)
  then
        error("Missing excess", 5));
end
```

5.2.2.2. Excess Material Value is not Standard O-EX-NS

If the assigned `Excess` is not equal to the recommended value in the shipyard design standard, which is the `mustExcess`, an error has to be reported. The severity of such an error depends on the actual assigned value `Excess`. If the value of `Excess` is less than the `mustExcess`, a more critical error has to be distinguished from the error than if the assigned value is bigger than the must one. Small excess values in production phase can only be corrected by replacing the structural part which result in more costs and material loss.

Listing 5.8: Inspection of excess for compliance with standards

```
algorithm "Excess not standard"
  when
        Excess : BlockLimit( Excess > 0,
        mustExcess > 0, Excess != mustExcess)
        Excess : BlockLimit( Excess < mustExcess)
  then
        error("Excess not standard", 5));

  when
        Excess : BlockLimit( Excess > 0,
        mustExcess > 0, Excess != mustExcess)
        Excess : BlockLimit( Excess > mustExcess)
  then
        error("Excess not standard", 3));
end
```

5.2.2.3. Excess Material Value is not Conclusive/ Feasible O-EX-NC

`mustExcess` can be equal to zero. In this case, material reserve of e.g. 5mm is to be assigned for `Excess`. Sequentially, zero-assigned `Excess` is an error and has to be reported. This kind of error is of low importance. Listing 5.9 shows the inspection sequence.

Listing 5.9: Inspection of excess conclusiveness

```
algorithm "Excess not conclusive"
  when
        Excess : BlockLimit(Excess > 0 &&
        Excess < 5, mustExcess == 0)
  then
        error("Excess not conclusive", 2));
end
```

5.2.3. Edge Preparation

To check the quality criteria related to edge preparations, two attributes of object `Limit` will be inspected i.e. `WeldSide` and `WeldCode`. The former defines the side on which an edge must be prepared and the latter specifies the shape of the edge preparation. Weld code or so-called bevel defines the angle and the gap between the adjacent structural parts, see Figure 3.15.

5.2.3.1. Edge Preparation (Bevel Code) not Existed O-EP-MI

The existence of a bevel code is very important criterion. If this code is not assigned to an edge, a critical error has to be reported. The `WeldCode` attribute in class `Limit` is checked. Missing bevel code is a major error and has a big impact on the production process and therefore, it is weighted with 5, Listing 5.10.

Listing 5.10: Inspection of missing edge preparation

```
algorithm "Missing edge preparation"
  when
        Edge : Limit( WeldCode == 0)
  then
        error("Missing weld code", 5);
end
```

5.2.3.2. Bevel Code is not Standard O-EP-NS

To check if the bevel code is assigned according to the shipyard standard or related standards like ISO 9692-1[26], the value of `WeldCode` is compared with the `mustWeldCode`. The `mustWeldCode` is a function of the structural part dimensions, the applied welding technique, and the existing welding facilities at the shipyard. Listing 5.11 shows the inspection sequence. Depending on the thickness of the inspected plate, the weld code can be checked, lines 3 to 12. In this example, three groups of weld codes are considered. One in thickness range between 3 and 8 mm, the second range includes plates with thickness more than 8 mm and up to 12 mm and finally, all plates more than 12 mm.

Listing 5.11: Inspection of edge preparation for compliance with standards

```
1  algorithm "Edge preparation not standard"
2    when
3          Edge : Limit( Plate.thickness > 3.0mm
4          && Plate.thickness <= 8.0mm
5          && WeldCode != 100)
6
7          Edge : Limit( Plate.thickness > 8.0mm
8          && Plate.thickness <= 12.0mm
9          && WeldCode != 300)
10
11         Edge : Limit( Plate.thickness > 12.0mm
12         && WeldCode != 330)
13   then
14         error("Weld code not standard", 5);
15 end
```

5.2.3.3. Bevel Code is not Conclusive O-EP-NC

The inspection of this criterion includes two sub-steps as described in subsection 3.6.2.2. In the first step, it will be checked if the adjacent plates have the same thicknesses. After passing the first test, it will be checked if the bevel codes for the adjacent plates are assigned on the same side.

Listing 5.12: Inspection of bevel code conclusiveness

```
algorithm "Edge preparation not conclusive"
  when
        Edge : Limit( WeldCode1 != WeldCode2)
  then
        error("Weld codes not the same", 5);
end

  when
        Edge : Limit( WeldSide1 != WeldSide2)
  then
        error("Weld codes on different sides", 5);
end
```

5.2.4. Ensure Required Minimum Dimensions for Seamless Welding Process

To check the compliance of the minimum dimensions with the standards, the components and seam arrangements must be identified. The components and features to be inspected are the plane plates, stiffeners and welding joints (seams), see Figure 4.13. Butt joints that connect the individual plates of a plate field are given as `Seam` while for fillet welds no separate elements are provided. The fillet seams exist in the ship's structure, where a component is perpendicularly encountered on another plate. Components such as plates and stiffening profiles are connected by fillet welds. Fillet seams are also used to connect plates, which meet each other perpendicularly. A common error for noncompliance minimum distance between fillet and butt seams occurs between the fillet welds on stiffeners and the butt welds of the plate fields on which the stiffeners exist. The minimum distances between butt seams also must be observed. Same observations must be also applied on the minimum angles between parts and seams. Therefore, the developed algorithms must consider three cases according to the combination of the controlled parts i.e. stiffener to stiffener, stiffener to seam and seam to seam.

To check the minimum distances and angles, the traces of stiffeners and seams are used. This trace as previously described, consists of several 2D segments which can be straight or circular segments. A straight segment has two points (start and end) and a zero-height amplitude. A circular segment by way of contrast has non-zero amplitude. These differences make the control algorithms depending on the geometrical definition i.e. three cases must be considered when controlling the minimum distances and angles between parts: straight-against-straight, straight-against-arc, and arc-against-arc. Two conditions must be checked. Is there an intersection point between the parts? And does the intersection point lie on both of the segments? The minimum dimension criterion between two segments can be violated when one of them extends over a bordered region of the other. This region is defined by the minimum required distance d_{min}, see Figure 5.30.

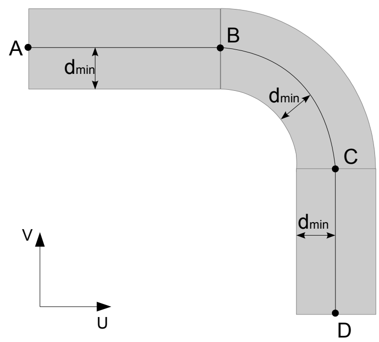


Figure 5.30.: Minimum distance for a straight-circular line. Straight segments AB & CD, circular segment BC

The bounded region is parallel for straight segments and is the bounded region between two arcs of concentric circles parallel to the original circular segment for circular segments, see Figure 5.30. If the segments of the second component or seam are within this region then the minimum distance criterion is not fulfilled and an error must be registered. By considering the individual segments of stiffeners and seams, it is possible to determine the closest segments from both components. The distance between the both segments can be computed and compared with the threshold through the mathematical definition of line- or circle-equations. After finding the intersection point, it is necessary to find if it is on the line segment. This can be done using the following considerations:

Method 1: If the point is on the line then:

$$\frac{(u - u1)}{(u2 - u1)} = \frac{(v - v1)}{(v2 - v1)} \tag{5.11}$$

The computed values must be the same within an acceptable tolerance. To test if the point is on the segment, then: $u1 < u < u2$, if $u1 < u2$ or $v1 < v < v2$, if $v1 < v2$.

Method 2: If the distance between the start and end points d_{SE} of a segment is bigger than distances between the intersection point I and each point of the segment d_{SI} and d_{SE} as shown in Figure 5.31. The same considerations are applied for circular segments.

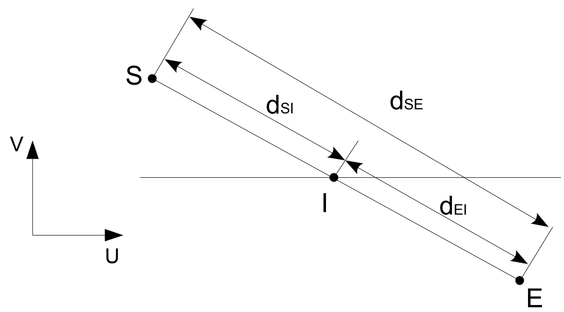


Figure 5.31.: Test if intersection point is in a segment

The inspection process of the required minimum angles and distances between the structural parts including line and arc segements are discussed in details in Appendix A.5.

5.3. Ensure Structural Parts Functions

Notches must be provided only on the structural parts which their functions allow. If a plate exist in a watertight space, any holes and notches on it are prohibited.

5.3.1. Check Notches

Checking the correctness of the notches includes the inspection as to whether they are provided at the right place or whether they are sufficiently large to serve the purpose for which they are provided. The latter is the easiest to control, where the size of the existing notches is compared with guide values based on the design requirements. The control of existence of notches is more challenging because the locations where the notches are required have to be topologically identified depending on the neighboring structural parts. This will be discussed later in this subsection.

5.3.1.1. Check Size of Notches O-NO-NC

According to the design principles for welded structures, notches must have a minimum size. The minimum value is $R_{min} = 25mm$ or 2 $\times$ plate's thickness, whichever is the greater of the two values, subsection 3.6.2.2. If different notches are provided on the plate, each notch has a reference object `NotchRef` from the object `FlatPlate`, which defines the identification number `CompID` of the notch. Each CAD system has its own set of standard notches which can be applied in the ship structure. Notches can be provided for part edge or part corners or for both of them. Some examples are provided in Appendix A.3. Among those are semicircular notches, which are defined by the attribute Radius and complex shape which are defined by up to seven parameters. For arbitrary shapes, the parameters number can be increased. As shown in Figure 4.13, each `Notch` which is a specialization of object `Component` has a `CompID`. All notches in a panel which have the same shape are grouped together in a `NotchGroup`. Its shape is defined by an object of type `NotchShape`. Each notch in a panel belongs also to a plate in a panel. To determine which notch is considered, a `NotchRef` is connected to an object of type `FlatPlate`. The `CompID` of a notch is a unique number in the scope of a panel. The algorithm to check if the size of a notch is standard is shown in Listing 5.13. An approach is developed for evaluating the notches regarding their sizes. The direct comparison of a shape parameter with the minimum radius is only useful if the parameter also indicates a radius, line 4. For notches with multiple parameters, a reference value returned by the method `FindRefValue` must be used to be compared with the minimum value R_{min}, line 10. This kind of error is weighted with 4, lines 6 and 12.

Listing 5.13: Test standard notch size

```
1  algorithm "Notch size not standard"
2    R_min == (25 mm > 2 * plate.thickness ? 25 : 2 * plate.thickness)
3    when
4          Notch size : NotchShape(Parameters == 1, R == Parameters.value , R < R_min )
5    then
6          error("Notch size not standard", 4);
7  end
8
9    when
10         Notch size : NotchShape(Parameters > 1, R == FindRefValue , R < R_min )
11   then
12         error("Notch size not standard", 4);
13 end
```

Since notches are provided to reduce the welding residual stresses, it is advantageous if notches are as wide and as large as possible. The height and width of a notch are the most important parameters to evaluate the notch size. Height and width relate to the distance of the seam to notch contour. The selected heights and widths are listed as comparison values. If the two values are specified, the smaller one is chosen and stored as the `ReferenceValue`. When starting the inspection, the list of all panels objects `Panels` and a list of all notches definitions objects `NotchDefs` will be used as inputs.

Notches definitions `NotchDefs` are prepared in advance for all possible notches. Systematically, the `foreach` loops select the notches references related to the object `FlatPlate` and passes the identifier `CompId` of the referenced notch together with the `Panel` and `NotchDefs` to the method `FindRefValue`, see Listing 5.14. This method compares the value in the list `NotchDefs`, which belongs to the referenced notch. Several `foreach` loops get the notch group, which the referenced notch belongs to and then through the group's attribute `NothDefId` they get the definition of the notch shape `NotchDef`. Through `NotchDef` the comparison value for the notch shape is available and will be returned by the method as shown in Listing 5.14. The returned value will be evaluated by the **if**-Condition. If the value smaller than $25mm$ or 2 $\times$ plate's thickness, an error has to be reported.

Listing 5.14: The method to find the reference value

```
FindRefValue(Panel, NotchId, NotchDefs)
  foreach (NotchGroup in Panel.NotchGroups)
    foreach (CompId in NotchGroup.CompIds)
       if (NotchId == CompId)
          foreach (NotchDef in NotchDefs)
               if (NotchGroup.NotchDefId == NotchDef.NotchDefId)
                  return NotchDef.RefValue;
```

5.3.1.2. Check Missing Notches O-NO-MI

The developed method for searching for missing notches focuses on notches at corners of plane panels. Notches at corners are provided according to the assembly sequence. The following conditions have to be satisfied to judge the necessity of a notch at a panel corner:

- Purpose of panel admits existence of notches i.e. watertight or not.
- Edges at corner are connected with adjacent objects.
- If adjacent objects are plane panels, they must have different orientations in space.

Listing 5.15: Test notch existence

```
1  algorithm "Missing notch"
2  foreach (Panel (P0) in Panels)
3        if (Panel (P0) not watertight)
4          if (Panel has two different adjacent plane panels P1 and P2)
5            if (DifferentOrientation(P0, P1) == true
6               && DifferentOrientation(P0, P2) == true)
7                 if (FindMissingNotches(P0.Plates, P0.CornerPoint) == false)
8                 then
9                   error("Missing notch", 4);
10 end
```

The inspection of whether the function of the space where the plate exists allows a notch at the panel corner (line 3) is achieved by comparing the value of the attribute `DataType` with the object `PlanePanel`, see Figure 4.13. The value of this attribute is a three digit number expressing the function of the space where the panel has to be assembled e.g. 154 is an oil tight bulkhead in side tank. Line 4 is to check whether the considered plane panel is bound by two other plane panels to form a corner point, where the possible existence of a notch must be checked. The orientation of adjacent panels can be determined using the object `Local_Coordinate_system`, see Figure 4.14. An example of this object is a vector which defines the orientation of the panel in the space. It has three references to three objects. One reference is to the local coordinate origin. The other references define the unit vectors in two perpendicular directions `U_Axis` and `W_Axis`. The third unit vector can be determined by performing the cross product. The test if two panels have the same or different orientation (lines 5 and 6) can be performed as described in Listing 5.16.

Listing 5.16: Test panel orientation

```
Method DifferentOrientation (Panel1, Panel2)
        if (Panel1.Local_Coordinate_System.W_Axis != Panel2.Local_Coordinate_System.W_Axis)
                                return true;
        else
            return false;
```

Are the above mentioned conditions for the existence of a notch fulfilled? It should be checked whether a plate at this corner has a notch. Limits of a panel are the same for plates that lay on the edge of the panel. The detailed contour of plates contains the features such as the cutouts and notches on the edges. A corner point of a plate is not represented in the detailed contour definition, when the notch existed on this corner. To check if a notch exists on the panel corner, the corner point of panel's limit (line 7 Listing 5.15) is checked as to whether it is found under the detailed contour of the plates belong to the considered panel. If the corner point is found, the missing notch on this corner must be reported. Listing 5.17 shows the described method to find a missing notch:

Listing 5.17: Method FindMissingNotches

```
1 Method FindMissingNotches (Plates, CornerPoint)
2         foreach (Plate in Plates)
3            foreach (Segment_2D in Plate.PolyLoop)
4               if (Segment_2D == CornerPoint)
5                  return true;
```

In the first line, all the plates belong to the considered panel and the corner point between the two panels bounding it are passed to the method. Two `foreach` are used. The first one is used to loop over the plates and the second one loops over the `Segment_2D`s to define the detailed contour of a plate. `if`-condition line 4 checks whether one point of the detailed contour is the same as the corner point. If the corner point is found in the detailed contour, an error with a weight of 4 must be reported: line 5.

6. Implementation

6.1. PDQMS Implementation

In this section, different aspects related to the implemented PDQMS will be discussed: the integration with the CAD system environment observing the introduced roles and the implemented information models. Additionally the mapping of the described quality requirements, introduced in chapter 3, to the information model will be shown.

The quality management system has been implemented within the Windows operation system environment using the following tools:

- programming language: C#;
- CAD system: Aveva Marine;
- object relational mapping (ORM) tool: ice.Net [28];
- database management system (DBMS): MS SQL Server.

6.1.1. Integration of Quality Methods into a CAD system

An overview of the architecture of the developed product data quality approach is shown in Figure 6.1. In this scenario, the CAD system AVEVA Marine is applied for the modelling of the ship structural steelwork, though all information defined in the design process is stored in the AVEVA internal database (Dabacon). Both the quality inspector and the quality manager are provided with different tools specially tailored to their specific tasks. The quality manager is responsible for defining the quality criteria and, if relevant, the related tolerances to be applied for a certain newbuilding project. This information is realized in this research as an XML file. Each file contains the applied criteria with the corresponding tolerances and thresholds for each usage scenario. By doing so, the quality criteria are set up once and used as many times as the quality inspector performs quality checks. The middle layer consists of a database (MS SQL server) in which the ship structure is mapped by using the API provided by AVEVA. Quality assessment results are linked to these data as soon as quality checks are performed by the quality inspector who is responsible for managing this database. For this, an interface is implemented to access the quality requirements and parameters set up by the quality manager. Inspection results, reports and additional data generated for healing of error prone structures are controlled by the quality inspector. An inspection report contains, apart from administrative related information (who, when, what, how, statistics), the quality criteria being applied including tolerances and quality parameters and references to the structural parts checked for conformity. Additionally all components which did not pass the assessment are listed including the reason. Upon the inspection reports and with aid of the generated macros, designers are able to heal the ship product model data as a part of their responsibilities. Figure 6.2-A shows an example of the quality inspection report and Figure 6.2-B shows a screen shot for deficient design with a visual guidance.

6.1.2. Quality Criteria vs. Information Model

The formulated quality criteria in section 3.6 can be mapped to functions analyzing certain information model object instances. The mapping is shown in Table 6.1. In the first column, the quality criteria identifier as described in chapter 4 are addressed. The measurement requirements and the reference values for each quality criterion are shown in the middle column. The applied values are functions of the parts dimensions, type of the parts, the functions of the parts or the features, and the applied technology as well as the available facilities by the shipyards. The inspected objects or attributes from the product data model as described in chapter 4 are shown in the third column.

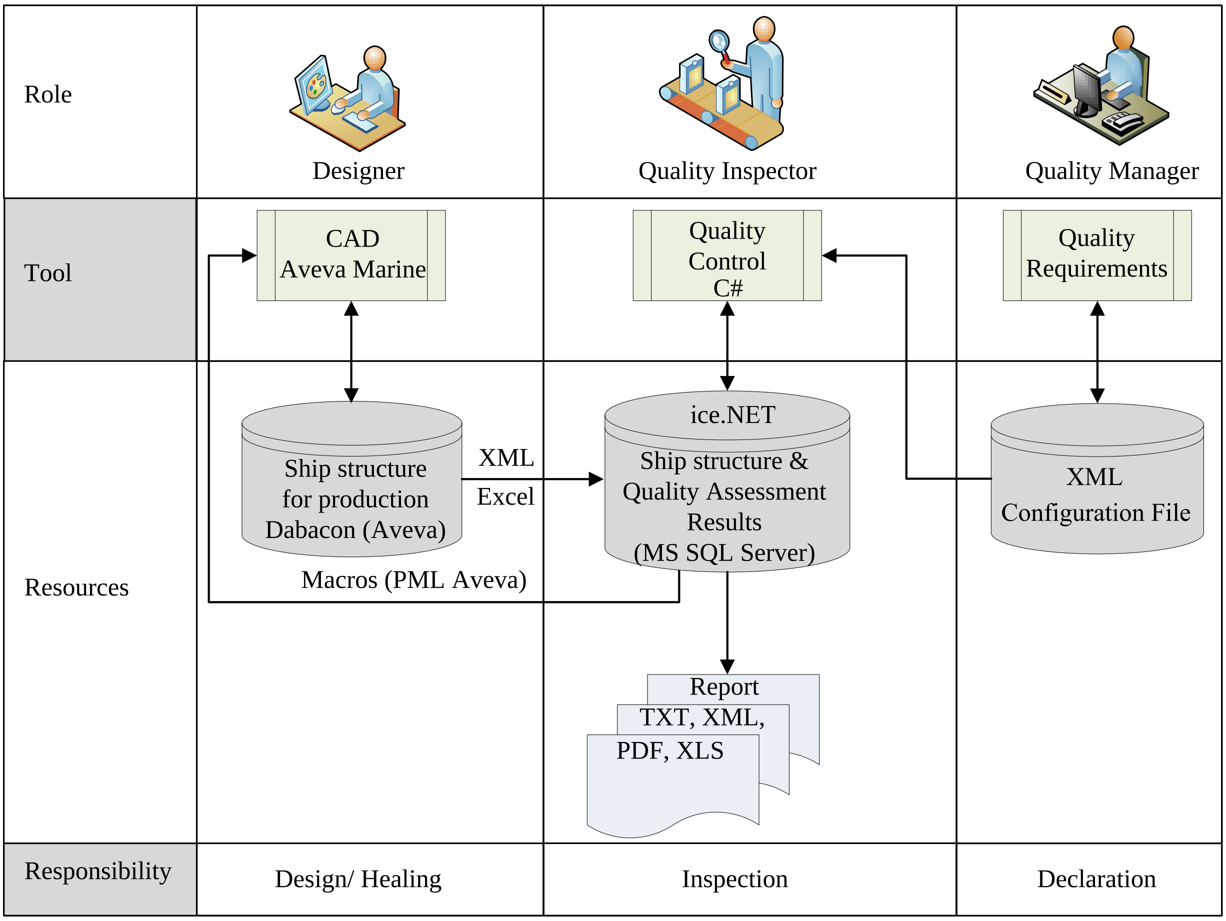


Figure 6.1.: Product data quality management system architecture

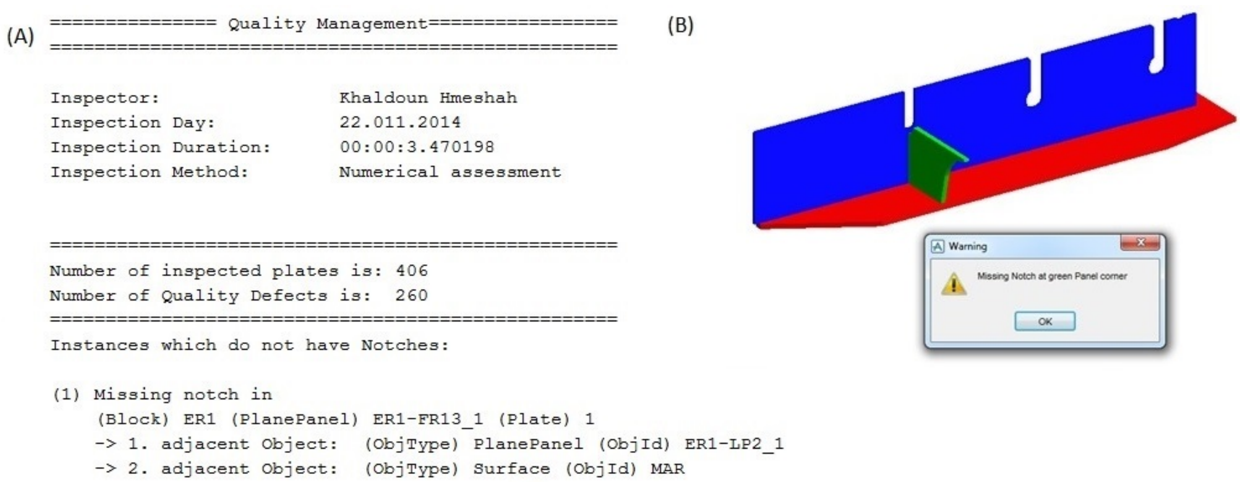


Figure 6.2.: (A) Example of quality inspection report (B) guided visualization for subsequent error correction.

QC-Identifier	Reference value or measure requirement	Inspected attributes or objects
O-EX-MI	Excess $\neq 0$	Excess of object BlockLimit
O-EX-NS	Excess = mustExcess	Excess of object BlockLimit
O-EX-NC	mustExcess	Excess of object BlockLimit
O-EP-MI	Bevel_Code $\neq 0$	Bevel_Code of object Limit
O-EP-NS	F(Thickness, Technology) E.g. $3 < t \leq 8$ Bevel_Code 100 $8 < t \leq 12$ Bevel_Code 300 $t > 12$ Bevel_Code 330	Bevel_Code of object Limit
O-EP-NC	Same bevel code and weld side for the adjacent edges	Weld_Side & Bevel_Code of object Limit
O-NO-MI	The attribute Data_Type does not specify water or oil tight panel. A panels connected with two other panels having different orientation.	Data_Type of object PlanePanel FlatPlate object
O-NO-NS	E.g. notch radius has to be more than 25 mm or 2× plate thickness, whichever is larger [102]	Notch_Id & Notch_Type of object NotchShape Thickness of object FlatPlate
O-SSDI-NS	E.g. 30 mm + 2× t [102]	Thickness of object FlatPlate SeamTrace object
O-PPDI-NS	F(shipyard facilities) E.g. 150mm	StiffenerTrace object
O-PSDI-NS	E.g. 50 mm + 4× t [102]	Thickness of object Plate SeamTrace object StiffenerTrace object
O-SSAN-NS	F(shipyard facilities) E.g. $20°$	SeamTrace object
O-PPAN-NS	F(shipyard facilities) E.g. $20°$	StiffenerTrace object
O-PSAN-NS	F(shipyard facilities) E.g. $20°$	StiffenerTrace object SeamTrace object
O-PN-MI	Position Number $\neq 0$	PosNo attribute of StructuralPart object
O-PN-NS	F(shipyard standards) E.g. Position Numbers for plates between (1000 - 10000)	PosNo attribute of StructuralPart object
O-PPPN-NC	F(parts properties) Identical parts must have the same position numbers	Compare shapes of two StructuralPart objects

Table 6.1.: Quality criteria and information model instance parameters

6.2. CAD System

AVEVA Marine is a design and drafting system for shipbuilding structures and outfittings. The wide application of this system, the ability of customization and various methods of data access are the major reasons for choosing this system. The database of AVEVA Marine data model contains all information relevant for the design and manufacture of a ship. Since the investigations in this work focus primarily on the results of the detailed design, it is important to consider the ship structural data resulting from this phase. The overall structure of the ship is divided into a set of blocks. A block represents a limited 3D space of a ship. These blocks can reflect the actual assembly breakdown of the ship. Each block consists of several panels, that represent the required steels structure. A panel consists of minimum one plate, to which any combination of stiffeners, brackets, flanges, etc. can be added, see Figure 6.3. All parts will be described through different parameters. Some parts have specific parameters such as plate thickness, material quality or stiffener cross section.

6.2.1. Data Extraction

Data have to be extracted from the CAD system before inspection. There are many methods in AVEVA Marine for the extraction of model data for the shipbuilding structure. It is important to

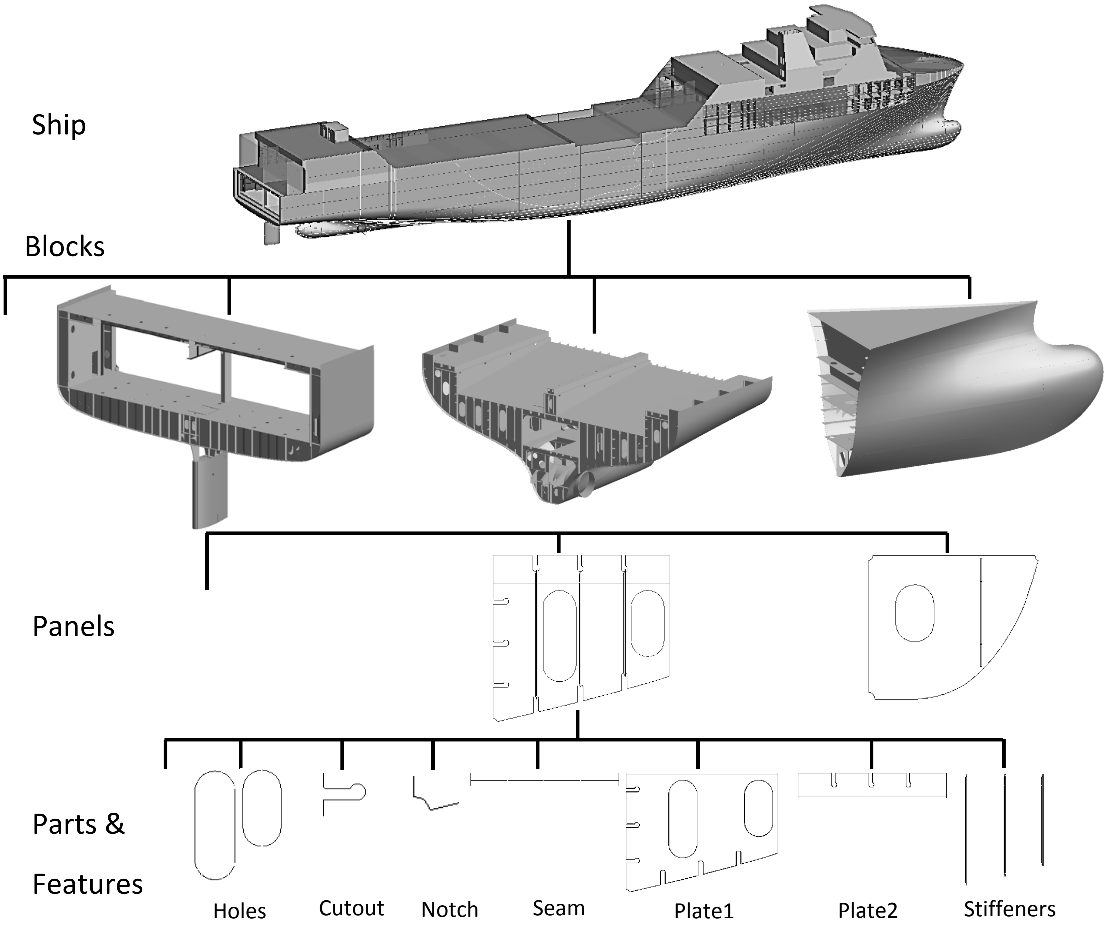


Figure 6.3.: AVEVA Marine model hierarchy

distinguish between access to design data and production data. Production data are available only at the end or during the detailed design. For read-only data access of design data, four methods will be discussed [105].

- *Hull XML Interface (TXHSTL)* is designed especially for data exchange models of the early design. The model contains all relevant information for the early design phase of the steel structure. Manufacturing details such as welding seam shapes, part position number or profile endcuts are not included in the model. Structural parts are described topologically. The smallest component to be extracted from the model is the panel. The interface can be operated only within AVEVA Marine Basic Design application. The extracted data can be inspected outside the AVEVA Marine environment. Inspection of production related properties, such as edge preparation or parts numbers is not possible on the basis of AVEVA Marine XML. For more information see Figure A.1.

- *The Data Extraction (DEX)* is a reading interface for the AVEVA Marine databases. The structure of the DEX query language is a tree-like hierarchy. The root keyword of a query always describes the application branch in AVEVA Marine (e.g. HULL for *Hull modeling* or PIPE for *Pipe Modelling*). Only one attribute can be determined per query.

- *Programmable Macro Language (PML)* is a specific programmable macro language provided by AVEVA Marine. Macros are ASCII files containing commands to be run sequentially as stated in the macro file. They contain also programming constructs such as IF statements, DO loops and variables like the object-oriented programming languages. Macros can be run by dragging and dropping them within AVEVA Marine. Using PML, production information like position numbers for each part can be extracted from the database.

- *Input Schemes* is the description language for the internal planar shipbuilding structure. The syntax of the input schemes follows the rules of the general AVEVA Marine Description Language. One input scheme is for each panel. Components and geometry details are formulated in so-called statements. More information is contained in Listing A.1 and Listing A.2. Historically, the input schemes are the basis of the model description in AVEVA Marine. In the current AVEVA Marine modeling, the input schemes are automatically generated during interactive modeling. They can also be generated at any time from the existing model. If the input schemes are used for the purpose of data inspection, algorithms for reading and interpretation of the included information must be developed.

6.3. Object Relational Mapping

To overcome the complexity of building a database, an Object Relational Mapping (ORM) approach is applied. ORM is a technique which allows the connection of an object model to a relational database. The mapping is delegated to tools to manage the persistence and to work at code-level with objects created as a model, see Figure 6.4. On the left side, a class diagram representing the data model is created. This diagram includes objects, attributes, and relationships. The constraints have to be mapped to the database. These tools establish a bidirectional link with data in a relational database and objects in code. In Table 6.2, the main mapping terminologies are listed.

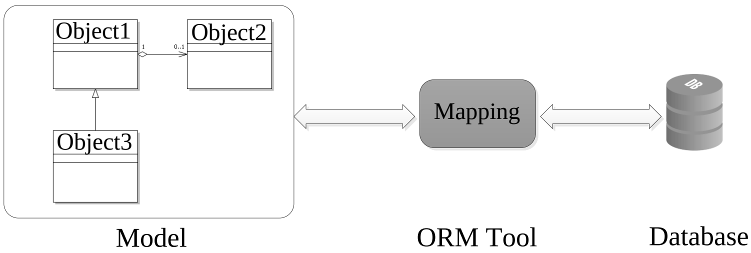


Figure 6.4.: Object relational mapping concept

Term	Definition
Mapping	The act of determining how objects and their relationships are persisted in permanent data storage, in this case relational databases
Property	A data attribute
Relationship mapping	A mapping that describes how to persist a relationship (association, aggregation, or composition) between two or more objects

Table 6.2.: Mapping terminology

The ORM tool used in this research is ice.Net platform. The main components of this platform are the information models or data models, the application, and a formal notation to precisely define the information models into the application component such as the Unified Modeling Language UML, see Figure 6.4. UML provides a standard way to visualize the design of a system. The integration between the information model (static aspects such as objects, attributes, types etc.) and the behavior (dynamic aspects, real implementation and methods) is shown in Figures 6.5 and 6.6.

The models in Figures 6.5-left and 6.6-left contain the static characteristics of the information system. The models in Figures 6.5-right and 6.6-right, or so-called business objects, provide the functionality or the dynamic characteristics (behavior, functionality of the information system). The implementation of the functionality is provided by the object-oriented methodology. The structure of this functionality is described in terms of entities (types, classes).

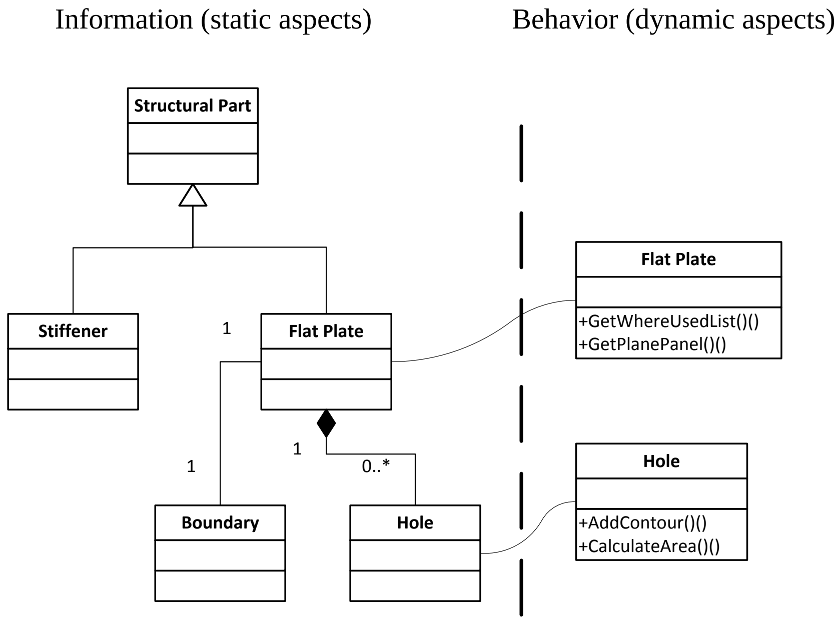


Figure 6.5.: Integration of the static and dynamic aspects (ice.NET framework)

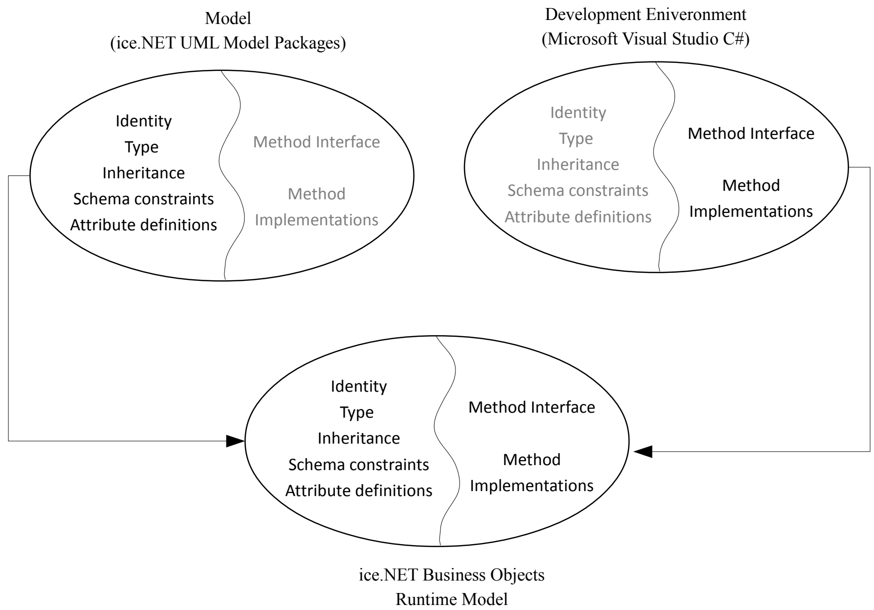


Figure 6.6.: Integration of the static and dynamic aspects at run-time

The steps required to create a database with the required application (methods and functions) to check the ship product data against the quality criteria are shown in Figure 6.7. The quality manager starts to build all data models using ice.NET Studio in different packages as described in chapter 4, (step (1)). This step also includes the set up of the used database. The development of the business object, combining (dynamic) logic with (static) data models, is simplified using ice.NET Business Object Builder BOB, (step (4)). After exporting the modelled data models (step (2)) and preparing the configuration file (step (3)), BOB is called to to generate different C# files (steps (4) and (5)). The configuration file from step (3) includes information to control BOB. The most relevant section in this file is <packages> section, that determines for which model package the business objects should be created. The required packages are described in chapter 4. The generated files from step (5) include: one business object interface for each object type in the data model, business objects base implementations that provide C# properties and methods for all attributes and relationships, factory classes for registering the business objects as well as all object type names, relationship type names and attribute names defined as C# constants. The quality manager is now able develop the application (step (6)). The application includes methods and functions to inspect the quality criteria, to perform some calculation such as computing weight, area, volume, etc. or to generate macros for displaying the deficient designs. These methods must be written within the implementation files from step (5). In this work, tens of thousands of programming lines are written (≈ 34000 lines).

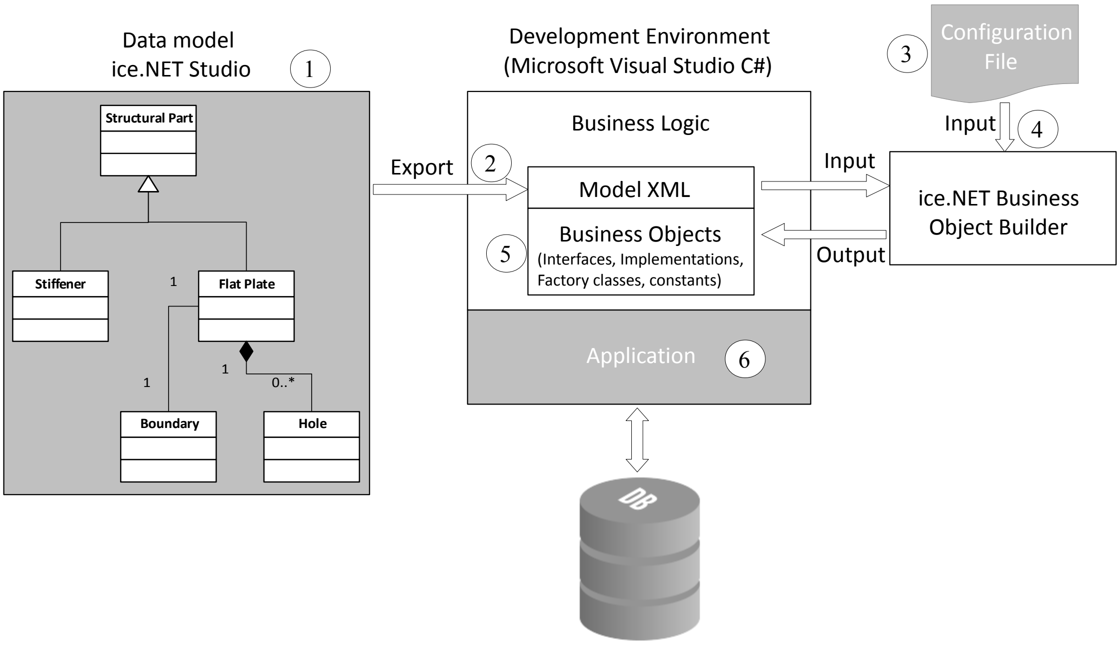


Figure 6.7.: Using ice.NET business builder to generate the classes

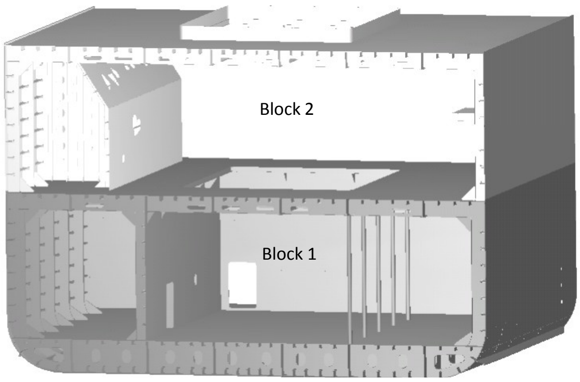
7. Test Cases and Results

In this chapter, different test cases will be used to discuss the applicability of the developed PDQ system on real ship structures. The test structures vary from simple cases with a few plates to complex structures. Three main test structures will be addressed. These structures contain different numbers of structural parts, see section 7.1. The case studies address the quality criteria discussed in section 3.6. The complexity of the test studies differs depending on the inspected quality criterion. The implemented functions to analyze geometrical and topological relationships between even complex ship structural components can be successfully tested with help of systematic parameter variations. The underlying geometry engine is implemented fully independently of the CAD system applied for modelling the ship structure.

7.1. Tested Structures

7.1.1. Two Blocks

Two hull blocks of a vessel consisting of 158 plane panels which in turn define 179 plates, see Figure 7.1. The total number of holes is 237, the number of stiffeners is more than 300, and the number of seams is 21.

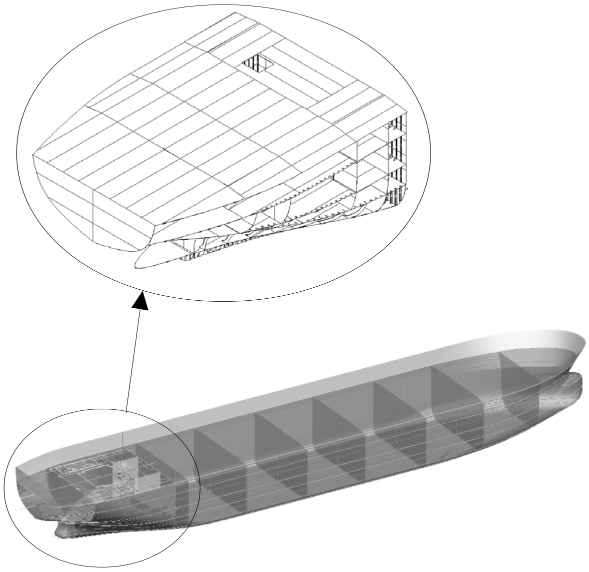


Object type	Number of objects
Blocks	2
Panels	158
Plates	179
Holes	237
Stiffeners	303
Seams	21

Figure 7.1.: Digital Mock-up CAD-model of two hull blocks (left). The types and the number of the objects (right)

7.1.2. Bulk Carrier Test Model

The aft-part CAD-Model of a Bulk Carrier is used as a reference model to prove the overall concept developed for the PDQMS, see Figure 7.2-left. The objective is to check the conformance of the modelled ship structure with the formulated quality criteria. In Figure 7.2-right, the number of objects of different types found in this digital mock-up is listed. This digital mock-up is used to test the implementation's performance within a realistic environment.

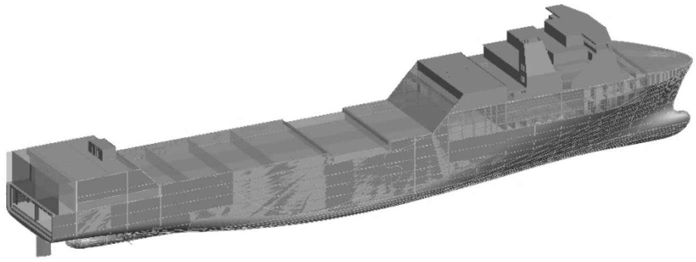


Object type	Number of objects
Blocks	7
Panels	195
Plates	406
Stiffeners	1392
Notches	638
Seams	201

Figure 7.2.: Digital Mock-up CAD-model of a Bulk Carrier (left). The types and number of the objects (right)

7.1.3. RoRo Vessel Test Model

The CAD-Model of a RoRo vessel Figure 7.3 left is used to prove the approach developed for the PDQMS. The CAD-model consists of 77 blocks. The number of objects of different types found in this digital mock-up are listed in Figure 7.3-right. The layout of this model and block distribution is shown in Figure 7.4. The layout shows the complexity of the ship structure and the large number of elements it can be constructed.



Object type	Number of objects
Blocks	77
Panels	3271
Plates	3984
Stiffeners	6211
Notches	10117
Seams	609

Figure 7.3.: Digital Mock-up CAD-model of a RoRo vessel (left). The types and number of the objects in the RoRo vessel (right)

7.2. Quality Management Results - Case Studies

7.2.1. Inspection Results of Parts Information

In this subsection, quality criteria regarding position number will be discussed. The inspection of the missing position number criterion O-PN-MI is applied on the test models of the Bulk Carrier and RoRo vessel, Figures 7.2 and 7.3 only, because no information is available for position number for the first test model, see Figure 7.1. The inspection is performed according to the introduced algorithm in subsection 5.1.1. The results of the inspection were only one case for the Bulk Carrier and 11 for the RoRo vessel. The inspection of position numbers, which do not conform with the standard values O-PN-NS, is performed according to the introduced algorithm in subsection 5.1.2. Three cases were detected for the Bulk Carrier and 2 for the RoRo. The standard position number for plates is assumed to be in the range ($0 < \text{PosNo} \leq 1000$). As mentioned before, the range is

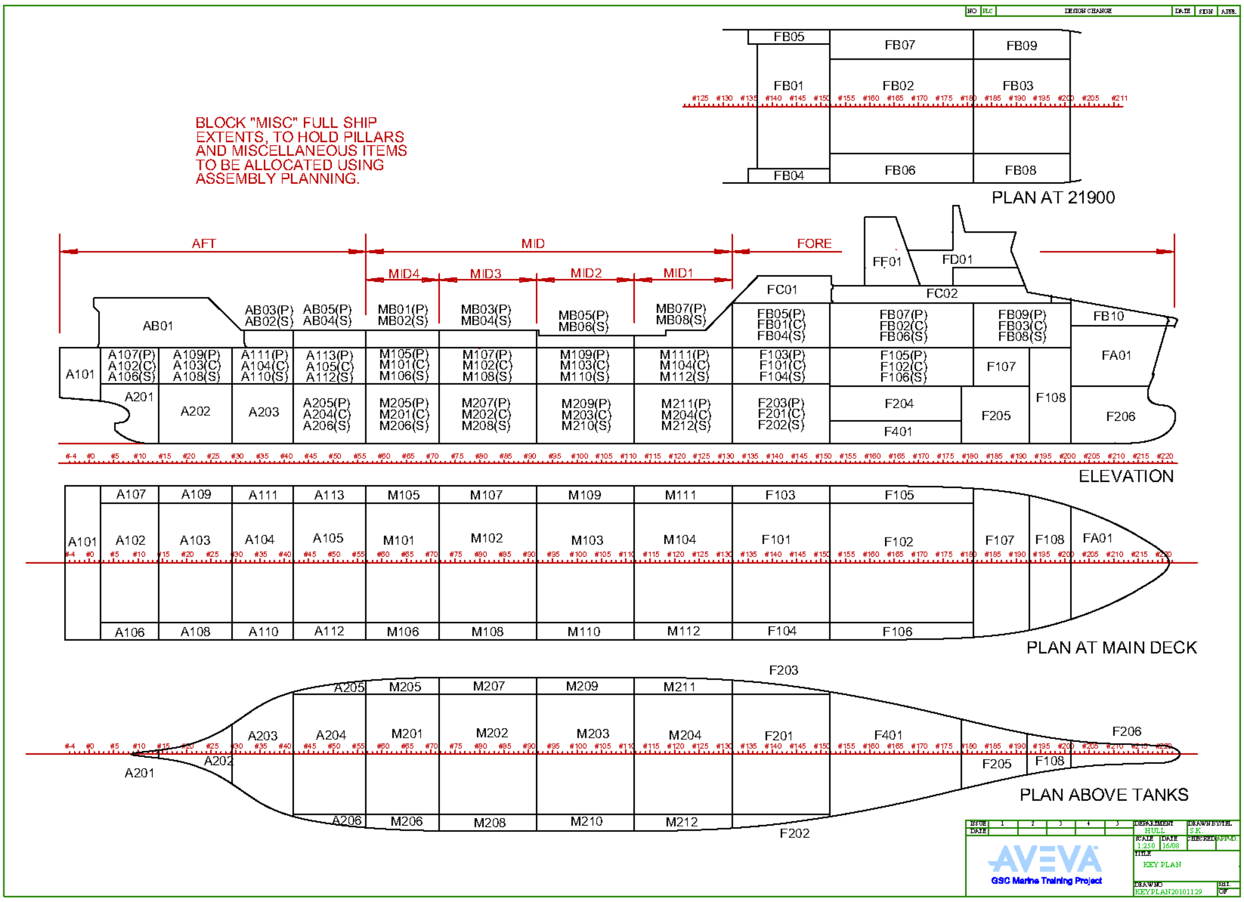


Figure 7.4.: Layout of a RoRo vessel

specific for each project. The third inspection step regarding the conclusiveness of position number `O-PPPN-NC` is based on different algorithms depending on the applied 2D and 3D representations of structural parts. In the following subsection, various results of similarity evaluation of structural parts using the addressed algorithms will be discussed for 2D and 3D cases.

7.2.1.1. 2D Case

Evaluation of similarity in 2D space is performed using Fréchet distance as described in subsection 5.1.3.1. The implemented algorithms have been tested on simple structures as well as on the above described ship structure models. As an example, the two identical plates depicted in Figure 7.5 are evaluated for identity. The chosen tolerance values are $\delta = 0.4mm$ and $\sigma = 0.5mm$, with δ the Fréchet tolerance and σ the tolerance to approximate the shape contours by polygons. In this case the algorithms yield that both plates are to be considered identical which holds for the outer contour as well as for the inner contours, the holes.

Contrary, Figure 7.6 shows two plates which share the same outer contour but have defined different inner contours: different dimensions of the lightening holes. Applying the same tolerance values as in the example above means that both plates are not identical due to their different hole arrangements. When the Fréchet tolerance δ is increased to a value larger than $50mm$, the two plates are assumed to be identical: this large value is not acceptable in a real test case.

Fréchet distance is applied on the test model with two blocks shown in Figure 7.1 with two tolerance values $\delta = 0.1mm$ and $\sigma = 0.5mm$. Figure 7.7 shows the inspection result. The matrix is composed of 179 rows and the same number of columns, each matrix element represents the comparison of two plates. Matrix elements representing two identical parts are shown in black, different parts appear in gray.

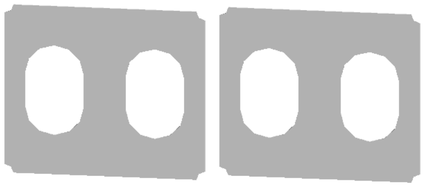


Figure 7.5.: Two identical plates

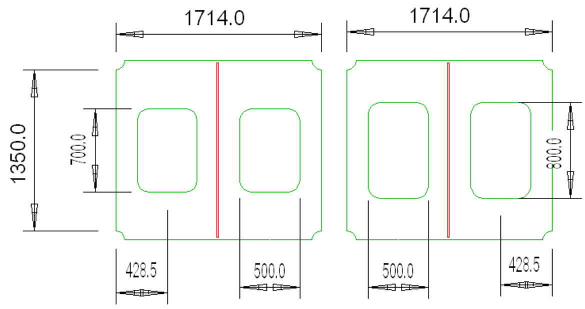


Figure 7.6.: Two plates: same outer contour but with different holes

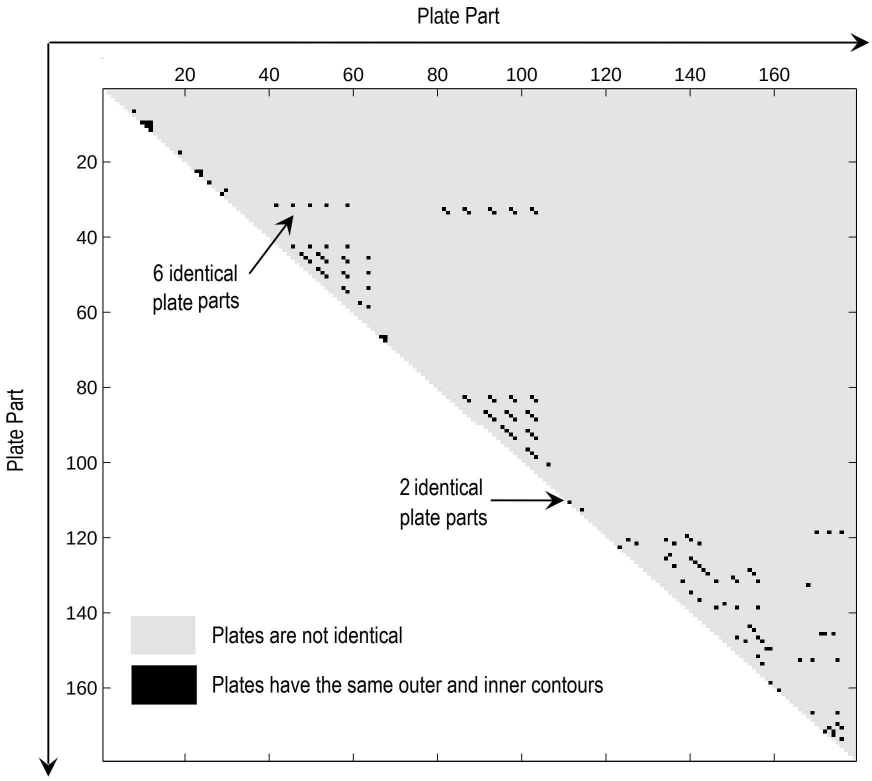


Figure 7.7.: Result of identity assessment for the first test CAD model

Apart from the identification of the identity of two plates, as an additional result, the number of plates of identical properties including shape is derived. The graph shown in Figure 7.8 refers to the same two blocks: 17 pairs of identical plate parts have been detected whereas the identity of five or six parts occurred only three times respectively.

The computing time is moderate for analyzing the existence of identical parts for even complex ship structure blocks on a standard PC due to the optimized comparison process as described in subsection 5.1.3.1. The importance of applying the different algorithms in a proper order is shown by the following example. The two blocks contain two plates with as many as 27 circular holes each, see Figure 7.9. Profiling the run-time revealed the fact that more than half of the total computing time was spent for the processing of these two plates. An additional comparison on the area and centroid of holes before applying the more "time consuming" Fréchet algorithm could reduce the overall analysis time by more than a factor of two.

The inspection is also applied on the Bulk Carrier with the same tolerance values $\delta = 0.4mm$ and $\sigma = 0.5mm$. The result of the inspection is also shown as a symmetrical colored matrix, see Figure 7.10. The inspection of 406 plates is accomplished within a couple of minutes. The total number of identity cases is 329. A graph for plates with the same properties is shown in Figure

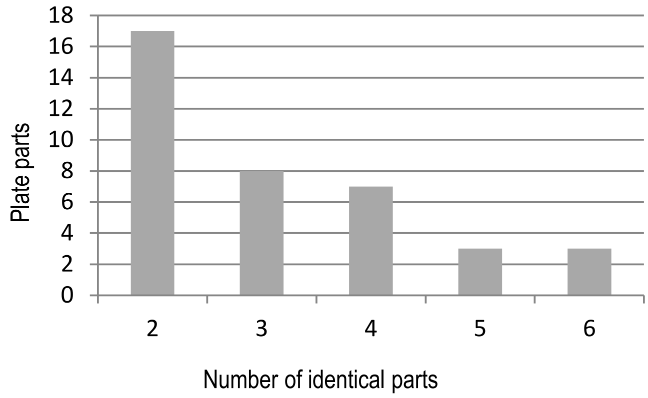


Figure 7.8.: Relationship between plates and the number of identity occurrence

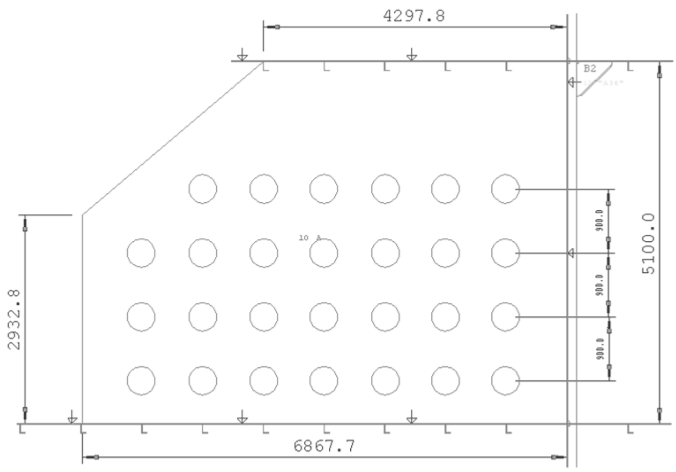


Figure 7.9.: A plate with many holes of two blocks test case leading to large processing time

7.11. Applying the same tolerances on the RoRo vessel CAD-model results in 2334 identity cases. The inspection run-time was around two hours. The result discussed above is applied to check the effectiveness of the developed algorithms to detect shape identity of plate parts disregarding the position number.

The inspection of the quality criterion O-PPPN-NC checks which parts have the same position number with different properties including shape. Therefore, a deviation of the results are expected. 147 errors were detected for plates which have the same position numbers in the Bulk Carrier CAD-model. For the RoRo product model data, 7337 errors were detected. The big number of errors is caused because of the multiple registration of errors. For example, for 4 identical parts, 6 errors will be registered where the evaluation of similarity for the first plate results in 3 cases and for the second one 2 cases and so on. The test is done throughout the whole CAD-model i.e. two different plates with the same position number in different blocks will be identified as an error. If the inspection is tested block-wise, the number of errors is reduced to 15 instances.

7.2.1.2. 3D Case

The evaluation of similarity in 3D space is covered in three algorithms i.e. shape distribution, 2D-slice, and Monte Carlo algorithms as described in chapter 5. The results of identity and similarity evaluation will be discussed for each method in the following subsections.

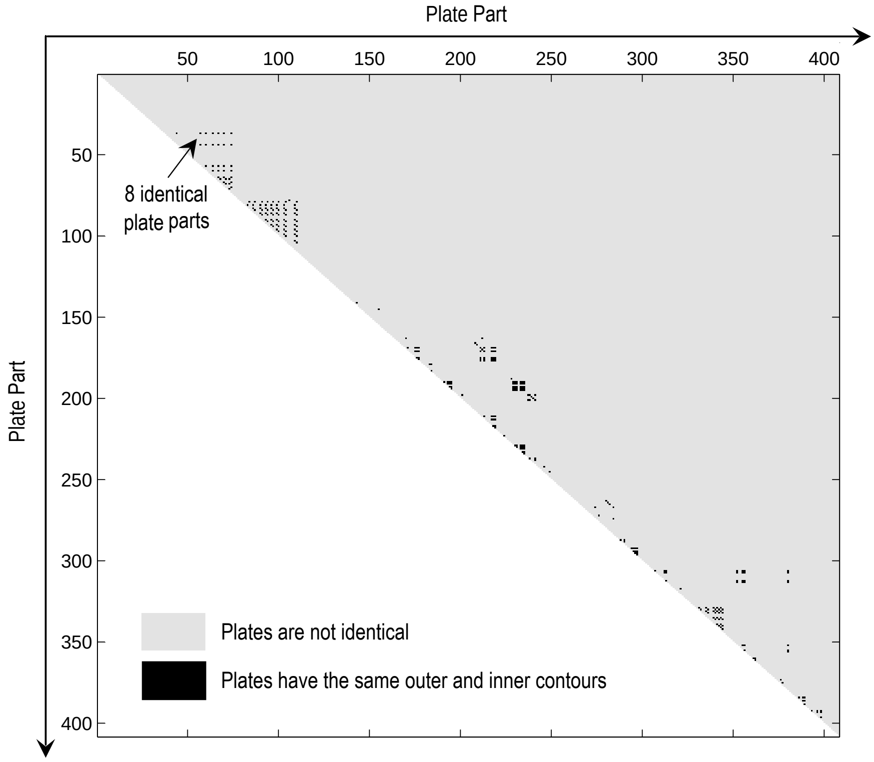


Figure 7.10.: Result of identity assessment for the Bulk Carrier

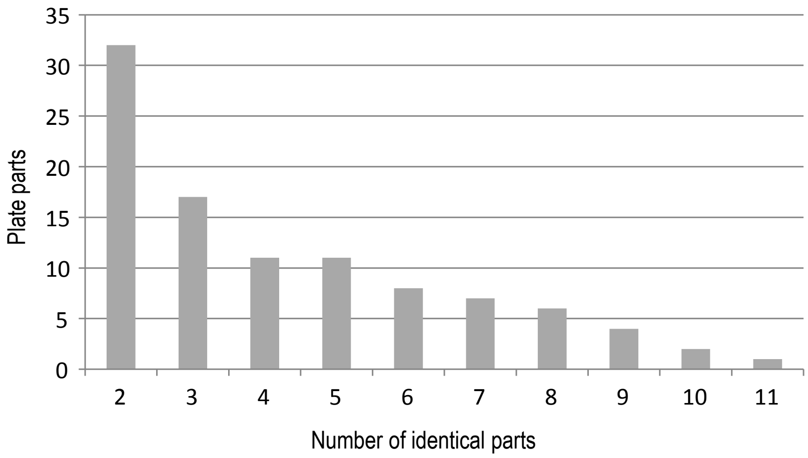


Figure 7.11.: Relationship between plates and the number of identity occurrence

1. Similarity Evaluation Using Shape Distribution

In this section, the shape distribution method as described in chapter 5 is implemented and tested for the selected cases. The key factor of this method is the number of points to be generated and uniformly distributed on the surface of the 3D object. In the literature (see e.g. [79] and [123]), 1024 points are suggested to be generated to get satisfactory results without negative effect on the computation time. A convergence study is also performed to analyze the impact of the number of points on the results for cases with 1024 and 2000 sample points.

In the first case, the two blocks is checked for similarity using 1024 as predefined number. The inspection results are shown in Figure 7.12 as an upper triangular matrix, for a larger representation of the similarity see Appendix A.7. The horizontal and vertical axes represent the checked plate parts. Each cell represents the comparison result of two parts. Two identical parts are represented by a black cell while two completely different parts are marked by a grey one. The assigned color depends on the similarity value or so-called absolute difference (S), see subsection 5.1.3.2.1. For identical parts, this value is equal or close to zero. For completely different parts the value equals or is close to two and the remaining cases differ between them. The closer the similarity value is to zero, the more similar the compared parts are.

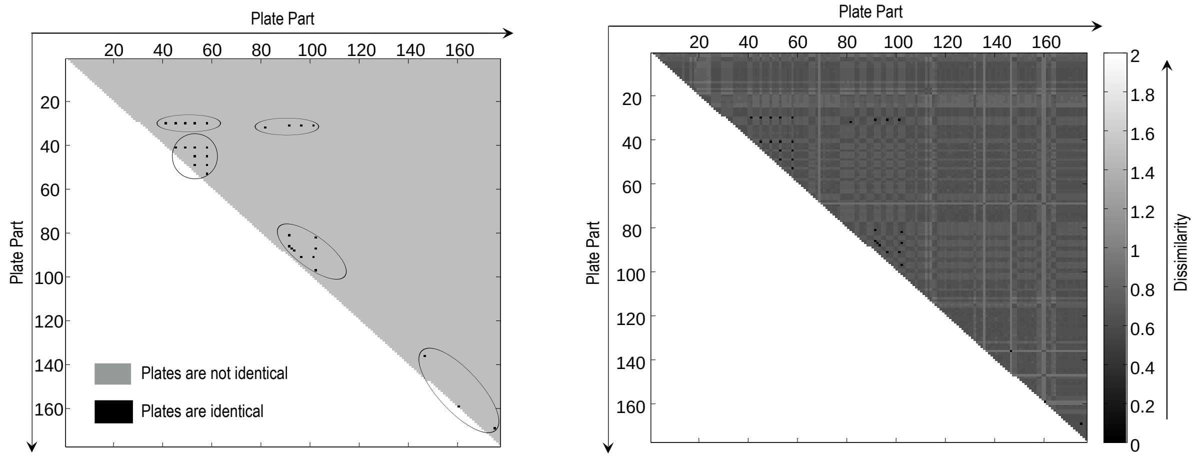


Figure 7.12.: Identity (left) and similarity evaluation (right) for the first tow blocks using 1024 points

Because of the dependency on the number of the random points as well as on the way the points are generated, a similarity ratio equal to zero is not to be expected. For this inconvenience, an experimentally minimum value is defined as the lower limit to consider two parts as identical e.g. $S_{min} = 0.0125$. Increasing this value will increase the number of the identical plates. According to this assumption, it is not expected to get the same results for similarity evaluation as those obtained using Frećhet distance, see Figure 7.7. The dark color distribution in Figure 7.12-right for similarity evaluation does not mean that the parts are actually similar, because all of the similarity ratios are less than 0.8. The similarity ratio-occurrence relationship is shown in Figure 7.13.

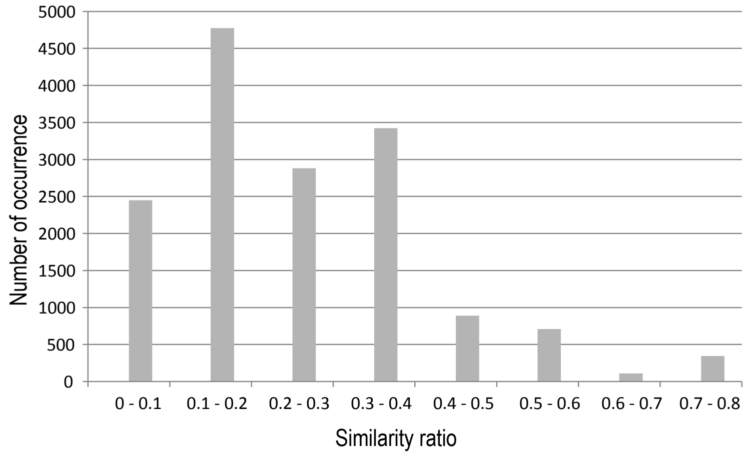


Figure 7.13.: Similarity ratio-occurrence distribution for the two blocks with 1024 points

The advantage of this method compared with the Frećhet distance is that not only the identity can be evaluated, but also the similarity. Therefore, this method can be applied in two scenarios: to retrieve the similar parts from a CAD-model database if the designer chose not to start the modelling from scratch and as a pretest for similarity evaluation with other methods, when the time is crucial because the computation time is less than other comparison methods.

The next test case is the CAD-model of the Bulk Carrier. The same number of points (1024) is applied. Identity and similarity evaluation results are also shown as an upper triangle matrix, see Figure 7.14 for a larger representation of the similarity see Appendix A.7. The computing time is moderate for analyzing the shape similarity for this complex ship structure blocks on a standard

PC. Also in this case, only partial agreement (black cells) with the results of similarity evaluation using Frećhet distance is achieved for the assumed minimum limit $S_{min} = 0.0125$.

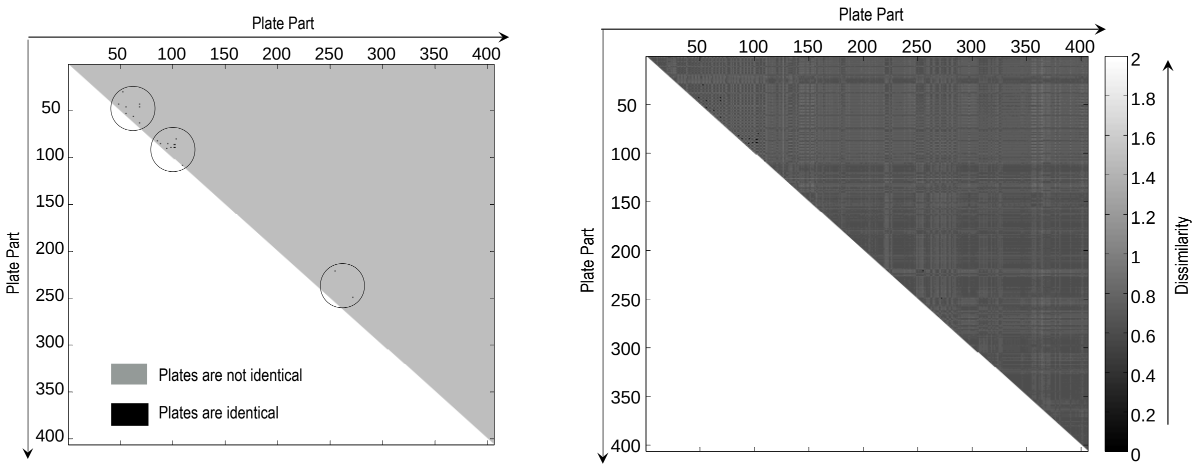


Figure 7.14.: Identity (left) and similarity evaluation (right) for the Bulk Carrier CAD-model using 1024 points

All computed similarity ratios are less than 0.8 and the most computed ratios are up to 0.5. The similarity ratio-occurrence relationship is shown in Figure 7.15.

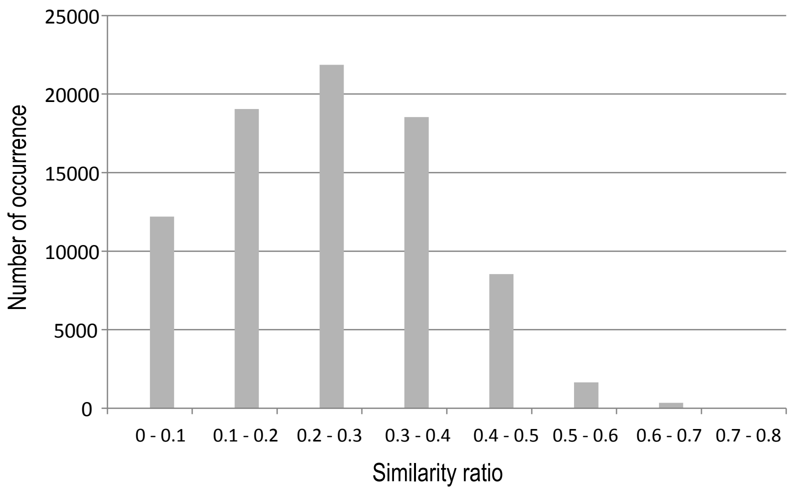


Figure 7.15.: Similarity ratio-occurrence distribution for the Bulk Carrier CAD-model with 1024 points

1.1. Impact of Points Number on Similarity Evaluation

To check the influence of the number of randomly generated points, the first and Bulk Carrier CAD models were tested again with bigger number of random points n = 2000 and the same minimum similarity ratio of $S_{min} = 0.0125$ was also applied as a minimum limit for identity evaluation. Figure 7.16 shows the identity and similarity results for the tow blocks CAD-model, for a larger representation of the similarity see Appendix A.7. Application of more points had a positive effect on the identity evaluation, where the number of identical parts increased and a better agreement with identity results using Frećhet distance was achieved, see Figure 7.7.
The distribution of the similarity ratio-occurrence is also affected by using more random points, see Figure 7.17. The most occurrences (about 4000) are shifted to the first range between 0 and 0.1, whereas the first case there were only 2500 and the overall distribution became linear. The changes in similarity ratio-occurrence distribution is due to the increased number on the surface of

the parts, which enhance the computation of the distances between the points pairs and therefore leads to more accurate computation of shape distributions.

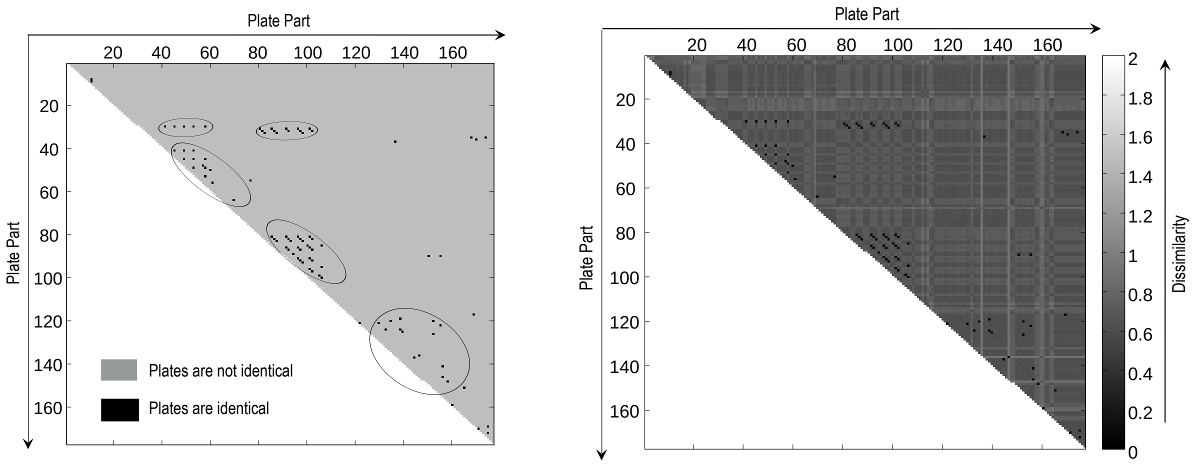


Figure 7.16.: Identity (left) and similarity evaluation (right) for tow blocks CAD-model using 2000 points

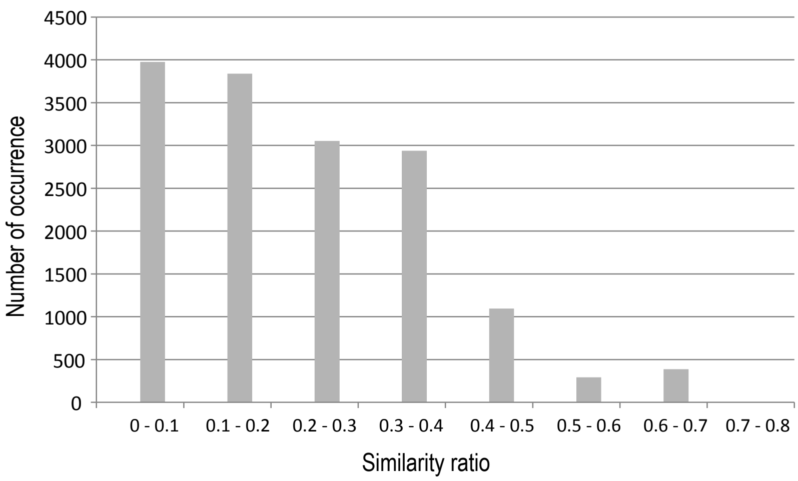


Figure 7.17.: Similarity ratio-occurrence distribution for the tow blocks CAD-model using 2000 points

The test with n=2000 was also performed on the CAD-model of the Bulk Carrier vessel, and the identity and similarity results are shown in Figure 7.18, for a larger representation of the similarity see Appendix A.7. The number of identical parts increased and a better agreement with the result obtained using Frećhet distance was achieved, see Figure 7.10. Analyzing the results shows that too many parts are considered identical when they are not. Accordingly, the identity evaluation using shape distribution is not reliable and the application of further features like area, volume and weight are necessary to increase the discrimination ability of this method to exclude the improper identity cases.

The similarity ratio-occurrence distribution for the Bulk Carrier CAD-model with n = 2000 is shown in graph 7.19. Profiling this graph leads to a similar conclusion. The most occurrences are also shifted toward the smallest values of similarity ratios but not to the same degree. The different behavior between both CAD-models can be traced back to the difference in the number and dimension of the parts.

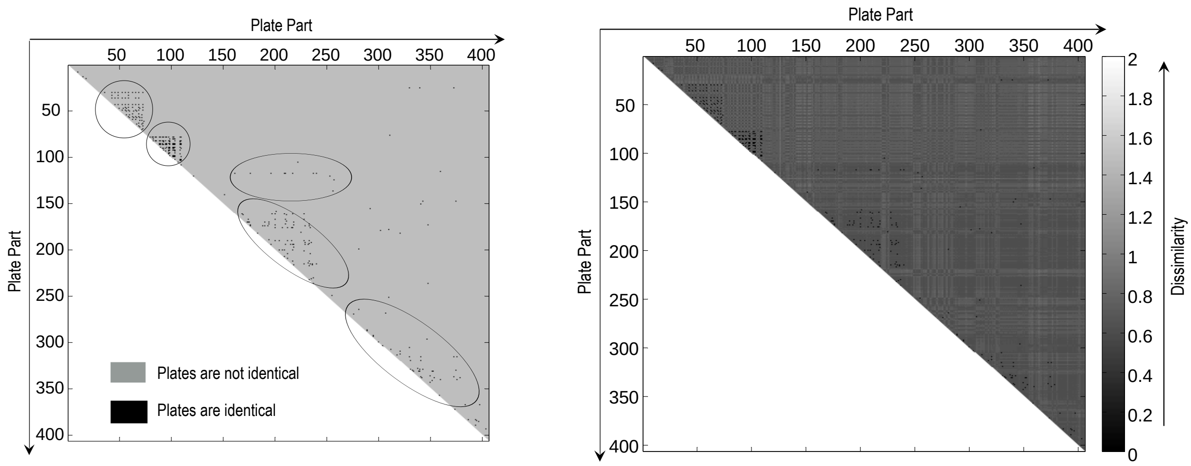


Figure 7.18.: Identity (left) and similarity evaluation (right) for the Bulk Carrier CAD-model using 2000 points

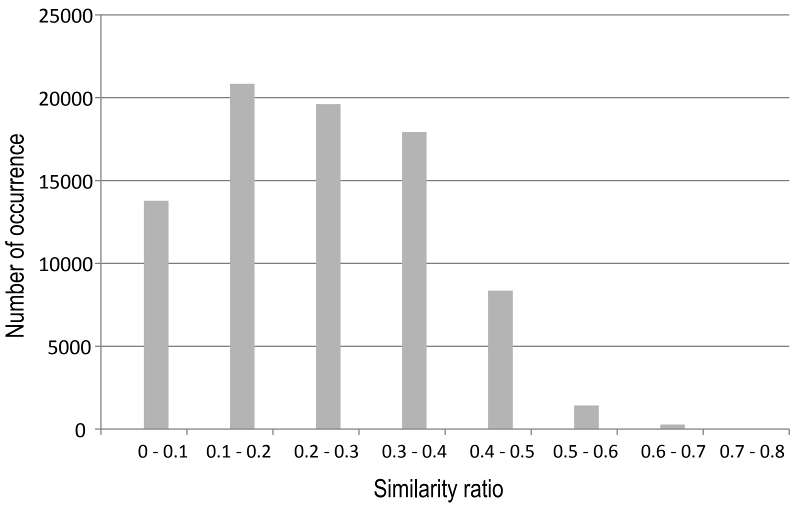
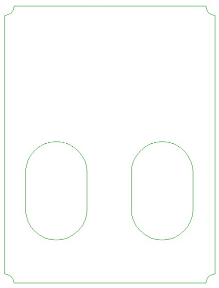


Figure 7.19.: Similarity ratio-occurrence distribution for the Bulk Carrier CAD-model with 2000 points

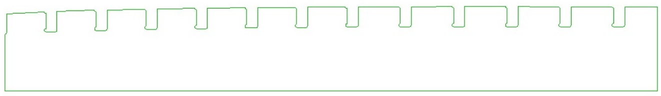
To analyze the effect of the number of the random points n on the similarity ratio and computation time, a convergencee study is done with different n values. Two parts with different properties are chosen, see Figure 7.20. Each plate is compared with itself. The computation time needed for each case is represented in the top graph, see Figure 7.21 and changes of similarity ratio is shown in graph 7.21 bottom. The results shown in Figure 7.21 reveal that the time needed for the computation of similarity ratio increases linearly with increasing the number of random points `n`. The computation time for plate 2 is more than the time needed for plate 1 due to the difference in the numbers of triangles building up the meshes. The similarity values start for both parts at some higher values (0.054 and 0.02 respectively). For n = 3000, the similarity ratios for both parts fall below 0.01 (circle). After this value, no significant change in values of similarity ratio with an increasing number of points (n) is obtained.

2. Similarity Result Using 2D Slicing Algorithm

The 2D-slice algorithm was applied in different cases i.e. individual parts, two blocks CAD-model and the CAD-model of the Bulk Carrier. The evaluation of similarity was performed after transforming parts in the same canonical coordinate system according to their main principal axes. After performing the transformation, a set of 2D slices was obtained along each axis. The number of cutting positions along each axis is given by the user. The computation time depends on the number



Property	Value
Area	6.412 m^2
Volume	0.025 m^3
No. of Triangles	692



Property	Value
Area	26.4 m^2
Volume	0,156 m^3
No. of Triangles	1280

Figure 7.20.: Plate 1 and table of properties (top) Plate 2 and table of properties (bottom)

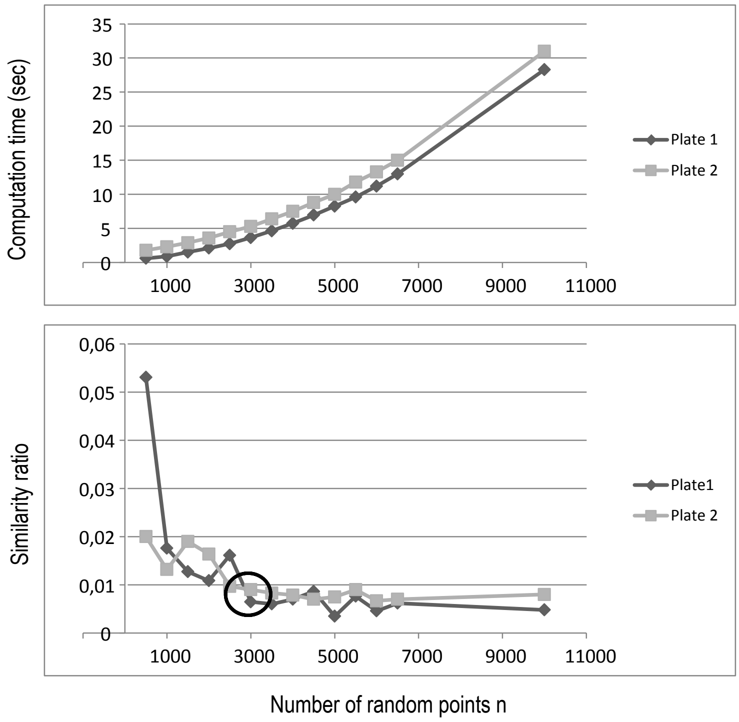


Figure 7.21.: Time-number of points (top) Similarity ratio-number of points relationships (bottom)

of the resulted slices. Therefore, an appropriate number should be chosen to provide a satisfactory result. This problem is solved by considering changes of features along the part's edges. After constructing the set of slices for both parts to be tested for similarity, the Frećhet distance algorithm is applied to each pair of slices with the same position. If the total number of the identical slices equals the total number of slices, the two parts are considered to be identical. If the slices are partially identical, the similarity ratio will be computed.

In the first test case, the implemented method was applied to two identical parts, which were randomly oriented in the 3D space, see Figure 7.22. The thickness of each plates is 12 mm it was assumed that the weld preparation is of type Y-joint, see Figure A.8. For this joint, the base height c falls in the range $2 \leq c \leq 4$. Taking c = 3 mm, then the minimum required number of slices n in z direction must be $n > \frac{t}{c/2} = \frac{12}{1.5} = 8$ to ensure that the slices in z direction capture all features. Taking n = 10 , the resulting sets of slices are shown in Figure 7.23. Because of the existence of holes inside the part, the final number of slices is more than n, see Table 7.1.

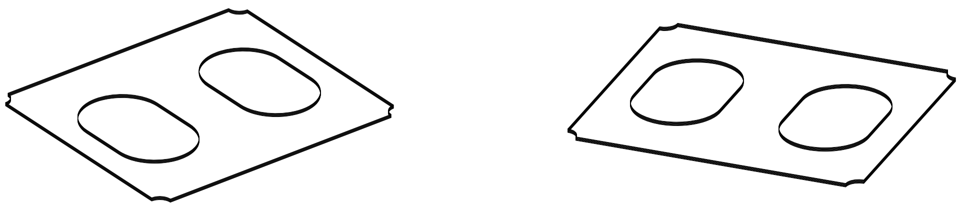


Figure 7.22.: Two different oriented parts in space

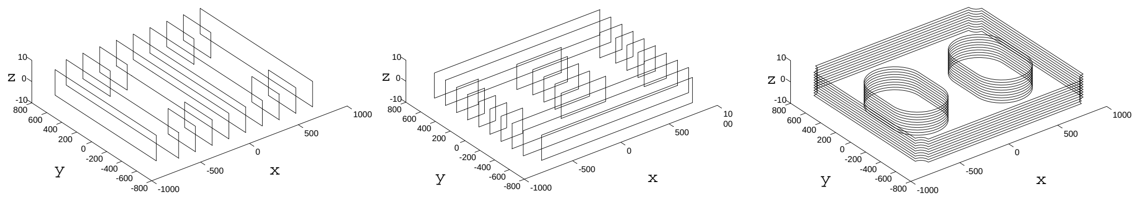


Figure 7.23.: Resulted set of slices along x, y and z axes

Axis	Number of sections	Number of polygons
x	10	14
y	10	20
z	10	30
Sum	30	64

Table 7.1.: Resulted sets of slices along x, y and z axes

The test of identity is performed using a tolerance of $\sigma = 0.5$ mm for Fre´chet distance. In the next test case, the implemented method was applied on the tow blocks CAD-model with a basic number of slices n = 20 along each axis with the same tolerance $\sigma = 0.5$ mm. The evaluation result of the identity and similarity is shown in Figure 7.24. The result is consistent with result of similarity evaluation using Fre´chet distance Figure 7.7.

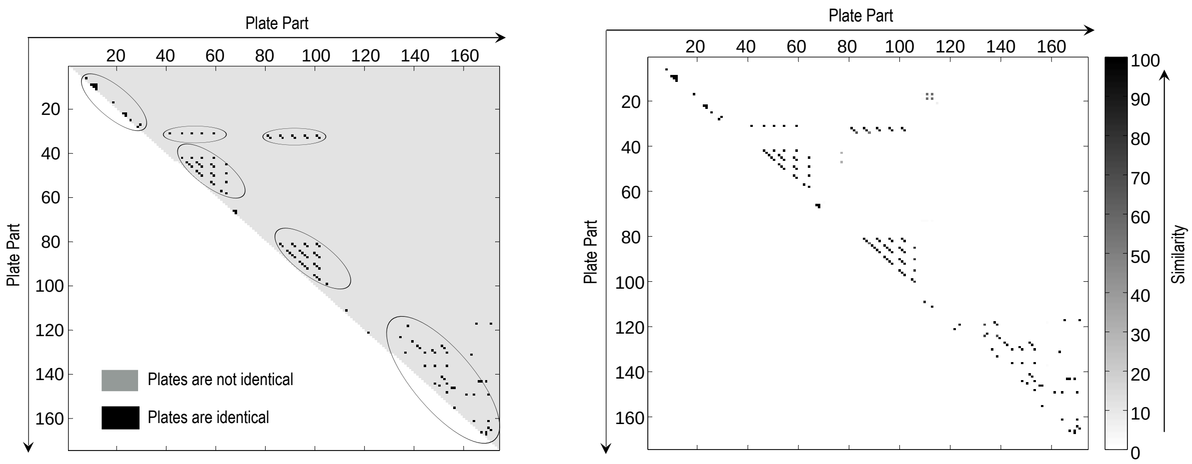


Figure 7.24.: Identity (left) and similarity evaluation (right) of the tow blocks CAD-model using 20 slices along each principal axis

The same parameters were also applied on the Bulk Carrier CAD model. The result is shown in Figure 7.25. It is consistent with the result obtained using the Fre´chet distance in 2D case, see Figure 7.10.

The discussed test cases show the applicability of the introduced algorithms, which provide a precise result like the one obtained in the 2D case. The algorithm is primarily applicable for the identity evaluation.

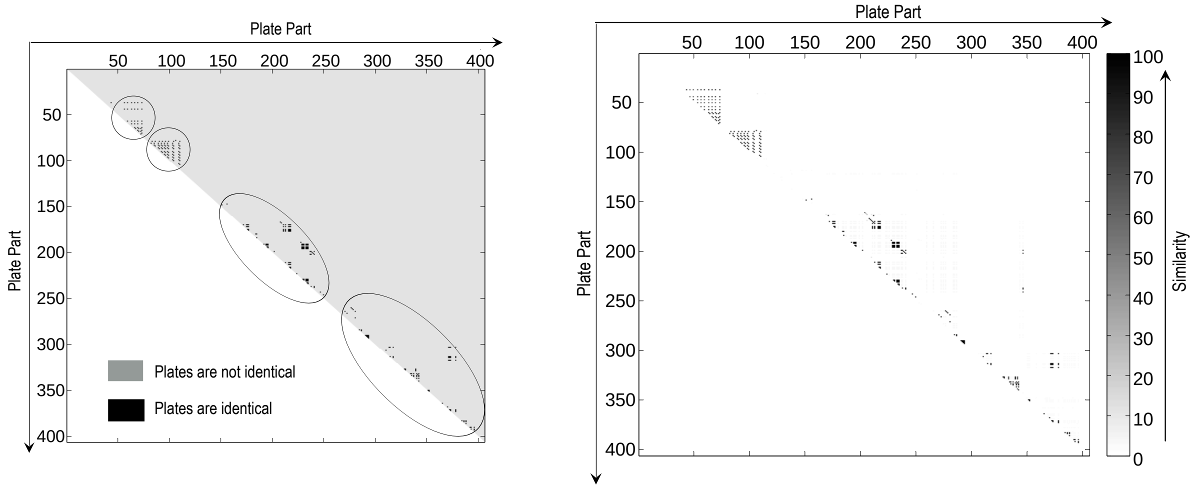


Figure 7.25.: Identity (left) and similarity evaluation (right) of the Bulk Carrier CAD-model using 20 slices along each principal axis

3. Similarity Result Using Monte Carlo Method

As described in chapter 5, this method depends on the generation of random points within the bounding box of the 3D object. To get a reliable result, a comparison of two successive executions is performed. When the resulting difference is not as small as required, the number of generated points increases. The test starts with a small number of random points e.g. n = 200 and then n will be increased. If the similarity ratio for both executions is the same or within a predefined tolerance, the test will stop. If not, another number will be selected until the maximum allowed number of points is increased or stop condition is fulfilled.

In the first test case, the Monte Carlo algorithm is applied on the first test case. The results are represented in the identity and the similarity matrix, see Figures 7.26-left and 7.26-right respectively. The identity matrix shows the identical parts with similarity ratio equal to 100, however similarity matrix shows all obtained values. This method has two significant benefits. First, a precise identity and second, a powerful similarity evaluation mechanism when compared with the other addressed methods, see subsection 7.2.1.3 for more details.

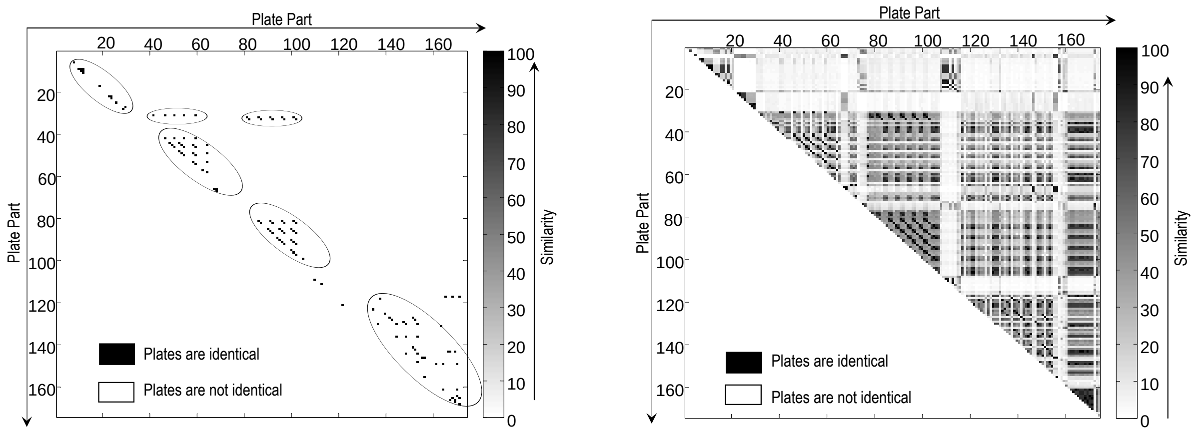


Figure 7.26.: Similarity evaluation of the tow blocks CAD-model using Monte Carlo method

The results of identity matrix of Monte-Carlo, Figure 7.26-left, shows complete agreement with the results using Frećhet distance algorithm in Figure 7.7. The identical parts are shown as black cells.

In the second test case, the CAD-model for the Bulk Carrier vessel is checked for similarity. Figure 7.27-left shows the identity evaluation, where only the identical parts with a similarity ratio equal to 100 are shown. Figure 7.27-right shows all obtained results. Two identical parts are marked as a black cell, two completely different parts as a white cell and partially similar parts in different gray color depending on the similarity ratio. The darker the color is, the more similar the parts are. Also in this case, a complete agreement with the result of similarity evaluation using Frećhet distance, Figure 7.10 is achieved.

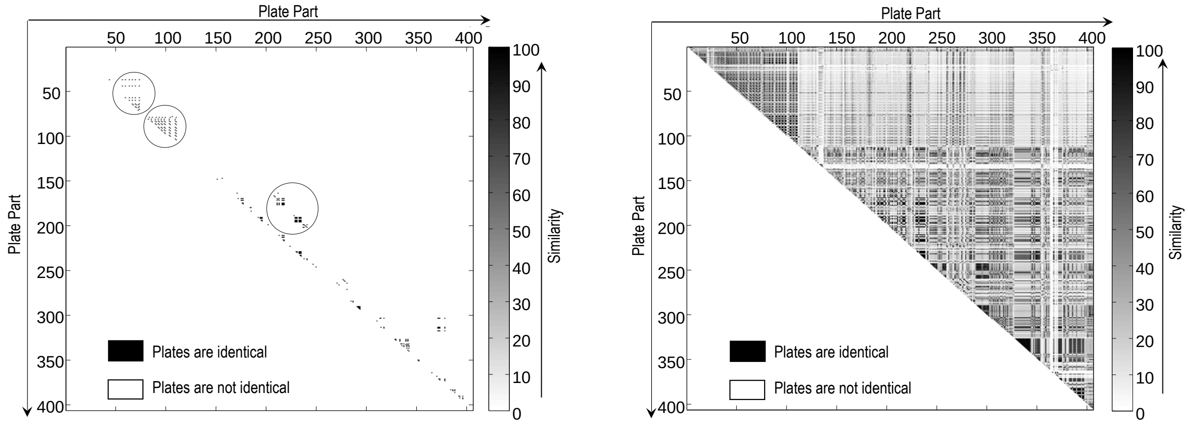


Figure 7.27.: Similarity evaluation of the Bulk Carrier CAD-model using Monte Carlo method

7.2.1.3. Comparison of the Implemented Methods

To compare the performance of the implemented methods, 10 plate parts of different shapes and dimensions are selected. Plates pairs 1 & 2, 4 & 5, 6 & 7, and 9 & 10 are identical, see Figure 7.28. The first two plates are curved hull plates.

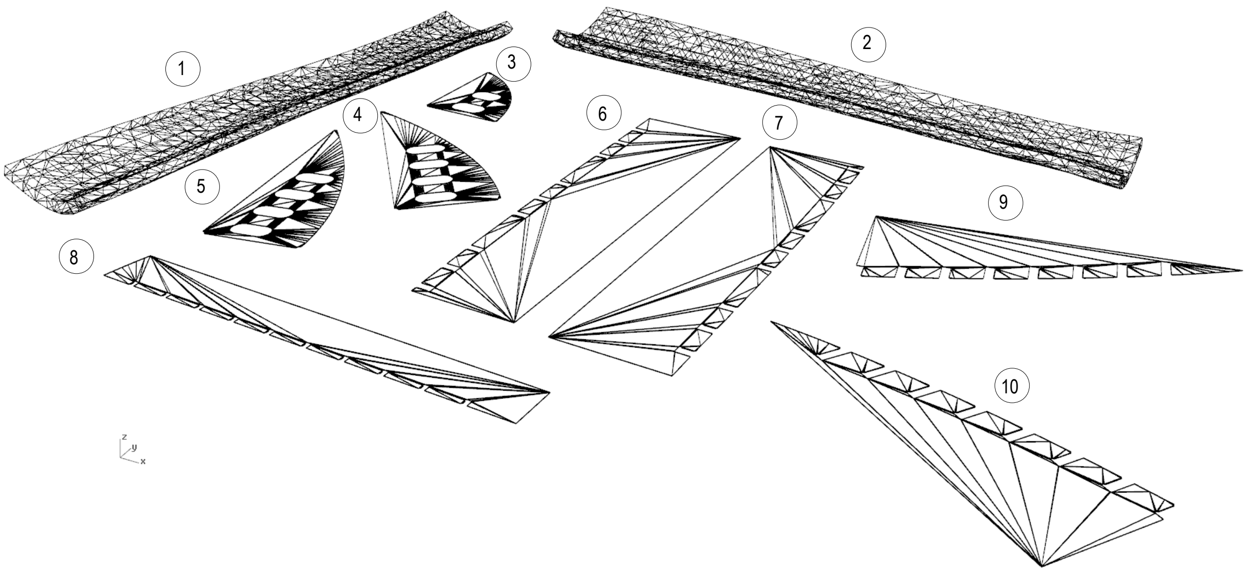


Figure 7.28.: Selected plates for comparing the performance of the three methods

Figure 7.29 shows the identity evaluation results using shape distribution, 2D-slice, and Monte Carlo methods. For the shape distribution, a random number n = 3000 and a minimum similarity ratio $S_{min} = 0.02$ are applied for the identity evaluation. For the 2D-slice algorithm, 20 slicing positions along each axis and a minimum Frećhet distance $\sigma = 0.5$ mm are required. For the application of Monte Carlo algorithm, no special parameters are applied. Analyzing the results of shape identity evaluation for the mentioned methods shows a precise evaluation of identity as expected. The addressed methods provide the same correct results. Because of the characteristics of the shape distribution method, the identity evaluation was only correct for a minimum similarity ratio equal to $S_{min} = 0.02$ instead of zero.

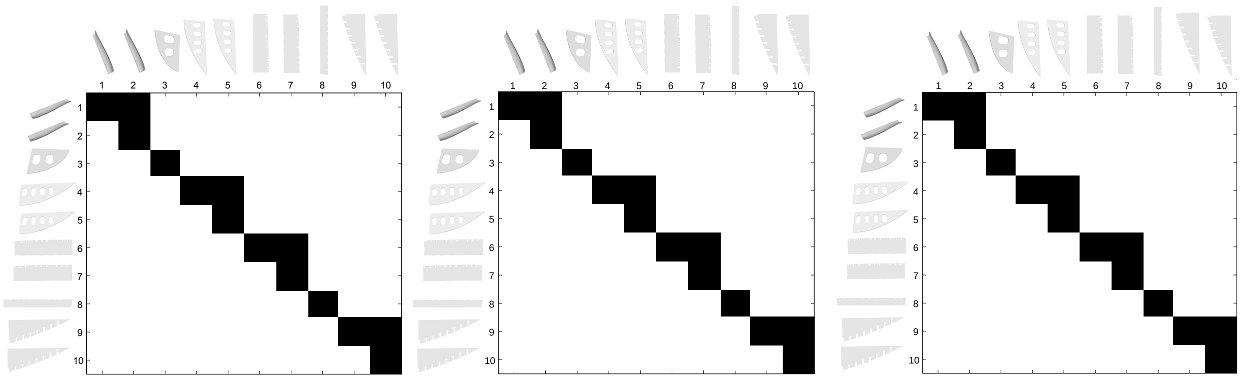


Figure 7.29.: Identity evaluation for 10 parts using shape distribution (left), 2D-slice (middle), and Monte Carlo (right) methods

Similarity evaluation for the selected parts is also performed against the mentioned methods and the results are shown in Figures 7.30 and 7.31. The similarity degree using shape distribution method is given as previously described in a range between 0 and 2, where identical parts have similarity degree equal to 0 and two completely different parts have a value equal to 2. The similarity ratio for 2D-slice and Monte Carlo is given as a percentage, where identical parts have a ratio equal to 100 %. As shown in Figures 7.30 and 7.31, each methods provide different results for the similarity. This difference in similarity evaluations can be traced back to the characteristics of each method and its preprocessing steps, for example pose estimations, random points generation. The shape distribution method is the only method that can provide similarity evaluation for each pair of parts, because it is independent of the pose estimation. The 2D-slice algorithm is highly dependent on the pose estimation, so only very similar parts can have an evaluation of similarity, Figure 7.30-right only identical parts are identified. The Monte Carlo method is less sensitive for the pose estimation and it is able to evaluate the similarity for partially overlapped shapes, see Figure 7.31. Analyzing the identity and similarity results shows that the Monte Carlo method provides the best evaluation results among the three methods.

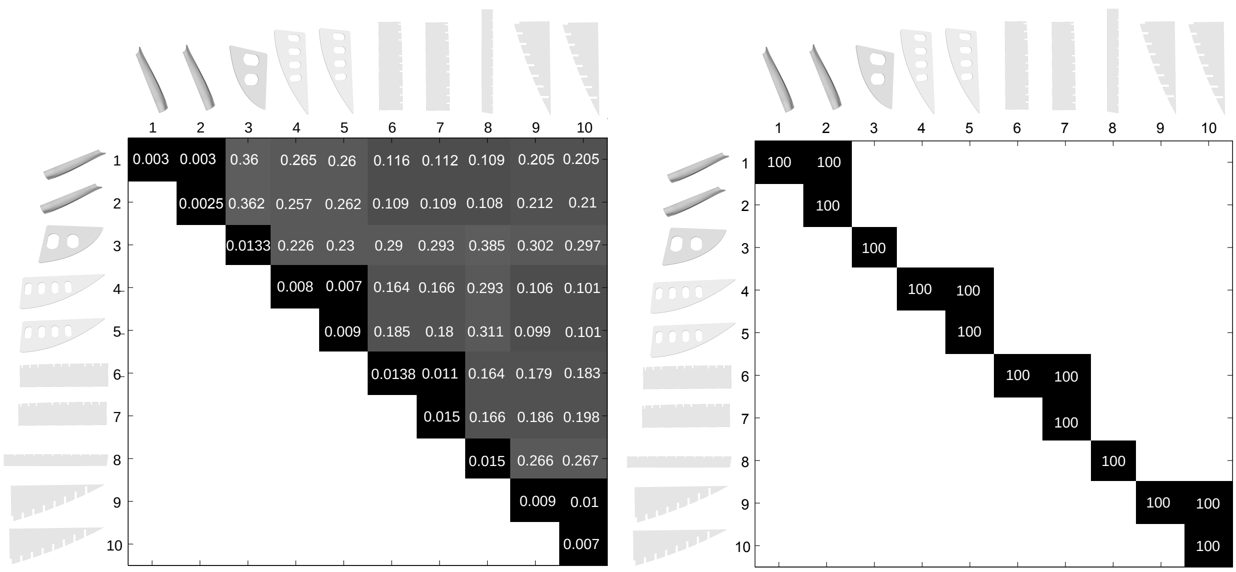


Figure 7.30.: Similarity evaluation for 10 parts using shape distribution (left) and 2D-slice (right)

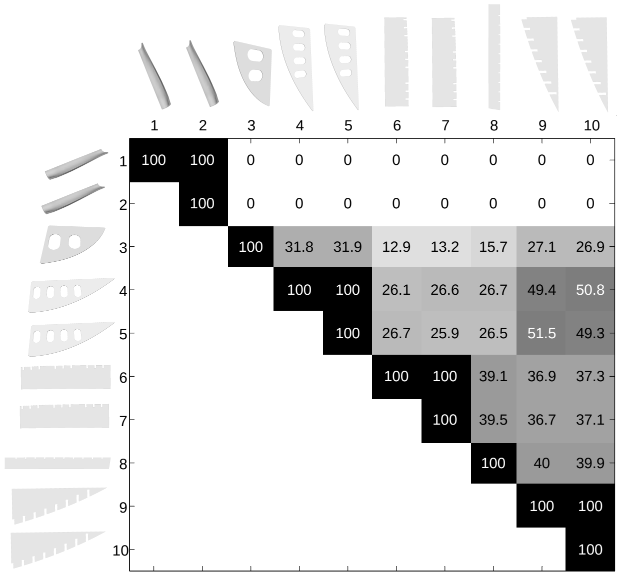


Figure 7.31.: Similarity evaluation for 10 parts using Monte Carlo method

7.2.2. Inspection Results for Features Quality Criteria

Quality criteria regarding weld preparation, notches, and excess material are inspected using the test cases for the Bulk Carrier and RoRo ship. Each mentioned group has sub criteria as discussed in subsection 3.6.2.2. The defined tolerances and thresholds are applied and for criteria with no recommended values, optional values have been chosen. The algorithms discussed in Chapter 5 are applied to perform the necessary topological analysis. Apart from the complex test CAD-models, simple structure with special design built up of five plates is used to serve as a reference model. Two plates `M209-FR110_3` and `M209-FR110_4` lie in the image plane, see Figure 7.32. The upper left and right corners of the plate `M209-FR110_3` fulfill the conditions for notches, quality criterion `O-NO-MI`, Table 6.1. One notch is provided at the upper left corner. Therefore the quality inspection correctly results in a warning about a missing notch at the upper right corner. A warning in this case means that the designer has the ability to evaluate the severity of missing the notch at this position. Since the corners of the plate `M209-FR110_3` are not surrounded by other two plates having a different orientation, no more warnings are raised. The notch provided at the lower left side of the bottom plate has a radius of 20 mm, Figure 7.32-left, which is smaller than the advised value in Table 6.1 for the quality criterion `O-NO-NS`. Accordingly, an error is reported.

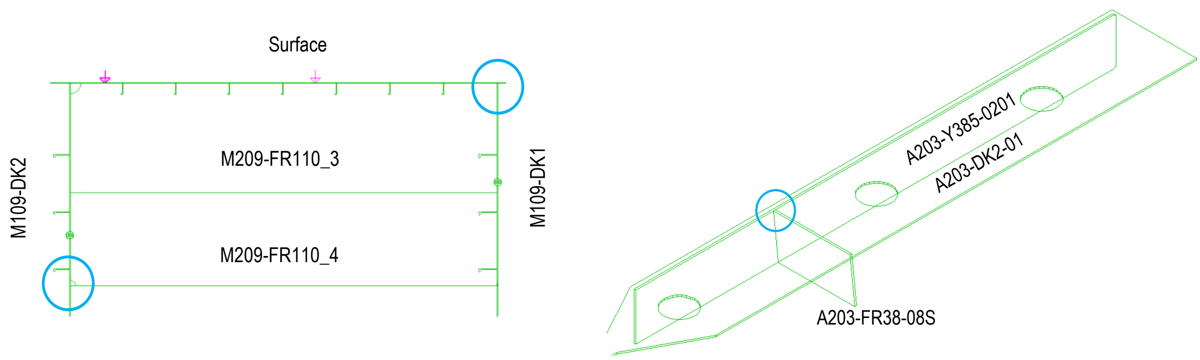


Figure 7.32.: Two quality problems regarding notches criteria (left) missing notch problem (right)

At the marked position in Figure 7.32-right, a missing notch is reported, where plate `A203-FR38-08S` is surrounded by `A203-DK2-01` and `A203-Y385-02`, which have different orientation in space relative to the considered plate `A203-FR38-08S`.

The CAD-model shown in Figure 7.2 is tested against the edge preparation and notch quality criteria. The quality inspection for this mock-up regarding the edge preparation and the notch criteria results in the following quality issues. Only a single edge with a missing edge preparation (bevel code information) `O-EP-MI` was detected. Three instances of edge preparation which do not comply with the predetermined standard values `O-EP-NS` were identified and ten occurrences of inapt data regarding the conclusiveness of the bevel code `O-EP-NC` were detected. One missing excess `O-EX-MI` is reported and two assigned excesses are not standard `O-EX-NS`. Only one excess is not conclusive `O-EX-NC`. A large number (260) of missing notches `O-NO-MI` at plate corners bounded by two other structural parts were identified, which can be caused by the incorrect assignment of plate functions i.e. watertight or non-watertight. Only three notches have been detected, which were not conform to the recommended values of the quality parameters database `O-NO-NS`.

The same tolerances and values were also applied on the CAD-model of the RoRo vessel. For edge preparation quality criteria, 90 instances of missing edge information, 102 instances for edge information not compliance with the standards, and 94 instances for not conclusive edge preparation are reported. Regarding the excess material quality criteria, 57 instances were reported for missing excess information, 17 instances for not standard excess information, and 15 instances for not conclusive excess information. Finally, 354 instances for missing notches are reported and a large number of instances (3934) for notches which do not have standard sizes were reported. This last issue emphasizes the importance of respecting the design standards at the design phase to reduce the time wasted at the production phase. For the tow blocks CAD-model, only notch information is provided, therefore, only quality criteria regarding notch information are inspected. 118 missing notches were reported and 44 instances of notches with a radius less than the standard value were identified. Table 7.2 outlines the inspection results of the features quality criteria for the test CAD-models.

	Missing Notch	Notch not Standard	Missing Excess	Excess not Standard	Excess not Conclusive	Missing Bevel	Bevel not Standard	Bevel not Conclusive
Test case 1	118	44	-	-	-	-	-	-
Bulk Carrier	260	3	1	2	1	1	3	10
RoRo vessel	354	3934	57	17	15	90	102	94

Table 7.2.: Inspection results for test CAD-models against feature quality criteria

7.2.3. Inspection Results of Weld Arrangements

This subsection addressing the quality management inspection results regarding the weld arrangements which include the inspection of the required minimum distances between seam-seam `O-SSDI-NS`, part-seam `O-PSDI-NS`, and part-part `O-PPDI-NS` as well as the required minimum angles between seam-seam `O-SSAN-NS`, part-seam `O-PSAN-NS`, and part-part `O-PPAN-NS`. The reference values of these dimension are addressed in Table 6.1. Thresholds and tolerances which are shipyard specific values have been applied and are discussed respectively. For approving the quality control mechanisms of the geometry related quality criteria, special configurations of structural components have been modelled representing different problematic relationships, see Figure 7.33-left. This construction is not a realistic ship structure arrangement but serves as a benchmark for the implemented quality management functions. The mock-up consists of one plate, supported by four stiffeners (1 to 4) of which three have a curved trace line. Applying a minimum distance criterion with a parameter of 50 mm, three zones are automatically detected not meeting this quality criterion (shown within circles). The structure in Figure 7.33-right also shows a benchmark configuration which is specially designed to test the minimum angle requirement. In this case, five stiffeners were modeled resulting in three intersections marked with circles. A minimum angle of 20° between two intersecting structural components was formulated as the relevant quality criterion yielding to the three intersections not meeting this criterion.

Since the recommended values for the minimum distances between part-seam and seam-seam are functions of the plate thickness, the number of the inapt data is independent of reference values.

24 occurrences of `O-PSDI-NS` and 4 of `O-SSDI-NS` were identified for the whole aft part of the Bulk Carrier. However, for the criterion minimum distance between two parts `O-PPDI-NS`, a parameter will influence the number of identified quality issues. Four values (10, 50, 150, 850 mm) were applied for the `O-PPDI-NS` criterion and the detected inapt data resulted in (0, 0, 0, and 53), respectively. Three angle values (5°, 20°, 30°, and 50°) were applied for the minimum angle criterion. The detected inapt configurations were 0 for the `O-PPAN-NS` criterion, (0, 11, 11, and 12) for the `O-PSAN-NS` criterion, and (0, 3, 4, and 5) for the `O-SSAN-NS` criterion respectively.

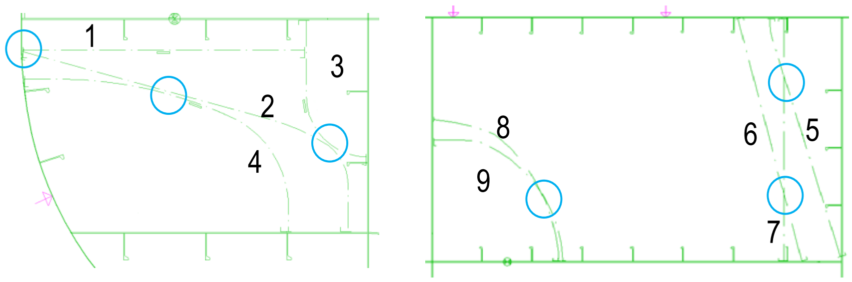


Figure 7.33.: Examples for minimum distance (left) and minimum angle (right) criteria violation

The CAD-model of the RoRo vessel was also tested against the weld arrangement quality criteria. For the minimum distance criteria, the same predefined required distances were applied i.e. 10, 50, 150, and 850 mm for distances between two parts. (4, 5, 27, and 3255) instances were reported for non compliance of distance between two adjacent stiffeners. The minimum distances between seams and parts as well as seam and seam was constant and therefore the same number of errors in all cases was reported. Three cases for non compliance arrangements between seam and stiffeners and no cases for the minimum distance between two seams were reported. The same values (5°, 20°, 30°, and 50°) were also applied for the minimum angle requirements and (0, 2, 2, and 8) instances were reported respectively for the angles between two adjacent stiffeners, (0, 0, 1, and 11) for seam and stiffener combination. No errors were identified relating to the minimum angle between two adjacent seams. The inspection results for the mentioned cases are shown in the following Tables:

	Min. Dist. Seam-Seam	Min. Dist. Seam-Part	Min. Dist. Part-Part	Min. Angle Seam-Seam	Min. Angle Seam-Part	Min. Angle Part-Part
10 mm & 5°	0	1	0	0	0	0
50 mm & 20°	0	1	0	0	0	0
150 mm & 30°	0	1	0	0	0	0
850 mm & 50°	0	1	209	0	0	0

Table 7.3.: Inspection results for the first test case against weld arrangement quality criteria

	Min. Dist. Seam-Seam	Min. Dist. Seam-Part	Min. Dist. Part-Part	Min. Angle Seam-Seam	Min. Angle Seam-Part	Min. Angle Part-Part
10 mm & 5°	4	24	0	0	0	0
50 mm & 20°	4	24	0	0	11	3
150 mm & 30°	4	24	0	0	11	4
850 mm & 50°	4	24	53	0	12	5

Table 7.4.: Inspection results for Bulk Carrier CAD-model against weld arrangement quality criteria

	Min. Dist. Seam-Seam	Min. Dist. Seam-Part	Min. Dist. Part-Part	Min. Angle Seam-Seam	Min. Angle Seam-Part	Min. Angle Part-Part
10 mm & 5°	0	3	4	0	0	0
50 mm & 20°	0	3	5	0	0	2
150 mm & 30°	0	3	27	0	1	2
850 mm & 50°	0	3	3255	0	11	8

Table 7.5.: Inspection results for RoRo vessel CAD-model against weld arrangement quality criteria

7.3. Results Assessment

The assessment of the inspection results depends on the applied project requirements configuration applied by the quality or project manager. According to this dependency, the assessment behaves dynamically for each configuration of quality criteria i.e. one acceptable assessment may not be acceptable for another configuration of requirements. The assessment includes computing of quality score depending on the number of the detected errors. Depending on the detected errors, the error rate can be determined. The required times for errors correction is also estimated and finally a block-wise representation of the inspected data is created to show the vessel blocks in different colors. The blocks with the most errors will appear in red and the blocks with the minimum number of errors in green. The remaining blocks appear in color range between green and red. This colored representation supports the design team to focus their efforts on the faultiest blocks.

7.3.1. Error Rate

Depending of the applied usage scenario, the error rate supports the product data receiver to get an overall view of the quality grade according to the required criteria and therefore to make the decision about accepting or rejecting the modelled data. An example of usage is the scenario where the shipyard outsources a part or the whole design activities to a design agent, see Figure 7.34.

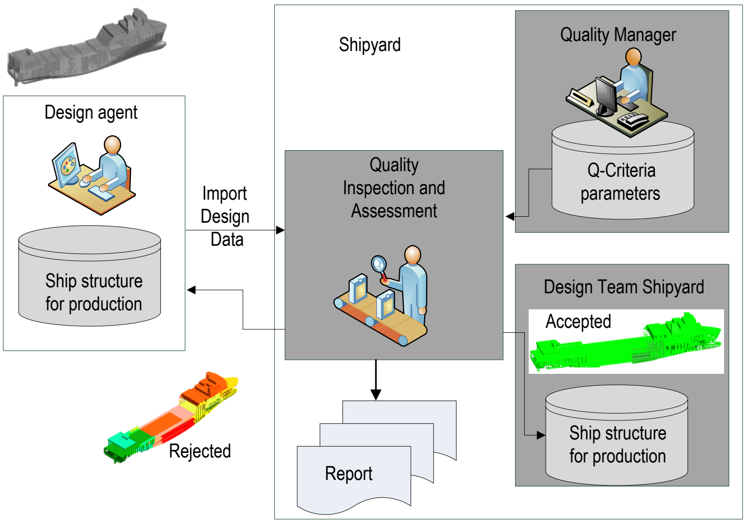


Figure 7.34.: Application scenario of the inspection results assessment

The error rate is ranged in a scale between 1 and 5, see subsection 4.5.1. 5 refers to data with very bad quality and 1 to free-of-error. Depending on the obtained quality scores for the RoRo vessel in Table 7.6, the error rate can be computed as:

$$Error\,Rate = \frac{\sum Quality\,Scores}{\sum No.of\,Errors} = \frac{32403}{8026} \approx 4$$

Criterion	QC-Identifier	Weight	No. of Errors	Quality Score
Missing excess	O-EX-MI	5 (KO)	57	285
Not standard excess (big)	O-EX-NS	3 (Major Error)	17	51
Not standard excess (small)	O-EX-NS	5 (KO)	27	135
Not conclusive excess	O-EX-NC	2 (Error)	15	30
Missing bevel code	O-EP-MI	5 (KO)	90	450
Not standard bevel code	O-EP-NS	5 (KO)	102	510
Not conclusive bevel code	O-EP-NC	5 (KO)	94	470
Missing notch	O-NO-MI	4 (Fatal Error)	354	1416
Not standard notch	O-NO-NS	4 (Fatal Error)	3934	15736
Not standard distance between two seams	O-SSDI-NS	4 (Fatal Error)	0	0
Not standard distance between two stiffeners	O-PPDI-NS	4 (Fatal Error)	3303	13212
Not standard distance between stiffener/seam	O-PSDI-NS	4 (Fatal Error)	3	12
Not standard angle between two seams	O-SSAN-NS	4 (Fatal Error)	0	0
Not standard angle between two stiffeners	O-PPAN-NS	4 (Fatal Error)	2	8
Not standard angle between stiffener/seam	O-PSAN-NS	4 (Fatal Error)	0	0
Missing position number	O-PN-MI	1 (Warning)	11	11
Not standard position number	O-PN-NS	5 (KO)	2	10
Not conclusive position number	O-PPPN-NC	5 (KO)	15	75
$\sum$			8026	32403

Table 7.6.: Quality score for the RoRo-Vessel

The inspection results of the Bulk Carrier model are also assessed in the same way. Table 7.7 shows the quality scores for 18 quality criteria:

Criterion	QC-Identifier	Weight	No. of Errors	Quality Score
Missing excess	O-EX-MI	5 (KO)	1	5
Not standard excess (big)	O-EX-NS	3 (Major Error)	2	6
Not standard excess (small)	O-EX-NS	5 (KO)	0	0
Not conclusive excess	O-EX-NC	2 (Error)	1	2
Missing bevel code	O-EP-MI	5 (KO)	1	5
Not standard bevel code	O-EP-NS	5 (KO)	3	15
Not conclusive bevel code	O-EP-NC	5 (KO)	10	50
Missing notch	O-NO-MI	4 (Fatal Error)	260	1040
Not standard notch	O-NO-NS	4 (Fatal Error)	3	12
Not standard distance between two seams	O-SSDI-NS	4 (Fatal Error)	4	16
Not standard distance between two stiffeners	O-PPDI-NS	4 (Fatal Error)	53	212
Not standard distance between stiffener/seam	O-PSDI-NS	4 (Fatal Error)	24	96
Not standard angle between two seams	O-SSAN-NS	4 (Fatal Error)	5	20
Not standard angle between two stiffeners	O-PPAN-NS	4 (Fatal Error)	0	0
Not standard angle between stiffener/seam	O-PSAN-NS	4 (Fatal Error)	12	48
Missing position number	O-PN-MI	1 (Warning)	11	11
Not standard position number	O-PN-NS	5 (KO)	2	10
Not conclusive position number	O-PPPN-NC	5 (KO)	15	75
$\sum$			406	1619

Table 7.7.: Quality score for the Bulk Carrier

The corresponding error rate is:

$$Error\,Rate = \frac{\sum Quality\,Scores}{\sum No.of\,Errors} = \frac{1619}{406} \approx 4$$

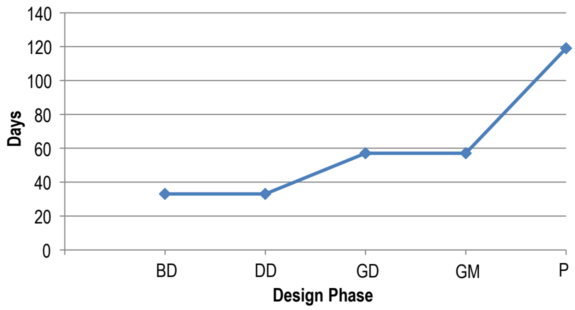
7.3.2. Quality Cost

Depending on the number of errors, the design agent can decide to correct the product data or in the worst case to start a new design. This decision can be made by comparing the needed time for the correction and the time needed to start a new design from scratch. Some guiding values for the required correction time depending on the detection phase can be found in Appendix A.1. Table 7.8 shows error correction times for the RoRo model using the guiding values. The value in each line represents the multiplication of the number of detected errors by the time required for error correction. The estimated times in Table 7.8 can be transformed to work-days of 8 eight hours per day assigned to a design team of five persons as shown in Figure 7.35.

Criterion	No. Error	BD	DD	GD	GM	P
Missing excess	57	570	570	855	1140	1995
Not standard excess (big)	17	170	170	255	255	510
Not standard excess (small)	27	270	270	405	540	1080
Not conclusive excess	15	150	150	225	300	600
Missing bevel code	90	900	900	1350	1350	5400
Not standard bevel code	102	1020	1020	1530	1530	6120
Not conclusive bevel code	94	940	940	1410	1410	4700
Missing notch	354	3540	3540	5310	5310	14160
Not standard notch	3934	39340	39340	59010	59010	118020
Not standard distance between two seams	0	0	0	0	0	0
Not standard distance between two stiffeners	3303	33030	33030	66060	66060	132120
Not standard distance between stiffener-seam	3	30	30	60	60	120
Not standard angle between two seams	0	0	0	0	0	0
Not standard angle between two stiffeners	2	20	20	40	40	80
Not standard angle between stiffener-seam	0	0	0	0	0	0
Missing position number	11	55	55	110	165	330
Not standard position number	2	10	10	20	30	80
Not conclusive position number	15	225	225	300	375	750
$\sum$	8026	80270	80270	136940	137575	286065

Table 7.8.: Time cost of error correction according to detection phase and error's nature [Minutes] for the RoRo vessel

BD refers to basic design, DD refers to detailed design, GD refers to generation of drawings, GM refers to generation of manufacturing data, and P refers to production.



	BD	DD	GD	GM	P
Correction Days	33	33	57	57	119

Figure 7.35.: Correction days-design phase relationship according to the detection design phase for the RoRo vessel

The range between the smallest and the biggest number of the estimated days is: $R = T_{max} - T_{min} = 119 - 33 = 86$ Days. It shows that if the errors are detected too late in the production phase, 3 extra months are needed to correct the data than if the errors are detected at the basic design stage. The mean absolute deviation is:

$$\bar{s} = \frac{1}{n}\sum^{n} |x_i - \lambda|$$

λ is the Mean, Median, or the Mode or so-called measures of central tendency. The calculated values are shown in Table 7.9.

Measure of central tendency	Mean absolute deviation
Mean $\overline{s} = 60$	23.8
Median = 57	22
Mode = 33 and 57	26.8 22

Table 7.9.: Measure of central tendency and mean absolute deviation

The mean absolute deviation (MAD) from the median (22) is less than or equal to the mean absolute deviation from the mean (23.8).

Variance:

$$s^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{s})^2$$

where $\overline{s}$ is the mean.

$s^2 = 991.4$.

The standard deviation is a numerical value used to indicate how widely the individual correction-times vary. Standard deviation is the squared root of the variance. For the estimated correction times is equal to $s = \sqrt{s^2} = 31.5$ Days. This means that most design phases have a correction-time within 31.5 days of the mean 60 days and that is true for the first two design phases. Coefficient of variation is the ratio of the standard deviation over the arithmetic mean: $v = \frac{s}{\overline{x}} = 52.5\%$. v indicates that the standard deviation s as a measure for the dispersion is 52.5 % deviated from the arithmetic mean.

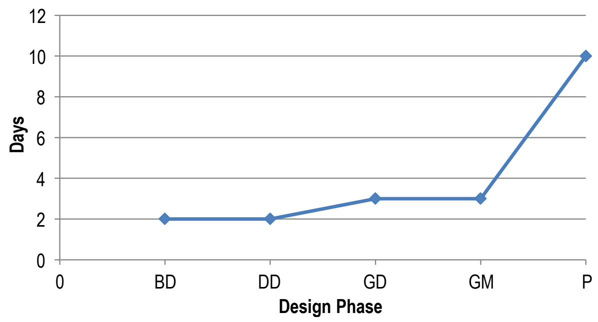
The same statistical study is performed on the inspection result of the Bulk Carrier. In Table 7.10, the estimated correction-times according to the number of detected error and the detection phase are shown.

Criterion	No. Error	BD	DD	GD	GM	P
Missing excess	1	10	10	15	20	35
Not standard excess (big)	2	20	20	30	30	60
Not standard excess (small)	0	0	0	0	0	0
Not conclusive excess	1	10	10	15	20	40
Missing bevel code	1	10	10	15	15	60
Not standard bevel code	3	30	30	45	45	180
Not conclusive bevel code	10	100	100	150	150	500
Missing notch	260	2600	2600	3900	3900	10400
Not standard notch	3	30	30	45	45	90
Not standard distance between two seams	4	40	40	80	80	160
Not standard distance between two stiffeners	53	530	530	1060	1060	2120
Not standard distance between stiffener-seam	24	240	240	480	480	960
Not standard angle between two seams	5	50	50	100	100	200
Not standard angle between two stiffeners	0	0	0	0	0	0
Not standard angle between stiffener-seam	12	120	120	240	240	480
Missing position number	1	5	5	10	15	30
Not standard position number	3	15	15	30	45	120
Not conclusive position number	26	390	390	520	650	1300
$\sum$	406	4200	4200	6735	6895	16735

Table 7.10.: Time cost of error correction according to detection phase [Minutes] for the Bulk Carrier

BD refers to basic design, DD refers to detailed design, GD refers to generation of drawings, GM refers to generation of manufacturing data, and P refers to production.

The estimated times in Table 7.10 can be transformed to work-days of 8 eight hours per day assigned to a design team of five persons as shown in Figure 7.36-right.



	BD	DD	GD	GM	P
Correction Days	≈ 2	≈ 2	≈ 3	≈ 3	≈ 10

Figure 7.36.: Correction days-design phase relationship according to the detection design phase for the Bulk Carrier

	Range	Mean $\overline{s}$	Median	Mode	Variance s^2	s [Days]	v %
Bulk Carrier	8	4	3	2 & 3	46	6.8	85

Table 7.11.: Measure of dispersion for Bulk Carrier

Obviously, the number of errors is less than those for the RoRo vessel, therefore, the number of the required days for correction is also less. The variance $v = 85\%$ is bigger than that for the RoRo vessel and this means that the result is more dispersed than for the RoRo vessel.

7.3.3. Guided Error Correction

To focus on the most faulty blocks during the correction works, a block-wise representation of the tested CAD models is applied as described in section 4.5. Figure 7.37 shows the block-wise representation of the RoRo model. Ten color distribution is applied according to the percentage of the errors. The blocks with the most errors are shown in red and the blocks without errors or with the minimum average are displayed in green. The colors between red and green are assigned to the remaining blocks.

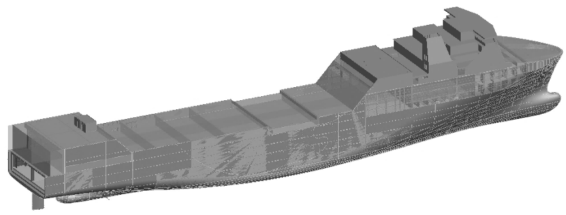
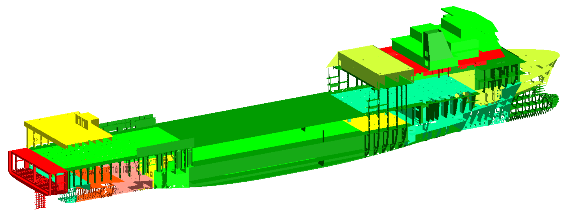



Figure 7.37.: Digital Mock-up CAD-model of a RoRo (left) Block-wise representation of the RoRo according to error rate (right)

The block-wise representation of the Bulk Carrier model according to the error percentage is shown in Figure 7.38.

7.3.3.1. Error Visualization of Faulty Designs Regarding Parts Information

In the previous subsection, the results of the inspection of parts information for the test models were discussed. After the detection of the faulty parts, the correction process can be started. In the proposed quality management system, the list of errors will be stored in the neutral database in form of reports. During the correction process, the designer must go through all these cases, which can have thousands of error instances. This process is troublesome and takes a lot of time, which leads to a decreasing productivity of the shipyard. Therefore, an error visualization mechanism will simplify the error identification in its context within the CAD system being used for the modelling i.e. error visualization individually or within the block it belongs to. This mechanism is realized

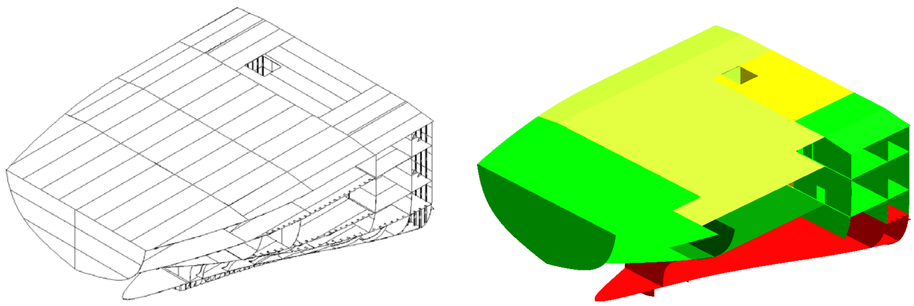


Figure 7.38.: Original Mock-up CAD-model of a Bulk Carrier (left) Block-wise representation of the Bulk Carrier according to error rate (right)

through macros written in the programming language which is offered by the used CAD system, see chapter 6. The CAD system applied in this study is AVEVA marine which offers a specific API in form a programmable macro language (PML). Depending on the API, a macro is automatically generated to display the faulty structural part(s). An error message is displayed on the screen specifying the type of the identified error related to a specific quality criterion. Figure 7.39-left shows the result of missing position number criterion inspection. By dragging the automatically created macro into the command window the faulty part will be displayed with an error message. Figure 7.40-right represents an error case in which the value of the position number (1202) does not comply with the project standards.

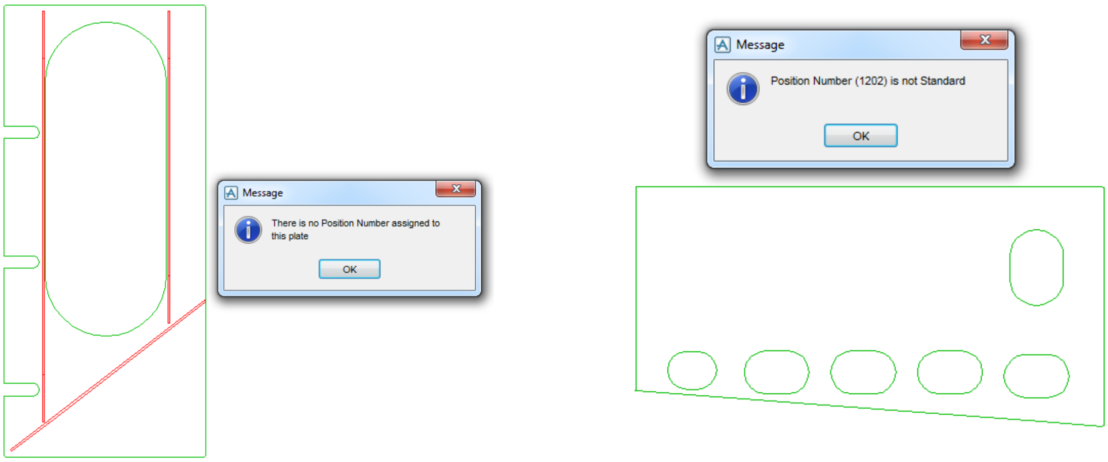


Figure 7.39.: Error visualization of parts information: Missing position number (left) not standard position number (right)

Figure 7.40 shows an example in which the same value of the position number (1391) is assigned to two different plates (in ellipse). Both plates are displayed within the block, to which they belong to. In this case the position number is not conclusive because the shapes of the two plates are different.

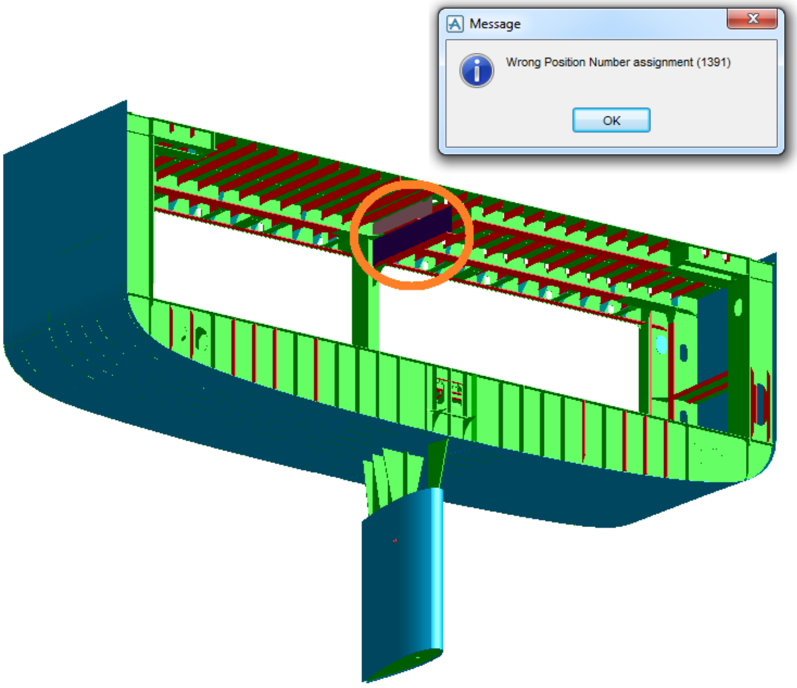


Figure 7.40.: Not conclusive quality criterion is met for two different plates (ellipse) having the same position number

7.3.3.2. Visualization of Faulty Designs Regarding Design Features

Missing a notch hinders the welding at this corner without additional correction works. The function of the plates enables the designer to identify the proper arrangement. Figure 7.41-left shows a missing notch at the corner of the blue plate, which is bounded by two other plates (green and orange) having different orientation. In Figure 7.41-right, the plate is provided with a notch which is smaller that the required value.

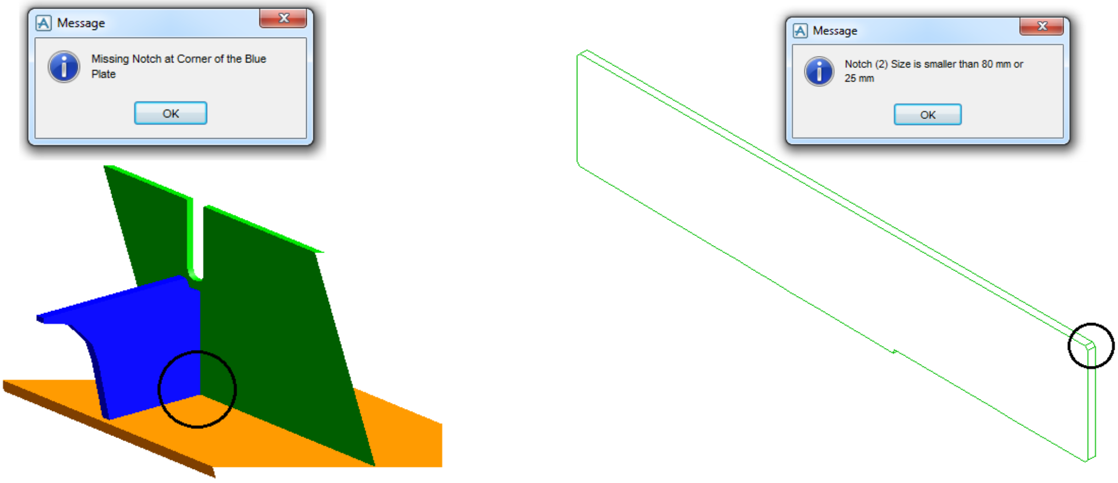


Figure 7.41.: Two quality problems regarding notches criteria: Missing notch problem (left) and notch is not of standard size (right)

7.3.3.3. Visualization of Faulty Designs Regarding Weld Arrangements

As for other quality criteria, after inspecting the product data model against the quality criteria regarding the weld arrangements, the corresponding macros of the faulty designs are generated to be utilized by the designer in the correction process. Figure 7.42-left shows an example for not observing the minimum distance criterion between seam and stiffener and Figure 7.42-right shows an example for not observing the required minimum distance between the adjacent stiffeners.

Figure 7.42 shows a design in which the quality criteria regarding the minimum distance between two seams is not met. The panel will be displayed with an error message specifying the error type and the concerned parts. Figure 7.43 shows two cases, where the minimum required angle between seam and stiffener as well as between two stiffeners is not fulfilled.

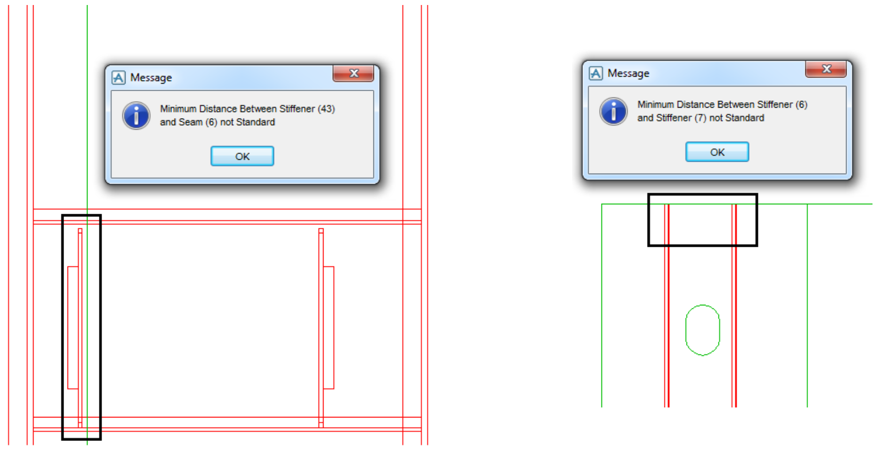


Figure 7.42.: Two quality problems regarding welding arrangements criteria: Minimum distance between the seam and the stiffener is not standard (left) and minimum distance between the two stiffeners is not standard (right)

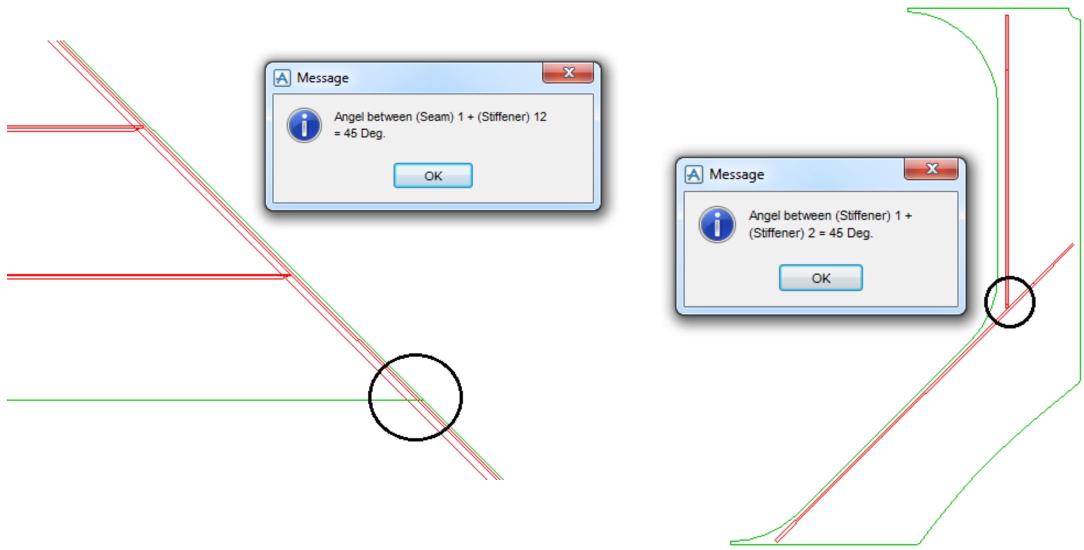


Figure 7.43.: Two quality problems regarding welding arrangements criteria: Minimum angle between the seam and the stiffener is not standard (left) minimum angle between the two stiffeners is not standard (right)

8. Conclusion and Outlook

The extent of digital development of product data forces companies to focus on the quality of developed product data models as they affect the quality and cost of the end product. The quality of manufacturing processes must be considered at early design phases to ensure compliance with the end-users' and companies' requirements. To obtain a high-quality end product, companies must pay attention to the early detection, and if possible prevention, of design errors, as well as to the overall costs and delivery time to the market. The shipbuilding industry has special characteristics and conditions such as the fierce competition regarding the total costs of design and construction. In addition, modelling processes done at the same time in broad project groups result in continuous engineering changes. Due to the diverse specifications and requirements regarding the design and production, design processes can not be standardized. To ensure a seamless production and on time delivery, all these characteristics, requirements, and conditions must be strictly considered. The early detection of design errors contributes to the reduction of engineering changes, and therefore substantially reduces product development time, rework and cost. The aim of this thesis is to develop a quality management approach taking into account the specific requirements of the shipbuilding industry. The approach is designed to be applied in the detailed design phase, especially in the detailed design of structural components and before starting the production.

The term “product data” represents the numerical data of the product information which is built upon a mathematical model. The context of quality of product data model is wide. It is represented by the consistency, completeness, and suitability of data to fulfill its goal. Quality of product data can be measured by its accuracy and appropriateness joined with the timeliness with which those data are provided to all the people who need them. The necessary terminology and the research question were introduced. The reasons for faulty product model data and the impact of design problems as well as types of frequently occurring errors were comprehensively addressed. To achieve the research goal of developing a quality management system for automated quality assurance of product model data, product specific information models were designed, whilst extensive algorithms were developed and implemented to enable processing of information data in a real context. The quality concept in technical domains, cost of quality, and characteristics of quality management systems were introduced. A comprehensive study of the international product and process requirements and standards governing the product lifecycle from the representation of product or manufacturing information, quality and quality control in the design and digital environment for simple and complex products were also presented. The major attempts and concepts to enhance the quality of product data including product modelling, CAD-model repair, data exchange and system interoperability, and the product data quality frameworks have been studied.

All design activities and applied systems and techniques within the ship lifecycle were given. A general review of all requirements specific to the marine industry was introduced. All requirements and standards that regulate the ship lifecycle, starting from the initial planning, passing through the design, operation, and ending with the recycling, were discussed. These requirements are formulated by different actors such as the shipowner, shipyard, classification society and international and national organizations. With the introduction of the international standards ISO STEP-59 and ISO/PAS 26183 (SASIG), the objective of this thesis was further refined. A new approach for the classification of faulty design information in the detailed design phase was introduced. Subsequently, a set of quality criteria were formulated to ensure a seamless downstream process in the ship construction chain. Those criteria focus on structural part information, constructional features, and standardized weld arrangements. They are identifiable elements for detecting quality defects in product data by means of logical or numerical tests.

The core of this research was introduced, that is, the quality management system. A product data quality (PDQ) approach was introduced based on the ISO STEP-59. The PDQ process in a real design process was discussed. The introduced PDQ process included four main steps: data inspection, evaluation, correction, and finally knowledge capturing for error prevention and best design practice enhancement. Usage scenarios were introduced for internal quality assurance or for collaborative control between design creator and manufacturer. The system architecture was addressed, where all actors, tools, resources, and responsibilities were identified. Three main actors, namely, designer, quality inspector, and quality manager form the quality cycle. The framework of the supposed system is built upon three main elements, namely ship structure model, quality of product data model, and support resources models. Each model and its sub models were introduced and the interrelations between them were discussed. The quality criteria, requirements of the acceptable measurements, and the representation of inspection results were addressed. In this context, the requirements of how to measure each quality criterion needed to be clearly defined. For the quality criteria, measured by means of numerical tests, the proper applicable numerical thresholds and tolerances depending on the shipyard and project requirements as well as on the rules of the classification societies regarding the production-ability and manufacture-ability. A new approach for the assessment of the inspection result, based on integral values such as quality score, cost score, as well as visual correction guidance, was developed.

To check the compliance of the product model data with the formulated quality criteria, different algorithms were developed and discussed. The complexity of the introduced algorithms varies depending on the design error nature and the processed information. For inspection of product data regarding shape aspects, 2D and 3D cases were distinguished. Some algorithms from different scientific areas were applied in the marine engineering context. Two novel algorithms were developed in the context of this research for evaluation the similarity of structural parts. Some other algorithms for ensuring optimized manufacturing processes as well as optimized welding arrangements were also introduced. Complex analysis was required for some quality criteria such as notches, where the topological and the geometrical relationships of the neighboring parts must be analyzed. The implementation infrastructure and the applied CAD system (AVEVA Marine), programming environment, as well as the quality criteria measurement requirements such as numerical threshold and tolerances were presented against the hull structure information model.

Three CAD models of ships were utilized as real test cases to prove the concept of applicability of the developed system as well as the implemented algorithms and methods. The underlying geometry engine was implemented fully independently of the CAD system applied for modelling the ship structure. With the help of systematic parameter variations, the implemented functions to analyze geometrical and topological relationships between even complex ship structure components were successfully tested. Qualitative and quantitative evaluations of the developed methods were applied. Some unrealistic cases which serve as benchmark configurations were specially designed and successfully tested. Some problematic geometrical and topological relationships, such as minimum angle and distance requirements of structural parts as a sub category of weld arrangement criteria. Based on the inspection results, a comprehensive assessment was performed, including the calculation of the error rate, quality score, and block-wise representation. A visual guidance of the deficient designs within the CAD system used was also introduced. The visual guidance assists the designer to set up the priority list of design error corrections, which leads to significant time savings as the designer can analyze the detected errors within the CAD system instead of simply receiving a report with the listed errors.

This research has demonstrated the feasibility of the introduced PDQMS to automate the control of the quality of product model data against the production constraints originated from the classification societies' or the shipyard requirements. This research represents the first attempt to develop a quality management approach to be applied in the shipbuilding industry. It makes use of different well-known international standards like ISO STEP-59 and ISO/PAS 26183 (SASIG), which are already applied in the automotive industry.

This system can be extended by implementing additional quality criteria obtainable by analyzing the frequently occurring design errors at shipyards. These criteria include the inspection of the correctness assignment of manufacturing attributes like robustness of naming, end-cuts and shrinkage. The correctness of the mathematical representation of product model data represents a key factor for the consistency and robustness of product data. Quality criteria regarding erroneous topology and geometry, such as those addressed in ISO/PAS 26183 like open edge loop, open closed shell, disconnected face, erroneous b-spline curve definition and discontinuity of curves and surfaces can also be investigated. Development of an automatic mechanism for product data repair is vital in the product development process. Depending on the used CAD system, shapes of the structural parts can have different topological and geometric representations, therefore the algorithms for repairing product data must be developed in a robust way to consider all these differences. Furthermore, unintentional distortion of design data must be prevented while repairing the data. Ongoing development of PDQMS will contribute to bridge the interoperability gap between the different CAX systems used throughout the product development process and enable the users in the downstream processes to utilize product data with greater reliability. The development of a mechanism to transform the designer's implicit knowledge into explicit quality criteria is also suggested for the future research. The use of different CAD systems applied in the shipbuilding industry must be taken into consideration. Different CAD systems can be seamlessly integrated in the proposed PDQMS by implementing the proper adapters to extract the relevant production data for inspection. The current research studies were limited to ship's structure and, in particular, steel parts. Additional research and development is intended to consider more aspects like outfitting components (HVAC, pipes, etc.). A hybrid repairing approach comprising the knowledge based, design history and design intention approaches could be investigated in the future to determine a feasible error correction of product data. In addition to the proposed system, several preventive procedures could also be considered to ensure the quality of product data including the proper training of designers, appropriate documentation of the best practice recommendations and previous experience, a standardization of approved design solutions for a given design tasks, and finally standardization of proven methods to derive optimal design solutions.

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A. Appendix

A.1. XML File and Input Scheme Structures in AVEVA Marine

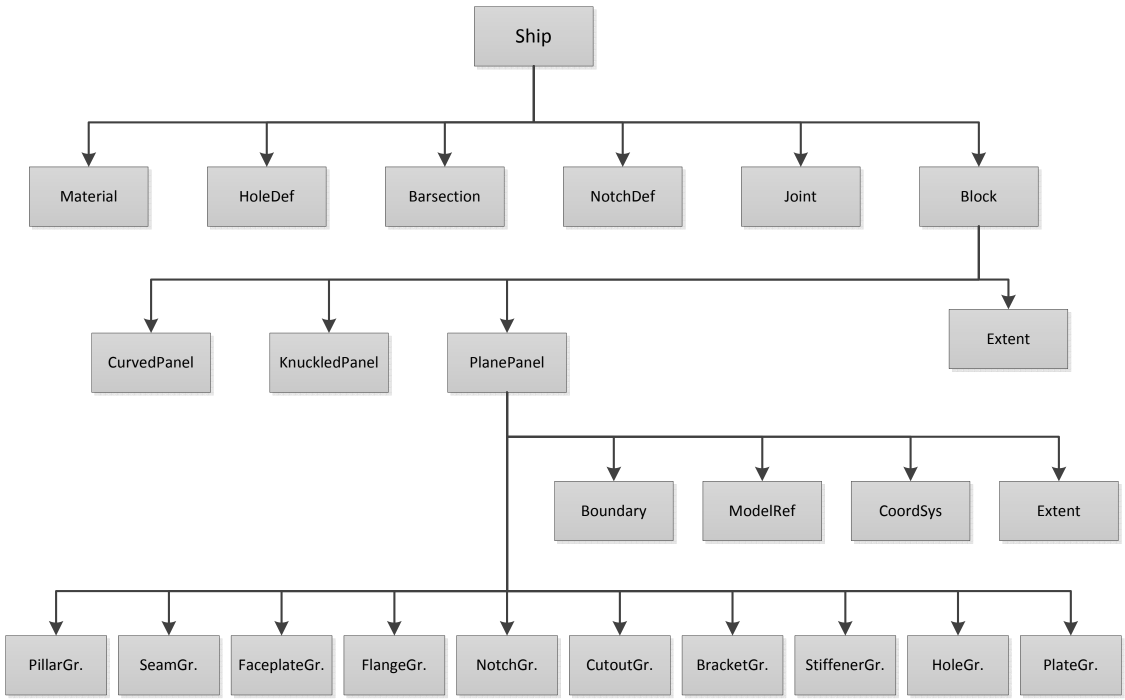


Figure A.1.: Structure of data in XML file

Listing A.1: Syntax AVEVA Marine *Input Schemes*

```
<comp_stmt >::= <BOandARY_stmt> |
                    <SEAM_stmt> |
                   <PLATE_stmt> |
                    <HOLE_stmt> |
                   <NOTCH_stmt> |
                  <CUTOUT_stmt> |
               <STIFFENER_stmt> |
                  <FLANGE_stmt> |
                  <PILLAR_stmt> |
                 <BRACKET_stmt> |
            <DOUBLINGPLATE_stmt> |
                    <BEAD_stmt> |
                     <EXC_stmt> |
                     <CMP_stmt> |
                    <WELD_stmt> |
                 <MARKING_stmt> |
               <SHRINKAGE_stmt> |
                   <POINT_stmt> |
                   <CURVE_stmt> |
                     <PLN_stmt> |
    <statement>::= <identifier> |
```

```
                    <PANEL_stmt> |
                     <ONLY_stmt> |
                     <comp_stmt> |
            <COMMENT_statement>
 . . .
```

Listing A.2: *Input Schemes* example

```
a101−fr1 −01
PAN,   'A101−FR1−01', SP, BLO='A101', DT=181, X=FR1;
BOU,   'A101−DK1−01'/
       SUR='MTP', REF/
       'A101−DK1−01', COR=550, SID=BOT/
       SUR='MTP';
SEA,   BEV=20, Y=1475,−1475, NO=1,2, BVS=AFT;
PLA,   Y=2437.57,106.18,−2495.83, Z=14968.94,14948.13,15010.58, MAT=20,
       MSI=AFT, POS=255(−1)253, NO=1(1)3;
NOT,   R75, COR=4,3;
NOT,   KS15, COR=2,1;
FLA,   PRO=10,500,30, LIM=3, POS=92, NO=1, Y1=8995, CON=15, CUT=1100,
       BEV=20, BVS=TOP/ Y2=1475, CON=15, CUT=1100, BEV=20, BVS=TOP;
FLA,   PRO=10,500,30, LIM=3, POS=91, NO=2, Y1=−8995, CON=15, CUT=1100,
       BEV=20, BVS=TOP/ Y2=−1475, CON=15, CUT=1100, BEV=20, BVS=TOP;
NOT,   KU40*10, LIM=3, Y=−1475,1475;
CUT,   308, '_RSO_DK1', SL1(1)11,SL13,SL14, SID=AFT, CLI=020, WEL=2,
       WCL=2, WPR=2, WSH=2, NO2=1(1)13;
CUT,   308, '_RSO_DK1', SL−1(−1)−11,SL−13,SL−14, SID=AFT, CLI=020, WEL=2,
       WCL=2, WPR=2, WSH=2, NO2=14(1)26;
BRA,   GC, MAT=15, NOA=KS10, POS=261, CNO=1, MSI=PS, A=500, B=400, C=225,
       D=230, RA=15, ORI=FR1−20,LP−12,15250, UAX=FR1−20,LP−12,14750,
       VAX=FR−1−330,LP−12,15250;
```

A.2. Error Cost

Criterion	BD*	DD*	GD*	GM*	P*
Missing excess	10	10	15	20	35
Not standard excess (big)	10	10	15	15	30
Not standard excess (small)	10	10	15	20	40
Not conclusive excess	10	10	15	20	40
Missing bevel code	10	10	15	15	60
Not standard bevel code	10	10	15	15	60
Not conclusive bevel code	10	10	15	15	50
Missing notch	10	10	15	15	40
Not standard notch	10	10	15	15	30
Not standard distance between two seams	10	10	20	20	40
Not standard distance between two stiffeners	10	10	20	20	40
Not standard distance between stiffener/seam	10	10	20	20	40
Not standard angle between two seams	10	10	20	20	40
Not standard angle between two stiffeners	10	10	20	20	40
Not standard angle between stiffener/seam	10	10	20	20	40
Missing position number	5	5	10	15	30
Not standard position number	5	5	10	15	40
Not conclusive position number	15	15	20	25	50

Table A.1.: Error time cost according to its nature and detection phase

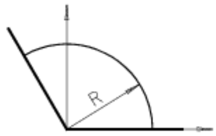
All values in the Table A.1 are given in minutes.

*BD: Basic Design, DD: Detailed Design, GD: Generation of Drawings, GM: Generation of Manufacturing data, P: Production

A.3. Examples for Standard Notches & Corresponding Reference Values

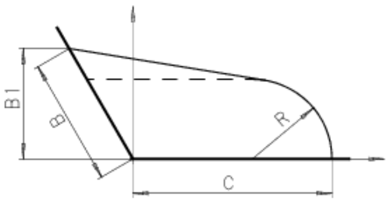
Table A.2.: Examples for standard notch shapes for plates with comparison value to check the notch-size, [104]

Notch Type R



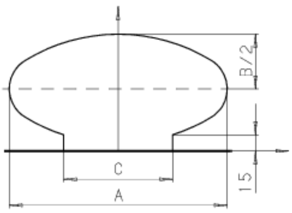
Position:	Corner, Edge
Parameter:	R
Comparison value:	R

Notch Type VU



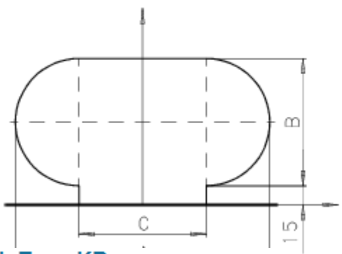
Position:	Corner
Parameter:	C B R or C R
Comparison value:	R or C

Notch Type KE



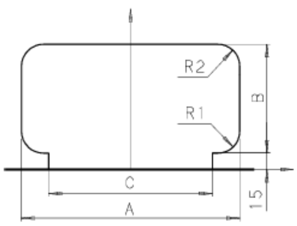
Position:	(Corner), Edge
Parameter:	A B C
Comparison value:	15+B or C/2

Notch Type KO



Position:	Edge
Parameter:	A B
Comparison value:	15+B or (A-B)/2

Notch Type KR



Position:	(Corner), Edge
Parameter:	A B C R1 [TAP R2=R1]
Comparison value:	15+B or C/2

A.4. STL Representation

The STL format is a polyhedral representation of the shape of an object with triangular facets. It is generated from a precise CAD model using a process known as tessellation, which generates triangles to approximate the CAD model. The STL file can either be in ASCII or binary format. In an STL file, triangular facets are described by a set of X, Y and Z coordinates for each of three vertices and a normal unit vector to indicate the side of the facet, which is outside the object, see Listing A.3. An example of a tesselated plate is shown in Figure A.2.

Listing A.3: STL file structure

```
 solid object_name
 facet normal u_n v_n w_n
   outer loop
     vertex u1 v1 w1
     vertex u2 v2 w2
     vertex u3 v3 w3
   endloop
 endfacet
 facet normal u_n v_n w_n
  outer loop
    vertex ...
     ...
    ...
  endloop
endfacet
endsolid object_name
```

Figure A.2 shows an example for a tessellated ship plate.

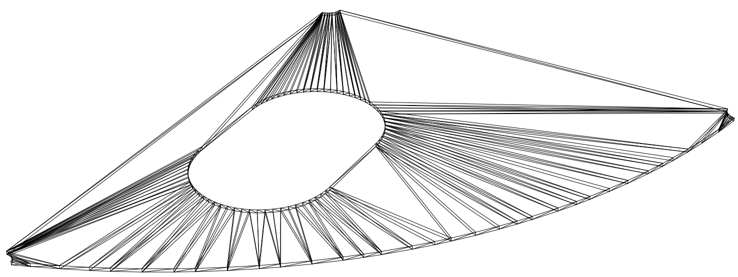


Figure A.2.: Tessellated plate

A.5. Check Angle and Distance between Segments

In this section, the steps to check the allowed distances and angles between parts of different representation are discussed. In the first part, the distance and angle between two straight line segments are discussed. In the second part, the distances and angles between a straight line segment and an arc are addressed. Finally, the distance and values between two arc segments are illustrated.

A.5.1. Angle Between Two Line Segments

For two straight objects, the first control step is to compute the angle and the distance between both of them. The computed values will be compared with the minimum allowed angle. The test scheme is performed as shown in Listing A.4:

Listing A.4: Test standard minimum angle between two straight line segments

```
algorithm "Minimum angle not standard between straight segments"
    Segement1, Segment2 //Input straight segments
    Angle = Compute Angle(Segement1,Segement2)

     if (Angle != 0 || Angle != Π)
     then

         if (Angle ≤ α_min)
         then
             I = get intersection point(s) (Segement1, Segement2);

             if (I ∈ Segment1 && I ∈ Segment2)
             then
                 error("Minimum angle not standard", 4);
end;
```

The angle between two vectors is calculated using the following formula:

$$Angle = \arccos(\frac{\vec{u} \cdot \vec{v}}{\|\vec{u}\| \cdot \|\vec{v}\|}) \tag{A.1}$$

The numerator represents the dot product $\vec{u} \cdot \vec{v} = u_1 v_1 + u_2 v_2$, where $u(u_1, u_2)$, $v(v_1, v_2)$ are coordinates of the first and second segments, respectively. The denominator is the multiplication of lengths of $\vec{u}$ and $\vec{v}$, where $\|\vec{u}\| = \sqrt{u_1^2 + u_2^2}$. If the angle is less than the minimum angle, it will be checked if both segments intersect. In the case of intersection, it will be checked if the intersection point exists in both segments. If the intersect point is in both segments, an error has to be reported. If the angle equals to zero or π it means that both segments lie on the same line or they are parallel. Parallel means that the both segments are collinear or they are shifted with an offset. If the two segments are parallel with an offset, then it will be checked whether the overlapping area, with offset less than the minimum distance, is within an acceptable tolerance as shown in Figure A.3.

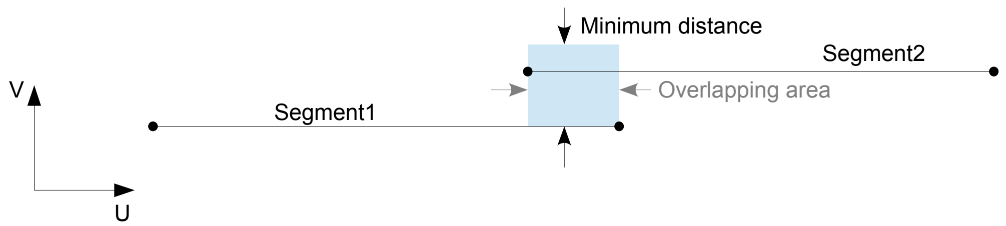


Figure A.3.: Overlapping area between two line segments

A.5.2. Distance Between Two Line Segments

The inspection of the minimum distance between two line segments is performed as shown in Pseudo code, Listing A.5. In the first step, the distance D between the first point Q_0 of the first segment `Segment1` and its foot point on the other segment `Segment2` will be computed, Line 4. If this distance is not equal to zero and less than the minimum required distance $Distance_{min}$, then successive help points will be generated along the first segment as well as their foot points on the second segment as shown in Figure A.4.

Listing A.5: Test standard minimum distance between two straight line segments

```
1  algorithm "Minimum distance not standard between straight segments"
2      Segement1, Segment2 //Input straight segments
3      bool continue = true //Boolean variable to stop the loop
4      D = distance between Segement1 & Segement2
5
6         if (D > 0 && d ≤ Distance_min)
7         then
8              displacementVector = calculate displacement vector;
9
10        while (continue)
11        currentPoint = Segment1.Q_1;
12        F_i = Get foot point of currentPoint on Segment2;
13        D = Get distance between F_i and currentPoint;
14
15             if (D ≤ Distance_min && F_i on Segment2)
16             then
17                  continue = false;
18                  error("Minimum distance not standard", 4);
19
20             else
21             then
22                  F_{i+1} = F_i + displacementVector;
23                  continue = check if F_{i+1} on Segement1;
24 end;
```

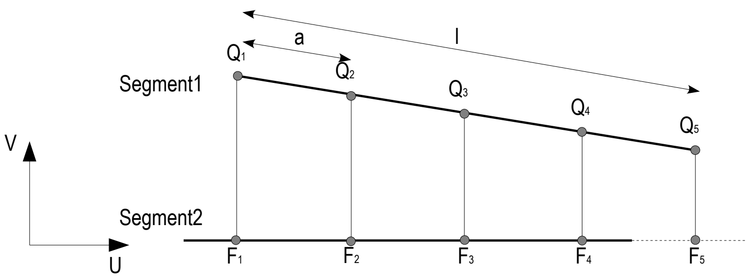


Figure A.4.: Check distance between line segments

This process is controlled through a parameter a given by the user. Based on this parameter and parameter t of line equation, the first point $Q_1(U_1, V_1)$ on the first segment can be calculated using the following equations:

$$\overrightarrow{OQ} = \overrightarrow{OQ_0} + t \cdot \overrightarrow{v}, t \in \mathbb{R} \tag{A.2}$$

$$a = \sqrt{(Q_1.U - Q_0.U)^2 + (Q_1.V - Q_0.V)^2} \tag{A.3}$$

$$l = \sqrt{(Q_4.U - Q_0.U)^2 + (Q_4.V - Q_0.V)^2} \tag{A.4}$$

$$t = \frac{a}{l} \tag{A.5}$$

With the direction vector $\vec{v}$, t scalar value, Q_0 and Q_4 the start and end points of `Segment1`. All other help points, for example Q_2, Q_3, can be determined using the position vector $\overrightarrow{OQ_{i+1}}$ from the last point Q_i and the displacement vector $\vec{a}$, which has a direction to the next point and length equals to a, Line 8:

$$\overrightarrow{OQ_{i+1}} = \overrightarrow{OQ_i} + \overrightarrow{a} \tag{A.6}$$

Within the `while`-loop, Line 11, a new help point will be generated each time. Its foot point on the second segment will be determined and the distance between them will be measured. If the distance is smaller than $Distance_{min}$ and the foot point is on the second segment (not on its extension like F_5 in Figure A.4), an error will be reported. If both conditions are not fulfilled, a new help point will be generated and it will be checked if the new points are on the first segment. If `continue` still has the value `true`, the loop runs again until `continue` values are `false` or an error in Line 18 is detected.

A.5.3. Angle between Line Segment and Arc Segment

If the considered segments are a line segment and an arc, the minimum distance and angles control will be performed according to Listing A.6. The distance D between the straight line segment and arc segment is the measure from the center M of the circle containing the arc and its foot point F_m on the line segment, see Figure A.5.

Listing A.6: Test standard minimum angle between straight line segment and an arc

```
algorithm "Minimum angle not standard between straight and arc segments"
    Segement1, Arc2
    D = distance between Segment1 & Arc2
      if (D < Arc2.Radius)
      then
          I1,I2 = intersection point(s) between Segment1 & Arc2

          if (I1 on Arc2)
          then
              T1 = tangent of Arc2 in I1
              Angle1 = Angle (T1, Segment1)

                if (Angle1 <= Angle_min && I1 on Arc2)
                then
                    error("Minimum angle not standard", 4);

                else if (I2 on Arc2)
                then
                    T2 = tangent of Arc2 in I2
                    Angle2 = Angle (T2, Segment1)

                       if (Angle2 <= Angle_min && I2 on Arc2)
                       then
                           error("Minimum angle not standard", 4);
end;
```

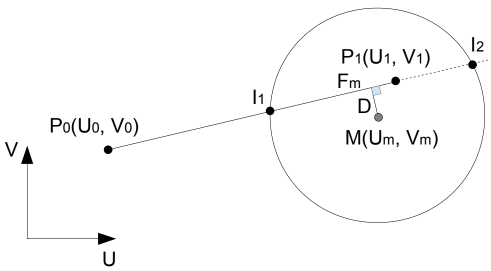


Figure A.5.: Line-circle intersection

If the distance D is bigger than the radius of the circle which contains the arc, then the circle and the straight line segment do not have any intersection points and the control will stop. If D is less than the radius, then two intersection points will exist, I_1 and I_2, see Figure A.5. The intersection points will be calculated by solving the line equation which passes through start and end points of the straight segment and circle equation, which contains the arc segment. The tangents in both intersection points as will as the intersection angle at those points will be determined. A criterion violation (minimum distance and angle are not standard) is then reported when two conditions are fulfilled i.e. a measured angle is less than the threshold $Angle_{min}$ and if the intersection point lies on the straight segment and on the arc as well.

A.5.4. Distance between Line Segment and Arc Segment

The check of the minimum distance between a line segment and a curved segment (arc) is performed as shown in Listing A.7:

Listing A.7: Test standard minimum distance between straight line segment and an arc

```
1  algorithm "Minimum distance not standard between two arc segments"
2            Arc1, Segment //Input segments
3            Distance_min //Minimum required distance
4            nextPoint = Arc1.P_s //Start point to create help circles
5            t //Accuracy value for the next circle generation
6            bool continue = true //stop condition for while-loop
7            while (continue == true)
8            C_1 = create circle (Distance_min, nextPoint)
9            C_2 = create circle (t, nextPoint)
10           S = get intersection point(s) (C_1, Segment)
11           I_1,2 = get intersection point(s) (C_2, Arc1)
12               if ( S == null)
13               then
14                   if (intersect on segment (I_1, Arc1))
15                   then nextPoint = I_1
16
17                   else if (intersect on segment (I_2, Arc1))
18                   then nextPoint = I_2
19
20                   else
21                   then continue = false
22
23               else (S != null)
24               then
25                   error("Minimum distance not standard", 4);
26                   continue = false
27 end;
```

The arc and the segment objects are passed to the algorithm along with the variable t (arc length), which represents the distance between the centers of the help circles. The `while`-loop line 5 will keep running until the Boolean variable become `false`. Within the loop, two circles will be created C_1 and C_2. The former is the circle with a radius equal to the $Distance_{min}$ and the latter has radius equal to $t < Distance_{min}$. Accuracy variable t is chosen by the user and is preferably smaller than $Distance_{min}$ to increase the accuracy of the inspection, see Figure A.6. From the start point P_S, two circles will be created with radii t and $Distance_{min}$, respectively. The first circle is the circle passing from Arc1 itself and the second one is the circle with radius t around the center point P_S. After determining the intersection points, points outside the segment will be excluded and only the point on the Arc1 itself will be considered P_1. This point will become the start point of Arc1 and from it a circle with a radius equal to $Distance_{min}$ will be created and checked if it intersects the line segment. If that is the case, an error will be reported, otherwise, another point P_2 will be determined in the same way and checked again. This process will keep running until an intersection point(s) is found or the end point P_E of Arc1 is reached.

A.5.5. Angle between Two Arc Segments

For the case with two arc segments, minimum distance and angle problems will be solved according to Listing A.8:

Listing A.8: Test standard minimum angle between two arc segments

```
algorithm "Minimum angle not standard between two arc segments"
          Arc1, Arc2
          D = distance between Arc1 & Arc2
          if (D ≤ (Arc1.Radius + Arc1.Radius) && D ≥ (|Arc1.Radius − Arc1.Radius|))
          then
              I_1, I_2 = intersection point(s) between Arc1 & Arc2
              if (I_1 on Arc1 && I_1 on Arc2)
              then
                  T_1 = tangent of Arc1 in I_1
                  T_2 = tangent of Arc2 in I_1
```

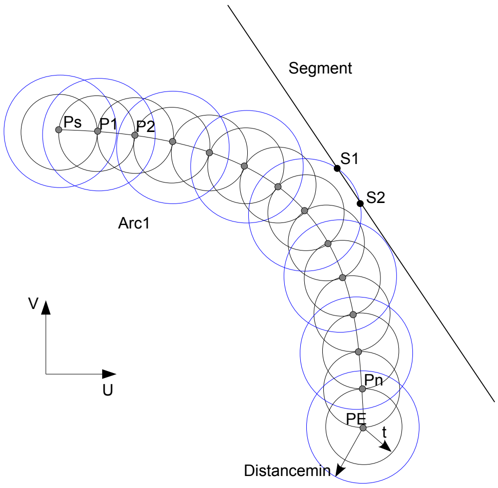


Figure A.6.: Minimum distance inspection between arc - line segment

```
11                  Angle1 = Angle (T_1, T_2)
12                       if (Angle1 <= Angle_min)
13                       then
14                           error("Minimum angle not standard", 4);
15
16              else if (I_2 on Arc1 && I_2 on Arc2)
17              then
18                  T_3 = tangent of Arc1 in I_2
19                  T_4 = tangent of Arc2 in I_2
20                  Angle2 = Angle (T_3, T_4)
21                       if (Angle2 <= Angle_min)
22                       then
23                           error("Minimum angle not standard", 4);
24
25 end;
```

Two circles $(X_{m1}, Y_{m1}, Arc1.Radius)$ and $(X_{m2}, Y_{m2}, Arc2.Radius)$ intersect if the following condition is fulfilled: $|Arc1.Radius - Arc2.Radius| \leq D \leq (Arc1.Radius + Arc2.Radius)$, with $D = \sqrt{(X_{m1} - X_{m2})^2 + (Y_{m1} - Y_{m2})^2}$, the distance between the centers of both circles, where the two arcs are segments of these circles. If both conditions are fulfilled, the intersection points will be calculated. In the next step, it will be checked if the first intersection point lies on the both arcs. If that is the case, then the tangents on the both arcs at this point will be created. If the angle between the created tangent is less than $Angle_{min}$ an error will be reported for not standard angle and distance. If the first condition line 7 is not fulfilled, then it will be checked whether the second intersection point is on both arcs line 16. If that is the case, the tangents at this point for both arcs will be created. If the angle between them is less than $Angle_{min}$ an error will be reported for not standard angle and distance. If both conditions are not fulfilled, the control process will end.

A.5.6. Distance Between Two Arc Segments

In this inspection step, the distance between arc segments will be determined to check if the minimum required distance is guaranteed. This process is performed as shown in Listing A.9:

Listing A.9: Test standard minimum distance between two arc segments

```
algorithm "Minimum distance not standard between two arc segments"
          Arc1, Arc2 //Input segments
          Distance_min //Minimum required distance
          nextPoint = Arc1.P_s //Start point to create help circles
          t //Accuracy value for the next circle generation
          bool continue = true //stop condition for while-loop
          while (continue == true)
          C_1 = create circle (Distance_min, nextPoint)
          C_2 = create circle (t, nextPoint)
```

```
10              S = get intersection point(s) (C1, Arc2)
11              I1,2 = get intersection point(s) (C2, Arc1)
12                  if ( S == null)
13                  then
14                      if (intersect on segment (I1, Arc1))
15                      then nextPoint = I1
16
17                      else if (intersect on segment (I2, Arc1))
18                      then nextPoint = I2
19
20                      else
21                      then continue = false
22
23                  else (S != null)
24                  then
25                      error("Minimum distance not standard", 4);
26                      continue = false
27  end;
```

Both arcs and the variable t are the input of this method. Variable t represents the distance between the centers of the help circles to check the minimum required distance, see Figure A.7. Within the `while`-loop line 5, two circles will be created C_1 and C_2. The former is the circle with a radius equal to the $Distance_{min}$ and the latter has radius equals to $t < Distance_{min}$. Accuracy variable t is chosen by the user and is preferably smaller than $Distance_{min}$ to increase the accuracy of the inspection, see Figure A.7. From the start point P_S, two circles will be created. The first circle is the circle passing from Arc1 itself and the second one is the circle with radius t around the center point P_S. After determining the intersection points, the point outside the segment will be excluded and only the point P_1 on the Arc1 itself will be considered. This point will become the start point of Arc1 and from it a circle with a radius equal to $Distance_{min}$ will be created and checked if it intersects with Arc2. If that is the case an error will be reported, otherwise, another point P_2 will be determined in the same way and checked again. This process runs until an intersection is found or the end point P_E of Arc1 is reached.

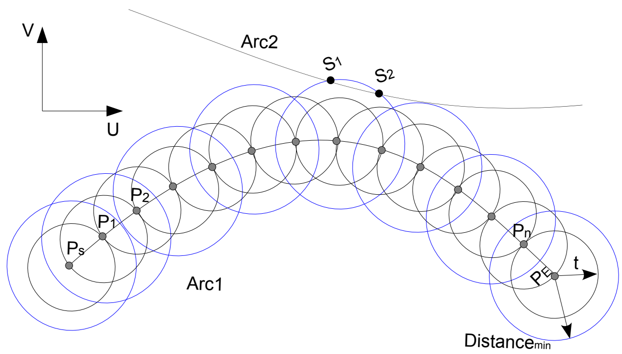


Figure A.7.: Minimum distance inspection between two arcs

A.6. Selected Types of Welding Preparation

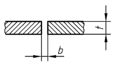
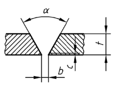
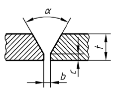
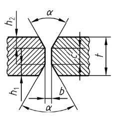
Workpiece Thickness t mm	Type of Weld Preparation	Symbol according to (ISO 2553)	Section	Dimension: Angle[a] α, β	Gap[b] b mm	Base height c mm	Flank height h mm
≤ 8	I-Joint	||		–	$\approx \frac{t}{2}$	–	–
					$\leq \frac{t}{2}$		
≤ 15					0		
$3 \leq t \leq 40$	V-Joint			$\alpha \approx 60°$	≤ 3	≤ 2	–
				$40° \leq \alpha \leq 60°$			
> 10	Y-Joint			$\alpha \approx 60°$	$1 \leq b \leq 3$	$2 \leq c \leq 4$	–
				$40° \leq \alpha \leq 60°$			
> 10	D(ouble)-Y-Joint			$\alpha \approx 60°$	$1 \leq b \leq 4$	$2 \leq c \leq 6$	$h_1 = h_2 = \frac{t-c}{2}$
				$40° \leq \alpha \leq 60°$			

Figure A.8.: Weld preparation for butt joints, subset of ISO 9692-1 [26]

A.7. Similarity Evaluation of Tested Structures

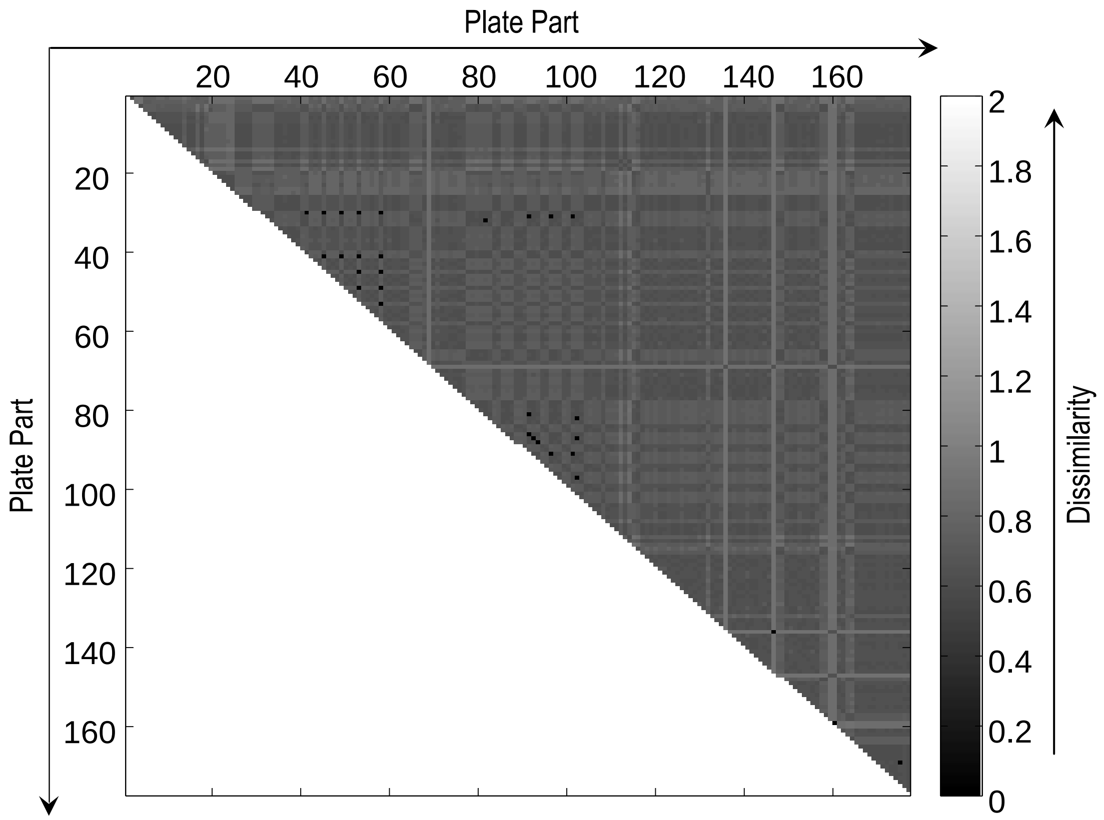


Figure A.9.: Similarity evaluation for the first tow blocks using 1024 points

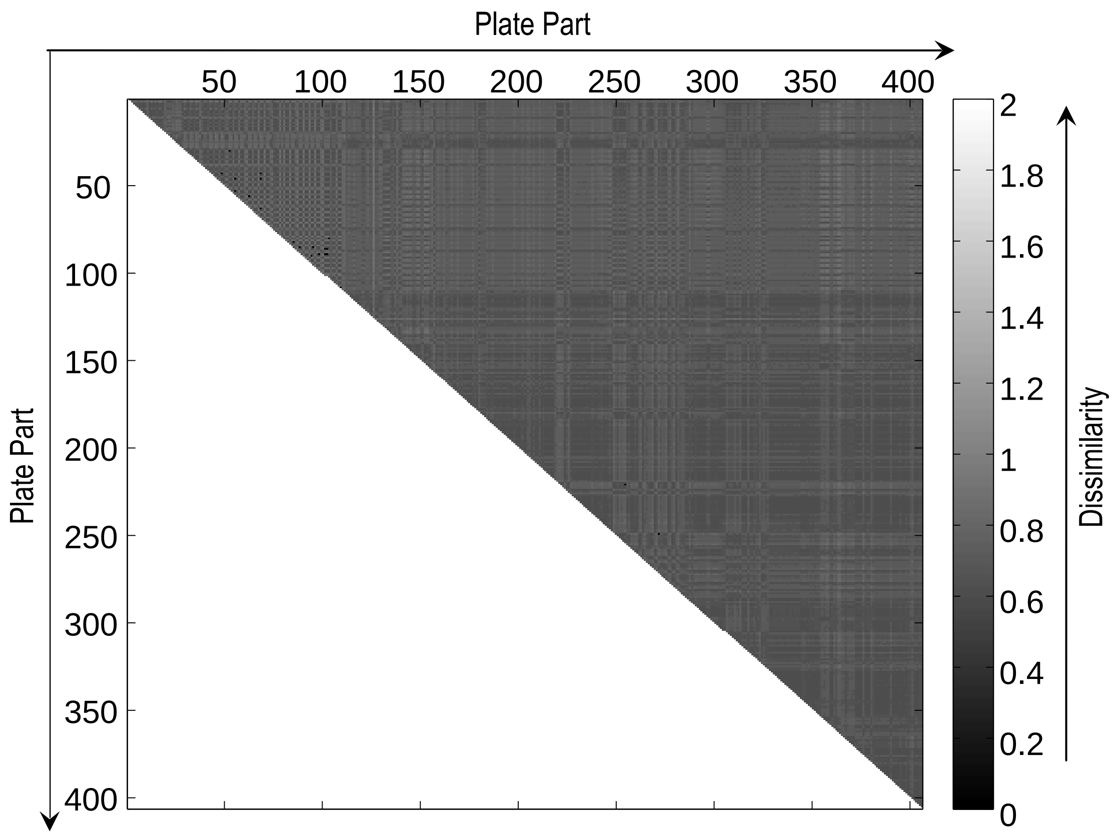


Figure A.10.: Similarity evaluation for the Bulk Carrier CAD-model using 1024 points

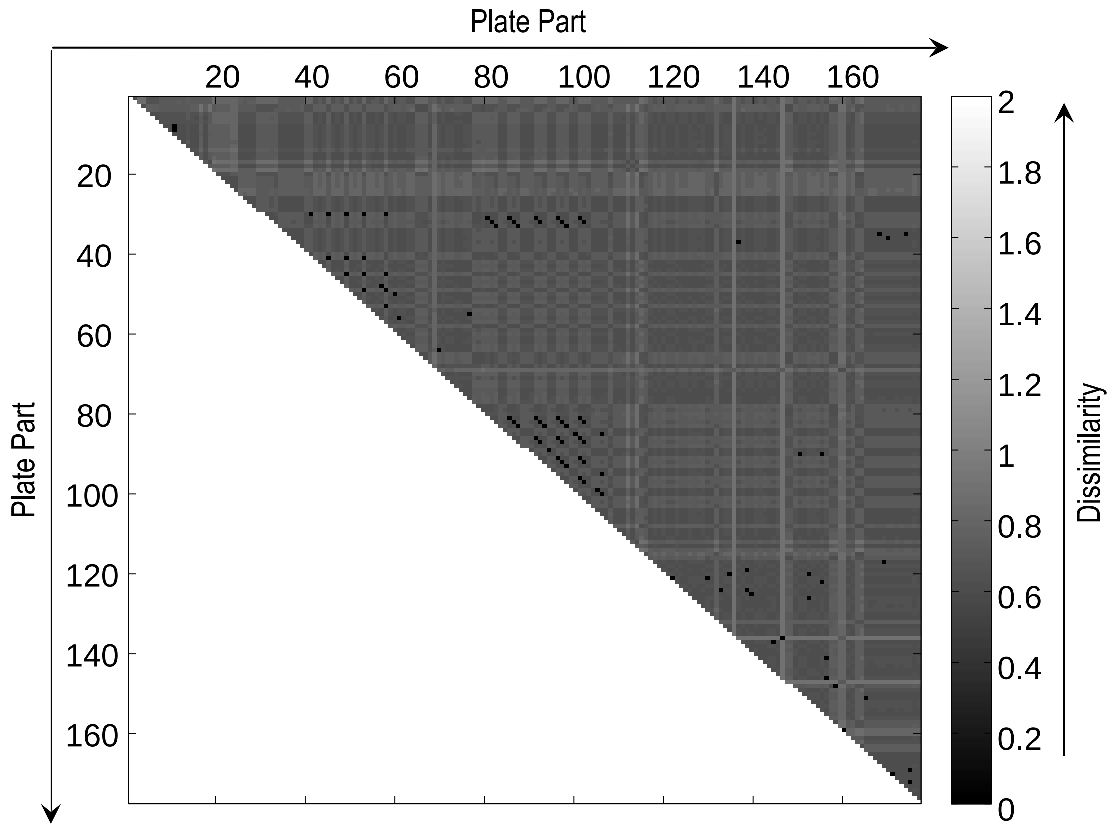


Figure A.11.: Similarity evaluation for the first tow blocks using 2000 points

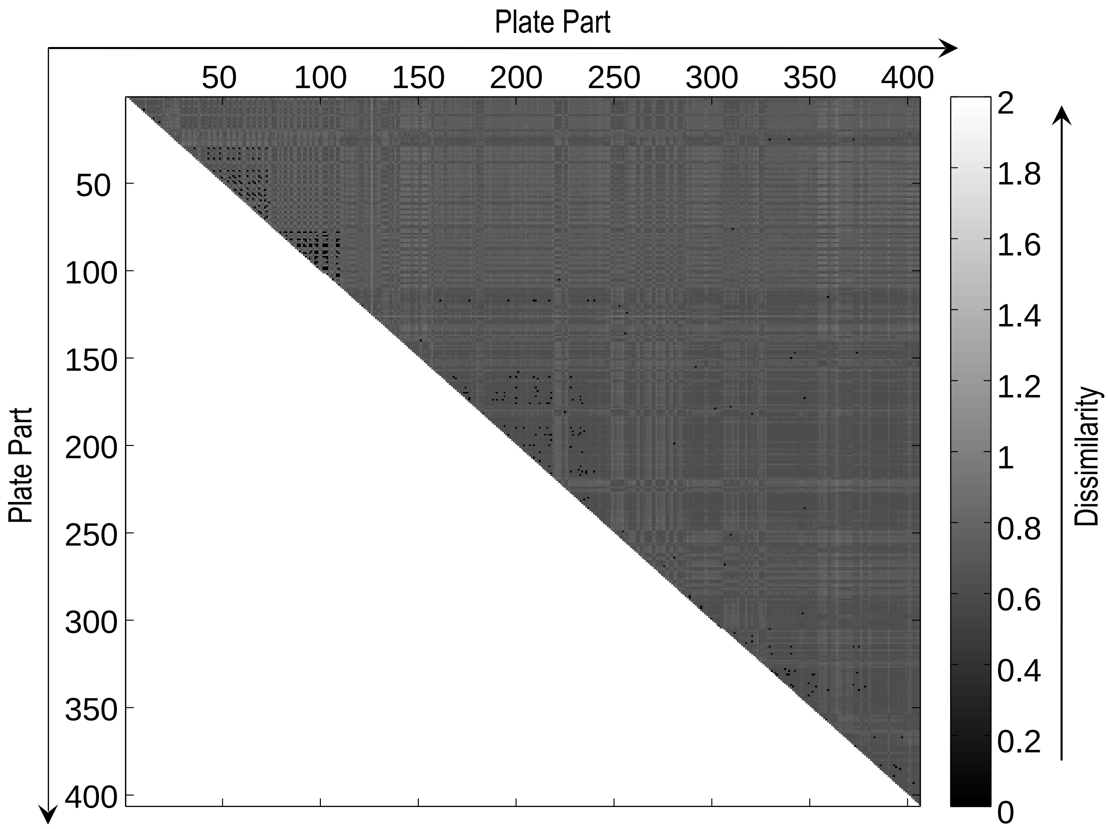


Figure A.12.: Similarity evaluation for the Bulk Carrier CAD-model using 2000 points

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