NAUTICUS - a life-cycle approach to ship design and decision support

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Abstract

New tools open up possibilities for improvement of the prevailing calculation procedures and acceptance criteria used by the Class Societies. DNV's criteria have since early 1970's incorporated state-of-the-art computational methods for hull assessment, such as direct loads and stress response calculations using Finite Element Analysis (FEA). Such methods, also known as first-principle calculations, have during the 1990's also been adopted as an industry standard by most of the other Class Societies.

DNV is now taking the next step, further refining the first-principle basis of our acceptance criteria. This includes more extensive use of Finite Element Analysis, as well as enhanced criteria for fatigue evaluation. More radical than this, DNV now introduce alternative acceptance criteria to cater for a risk-based approach, combined with an alternative survey scheme for the in-service period. Altogether, these new criteria is the basis for the NAUTICUS class notations, which, supported by the NAUTICUS information system sets a new standard for information availability and decision support.

The NAUTICUS information system is being developed to include comprehensive support for hull condition and maintenance monitoring, utilising state-of-the-art Product Model technology, including creation of a 3D graphical model. Thereby, the system will benefit yards, owners and class, by speeding up the design and classification processes while maintaining or even improving the quality of the ships. Further, it may contribute to more cost-efficient management of both safe and environmental friendly ships.
What is a Product Model?

In DNV terms, a Product Model is a vessel unique database where class related information regarding the hull, equipment and operation is accumulated over the specific ship's lifetime. The Product Model will be created and maintained by DNV. A 3D graphical model is part of the Product Model, and will cater for easy access to information stored in the Product Model.

Essentially, the Product Model is a database of the ship, where each individual structural element, as well as the components and systems, are defined and its characteristics stored. For the hull, a 3D graphical model is also created, where the status of structural elements may be shown, such as Rule thickness, as-built thickness, measured thickness, steel grade, coating condition and so on. This model will accumulate information and experience throughout the ship's lifetime. As an example, the calculation models and results from the plan approval may be stored in the ship's Product Model for possible re-use in the in-service phase.

The Product Model will be updated by inspection data from class, or the owner may also add his own survey data. Thereby, a complete and easily accessible picture of the condition of the vessel may be obtained. All of this information has of course been available to class and owner before, but in a less systemised and accessible form - partly in databases and calculation programs, partly on drawings and partly in peoples minds. An example of how a Product Model may link various representations of information is illustrated in the figure. It shows how the NAUTICUS information system will allow to link a 3D graphical model with 2D drawings, which could in turn be linked to a picture showing a detail of e.g. an area with cracks.
What is NAUTICUS?

NAUTICUS encompasses products and services based on the use of Product Model technology developed by DNV:

1. **NAUTICUS class products and services:**
   These are offered through a set of NAUTICUS notations. These notations comprise a family of new voluntary class notations, each contributing to more efficient interaction with class. In addition they give the owner access to information and tools tailored to increase the efficiency in management of his vessels.

2. **Nauticus Production System:**
   The Nauticus Production System includes a completely new information system and an infrastructure that will provide "information at the fingertips" of both all DNV surveyors and DNV's customers.

3. **NAUTICUS calculation software:**
   Highly sophisticated, yet efficient and user friendly calculation tools for analysing the hull structure as well as machinery components.

The NAUTICUS Product Model technology represents a life-cycle approach to unified storage and retrieval of information and knowledge related to the ship. Instead of isolated representations of information and knowledge in a multitude of databases and programs, or what is also called "islands of automation", the Product Model provides a unified view into all relevant information. Object-oriented and component-based software is the foundation for realising computerised Product Models.

Key elements of the NAUTICUS philosophy are the also the life-cycle approach to information management combined with easy access to information and state-of-the-art IT solutions. Through NAUTICUS, owners may access decision support services such as weight estimation for steel renewal, coating area estimation, library of digital drawings, hull and machinery damage statistics and reports, etc. This may in turn contribute to benefits such as shorter stay in dock, more exact and optimal cost estimates, as well as better planning of maintenance and repairs - at lower cost

Why NAUTICUS?

At the time when DNV launched its Nauticus project, it had been recognised that there was a need for streamlining and speeding up many of the work processes involved in ship classification.

One such area of concern was the time spent on performing structural analysis during the design phase. This was critical both with respect to cost, being related to the total time spent on the design and construction phase, and with respect to the quality of the final design. The quality issue can be realised from the fact that the quality of the final design will be improved if one avoid serious mistakes during the early design, i.e. eliminating the need for high-cost
"fix-it" design loops late in the design process. Hence, efficient tools allowing for more analysis iterations during early design will increase the chances both for saving costs and achieving better quality.

Another issue was a desire to improve the experience feedback service, which draws on the knowledge base class builds up during systematically collection of information and statistics from numerous of surveys. As an example, trend analysis of thickness measurements over time may allow examination of diminution rates and rates of change, giving a clearer picture of expected life of structural members. Building up Product Model databases with condition information over vessels' life-cycle, across a wide number of vessels, will eventually also contribute to get a clearer picture of how structure and components performs, which will in turn aid future Rule development.

Finally, DNV saw a move towards risk-based approval and maintenance criteria. This will put heavy demands on the ability to perform analysis based on updated computerised models of the vessel, in turn enabling assessment of the true condition of the vessel. As an example, such an approach may facilitate the use of a more rational steel renewal criteria, rather than the prescriptive criteria traditionally used, and should produce an overall improvement in safety. In other words: the risk-based approach will focus on the actual values, which should be applied for structural safety. Hence, criteria could be relaxed in low risk areas and tightened for high-risk areas.

All these areas of concerns addressed by the Nauticus project should benefit owners through more cost-efficient management of both safer and more environmental friendly ships. For example, by moving from prescriptive to rational renewal criteria, owners may experience reducing the cost while maintaining, or even improving, their level of risk.

**NAUTICUS class products & services**

Some general principles applies to the NAUTICUS family of class notations:

- They are voluntary, i.e. the owner may select to remain with the traditional class schemes.
- They offer alternative classification schemes, i.e. survey and analysis/acceptance criteria schemes, which replace parts of the traditional main class (1A1) scheme. This is new, as voluntary notations traditionally have offered schemes in addition to main class.
- All NAUTICUS notations indicate that a certain information standard provided by DNV is in place, and that the owner is offered access to this information through DNV Exchange as an IT interface. Availability of this information standard serves as a starting point to give the owner access to a range of new class services and decision support features.
- Each of the additional NAUTICUS notations shall contain a class service aimed at the ship when in operation. A class service is in this context a service, which lays obligations on the owner and DNV, and presents an alternative survey scheme, information requirements, calculation features and/or acceptance criteria.
**NAUTICUS class notation**

The starting point of the NAUTICUS family of class notations is the class notation **NAUTICUS**. It applies to the ships in operation, and indicates that a Product Model, including a 3D graphical model, is in place to support advanced information processing, decision support services and efficient re-analysis.

The NAUTICUS notation sets a standard for information content and information availability through access to the ship's Product Model and selected IT support tools. The notation may be assigned on its own or in combination with other NAUTICUS notations describing specific features or services.

The 3D graphical model, which is part of the Product Model, generates colour coded visual display of selected compartments or structural members. It will gradually be extended with visual feedback on e.g. coating condition, the extent of corrosion, and the presence of other defects such as pitting and cracking. This will provide more easy interpretation of the vessel condition at a glance. Clicking on a particular structural element or component may access the full range of data held on that piece. The figure shows an example of how the 3D graphical model may contain information about cracking, and give access to more details on the crack in a 2D drawing view.

[Diagram showing an overview of crack in 3D and a crack in 2D detail view]

DNV Exchange is the name of the IT interface through which DNV customers may gain access to the Product Model. Various NAUTICUS tools will be made available through DNV Exchange, enabling decision support services such as:

- weight estimation for steel renewal,
- coating area estimation,
- library of digital drawings,
- hull and machinery damage statistics and reports, etc.
This may in turn contribute to benefits such as:

- shorter stay in dock,
- more exact and optimal cost estimates, as well as
- better planning of maintenance and repairs - at lower cost.

Using a regularly updated Product Model will allow much easier and more effective use of the information held by both class and the owner himself. In the future, the supporting software may e.g. compare as-built scantlings towards measured scantlings and highlight areas which need attention, or where renewal is recommended or necessary. Through DNV Exchange, giving access to complete and updated class status and condition of the vessel, all parties will get a much better picture of the vessels true condition. Thus, both owners and class can see where to focus their attention, in turn leading to more safe and environmental friendly ships.

**NAUTICUS (Newbuilding) class notation**

NAUTICUS (Newbuilding) is an additional class notation, which signifies that the vessel's strength has been calculated in accordance with extended Rule requirements for the notation, and that a Product Model has been created for the vessel. Calculation models and results from the plan approval process will be stored in the ship's Product Model for possible re-use in the operational phase. The Product Model will be created and maintained by DNV.

**Background**

The application of NAUTICUS (Newbuilding) in the Newbuilding phase represents a further development of the voluntary CSA-1 notation, and sets requirements to the calculation procedures for structural strength of the hull girder structure including comprehensive fatigue evaluations. This results in a state-of-the-art ship hull design, including in service experience from double skin designs. NAUTICUS (Newbuilding) also sets a requirement on DNV for creation of a Product Model.

NAUTICUS (Newbuilding) also applies to the operational phase, signifying that the vessel conforms to the extended design criteria. Further, the Product Model established by DNV in the newbuilding phase forms the basis for NAUTICUS notation during the operational phase. It should be noted, though, that a vessel may enter into the NAUTICUS class at any time during the in-service period without first applying the NAUTICUS (Newbuilding) notation. On the other hand, one will obtain a reduced fee if the vessel already applies the NAUTICUS (Newbuilding) notation.

A logical chain of DNV products supports the NAUTICUS (Newbuilding) notation:

1. DNV Rules giving design loads and acceptance criteria, as well as requirements for a procedure to be followed for the strength and fatigue calculations. Also, the Rule prescribes that a Product Model shall be created.
2. *Classification Notes* describe the procedures for strength and fatigue calculations in detail, ensuring that the model formulation is linked up to the rule requirements.

3. *Software* to support the calculations prescribed by the Rules. NAUTICUS Hull is a comprehensive software package including geometric modelling tools and advanced calculation tools for FE analysis. The software is specially designed to match DNV’s Rules and procedures, but may be used for general-purpose analyses as well.

**Principal benefits of applying NAUTICUS (Newbuilding)**

1. Quick assignment of NAUTICUS notation when entering in-service period - at a reduced fee!
2. State-of-the-art *documentation standard* with easy access to calculation results and design assumptions throughout the ship’s life.
3. Owner's access to *newbuilding information in the Product Model* through DNV Exchange.
4. Less time needed for model generation through *efficient modelling* procedures and software. Although use of DNV software is not required for applying the notation, DNV has developed the NAUTICUS Hull software both for internal and external use to increase effectiveness of modelling and performing FEA.
5. No hidden acceptance criteria – all requirements are based on *well documented Rules*.
6. *Rational steel distribution* through advanced structural calculations. Generally, advanced structural calculations give increased confidence in that the design is to a certain standard. The acceptance criteria are the same as for the rest of the main class. In addition finite element analyses provide:
   - Detailed results in terms of stress and deformations.
   - A good tool for rational steel distribution and detailed studies of local details.
   - Well-visualised results that are easy to communicate to the involved parties.

   DNV's extensive knowledge and experience with FEA and first-principle calculations has matured into to a highly rational steel distribution in vessels designed according to DNV criteria. The analyses are continuously being used to identify where increased scantlings are most needed in the vessel, thereby increasing the safety level and making the vessel more durable, in turn lowering the operational and life-cycle cost of the vessel. As an example, the figure illustrate areas for a tanker design where DNV criteria may differ from other Class Societies (note that even the illustration shows a very novel tanker design, the comments also applies to more conventional designs).
Deck longitudinals

Side longitudinals

Transverse Bulkhead

Double bottom longitudinals

Inner Bottom plating

- In the bottom there is always surplus in section modulus. On the other hand, DNV require more material in the inner bottom plate due to high lateral load from both sides.
- DNV require more material in the side longitudinals due to high risk for fatigue cracks. Note however that fatigue strength and size of longitudinals very much depends on local design.
- DNV require less material in the transverse bulkhead plating. This is because corrosion is not a problem for the vertical surfaces - corrosion will occur on stringer plates, not on the bulkhead plating. Note that damages are mainly found in areas with poor local design.
- DNV require less material in the double bottom longitudinals. Note that in cases where damages may occur at transverse bulkheads due to relative deflection, DNV procedure require analyses by fine mesh FE models to cater for this effect. Again, local design is of vital importance.
- Requirements for area in deck are more or less the same for all the major class societies. On the other hand, DNV require more material in the deck longitudinals to cater for sloshing loads and to give higher ultimate strength.

Finite Element Analysis

NAUTICUS (Newbuilding) requires a finite element calculation of the cargo holds during design. The figure shows an example of a FE model representing a tanker with two longitudinal bulkheads.

The finite element method (FEM) is a numerical analysis technique for obtaining approximate solutions to a wide variety of engineering problems. It has originally been developed in the 60’s to study the stresses in complex airframe structures and has since been extended and applied to the broad field of continuum mechanics. Finite element methods are especially efficient for structural analysis, with advantages such as detailed results in terms of stress and deformations. Hence, the analysis method provides a good tool for optimal steel distribution and detailed studies of local details.
Unlike many other numerical methods, it is difficult to estimate the error in results exactly when applying FEA. The results will always depend on the model formulation. Therefore it is particularly important to use recognised tools and procedures when applying FEA. As an example, the figure shows a local FE model of a bottom longitudinal, where the mesh density and regularity is essential, and is tightly linked to the acceptance criteria.

DNV pioneered the development of FEA software, and has performed such analyses for offshore structures and ships for more than 30 years. The extensive experience gained throughout this period has lead to development of well proven procedures for FE modelling. These "best practice" procedures are documented in the DNV Classification Notes.

Net scantlings approach The DNV procedure prescribe that the calculations are to be based on reduced scantlings, meaning that the corrosion addition is subtracted from the as-built scantlings. This is to ensure safe operation of the ship even though it may be corroded at the end of its lifetime. DNV introduced this principle in 1976. By using reduced scantlings for the calculations a well-maintained vessel will have a built-in margin.

Model extent DNV recommends a model extent of \( \frac{1}{2} + 1 + \frac{1}{2} \) tank/hold to keep semi-global moments to a minimum. Semi-global moments are bending moments on the hull girder that occurs due to simplified boundary conditions. (In this respect “simplified boundary condition,” means all simplification compared with a global hull model with correct mass distribution in dynamic equilibrium with the loads from the sea).

Stress check The results from the FEM model are used directly for control of stresses. The stresses shall not exceed acceptance criteria given in the Rules. In addition separate buckling controls are performed.

Extended fatigue calculations NAUTICUS (Newbuilding) requires an extended fatigue calculation procedure covering all longitudinals in deck, bottom, inner bottom, side and inner side in
the midship area. The relative deflections of longitudinals in way of transverse bulkhead are included from the FE calculation results.

For tankers, extended requirements for fatigue analysis of the knuckle between the innerbottom plate and hopper plate are introduced.

**Product Model from Newbuilding**

NAUTICUS (Newbuilding) requires a Product Model to be prepared by DNV during the newbuilding stage, and be made available at delivery. The scope of the content of this model will gradually be extended, eventually containing all relevant information from design and construction.

**NAUTICUS (Propulsion) class notation**

NAUTICUS (Propulsion) is a voluntary class notation, pioneering Rule development based on a risk-based philosophy. The notation offers an alternative to traditional in-service class procedures for propulsion machinery, based on performance evaluation, mechanical integrity and wear assessment, and fire/explosion/leaks hazards.

**Background**

The rule basis for NAUTICUS (Propulsion) stems from DNV’s New Machinery Project, developing risk-based class rules for machinery. Software tools for recording and performing trend and statistical analyses (see figure) support NAUTICUS (Propulsion).

Throughout the development phase of the Rules the focus has been to assess risk against the need to maintain an acceptable level of functional integrity. The analysis method used is based upon failure analysis in a functional hierarchy, where each main function analysed has been assessed with respect to failure frequencies and the consequences of failure. Consequences of failure have been evaluated in five main areas:
• safety of personnel,
• safety of ship and equipment,
• safety of the environment,
• safety of cargo and
• availability of the vessel.

Principal benefits of applying NAUTICUS (Propulsion)
1. Alternative survey scheme; risk-based and with condition monitoring. This caters for:
   - More focus on essentials.
   - Less unnecessary routine opening-up.
   - Better alignment of Class intervention with regular maintenance planning, contributing to increased operational flexibility.
2. Use of performance recording and comparing with baseline data. This contribute to:
   - More predictable surveys through evaluation against specific acceptance limits.
3. Systematic collection and analysis of maintenance and replacement intervals, and more extensive and standardised Class reports giving survey scope, condition and performance. Combined, this caters for:
   - Consistent performance monitoring vs. time (possibilities for trend analyses).
   - Consistent comparison within fleet (possibilities for statistical comparison).
   - Improved decision support for maintenance and operation.

Main areas of class involvement in a risk-based regime

Performance evaluation: This is based on regular monitoring of propulsion plant performance. Recorded data are processed through the NAUTICUS Propulsion tool and compared to baseline data.

Mechanical integrity and wear assessment: This is based on data from a fully implemented Planned Maintenance System. Emphasis is put on the overall maintenance strategy to be followed onboard and aims to monitor deviations between planned and performed maintenance actions for major components of the propulsion machinery. In addition, replacement and maintenance intervals for major parts are monitored, giving the possibility of providing useful statistical comparisons and feedback to the user.

Hazards: Evaluation of potential fire and explosion hazards is based on survey observations, combined with a general functionality assessment.
NAUTICUS software tools

NAUTICUS software includes advanced analytical software tools for assessment of hull and machinery. The various software packages available may be used as stand-alone applications or relevant parts may be accessed through the Product Model as part of the support tools offered in connection with specific class notations.

NAUTICUS Hull is the first program suite in the NAUTICUS software family, and has been developed to provide DNV and external users with a flexible tool for ship analysis. This tool allows approval engineers, designers, yards or ship owners to assess their new or existing designs with respect to structural and environmental integrity, operational costs, with special options for fatigue and ultimate hull girder capacity - all utilising data from the same 3D graphical model. The figure illustrate how NAUTICUS Hull may support a wide range of analyses, including traditional Rule Checks as well as state-of-the-art wave load and FE structural analysis.

Nauticus Production System

The Nauticus Production System encompasses tools that eventually will support all DNV work processes related to the handling a vessel throughout the entire life-cycle and all disciplines, including Newbuilding and Ships in Operation as well as hull, machinery and components. Note that this new production system will be used by DNV for all vessels entered into DNV class, not only those applying the NAUTICUS notation, although the content of the documentation and information will differ due to different survey scheme and acceptance criteria.

Through the Nauticus Production System owners may experience that the basic DNV class services in the operation phase will improve in terms of consistency, more useful deliverables and quicker delivery. If in addition applying the NAUTICUS notations, owners will further benefit from availability of the NAUTICUS information standard and associated tools to apply this
information. He may then also access a range of new services aimed at decision support in connection with management of the ship.

The figure illustrates an example of how the Nauticus Production System in the future may be used to retrieve relevant information for survey planning - including data from sister vessels. Also, other information, such as photographs, calculation models, sketches etc. will gradually be made available. Note that the standardised DNV work procedures are included into the software, guiding the user through all necessary steps, ensuring a uniform way of performing the survey job. This way, both the survey planning and the execution becomes easier and more effective, which in turn may lead to improved repair planning.

The new production system will allow DNV and its customers to harvest from improvements to the existing main class (1A1) services, such as:

- **Quicker response:**
  - Quicker delivery of certificates
  - Gradually only full term certificates
  - Instant reply to requests

- **Better survey planning, recording and reporting:**
  - More predictable surveys
  - Quicker reporting
  - Improved decisions

- **Better calculation tools:**
  - Quicker calculations
  - Improved documentation of results
  - Refined calculations when required

The Product Model will through the production system be updated as a knowledge repository, giving improved experience feedback and other services. Systematic collection of information and knowledge, is also fundamental in order to move towards a risk-based classification in the years to come.
3 levels of entering the NAUTICUS world

**DNV Exchange Basic:** To be used for the main class (1A1) services, containing the basic class status together with an access control screen. This will be available for free for all owners/ships flying DNV class, and is provided as a pure Web-based service. No software needs to be installed in the owner’s office to access the NAUTICUS world through DNV Exchange Basic.

**DNV Exchange Member:** The owner may for any ship independent of type order additional services, requiring a software package to be installed in the owner’s office. This software communicates (downloads) updated information from DNV's Nauticus Production System. An initial and annual fee will be charged for this software, as well for the additional services made available through the Member level.

**DNV Exchange Nauticus:** The owner will upon assignment of the NAUTICUS class notation get access to a new range of information. This requires additional software to be installed in the owner’s office, with a range of various NAUTICUS tools customised for owner's use.

The road ahead

DNV believes that the role of the Class Societies may undergo a change during the coming years:

- New technologies such as network services, utilising Intranets and the Internet, may allow shipyards, Class Societies and owners to work even closer together by selective sharing of updated information.
- Use of Product Model technology is ideal for introduction of a risk-based approach to classification.

Therefore, the NAUTICUS information system is prepared with extensive support for network services, and fully utilising the Product Model technology. DNV strongly believe this will make it an efficient production system for the future, taking DNV into the next millennium as the technology leader in ship classification.

During 1999, a NAUTICUS Modelling Centre is established in Poland in order support the process of gradually taking the DNV fleet of existing and new vessels into the NAUTICUS system. The result of this effort may introduce a new era of information availability, where access to a complete Product Model for any vessel may be given at any time and irrespectively of geographical location.