A Study on IT Solutions for Ship Design Automation using 3D CAD System

ゴドガテ, スシャント, ハリシュチャンダラ

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GODGHATE SUSHANT HARISHCHANDRA

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Department of Maritime Engineering,

Graduate School of Engineering,

Kyushu University

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CHAPTER 1

INTRODUCTION

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1 INTRODUCTION

1.1 Background

IT solution is the cutting edge technology in shipbuilding industry today. 3D CAD application is used as the modern technology tool for ship production design and construction. Many shipbuilders have implemented the virtual ship design concepts using 3D CAD system[1]. However, even today, the ship design and manufacturing process is time consuming and lot of manual operations and verifications involved in end to end ship design cycle. Hence it is a key to automate this end to end ship design process to reduce the ship design cycle time and increase the quality of design using an information system. Author with his long professional experience in IT solutions for automotive design and manufacturing, takes this opportunity to research the IT solutions for shipbuilding industry.

Automotive processes were sequential in nature, work was performed in silos and the result was unpredictable launch cost as shown in Fig. 1-1 below.
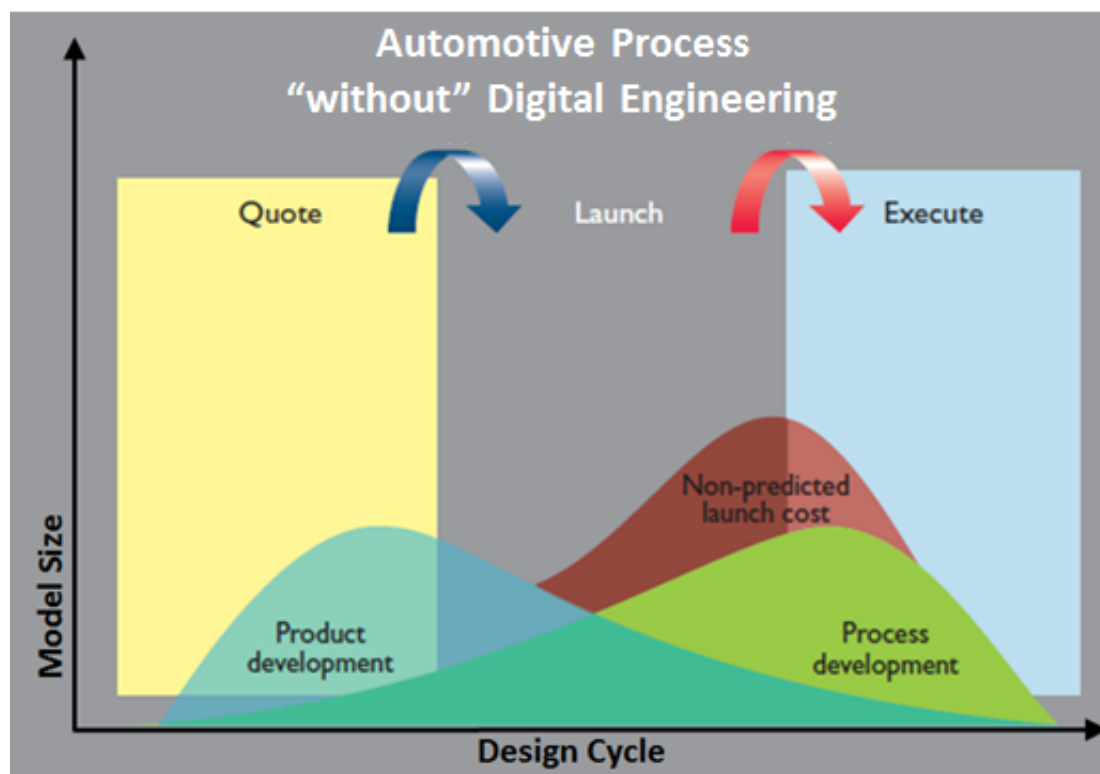
Fig. 1-1 Automotive Process without Digital Engineering

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Fig. 1-1 describes that, in automotive, the actual process development without the digital manufacturing is peak in the execution phase of the design cycle which increases the non-predicted launch cost. On the contrary, the digital engineering enabled concurrent product and process development helping the reduction in cost and time. Fig. 1-2 below shows the reduction in cost and process development ramp-up time at execution level with the use of digital engineering in automotive process.
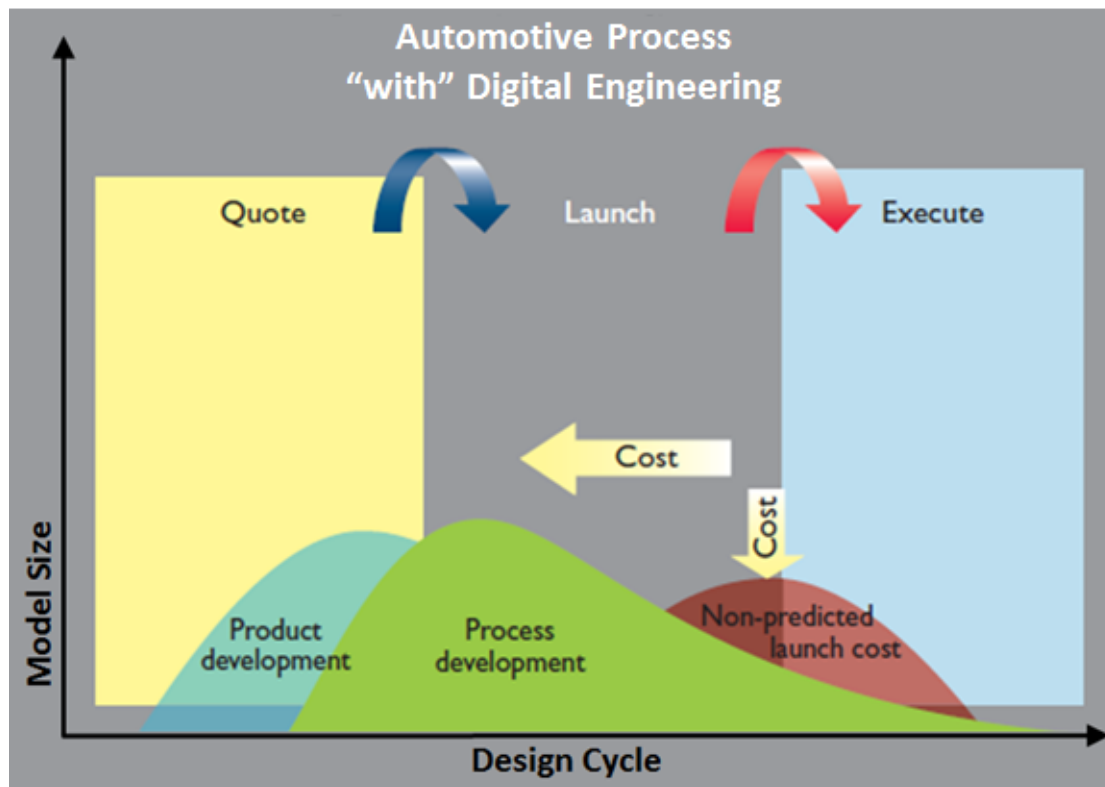
Fig. 1-2 Automotive Process with Digital Engineering

Following benefits are achieved in automotive manufacturing industry by adopting the high level of automation techniques using IT solutions.

➢ Reduced time to market

➢ Improved product quality

➢ Reduced prototyping costs

➢ More accurate and timely Request For Quote generation

➢ Ability to quickly identify potential sales opportunities and revenue contributions

➢ Savings through the re-use of original data

➢ A framework for product optimization

➢ Reduced waste

➢ Savings through the complete integration of engineering workflows

The benefits are simply represented by a time scale as shown in Fig. 1-3 below
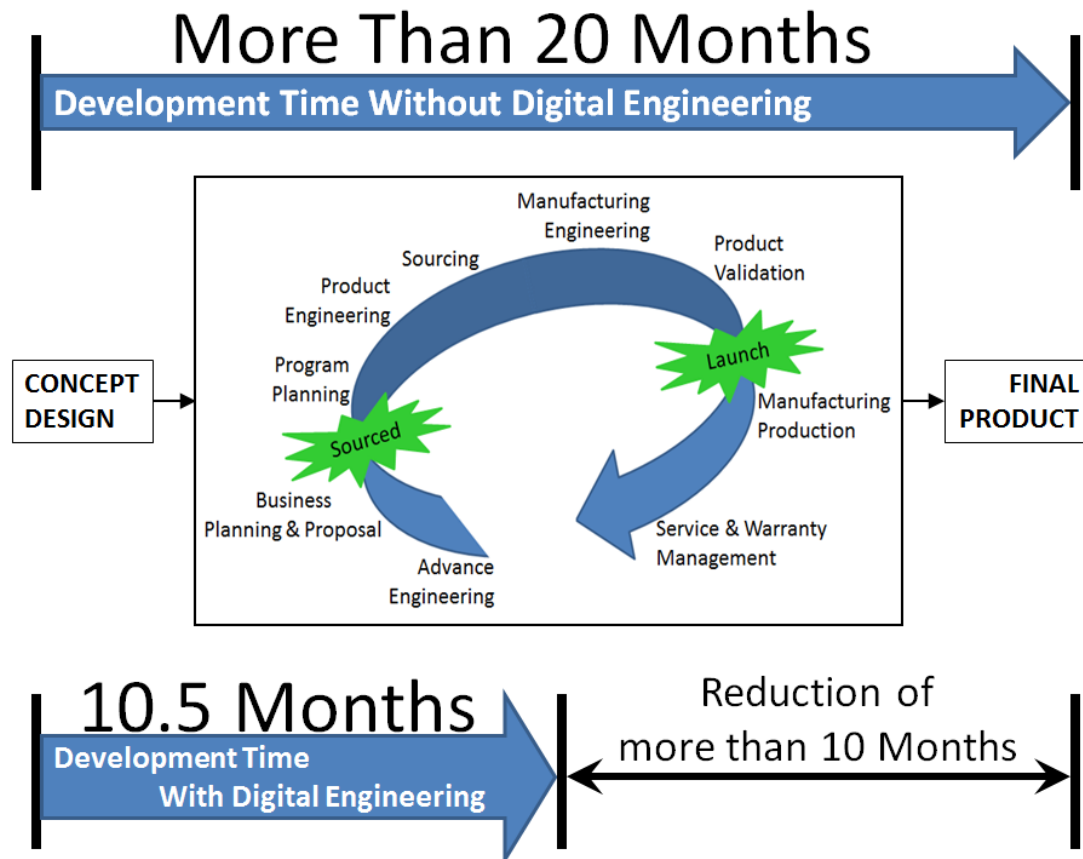
Fig. 1-3 Automotive Process Benefits Represented by Time Scale

On the similar lines of achievement in automotive manufacturing process, author's vision is to research and analyze the ship design and manufacturing processes in use and apply various research theories to achieve the best automation technology with multiple benefits similar to the achievements in automotive sector. Fig. 1-4 below describes the author's research concept to achieve benefits for ship design.

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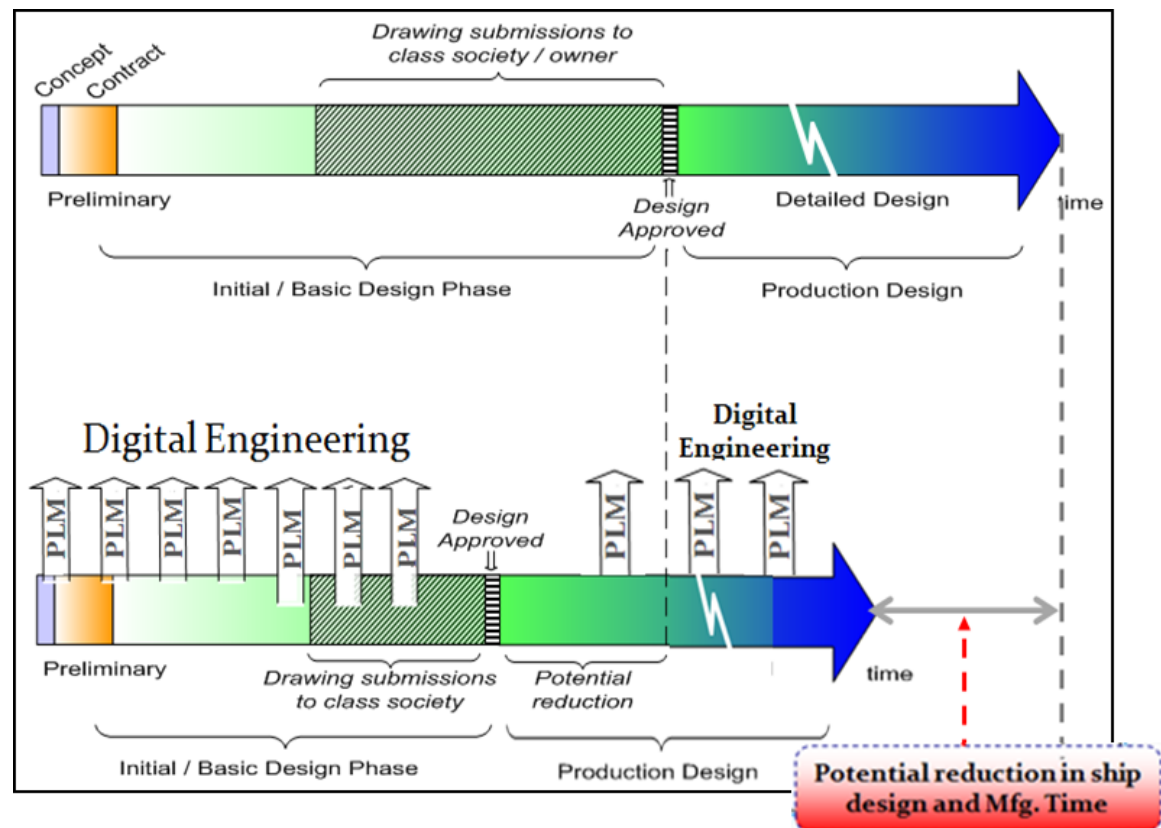
Fig. 1-4 Research Concept to Achieve Benefits for Ship Design

Fig. 1-4 shows the ship design cycle from its concept design to the production design without using digital engineering and also describes the potential reduction in ship design and manufacturing time by applying the digital engineering automation techniques. It can also be observed that the reduction in design time is throughout the design cycle and not just with respect to the particular design area which may largely help for the complete product lifecycle management (PLM).

1.2 Purpose

The main purpose of this research is to resolve various existing ship design automation problems which leads to inaccurate design, long design time for designing and verification of the shipbuilding and classification society rules, impact on original manufacturing schedule and delivery etc. Shipbuilders that have implemented ship design automation recognized that the rules are not fully reliable and has missing and contradictory logic due to enormous design requirements. This research will provide the best automation techniques that will help to resolve the missing and contradictory

design conditions and provide the error free automation rules that will be more reliable and accurate.

Estimation of accurate ship construction quotation is also a major concern in shipbuilding industry. Current estimation methods are based on lots of assumptions and past manufacturing records of similar type ship. This research will analyze the major quotation factors and provide the automation method for dynamic and real time estimation of the ship construction quotation.

1.3 Outline

This research study is conducted in three different phases. First phase described in second chapter, which is the key innovation of this research, will provide the analysis of automation rules for an expert system written in any programming languages using the Petri net graph theory. In second phase described in third chapter, author will provide an automation tool that can be used to quickly identify the design errors in the virtual ship model created using automation rules. In third phase described in forth chapter, a tool for the estimation of ship construction quotation is studied.

There are different standard processes adopted by different shipbuilding industries for manufacturing the same kind of carrier. Various tools are introduced in this industry to increase the quality of the product and to reduce time to market, manufacturing cost etc. However still today there are many challenges in this sector as compared to the automotive industry which is very-well optimized and well-defined process where KAIZEN is already in place.

There are various milestones in Ship Manufacturing process[2] e.g.

1. Receiving a Request For Quotation (RFQ)/ Request For Proposal (RFP)

2. Preliminary/Basic Design

3. Generate Quotation and Submit the Response to RFP with Quotation

4. Receiving Purchase Order

5. Detailed Design

6. Structure and Performance Analysis

7. Stability Check

8. Ship Design Approval

9. Production Planning

10. Manufacturing

11. Etc

Research on End-To-End ship design and manufacturing process is a very huge scope and it is difficult to cover all topics. However, digital design is a key area which covers maximum milestones of ship manufacturing process. Digital engineering is a key decision making milestone and is a decent scope for achievements of maximum benefits in ship manufacturing process. Author selected this milestone for further research and analysis and provides the best innovative techniques with practical test results on realistic ship design.

Computer Aided Design is commonly used now a day, however most of the shipyards use manual design processes. This is time consuming and tiresome job for the designers and experienced user. Moreover, the manual process needs a huge stock of know-how documentation and best practice manuals. It is mostly seen that the know-how is left with the senior designers who are already retired and industries especially the Japanese industries are struggling a lot on utilization of the past design experiences with these know-how. Hence automation of design knowledge became an important strategy for Japanese shipbuilding industry.

Author studied an expert system which is an example of a knowledge-based system. Expert systems are designed to solve complex problems by reasoning about knowledge, represented primarily as IF-THEN rules rather than through conventional procedural code. It is divided into two sub-systems.

1. The inference engine and

2. The knowledge base.

The knowledge base represents facts about the world and rules. The inference engine applies the rules to the known facts to deduce new facts. The goal of knowledge-based systems is to make the critical information required for the system to work explicit rather than implicit. In a traditional computer program the logic is embedded in code that can typically only be reviewed by an IT specialist[3]. With an expert system the goal was to specify the rules in a format that was intuitive and

easily understood, reviewed, and even edited by domain experts rather than IT experts. The benefits of this explicit knowledge representation were rapid development and ease of maintenance. The thesis provides the best automation techniques achieved in this research and analysis using an expert system with computer aided design application tool. Intergraph's Smart Marine 3D application tool is used to prove the research concept.

1.4 Summary

As described in section 1.1 and 1.2, with the use of cutting edge technology, significant achievements are made in automotive design lifecycle. On the similar line, if the same technology is applied for shipbuilding design, the design lifecycle time and the knowledge based systemization which is a key focus for shipbuilding industry can be achieved. Author continues his research and analysis using a combination of high end 3D CAD system and expert system knowledge for ship design automation techniques.

CHAPTER 2

APPLICATION OF PETRI NETS FOR SHIP DESIGN AUTOMATION USING 3D CAD

2 APPLICATION OF PETRI NETS FOR SHIP DESIGN AUTOMATION USING 3D CAD

2.1 Introduction

3D CAD systems are mostly used for ship design in shipbuilding industries today. However there is very limited focus on ship design automation. Most of the shipyards follow manual design using 3D CAD application. This is very time consuming and has possibilities of human error. Design accuracy is very important factor in ship design lifecycle[4]. Hence there is a huge scope of innovation in ship design automation. Ship design automation became an emerging trend in global shipbuilding industry. Ship design accuracy is fully dependent on designer's know-how, classification society rules and shipyards own design regulations. Many shipyards have started systemizing these design knowledge and all rules and regulations. In case of automated systems, the design errors must not be permitted. However, in a practical world, automation errors are seen due to the lack of design knowledge. These errors are very expensive in terms of the efficiency and productivity of a shipyard. Hence author researched these automation problems and innovated an error free construction method of rule based automation for ship design. This involves the complete automation lifecycle from basic design[5] to detailed design and then production design as shown in Fig. 2-1 below.
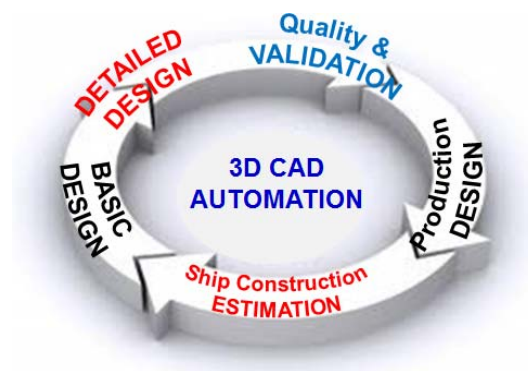
Fig. 2-1 Automation Lifecycle

The currently used rule based ship design automation[6] using a 3D CAD system is studied. One of the Japanese shipyards has implemented a high level of automation for ship design as described in section 2.2 below.

2.2 General Procedure of ship design using 3D CAD automation rules.

2.2.1 Basic Design to Production Design

Fig. 2-2 below shows the automation rules applied on ship basic design to production design. Each design phase in the figure shows one of the examples of automation result.
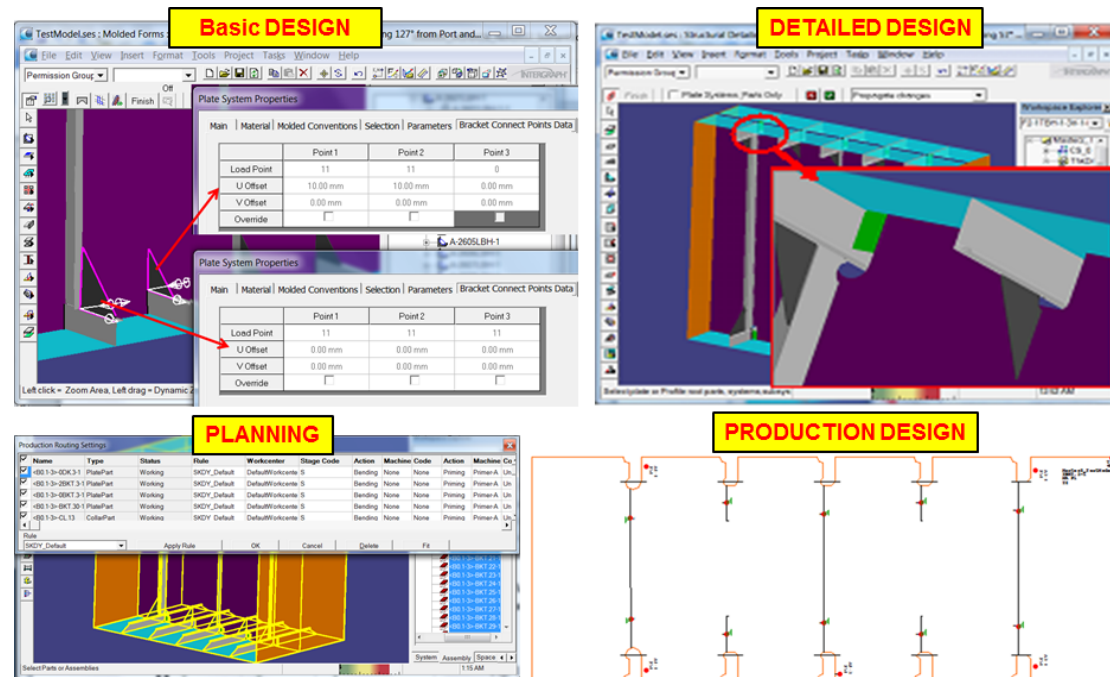
Fig. 2-2 Automation from Basic to Production Design

Basic design phase shows how the tripping stiffeners and tripping brackets[7] are offset from the molded surface of a support. This offset is set automatically based on the design conditions check. Detailed design phase shows the slot, corner feature and profile end cut features applied on the model automatically. Similar automation rules are also created for applying the bevel cut as welding information's, chamfer cut when there are plate thickness differences joining together, free edge treatments like grinding etc. Planning phase shows the automatic assembly creation and production routing information based on the assembly for the step-by-step production treatment of the part in manufacturing plant. Finally, the production design phase shows the final part shape/contour with plate thickness, assembly location information of all connected plate parts including bevel, tabs and chamfer to be applied on the part.

2.2.2 Design Quality Validation

The rule based ship design automation is also applied to verify the ship design. Fig. 2-3 below shows an automation results for ship design quality verification. Automatic design check is performed to verify the bracket and tripping stiffener offset whether it follows the standard design regulation. There are some situations during the design phase where the bracket supports need to be changed after the placement of brackets and thus the bracket offset is no more valid. In such cases, the bracket offset verification rule identifies those brackets and also helps to repair the offset automatically to design standards.
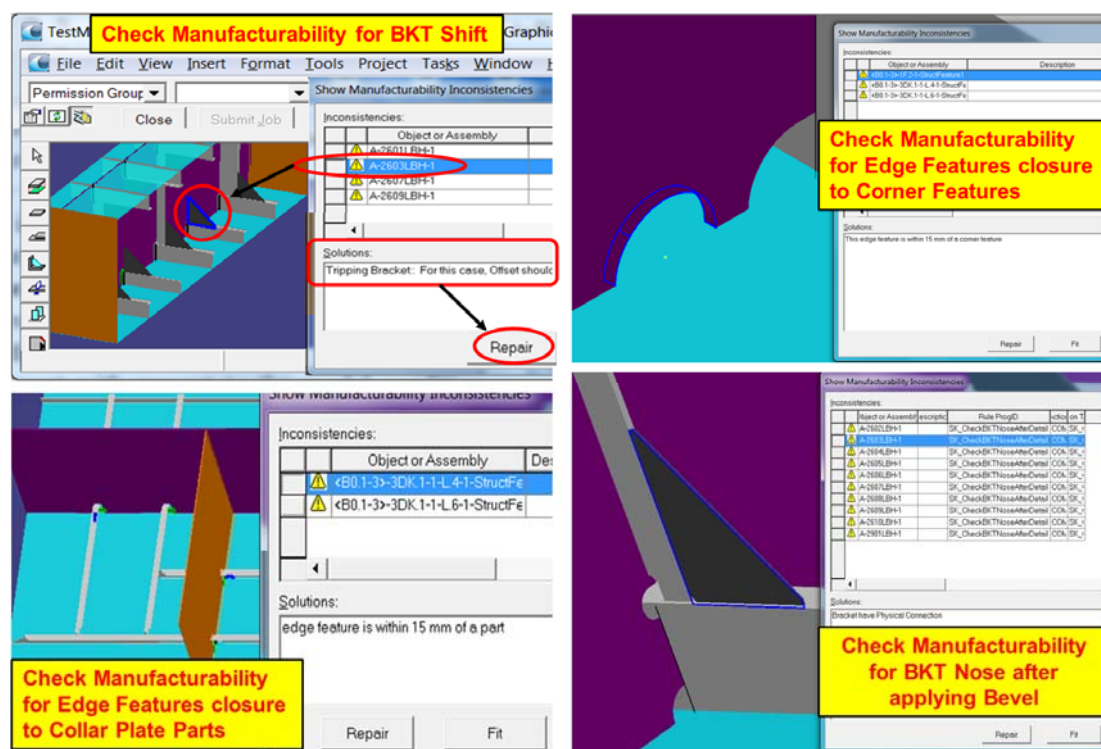
Fig. 2-3 Automation Results For Ship Design Quality Check.

There is a design regulation that the edge features and corner features must be maintained with a certain minimum distance between them. The design quality verification tool also called as check manufacturability identifies the features that does not maintain the design criteria and helps to repair the distance automatically to maintain the minimum criteria. Similarly the minimum distance criteria for edge features and collar plate parts can be checked and repaired if needed.

In case of bracket shapes, there is a nose on most of the bracket shapes. However, after applying the bevel, it is noticed that the bracket nose gets reduced due

to the bevel cut. An automation rule helps to identify the bracket with wrong nose and helps to repair the nose automatically.

2.2.3 Ship Drawings

All ship drawings that need to be submitted for classification society approval or to ship owners can be generated automatically using the ship drawing automation rules[8]. To generate these drawings, the 3D design model need to be completed as shown in section 2.2.4 below. Fig. 2-4 below shows the sample ship drawings from the 3D model.
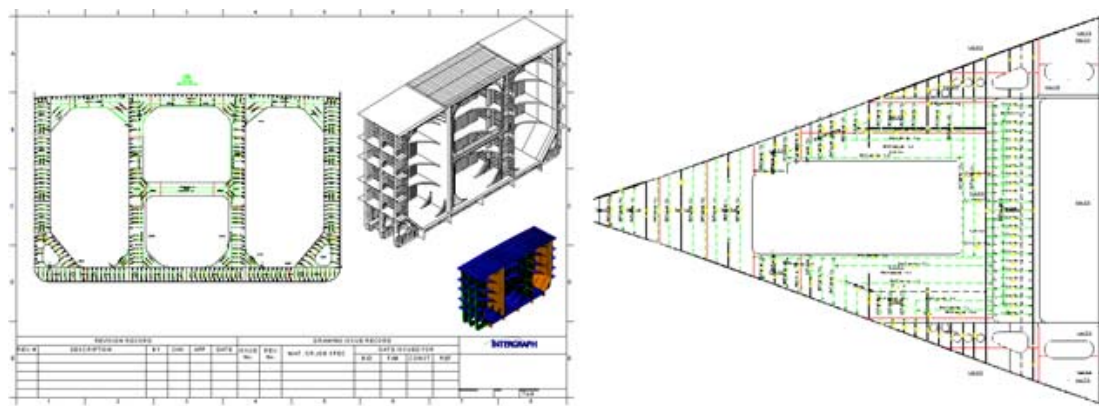
Fig. 2-4 Ship Drawings generated using Automation Rule

2.2.4 Complete Virtual Ship Model by Automation Rule

Fig. 2-5 below shows the complete ship design model of a Japanese shipyard which is created using an automation rules. It is important to note here that, there are huge numbers of automation requirements for many different kind of ship design features to achieve the complete virtual ship with minimum design time. Automated design features like end cut, slot, free edge feature, scallop and bracket in an engine room of this model are highlighted in this figure. It also shows the four hold and detailed ship objects in different view orientations from a 3D model.
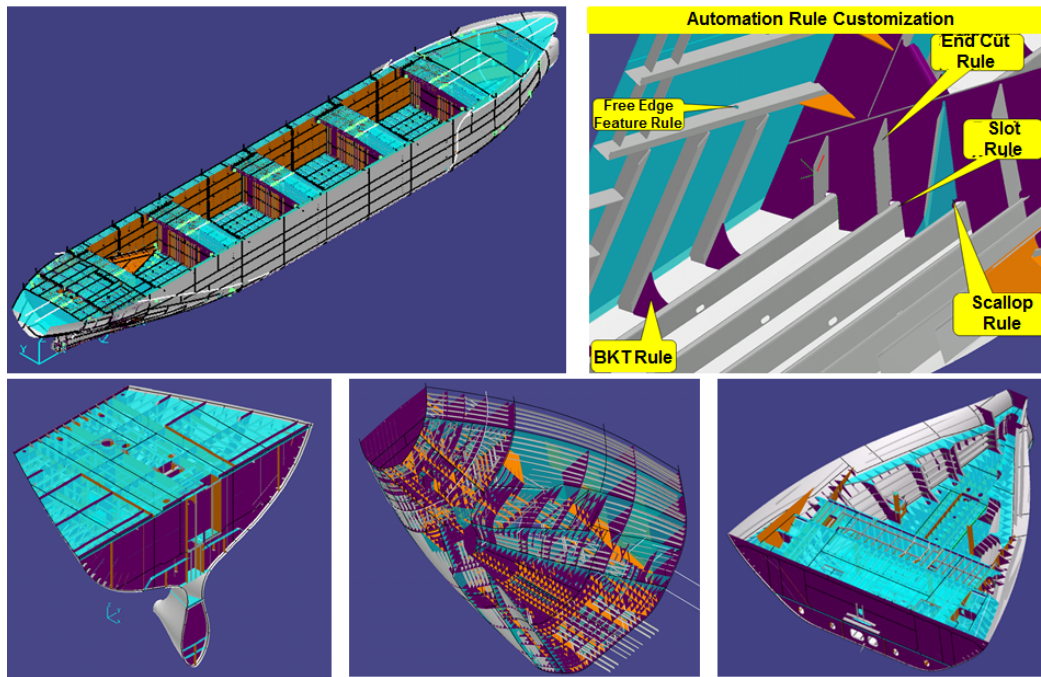
Fig. 2-5 Complete Ship Design using Automation Rules

This virtual model has also gone through the ship design quality verification and generation of all necessary ship drawings for classification society, design reviews and ship owner's verifications using the ship drawing automation rules[8]. To generate these drawing, the 3D design of a ship model need to be completed as shown in Fig. 2-5 above.

2.2.5 Nesting and Steel Cutting

With the use of production design data from 3D CAD model created using automation rules confirmed okay for manufacturing, the production data is exported in xml format which is then used for nesting system to optimize the material procurement at shipyard. Fig. 2-6 below shows the sample nesting result of the shipyard.
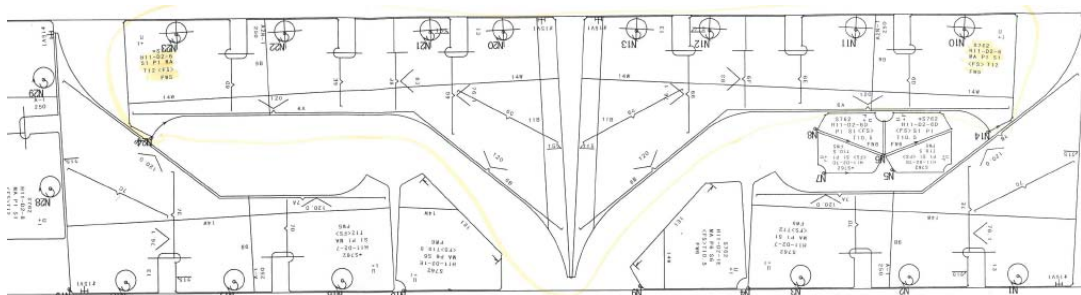
Fig. 2-6 Nesting Based on the Finalized Automation Model

Finally, the steel cutting is done in a shipyard using the rule based automation model data information. Fig. 2-7 below shows the profile and plate steel cutting results.
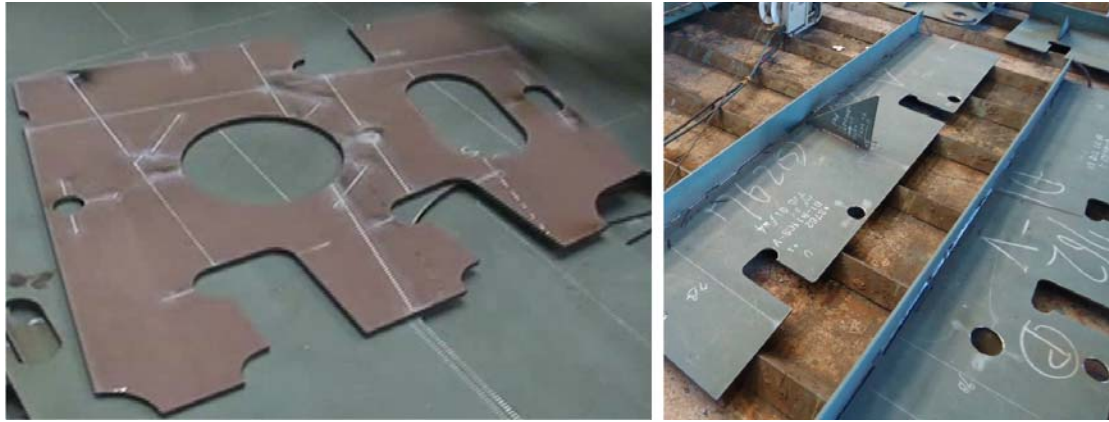
Fig. 2-7 Steel Cutting result from Rule Based Automation Model

As seen in section 2.2 above, the rule based design automation is now fully applicable in engineering design lifecycle of a ship design. Author started analyzing the accuracy and reliability of these design automation rules to invent the error free design automation techniques for shipbuilding industry. This thesis will introduce an automation techniques using 3D CAD system by elaborating the automation problems faced during the automation implementation and finally the research study will prove how the design automation problems are resolved by author's inventions. This theory will help shipyards to increase the quality of their production, reduce the design time and increase their reliability on automation rules.

2.3 Challenges in Implementation of Rule Based Ship Design Automation

The main challenges in designing automation programs are ensuring the correct sequencing of the interactions, communications between different computational executions, and coordinating access to resources that are shared among executions. The design automation problems are resulted by expert system using logical expression, flow diagrams and so on. An achievement in ship design automation is a key success of the shipyard. During the implementation of rule based design automation[6], it was learned that there is a long way to achieve the complete (100%) design automation (free of manual operations). Based on the knowledge from Japanese shipyard, it was recognized that the designers know-how based on the past experiences, classification society rules and shipyards regulations has to be pre-defined at basic design stage in an automation model. This is due to the fact that, many different design options are applicable for similar design condition[9]. In such situations, it becomes mandatory to predefine the shapes to be applied at basic design stage and leave the final results on detailed design automation rules to speed up the design process. However, there are more chances of human error in design definitions since the manual definitions are still involved in the design stages. User may define design conditions by mistake that may not be applicable for the certain design. In such situations, the automation rule should be smart enough to recognize the manual error and automatically correct the design condition based on ship design regulations of a shipyard.

During the research study on existing design automation rules of a shipyard, some design failure cases were observed as shown in Fig. 2-8 below. Figure shows that, in an existing automation rule, the profile end cut symbol used to create the profile end cut was wrong. In some cases, the profile end cut shape created was wrong due to the problem in automation logic. Similarly, the scallop shape applied on the slot shape is also wrong. In some cases, the slot that was applied on a transversal bulkhead was created at a wrong location. The location was different from the location of the profile penetrating the bulkhead. Similarly, in one of the flanged bracket type, the flange and web of the bracket was getting flipped. Finally, collar plate shape created on the slot was wrong. These unexpected design results were observed due to some problem in automation logic either by oversight or by the

enormous requirements leading to the contradictions or missing design test cases in the requirements.
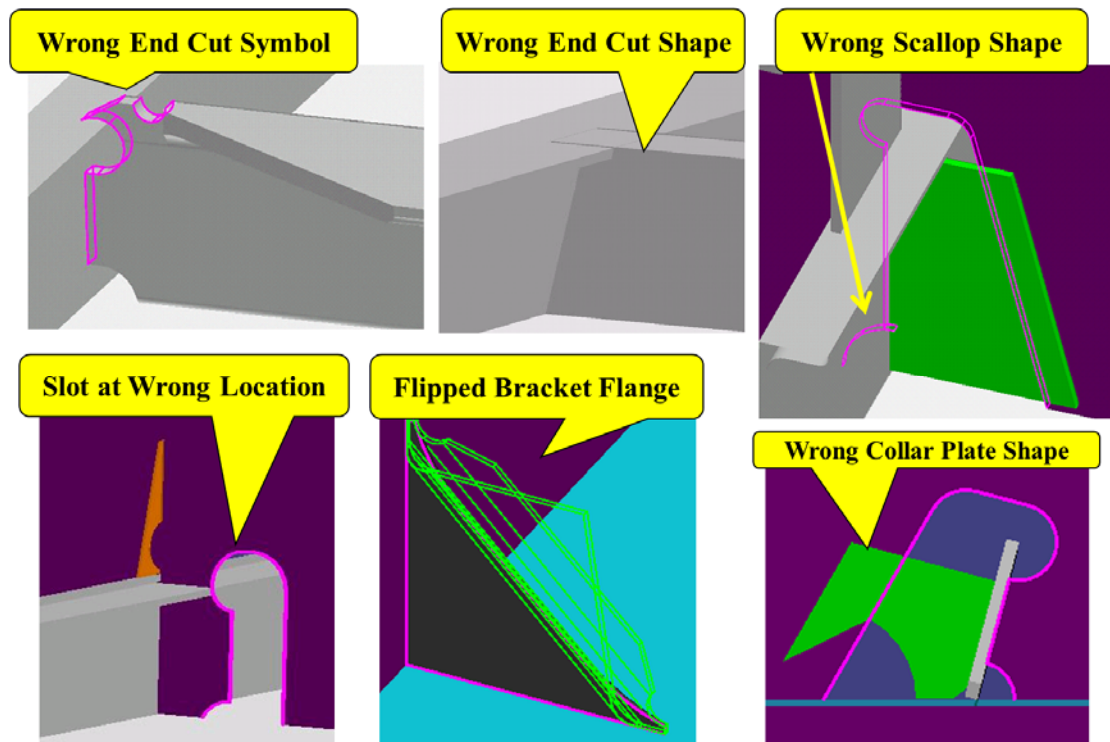
Fig. 2-8 Ship Design Failure Cases Based on Existing Automation Rules
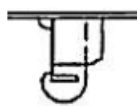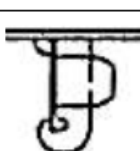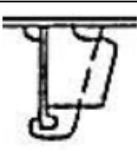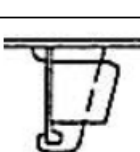
Additionally, it was also observed that some unexpected design results are obtained due to the use of predefined manual design conditions. Some of these test cases are studied from the detailed requirements specifications to the realistic test case in 3D CAD design model. The method applied to study these test cases was:

- Simulation using 3D CAD Model

- Model construction using Petri net based on the requirement specification and existing rules.

2.3.1 Automation Rule Failure for Slot-Collar Rule

Table 2-1 below shows the sample requirement for slot-collar features of a ship design.

Table 2-1 Slot-Collar Automation Rule Requirement

A1, A2, B1 and B2 represent the slot shape symbols for the slots created by the Angle and Bulb Plate penetrating profiles. "1", "2" and "3" represents the collar plate shape used on the top of the slots created. When collar plate shape "1" is attached on the A1 type slot shape, the slot-collar combination is called as A1-1 type. The slot-collar combination shape shown in A1 slot type row and "1" collar type column represents A1-1 slot-collar combination shape. Similarly A1-2, A1-3, A2-1, A2-2 etc represents other slot-collar combinations. Requirement shows that the A1-2, A2-1, B1-2 and B2-2 slot-collar combination do not exist.

Considering the requirements, limited set of a ship block is designed in 3D CAD model. Fig. 2-9 below shows the design of the model selected in such a way that the slot-collar combinations can be applied in the model.

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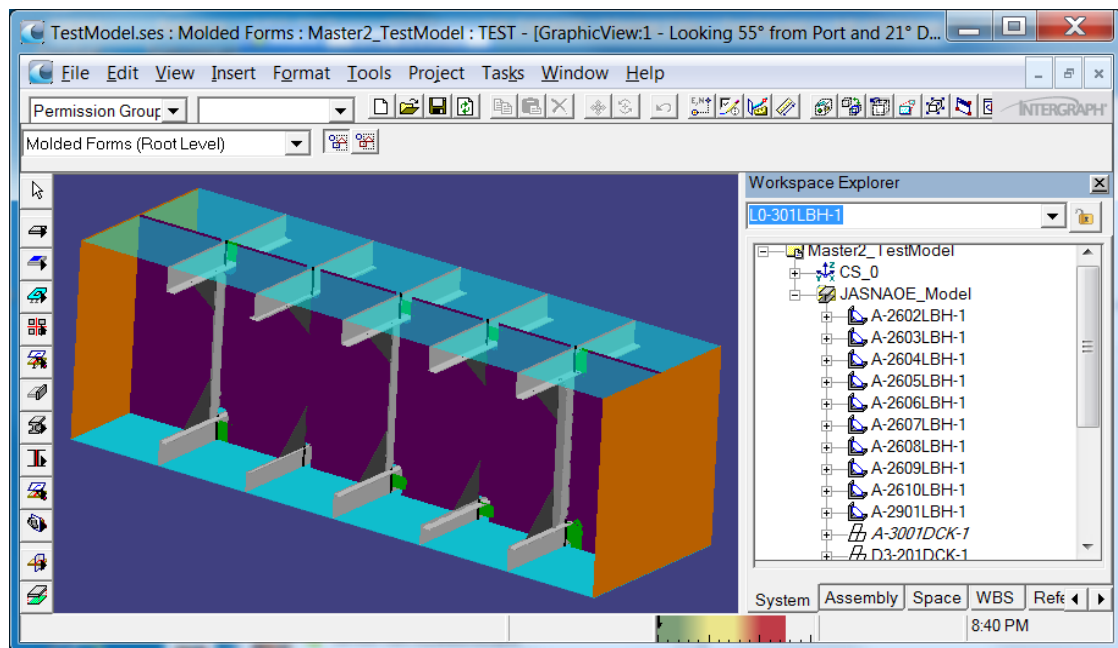
Fig. 2-9 3D Model for Slot-Collar Automation Rule

Author manually defined the various slot-collar combinations to be applied in the model as shown in Fig. 2-10 below. If the slot-collar shape combinations are not predefined in the model, rule applies the default slot-collar shape as defined in the automation rule.
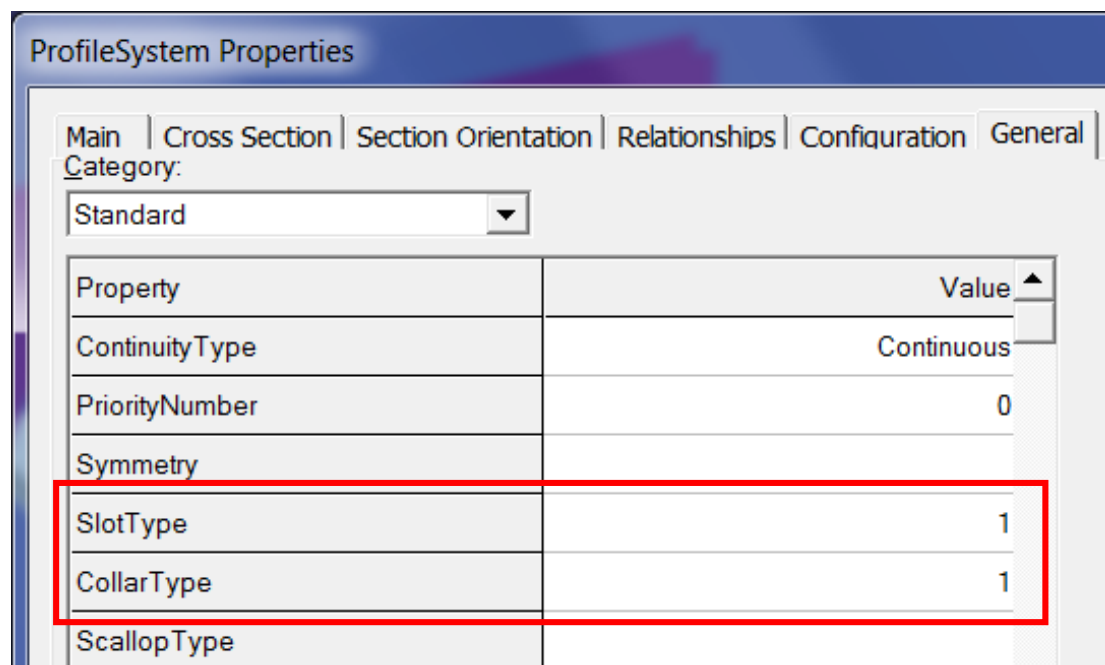
Fig. 2-10 User Defined Slot-Collar Combination

Fig. 2-9 above also shows the slot-collars created on the transversal bulkhead for the angle and bulb plate type penetrating profiles through this transversal bulkhead.

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For user defined slot type 1 and collar type 1 shown in Fig. 2-10, the slot-collar combination was applied correctly as shown in Fig. 2-11 below.
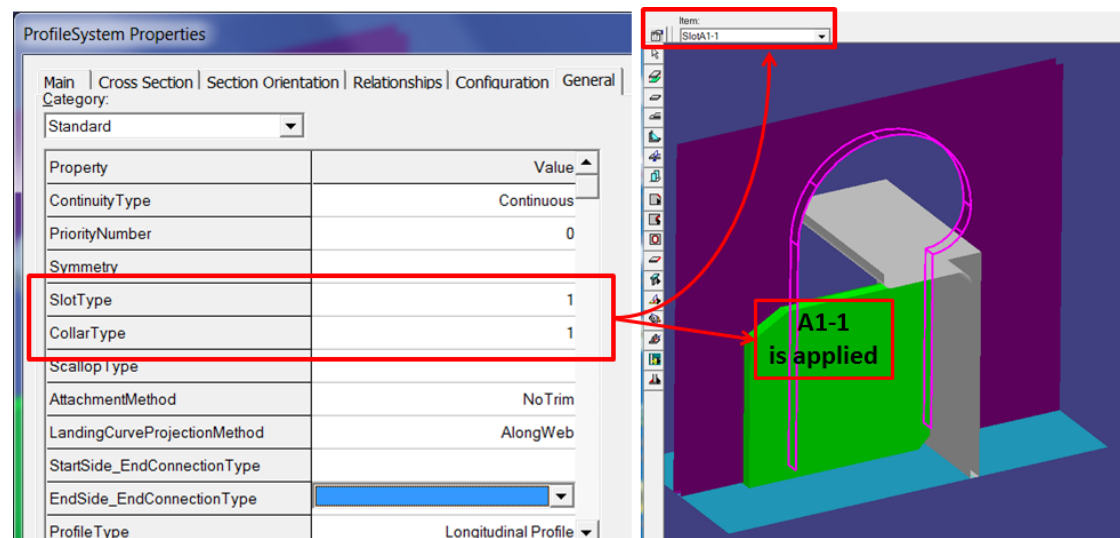
Fig. 2-11 Original Automation Rule Successful Test Case

However, as seen in Fig. 2-12 below, when the slot type 1 and collar type 2 was defined manually on the penetrating profile, the detailed automation rule was failed. The result was random for A1-2 combination as seen in Fig. 2-12. The slot and collar combination applied was totally unexpected.
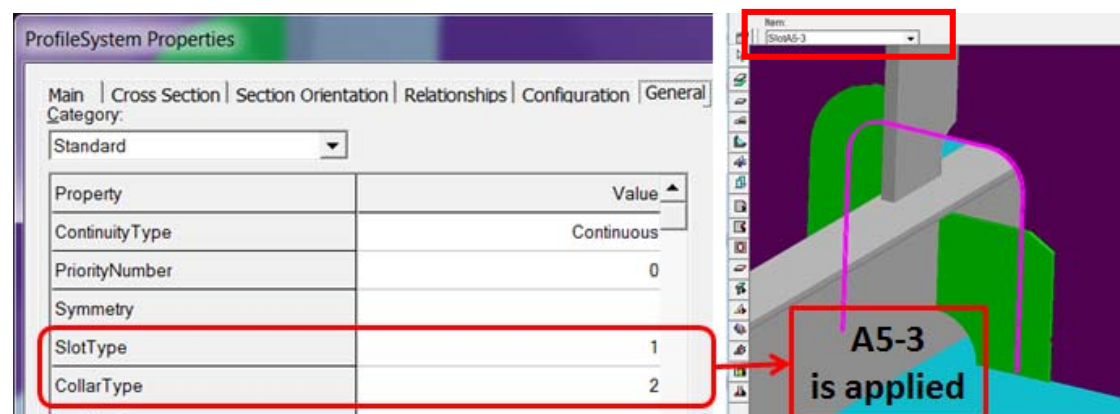
Fig. 2-12 Identification of Original Automation Rule Problem

Another problem was observed in the profile end cut automation rule as described below.

2.3.2 Automation Rule Failure for End Cut Rule

Table 2-2 below shows the sample requirement for Slot-Collar, End Cut and Profile End Scallop Combination Rule Requirement.

Table 2-2 Slot-Collar, End Cut and Profile End Scallop Combination Rule Requirement

End Cut of a profile above the slot must be "L" or "LS" type only.

There are various kinds of profile end cut shapes depending on the type of profile and how the profile is bounded. "S" represents the snip cut, "L" represents the lag touch and "LS" represents the lag touch with snip cut profile end cut shape. Each end cut type shapes of an angle profile type is as shown in Table 2-2. Depending on the design condition, the type of end cut "S", "L" or "LS" type is selected by the rule. E.g. as per the shipyard regulation, in case of end scallop design condition, it is described that the profile end cut type above the slot must be "L" or "LS" type only. Other end cut types are not useful in end scallop design condition.

In an automation rule for profile end scallop, to decide the type of scallop to be applied on profile, it is necessary to check the type of slot-collar combination applied on the base plate of a profile landing and also the profile end cut type ("L" or "LS") that is applied to the profile. End scallop requirement in Table 2-2 shows the end scallop shape with scallop dimensions to be applied on the profile end depending on the web size of the profile and slot type on which the profile end is landing where A1, B1, S1, T1, L21, L31, A2, A4, A5, B2, B4, B5, S2, S4, S5, T2, T4, T5 represents various types of slot shapes that are used in the shipyard. There are lots more types of slot-collar combination, profile end cut and profile end scallop shapes used in the shipyards. The requirement is to predefine the slot-collar combination and profile end cut symbol manually that has to be applied in the ship model however the profile end scallop type should be automatically selected in the rule.

As shown in Fig. 2-13 below, when user defines the "S" type of profile end cut shape manually on the profile which is on the top of the slot, the same end cut shape is applied even though the requirements as per Table 2-2 says that the profile end cut must be only "L" or "LS" type in this design condition. Since, there is no control over manual definition of ship design conditions; any user can define any kind of shapes manually if the user is not a design expert or even there could be a human error. Hence the automation rule actually should ignore the manually defined profile end cut type in such cases and apply "L" or "LS" type shape so that finally a profile end scallop as per requirement can be applied on this profile.
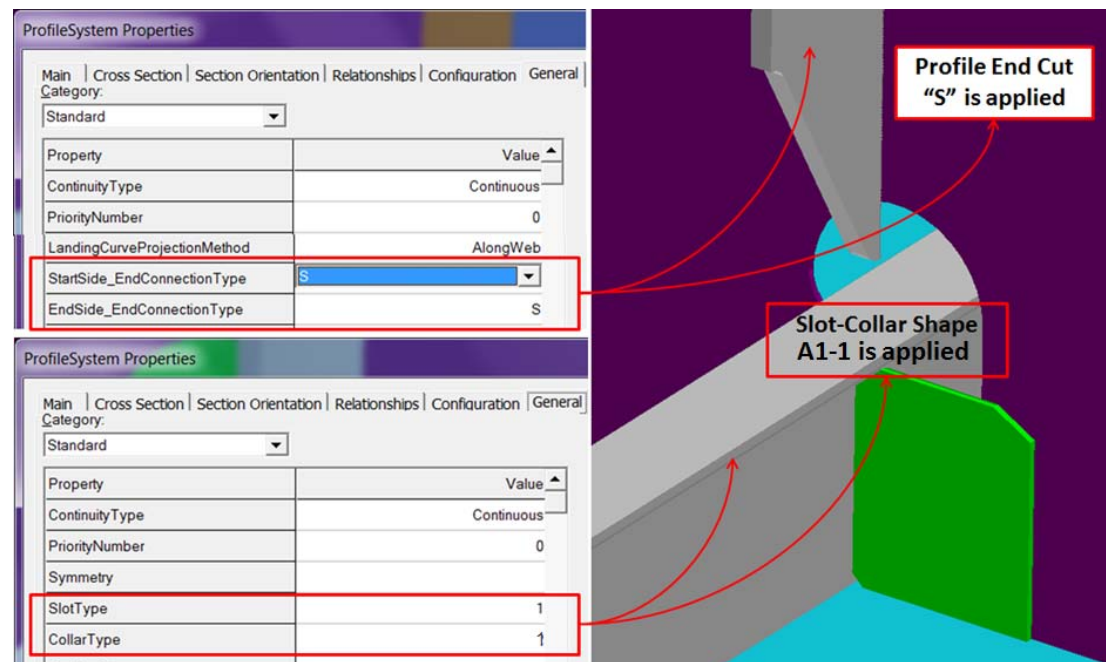
Fig. 2-13 Problem in Profile End Cut Shape Rule

These cases are the failure cases of automation rule used in the shipyard. Generally, if the programmers or CAD system developers develops the bug free systems, there won't be any need of a new tool which can identify the automation logic failures. However, this is not a case in shipbuilding industry, because even though the automation rules are perfectly developed for one shipyard, the similar rule will not work for any other shipyards since the design standards are fundamentally varied from shipyards to shipyards. Hence it is mandatory in shipyards that the automation rules are accuracy proven.

The above described automation failures forced shipyard experts to conclude that the ship design could not be fully dependent on the automation results. Designers have to check and verify the designs manually for whole ship. This was very time consuming and tiresome job even though using rule based automation. Experts also recognized that the logic will lead into manufacturing problems in later stage if the design verification is missed by oversight. Hence, author studied the rule from the detailed requirement specifications to the programing logic used to automate the rule. This expert system is analyzed using various mathematical and engineering theories like Max-plus algebra and max-plus linear discrete event systems, Petri network model-building study, Petri net graph theory etc. The objective was to research the

automation techniques that can help to identify the problems in automation rule which may unknowingly provide the unexpected design results.

2.4 Research Theory Suitable for Analysis of Ship Design Automation Rules

Based on detailed research and analysis of expert system using various mathematical and engineering theories described above, author concluded that the Petri net graph theory[10] [12] is most suitable to analyze the rule based design automations. This is because the Petri net graph theory provides the virtual simulation tool to verify correct sequencing of the multiple interactions that helps quick identification of problems. Further the theory also helps to redefine the rule execution method graphically and validate its accuracy by executing simulation including the mathematical analysis[13] [14] [15] supported by the theory.

Petri nets, also called place/transition nets, were introduced by Carl Adam Petri in 1962. Petri nets are graphical and mathematical modeling tool applicable to many systems such as various manufacturing systems, telecommunications, biological and computer systems. They are a promising tool for describing and studying information processing systems. Petri nets are powerful formalism for modeling a wide range of dynamic systems and system behaviors. Theory is widely used in computer science, system engineering and many other disciplines. As a mathematical tool, a Petri net model can be described by a set of linear algebraic equations, or other mathematical models reflecting the behavior of the system. It combines a well-defined mathematical theory with a graphical representation of the dynamic behavior of systems[14]. The theoretic aspect of Petri nets allow precise modeling and analysis of system behavior, while the graphical representation of Petri nets enable visualization of the modeled system state changes. Graph theory provides the visual expression of the design decision flow to quickly identify wrong decisions and make corrections in the automation logic right before it is implemented in production. Moreover, Petri nets provide the reachability concept[10] [11] [15] which is useful to identify problems in automation logic for the complex automation rule requirements.

A Petri net is a particular kind of bipartite directed graphs populated by three types of objects[14]. These objects are places, transitions, and directed arcs. Directed

arcs connect places to transitions or transitions to places. Pictorially, places are depicted by circles and transitions as bars or boxes as shown in Fig. 2-14 below. A place is an input place to a transition if there exists a directed arc connecting this place to the transition. A place is an output place of a transition if there exists a directed arc connecting the transition to the place.
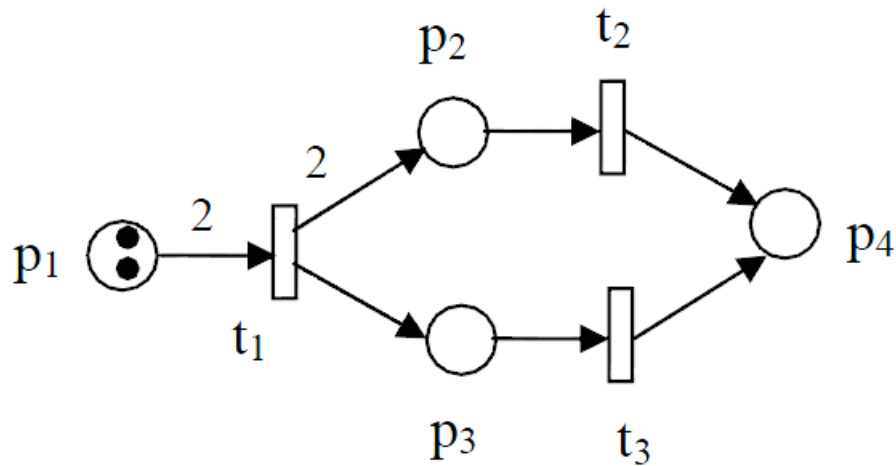
Fig. 2-14 Simple Petri net

In its simplest form, a Petri net can be represented by transitions together with input places and output places. This elementary net may be used to represent various aspects of the modeled systems. There are many simulation tools[13] [14] available to analyze the Petri net graph like DaNAMiCS, Renew, Petri Net Kernel (PNK), Platform Independent Petri net Editor (PIPE) etc. Author used PIPE simulation tool in this research.

An important issue in designing event-driven systems, such as any computer program application, embedded systems or CAD systems, is whether a system can reach a specific state, or exhibit a particular functional behavior. In general, the question is whether the system modeled with a Petri net exhibits all desirable properties as specified in the requirement specification, and no undesirable ones. This is called REACHABILITY[10] of a Petri net graph. In order to find out whether the modeled system can reach a specific state as a result of a required functional behavior, it is necessary to find such a transition firing sequence which would transform a marking M_0 to M_d, where M_0 represents the initial state and M_d represents the destination state, and the firing sequence represents the required functional behavior. It should be noted that a real system may reach a given state as a result of exhibiting

different permissible patterns of functional behavior, which would transform M_0 to the required M_d. The existence in the Petri net model of additional sequences of transition firings which transform M_0 to M_d indicates that the Petri net model may not exactly reflect the structure and dynamics of the underlying system. This may also indicate the presence of unanticipated facets of the functional behavior of the real system, provided that the Petri net model accurately reflects the underlying system requirement specification for e.g. Table 1-1 and Table 2-2. A marking M_d is said to be reachable from a marking M_0 if there exists a sequence of transitions firings which transforms a marking M_0 to M_d. A marking M_1 is said to be immediately reachable from M_0 if firing an enabled transition in M_0 results in M_1. Formal mathematical definitions of Petri net are as described below[10) 15)]:

$$P = \{P_1, P_2, \ .\ .\ .\ .\ , P_n\} \text{ is a finite set of places,}$$

$$T = \{T_1, T_2, \ .\ .\ .\ .\ , T_n\} \text{ is a finite set of transitions,}$$

Petri net graph is represented mathematically with the incidence, firing or control vector and marking state matrices. Incidence matrix of the Petri net graph is represented as[10) 15)]:

$$A = A^+ \ - \ A^- \tag{2-1}$$

Where,

  A^+ is the weight of the arc from transition to its output place

  A^- is the weight of the arc to transition from its input place

  A is an n×m matrix.

Let r be the rank of A, the partition A is represented as:

$$
A =
\begin{array}{cc}
\overset{\xleftrightarrow{m-r}}{} & \overset{\xleftrightarrow{r}}{} \\
\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} &
\begin{array}{l} \updownarrow\ r \\ \updownarrow\ n-r \end{array}
\end{array}
\tag{2-2}
$$

Where,

  A_{11} is a nonsingular matrix of order $(m - r)$

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A_{12} is a nonsingular square matrix of order r

The fundamental circuit matrix (B_f) is defined as:

$$B_f = [I_\mu : -A^T{}_{11} (A^T{}_{12})^{-1}] \qquad (2\text{-}3)$$

Where,

I_μ is an identity matrix of order $(m - r)$

The marking state ΔM is defined as:

$$\Delta M \ = \ M_d - M_0 \qquad (2\text{-}4)$$

Where,

M_0 is the initial marking state of the graph.

M_d is the destination marking state of the graph.

The reachability of a Petri net graph is defined as:

$$B_f \Delta M = 0 \qquad (2\text{-}5)$$

The Petri net graph is said to be reachable if the reachability of the graph "Bf ΔM" is equal to zero. Meaning that the tokens defined in the Petri net graph at various inputs places when combined together with the arcs, results into the active transitions throughout the graph and finally traverse to the end of the graph. On the contrary, the Petri net graph is said to be not reachable if the reachability of the graph "Bf ΔM" is not equal to zero. In this case, the token defined in the Petri net graph at various inputs places will not reach to the end of the graph when travelling through the places and transitions defined between the input and output places of the graph.

2.5 Research Objective, Concept and Method

The main research objective is to provide the best analysis method based on Petri net theory for rule based ship design automation using 3D CAD system. Ship design as a whole is a very huge research scope and it is quite difficult to cover the research on end-to-end ship design process. Hence a limited set of rule based design automation is selected in this research and the automation problems caused by the expert system using logical expression, flow diagrams and so on are analyzed. Author selected the automation rules from detailed design phase which is major area of automation. The slot, collar, end cut and profile end scallop features combination rule from detailed ship design is studied. Various combinations are used depending on the ship design conditions. The slot and collar shapes are totally different when an invert angle, bulb plate, flat bar or built up stiffeners are penetrating the bulkheads. Similarly the profile end scallop is totally different when the profile end is on the top of different slot-collar types. Generally, every shipyard uses the predefined standard shapes for every design conditions. Since there are various design conditions and many different feature combinations exist, the automation rule is very lengthy and complex. It is certain that the rule may have some contradictions or missing conditions. This research is focused on identifying and resolving the missing conditions in multiple features combination automation rule.

To achieve the automation methods on ship design, a virtual ship was designed using 3D CAD application method to prove the research concept. Automation rules are first simulated in a Petri net simulation model to identify the missing or contradicting conditions. Based on the analysis, author provided the additional automation rules, modification of existing rules to avoid the unexpected design results. Finally a progressive Petri net simulation model is recommended. The revised Petri net simulation model is then implemented in an automation rule using Microsoft Visual Basic programming language[16].

Section below describes the Petri net analysis on an automation rule for a single feature first and then a complex automation rule for the combination of features will be described.

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2.6 Petri net Analysis on Slot-Collar Automation Rule

The shapes described in Table 2-1 and Table 2-2 is applied automatically in detailed design automation rule created using Microsoft visual basic programming language. The sample automation rule created in visual basic programming language for slot-collar combination shape is as described below.

```
*************************************
'Slot Collar Combination Rule
If oProfilePart.SectionType = "IA" Then
    If sSlotType = "1" Then
        If sCollarType = "1" Then
            GetSlotType = "A1-1"
            Exit Function
        Else sCollarType = "3" Then
            GetSlotType = "A1-3"
            Exit Function
        End If
    Else sSlotType = "2" Then
        If sCollarType = "2" Then

            GetSlotType = "A2-2"

            Exit Function

        Else sCollarType = "3" Then

            GetSlotType = "A2-3"

            Exit Function

        End If

    End If

If oProfilePart.SectionType = "BP" Then

|

*************************************
```

The rule describes that, how the slot and collar combinations should be applied based on the user inputs described for "Slot Type" and "Collar Type" based on the

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penetrating profile type "IA, BP, etc.

Author researched and analyzed this automation rule using Petri net graph theory in PIPE simulation tool. Representing the VB logic in Petri net graph theory is same as defining the flow-diagram of the logic. However, Petri net graph provides more visual and immediate identification of the problem by real time simulation in the graph. Fig. 2-15 below shows the Petri net graph created from the above VB logic that was originally used for slot-collar combination in the 3D CAD software application.
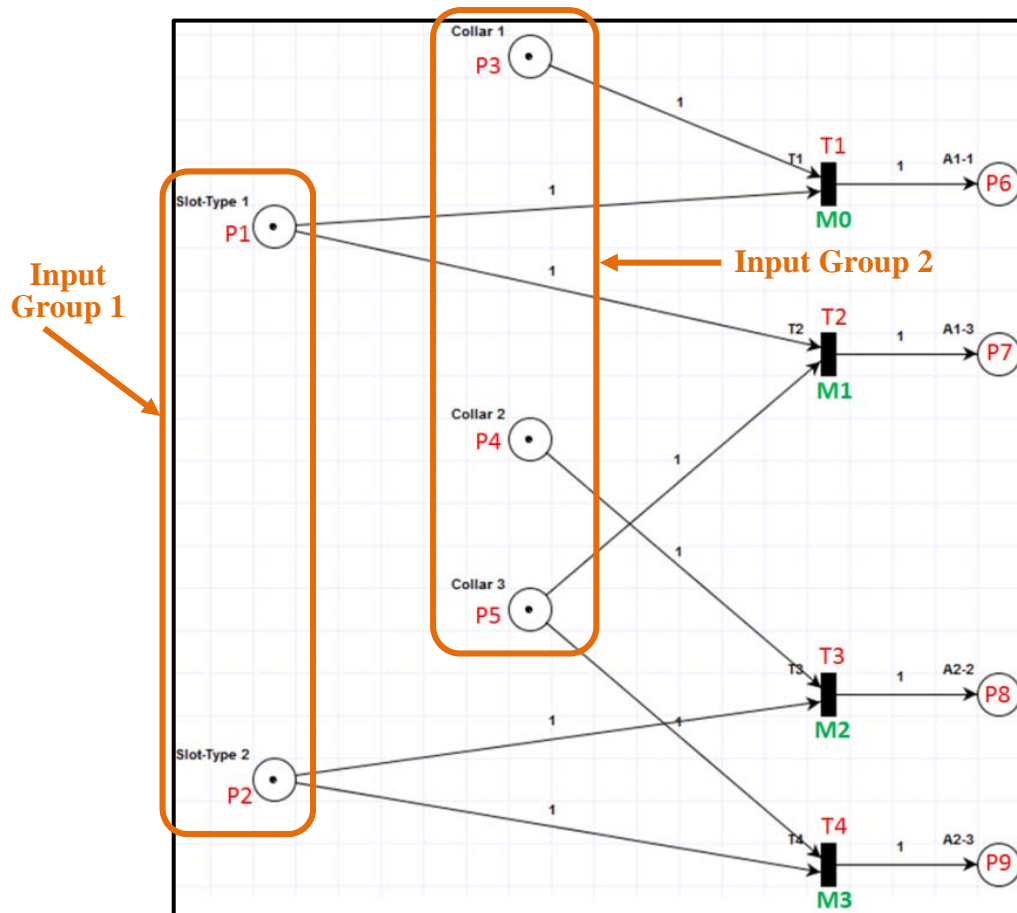
Fig. 2-15 Slot-Collar combination rule used by a shipyard

Input Conditions: The places P1 and P2 are the manual input conditions for slot types. This is considered as input group 1. The places P3, P4 and P5 are the manual input conditions for collar types. This is considered as input group 2. A combination of input group 1 and input group 2 defines the slot-collar combination selection in Petri net.

Output Conditions: P6 to P9 are the output conditions of this graph which represents the final slot-collar combination applied based on the combined selections from input group 1 and input group 2 described above.

T1 to T4 are the possible transitions based on the inputs selected by the user that drives the feasible output. Petri net graph is also represented mathematically with the incidence, firing or control vector and marking state matrices[10) 13) 15)]. Equation (2-6) is an incidence matrix of the graph shown in Fig. 2-15 above.

$$A = \begin{array}{c} \\ t1 \\ t2 \\ t3 \\ t4 \end{array} \begin{array}{ccccccccc} P1 & P2 & P3 & P4 & P5 & P6 & P7 & P8 & P9 \\ \begin{bmatrix} -1 & 0 & -1 & 0 & 0 & 1 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & -1 & 0 & 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 & -1 & 0 & 0 & 0 & 1 \end{bmatrix} \end{array}$$

(2-6)

Where,

A^+ is the weight of the arc from transition to its output place

A^- is the weight of the arc to transition from its input place

A is an $n \times m$ matrix (where $n = 4$ and $m = 9$).

2.6.1 Reachability Analysis for Single Feature (Simple Graph)

CASE I: When there is a token at Place P1 (Slot Type 1) and P3 (Collar Type 1) as shown in Fig. 2-16, the transition T1 will be active and can be fired.
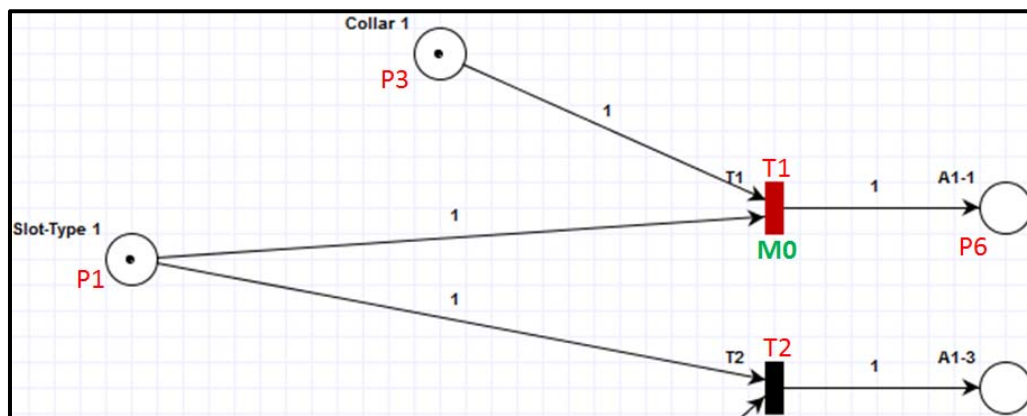
Fig. 2-16 Active transition for 1-1 slot-collar combination

As you can see in the graph, when user set the combination like slot type 1 (Place P1) and collar type 1 (Place P3) by defining the tokens at these places, the token moves to the destination place A1-1 (Place P6) slot collar combination by simulating the activated transition T1. Likewise, A1-3, A2-2 and A2-3 results are obtained

depending on where the token is placed at input conditions. As per the requirement, only one result should be obtained for use of any combination defined by the users. Hence the graph is reachable using the virtual simulation method in this case. Mathematical analysis is also done for various combinations of places that can be set by the user and reachability of the graph was studied.

The initial marking state of the graph shown in Fig. 2-16 is defined as:

$$M_0 = [1 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^T \tag{2-7}$$

And destination marking state of this graph is defined as:

$$M_{d1} = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0]^T$$

OR

$$M_{d2} = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0]^T$$

OR

$$M_{d3} = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1 \quad 0]^T$$

OR

$$M_{d4} = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1]^T \tag{2-8}$$

Let r be the rank of matrix A. Rank r = 4 for the matrix A described by Equation (2-6) above. The partition A as per the Equation (2-2) above would be represented by Equation (2-9) as shown below.

$$A_{11} = \begin{bmatrix} -1 & 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 & -1 \\ 0 & -1 & 0 & -1 & 0 \\ 0 & -1 & 0 & 0 & -1 \end{bmatrix}, \quad A_{12} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad A_{21} = 0, \quad A_{22} = 0 \tag{2-9}$$

The fundamental circuit matrix (B_f) is calculated from Equation (2-10) below.

$$B_f = [I_\mu : -A^T_{11} (A^T_{12})^{-1}] \tag{2-10}$$

And the marking state ΔM is calculated from Equation (2-11) below.

$$\Delta M = M_d - M_0 \tag{2-11}$$

The reachability of this slot-collar combination graph is calculated from Equation (2-12) below.

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$$\text{Bf } \Delta M = 0 \qquad\qquad (2\text{-}12)$$

Hence, the result of Equation (2-12) for M_{d1} is as shown in Equation (2-13) below.

$$[0 \quad 0 \quad 0 \quad 0 \quad 0]^{T} \qquad\qquad (2\text{-}13)$$

And the result of Equation (2-12) for M_{d2}, M_{d3}, and M_{d4} is non-zero. Since the tokens from input places should reach to any destination places, any one of the destination marking reachability should be zero. In this case, since destination marking M_{d1} is zero, the graph is considered as REACHABLE. This means that the automation result for slot type 1 and collar type 1 combination is applied correctly. Similarly, the combinations of slot 1 and collar 3 (Place P1 and P5), slot 2 and collar 2 (Place P2 and P4) and slot 2 and collar 3 (Place P2 and P5) are exactly the same conditions and hence the automation result is correctly applied for all of these combinations.

CASE II: When there is a token at Place P1 (Slot type 1) and P4 (Collar Type 2) as shown in Fig. 2-17 below, no transitions will be active and it cannot be fired.
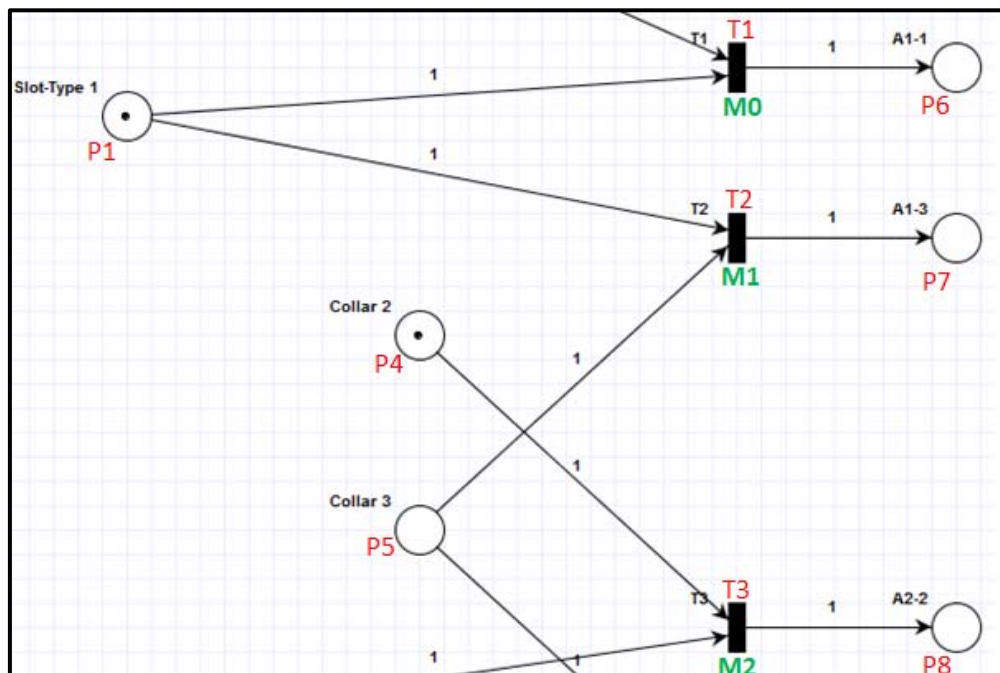

Fig. 2-17 Non-Active transition for slot1-collar2 combination

Meaning that the Token defined at input places cannot reach to any of the destination places. Hence this input combination is considered as NON-

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REACHABLE for this graph. Similarly, the mathematical analysis to confirm the reachability of this case is done as described below.

The initial marking state for this case is defined as:

$$M_0 = [1 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^T \qquad (2\text{-}14)$$

The destination of this graph could be the place P6, P7, P8 or P9. Hence the destination marking state of this graph are same as CASE I and are defined by Equation (2-8) above.

Reachability of this slot-collar combination graph is calculated from Equation (2-12) above. Hence the result of Equation (2-12) for M_{d1} is as shown in Equation (2-15) below.

$$[0 \quad 0 \quad 1 \quad \text{-}1 \quad 0]^T \qquad (2\text{-}15)$$

And the result of Equation (2-12) for M_{d2}, M_{d3}, and M_{d4} is non-zero. Thus all of the destination marking for this input conditions is Non-Zero and as per Petri net graph analysis, when reachability of a graph is non-zero, the places are not reachable. Similarly, the combinations of slot 2 and collar 1 (Place P2 and P3) are exactly the same conditions and hence the automation result is not applied correctly for this combination too.

The Petri net's graphical analysis shows that the automation rule fails for the combination of slot type 1 with collar 2 and Slot type 2 with collar type 1. At this stage, there is no indication to the designer about the automation rule failure and system applies random combination. Next section describes more detailed and complex automation rule failure cases and then the resolution techniques of such unexpected design issues.

2.6.2 Reachability Analysis for Combination of Features (Complex Graph)

The sample automation rule created in visual basic programming language for a combination of slot-collar, end cut and end scallop shape is as described in below Fig. 2-18. The programming rule describes that, how the slot and collar combinations should be applied based on the user inputs described for "Slot Type" and "Collar Type" based on the penetrating profile type "IA, BP, etc. Then this slot and collar combination when combined with the profile end cut rule based in the profile bounding condition on the top of slot, the end cut type that was set by the user manually e.g. "L", "S". "LE' "LS" or "LEP" is applied as it is. Finally the combination of slot-collar and profile end cut when combined with the profile end scallop rule, a scallop type "None", "Scallop-R_1", "Scallop-R_2" or "Scallop-R_3" is applied depending on the profile web size and profile type on the slot type A1-1 etc.

```
****************************************
'Slot Collar Combination Rule
If oProfilePart.SectionType = "IA" Then
     If sSlotType = "1" Then
          If sCollarType = "1" Then
               GetSlotType = "A1-1"
               Exit Function
          Else sCollarType = "3" Then
               GetSlotType = "A1-3"
               Exit Function
          End If
     Else sSlotType = "2" Then
          If sCollarType = "2" Then
               GetSlotType = "A2-2"
               Exit Function
          Else sCollarType = "3" Then
               GetSlotType = "A2-3"
               Exit Function
          End If
     End If
ElseIf oProfilePart.SectionType = "BP" Then
|
|
'Profile End Cut Rule
If ProfileEnd = "Bounded" And "OnSlot" Then
     If sEndCutType = "Blank or L or LS" Then
          GetEndCutType = "L or LS"
          Exit Function

          Else sEndCutType = "S or LE or LAP" Then
               GetEndCutType = "S or LE or LAP"
               Exit Function
          End If
     ElseIf ProfileEnd = "Free" Then
     |
     |
     'Profile End Scallop Rule
     If ProfileEnd = "Bounded" And "OnSlot" Then
          If sSlotType = " A1-1 OR A1-3 OR A2-2 OR A2-3" Then
               If sEndCutType = "S or LE or LAP etc" Then
                GetScallopType = "None"
                Exit Function
               Else sEndCutType = "L or LS" Then
                If sWebSize >= L_1 AND sWebSize <= L_2 Then
                   GetScallopType = "Scallop-R_1"
                   Exit Function
                ElseIf sWebSize >= L_2 AND sWebSize <= L_3 Then
                   GetScallopType = "Scallop-R_2"
                   Exit Function
                Else sWebSize >= L_3 Then
                   GetScallopType = "Scallop-R_3"
                   Exit Function
                End If
               End If
          ElseIf sSlotType = "A2 OR B2 OR S2 OR T2" Then
          |
     ElseIf ProfileEnd = "Free" Then
     |
     |
****************************************
```

Fig. 2-18 Sample Automation Rule in VB for Combination of Features

Fig. 2-19 below shows the Petri net graph created from the logic that was originally used for slot-collar, profile end cut and profile end scallop combination in the ship design.
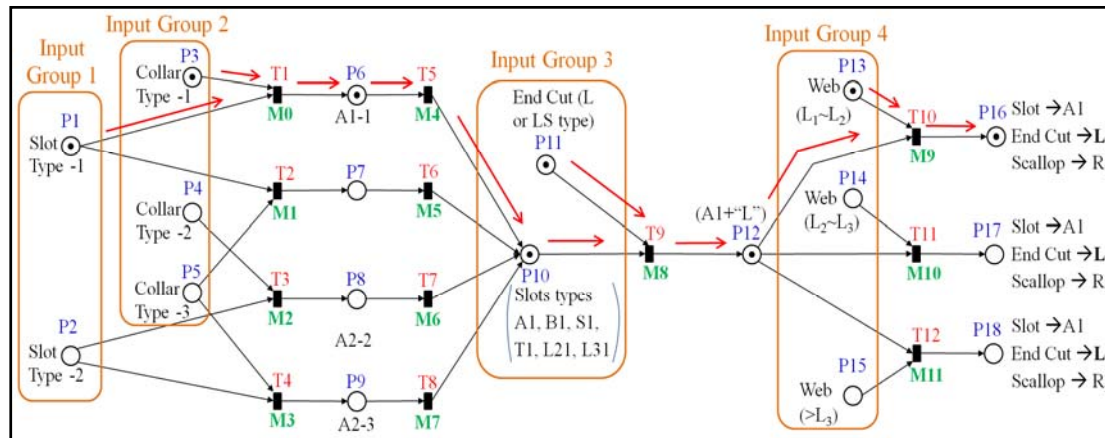
Fig. 2-19 Automation Rule Representation for Combination of Features by Petri Net Graph

Input Conditions: The places P1 and P2 are the manual input conditions for slot type. This is considered as input group 1. P3, P4 and P5 are the manual input conditions for collar types. This is considered as input group 2. A combination of input group 1 and input group 2 defines the slot-collar combination selection in Petri net. P11 is the manual input conditions for profile end cut type above the slot selection. This is considered as input group 3. Finally, P13, P14 and P15 are the manual input conditions for profile web size. This is considered as input group 4.

Output Conditions: P16, P17 and P18 are the output conditions of this graph which represents the final slot-collar combination, profile end cut type and profile end scallop applied based on the combined selections from input group 1, 2, 3 and 4 described above.

T1 to T12 are the possible transitions based on the inputs selected by the user that drives the feasible output. The Petri net graph for combination of features is represented mathematically with the incidence, firing or control vector and marking state matrices. Equation (2-16) is an incidence matrix of the graph shown in Fig. 2-19 above.

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18
T1	-1	0	-1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
T2	-1	0	0	0	-1	0	1	0	0	0	0	0	0	0	0	0	0	0
T3	0	-1	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
T4	0	-1	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0
T5	0	0	0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0
T6	0	0	0	0	0	0	-1	0	0	1	0	0	0	0	0	0	0	0
T7	0	0	0	0	0	0	0	-1	0	1	0	0	0	0	0	0	0	0
T8	0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0
T9	0	0	0	0	0	0	0	0	0	-1	-1	1	0	0	0	0	0	0
T10	0	0	0	0	0	0	0	0	0	0	0	-1	-1	0	0	1	0	0
T11	0	0	0	0	0	0	0	0	0	0	0	-1	1	-1	0	0	1	0
T12	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	-1	0	0	1

$A =$ （above matrix）　　　　(2-16)

Equation (2-17) is a Kth marking state of the graph.

$$M_k = M_{k-1} + A^T U_k \, , \, k = 1, 2, \ldots \tag{2-17}$$

Where,

　　U is the firing or control vector matrix.

　　Equation (2-18) defines the destination marking of the graph.

$$M_d = M_0 + A^T \sum_{k=1}^{d} u_k \tag{2-18}$$

CASE I: REACHABLE GRAPH

Inputs: Slot type as "1" (Place P1), collar type as "1" (Place P3), profile end cut type as "L/LS" (Place P11) and profile web size "L_1-L_2" (Place P13).

Outputs (Reachability): Fig. 2-19 shows the complete simulation steps by red arrow indication as the place and transition flow direction with final automation result when there is a token at above described inputs. As indicated by the tokens flow direction, when user set the combination like slot type 1 (Place P1) and collar type 1 (Place P3), the slot collar combination result will be A1-1 (Place P6, P10). This slot result when combined with the end cut type L or LS (Place P11), the result will be profile end cut L or LS on slot A1-1. The result again combined with the profile web size L_1 to L_2 (Place 13), the result becomes scallop-R_1 (Place P16). Thus the slot-collar A1-1 with profile end of L or LS on this slot A1-1 applies the profile end scallop of R_1. On the similar lines, based on the input conditions, the scallop-R_2 or scallop-R_3 results are

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obtained. The graph will be reachable for all of the following conditions which are exactly same as the above inputs.

1. The combinations of slot 1 (Place P1), collar 1 (Place P3), end cut L or LS (Place P11) and profile web size L_2-L_3 (Place P14), the output result will be Scallop-R_2 (Place P17).

2. The combinations of slot 1 (Place P1), collar 1 (Place P3), end cut L or LS (Place P11) and profile web size >L_3 (Place P15), the output result will be Scallop-R_3 (Place P18).

3. The combinations of slot 1 (Place P1), collar 3 (Place P5), end cut L or LS (Place P11) and profile web size L_1-L_2 (Place P13), the output result will be Scallop-R_1 (Place P16).

4. The combinations of slot 1 (Place P1), collar 3 (Place P5), end cut L or LS (Place P11) and profile web size L_2-L_3 (Place P14), the output result will be Scallop-R_2 (Place P17).

5. The combinations of slot 1 (Place P1), collar 3 (Place P5), end cut L or LS (Place P11) and profile web size > L_3 (Place P15), the output result will be Scallop-R_3 (Place P18).

6. On the similar lines, the combinations for Slot 2 (Place P2), collar 2 (Place P4) and Slot 2 (Place P2), collar 3 (Place P5), with input Place P11 and P13 to P15, the graph will be reachable to output Place P16 to P18.

CASE II: NON–REACHABLE GRAPH

Inputs: Tokens at Place P1, P4, P11 & P13 as shown in Fig. 2-20 below.
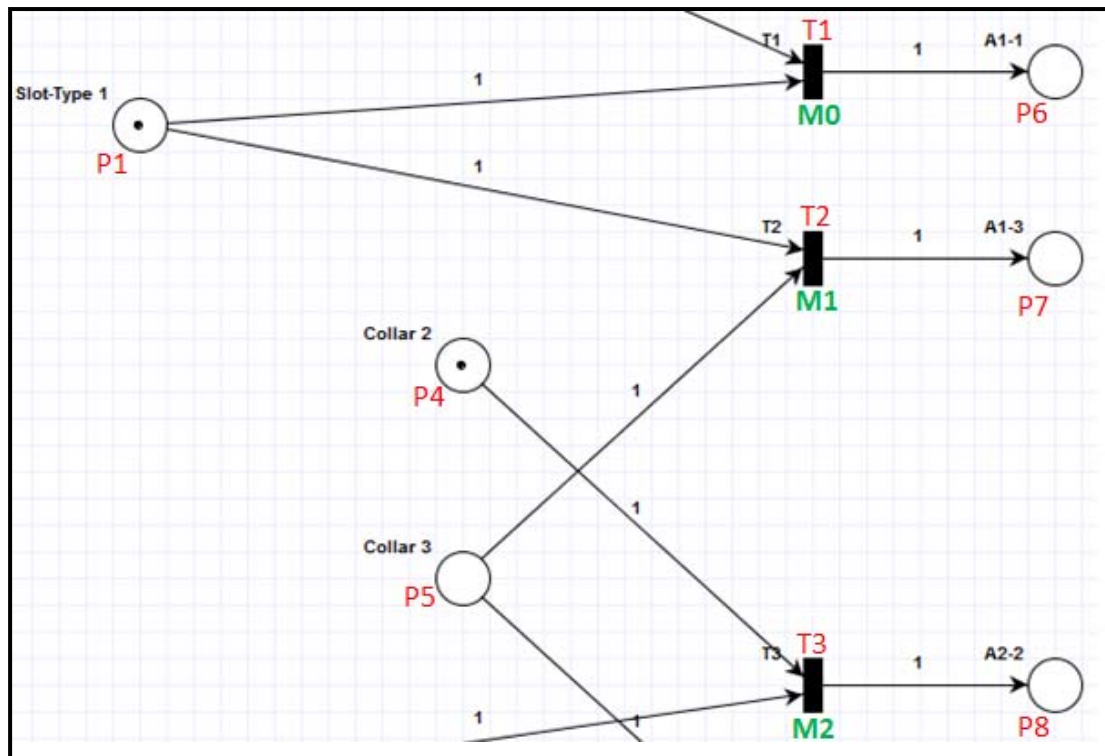
Fig. 2-20 Non-Active transition for 1-2 slot-collar combination

Outputs (Reachability): No transitions are active in this case and it cannot be fired. Meaning that the slot type 1 and collar type 2 combinations is not reachable in any case. This means that there is a problem in automation rule result and no slot-collar, profile end scallop will be applied in the design model. Similarly, the combinations of slot 2 and collar 1 (Place P2 and P3) are exactly the same conditions and hence the automation result will not be applied correctly for this combination too. This is why the original automation results in 3D model were wrong as described in "section 2.3.2".

Research has proved that the problems are exists in automation rule and need its resolution. Author has further analyzed and proposed the suitable solution as described in following section.

2.6.3 Resolution of Problems Found in Ship Design Automation Rule

This section describes the resolution of rule based automation problems based on combination of features (complex graph) analyzed using Petri net graph theory. As per the analysis, the problem in the original rule was that, the validation test cases of some of the combination of input groups used in the beginning of the net (input group 1 and 2) were missing. To resolve this problem, author introduced a new logical test condition that, for all input group utilization within the net, the number of immediate transitions of input group places should be equal to the total number of feasible combinations of all input group places. To support this logic, a mathematical theory is introduced by defining the regions in Petri net. A region in Petri net is described as the elementary net formed by the combination of input groups which leads to either a final output condition (Reachable) or an intermediate output condition which in turn combines with a different input group conditions. Region 1, 2 and 3 are as shown in Fig. 2-21 below.

Fig. 2-21 Region Definitions in Petri Net Graph
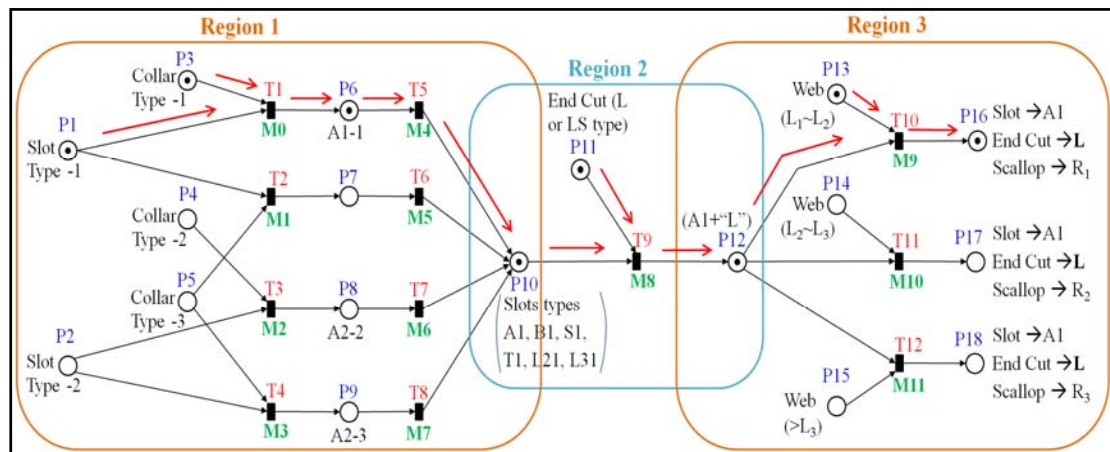
Equations (2-19) (2-20) and (2-21) below defines the total number of immediate transitions in Region 1, Region 2 and Region 3.

IG1 = Input Group 1 = {P1, P2}

IG1P = Total number of places in IG1 = 2

IG2 = Input Group 2 = {P3, P4, P5}

IG2P = Total number of places in IG2 = 3

R1 = Region 1 = {IG1, IG2}

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RT1n = Total number of immediate transitions in Region 1

$$RT1n = IG1P \times IG2P = 2 \times 3 = 6 \qquad (2\text{-}19)$$

As per equation (2-19), the number of immediate transitions calculated in Region 1 should be 6. Hence the Petri net graph is updated as shown in Fig. 2-22 below.
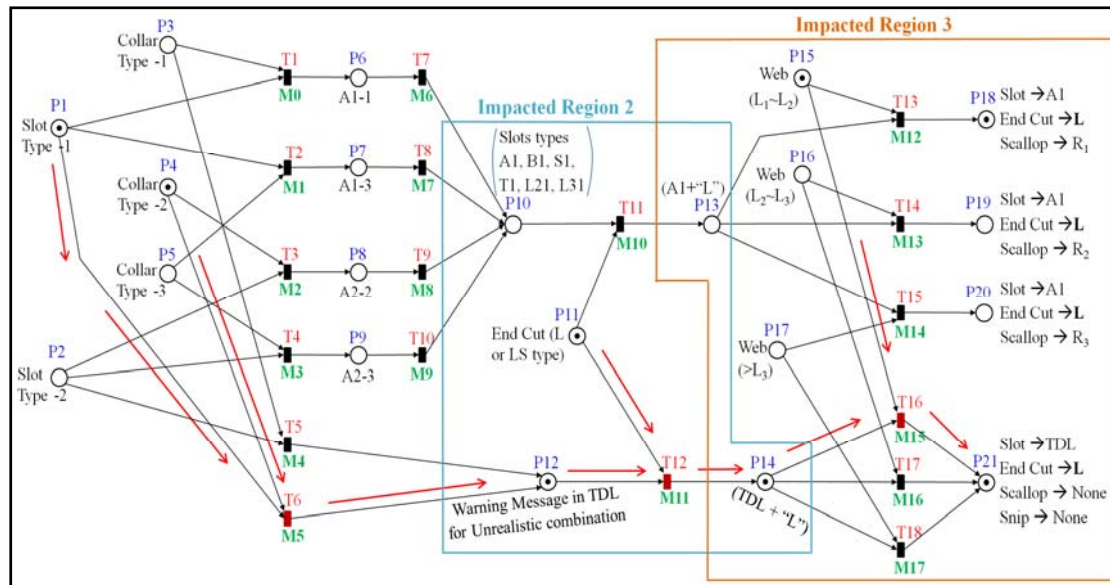
Fig. 2-22 Impacted Region in Petri Net Automation Rule Graph

As per the Petri net theory, each transition should result into an output place, the newly introduced transitions T5 and T6 in Fig. 2-22 of a proposed Petri net graph are resulting into a new place P12 as an output condition for an unexpected slot-collar combination input. This output condition is used to display the warning message when unrealistic design combination is selected by the user. Due to this change, the intermediate inputs for region 2 are impacted compared to the original net as shown in Fig. 2-22.

IG12 = Input Group from Region 1 to 2 = {P10, P12}

IG12P = Total number of places in IG12 = 2

IG3 = Input Group 3 as per Fig. 2-22 = {P11}

IG3P = Total number of places in IG3 = 1

R2 = Region 2 = {IG3}

RT2n = Total number of immediate transitions in Region 2

$$RT2n = IG12P \times IG3P = 2 \times 1 = 2 \qquad (2\text{-}20)$$

As per equation (2-20), the number of immediate transitions calculated in Region 2 should be 2. Petri net graph is updated accordingly as shown in Fig. 2-22 above. The new transition T12 is introduced as a new input condition which drives place P14 as an output condition. P14 continues the earlier warning message combined with the change in end cut type to "L" or "LS" type. Same as in Region 2, the intermediate inputs for region 3 are also impacted compared to the original net.

IG23 = Input Group from Region 2 to 3 = {P13, P14}

IG23P = Total number of places in IG23 = 2

IG4 = Input Group 4 as per Fig. 2-22 = {P15, P16, P17}

IG4P = Total number of places in IG4 = 3

R3 = Region 3 = {IG4}

RT3n = Total number of immediate transitions in Region 3

$$RT3n = IG23P \times IG4P = 2 \times 3 = 6 \qquad (2\text{-}21)$$

As per equation (2-21), the number of immediate transitions calculated in Region 3 should be 6. Petri net graph is updated accordingly as shown in Fig. 2-22 above. The new transitions T16, T17 and T18 are introduced which results into a new place P21 as an output condition. P21 is defined as no scallop and no snip features in the model for an unexpected slot-collar design conditions. Finally all input groups are utilized and the graph is updated as per Petri net theory. The incidence matrix of the updated graph is defined as Equation (2-22) below.

$$A =$$

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21
T1	-1	0	-1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T2	-1	0	0	0	-1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T3	0	-1	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
T4	0	-1	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
T5	0	-1	-1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
T6	-1	0	0	-1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
T7	0	0	0	0	0	-1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
T8	0	0	0	0	0	0	-1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
T9	0	0	0	0	0	0	0	-1	0	1	0	0	0	0	0	0	0	0	0	0	0
T10	0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0	0	0
T11	0	0	0	0	0	0	0	0	0	-1	-1	0	1	0	0	0	0	0	0	0	0
T12	0	0	0	0	0	0	0	0	0	0	-1	-1	0	1	0	0	0	0	0	0	0
T13	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	-1	0	0	1	0	0	0
T14	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	-1	0	0	1	0	0
T15	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	-1	0	0	1	0
T16	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	0	0	0	0	0	1
T17	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	-1	0	0	0	0	1
T18	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	-1	0	0	0	1

$$(2\text{-}22)$$

Thus, in all of the regions of a Petri net graph, the numbers of immediate transitions of input group places are made equal to the total number of feasible combinations of all input group places. With this new definition, within the net, all of the input groups are fully utilized for the simulation. Finally, a simulation test is performed on the newly updated graph as described below to verify the reachability of the graph for automation failure observed in CASE II of section 2.6.1 and 2.6.2 described above.

2.6.4 Verification of the Resolution of Problems Found in Ship Design Automation Rule

Since there is no problem for the reachable graph input conditions as per the analysis in CASE I of section 2.6.1 and 2.6.2 described above, no changes are made for those test conditions. However, to resolve the non-reachable test cases as described in CASE II above, the newly updated Petri net graph with extra logics is simulated again for verification of resolution.

Inputs: As shown in Fig. 2-22, above, the user manual input condition is described by adding a token at place P1 (Slot type-1), Place P4 (Collar type-2), place P11 (end cut type as "L" or "LS") and place P15 (the profile web size as $L_1 \sim L_2$), the newly added transitions T6 will become active now and it can be fired.

Outputs: The result will be place P12, a warning message in "to do list" (TDL) which shows that the selection is unrealistic design combination. The place P12 when

combined with place P11, the result will be place P14 indicates the profile end cut type as "L" or "LS" combined with the warning message in TDL. Finally the place P14 when combined with the place P15, P16 or P17, the result will become place P21. Result indicates that the scallop or snip shape will not be applied on the profile end on the top of the slot and a warning message for unrealistic design condition will be displayed in TDL. Thus the slot-collar A1-2 with profile end of L or LS on this slot A1-2 will result into no scallop and no snip on the profile. Similar result will be obtained when the input conditions are set to Slot 2 (Place P2) and collar 1 (Place P3).

Thus all input conditions became reachable now which shows that the non–reachable graph became fully reachable and proves the resolution of the automation failure observed above. Resolving the automation rule problem by Petri net graph, the identified problem was analyzed in VB rule as shown by the highlighted section in below Fig. 2-23.

```
********************************************
'Slot Collar Combination Rule
If oProfilePart.SectionType = "IA" Then
      If sSlotType = "1" Then
            If sCollarType = "1" Then
                  GetSlotType = "A1-1"
                  Exit Function
            Else sCollarType = "3" Then
                  GetSlotType = "A1-3"
                  Exit Function
            End If
      Else sSlotType = "2" Then
            If sCollarType = "2" Then
                  GetSlotType = "A2-2"
                  Exit Function
            Else sCollarType = "3" Then
                  GetSlotType = "A2-3"
                  Exit Function
            End If
      End If
ElseIf oProfilePart.SectionType = "BP" Then
|
|
'Profile End Cut Rule
If ProfileEnd = "Bounded" And "OnSlot" Then
      If sEndCutType = "Blank or L or LS" Then
            GetEndCutType = "L or LS"
            Exit Function

      Else sEndCutType = "S or LE or LAP" Then
            GetEndCutType = "S or LE or LAP"
            Exit Function
      End If
ElseIf ProfileEnd = "Free" Then
|
|
'Profile End Scallop Rule
If ProfileEnd = "Bounded" And "OnSlot" Then
      If sSlotType = " A1-1 OR A1-3 OR A2-2 OR A2-3" Then
            If sEndCutType = "S or LE or LAP etc" Then
                  GetScallopType = "None"
                  Exit Function
            Else sEndCutType = "L or LS" Then
              If sWebSize >= L₁ AND sWebSize <= L₂ Then
                  GetScallopType = "Scallop-R₁"
                  Exit Function
              ElseIf sWebSize >= L₂ AND sWebSize <= L₃ Then
                  GetScallopType = "Scallop-R₂"
                  Exit Function
              Else sWebSize >= L₃ Then
                  GetScallopType = "Scallop-R₃"
                  Exit Function
              End If
            End If
      ElseIf sSlotType = "A2 OR B2 OR S2 OR T2" Then
         |
ElseIf ProfileEnd = "Free" Then
|
|
********************************************
```

Fig. 2-23 Identification of Automation Failure Logic in VB Rule

Figure shows the missing logical conditions for combination of slot type 1 and collar type 2, similarly slot type 2 and collar type 1. Also it was observed that the end

cut type was applied same as it was defined by the user manually but was not changed to the design standard applicable type as per design requirements described in Table 2-2 above. The new logical conditions are then added in the visual basic program[16] as shown by the highlighted section in below Fig. 2-24.

```
*************************************          |
'Slot Collar Combination Rule                 |
If oProfilePart.SectionType = "IA" Then       'Profile End Scallop Rule
    If sSlotType = "1" Then                   If ProfileEnd = "Bounded" And "OnSlot" Then
        If sCollarType = "1" Then                 If sSlotType = "A1-1 OR A1-3 OR A2-2 OR A2-3" Then
            GetSlotType = "A1-1"                      If sEndCutType = "S or LE or LAP etc" Then
            Exit Function                                 GetScallopType = "None"
        ElseIf sCollarType = "2" Then                     Exit Function
            GetSlotType = "TDL"                       Else sEndCutType = "L or LS" Then
            Exit Function                                 If sWebSize >= L_1 AND sWebSize <= L_2 Then
        Else sCollarType = "3" Then                           GetScallopType = "Scallop-R_1"
            GetSlotType = "A1-3"                              Exit Function
            Exit Function                                 ElseIf sWebSize >= L_2 AND sWebSize <= L_3 Then
        End If                                                GetScallopType = "Scallop-R_2"
    Else sSlotType = "2" Then                                 Exit Function
        If sCollarType = "1" Then                         Else sWebSize >= L_3 Then
            GetSlotType = "TDL"                               GetScallopType = "Scallop-R_3"
            Exit Function                                     Exit Function
        ElseIf sCollarType = "2" Then                     End If
            GetSlotType = "A2-2"                       End If
            Exit Function                             If sSlotType = "TDL" Then
        Else sCollarType = "3" Then                       If sEndCutType = "ANY" Then
            GetSlotType = "A2-3"                              If sWebSize = "ANY" Then
            Exit Function                                         GetScallopType = "No Scallop/No Snipe"
        End If                                                    Exit Function
    End If                                                    End If
ElseIf oProfilePart.SectionType = "BP" Then               End If
|                                                     ElseIf sSlotType = "A2 OR B2 OR S2 OR T2" Then
|                                                         |
'Profile End Cut Rule                                     |
If ProfileEnd = "Bounded" And "OnSlot" Then           ElseIf ProfileEnd = "Free" Then
    If sEndCutType = "Blank or L or LS" Then              |
        GetEndCutType = "L or LS"                         |
        Exit Function                                 *************************************
    Else sEndCutType = "S or LE or LAP" Then
        GetEndCutType = "L or LS"
        Exit Function
    End If
ElseIf ProfileEnd = "Free" Then
```

Fig. 2-24 Resolution of the Automation Failure Logic in VB Rule

Automation rules used in 3D CAD systems are generally the additional customization of the rules on the top of the originally available CAD systems in the market. These rules can be customized in visual basic or any other suitable platform of the CAD system. Customized rules are built in a "dll" and are installed in the system where the CAD system is used. There is a relationship maintained between the "dll" and the CAD system so that the relevant logical action can be performed.

Author applied this analysis result and resolution technique by building a "dll" with this new automation rule in virtual ship CAD model for the same failure design condition and verified that the results are now acceptable to the shipyards. User

manually defined the unrealistic slot-collar design combination (slot type-1 and collar type-2) in the 3D model as shown in Fig. 2-25 below for the test verification.
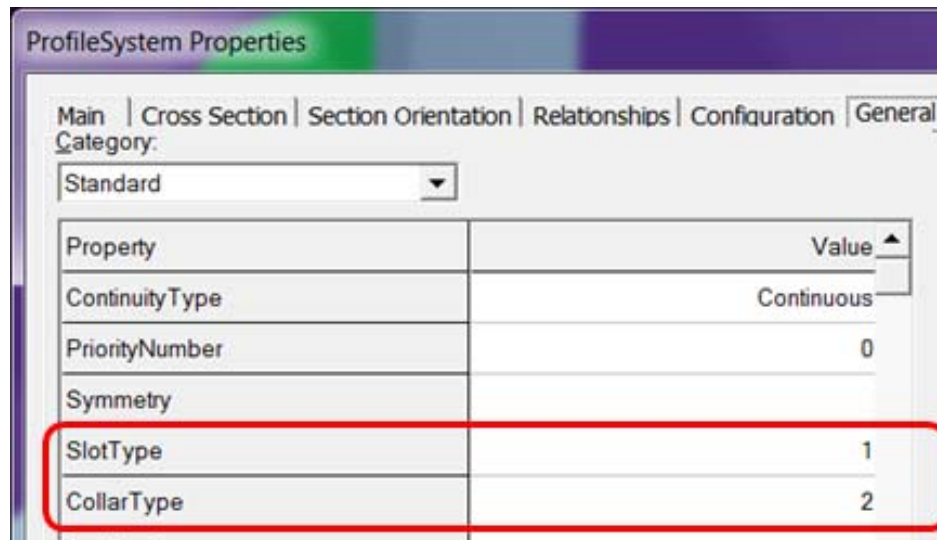

Fig. 2-25 Manual definition of Unrealistic Design Combination

After applying the detailed design automation rule on this combination in virtual ship model, the unrealistic slot-collar design combination was not applied and a warning message for the user is displayed in "to do list". This time the automation results were as expected. Fig. 2-26 below shows the "to do list" warning message to designer when unexpected slot and collar combinations are defined in the model.
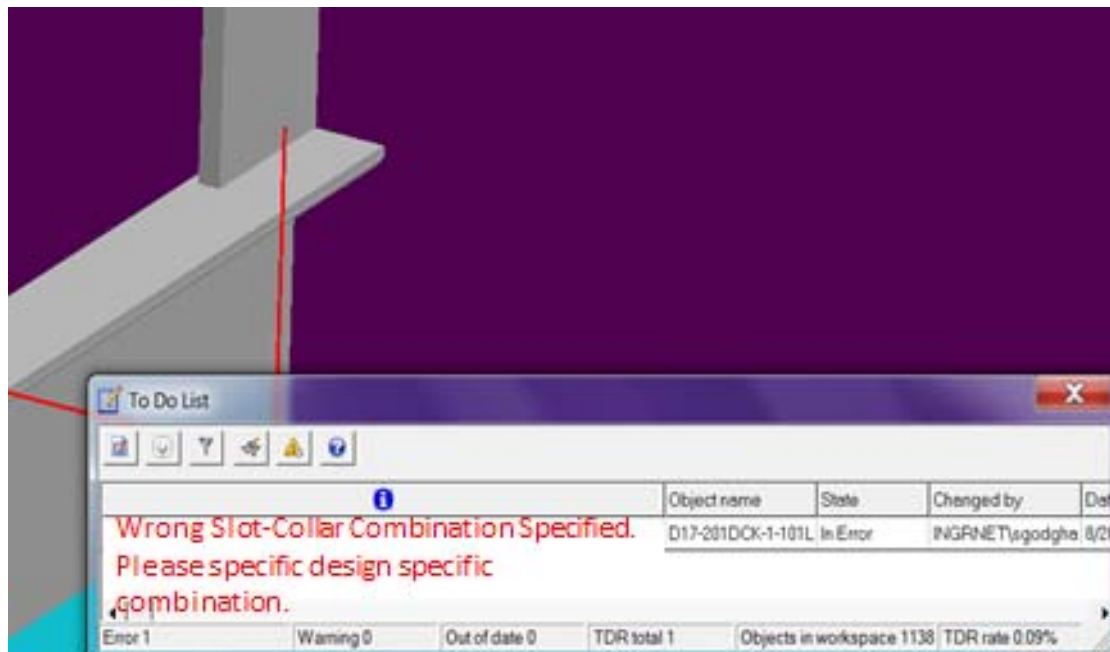

Fig. 2-26 Expected 3D result after Resolution of Problem

Similarly, Fig. 2-27 below shows the correct scallop on profile end even though the user defines the profile end cut as type "S". As per new logic, the user defined end cut type "S" is ignored if the profile is on the top of the slot. It is automatically changed to "L" or "LS" type and a scallop is applied on the profile end.
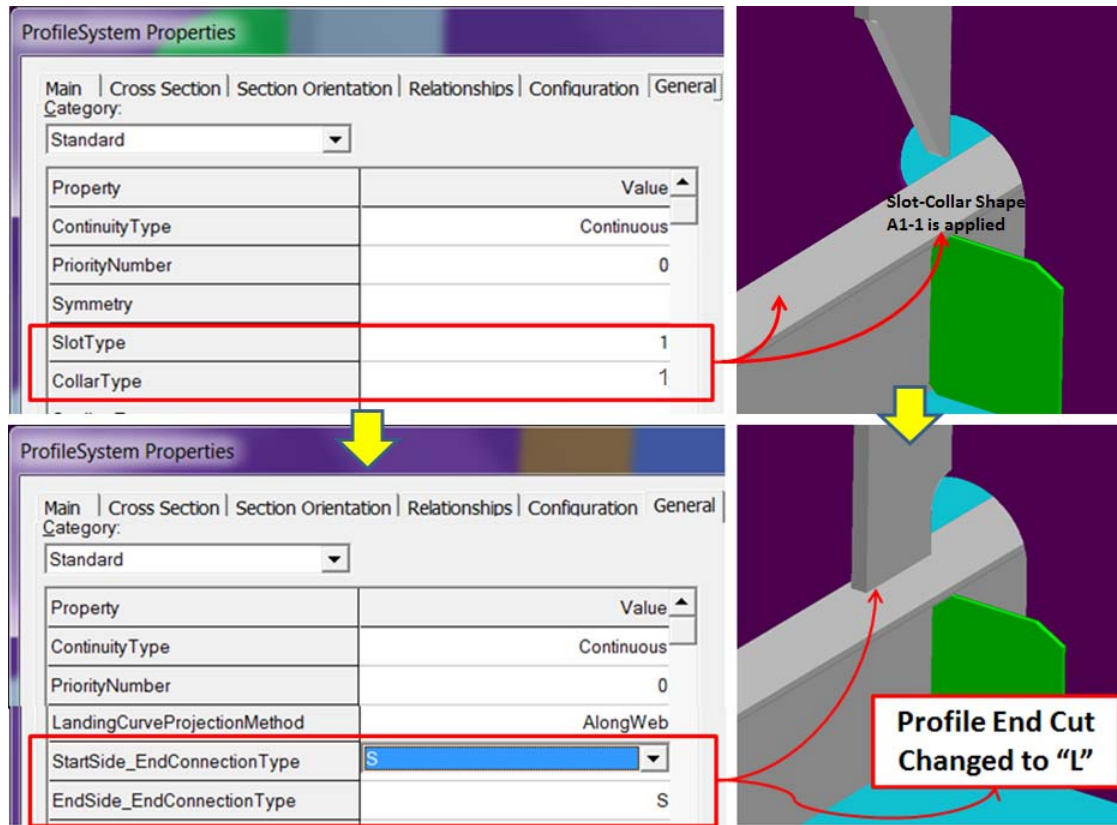

Fig. 2-27 End Cut Type Automatically Changed to "L" from "S"

2.7 Summary

This chapter has briefed about the existing 3D CAD automation rules used at the shipyard. The automation rules are used for end-to-end ship design process. However, author's analysis proved that there are some challenges in implementing the rule based design automation which directly impacts the design accuracy and design time. Author then provided an engineering theory which is best suitable for the implementation of design automation techniques. The theory is called as the Petri net graph theory which provides the visual and mathematical analysis on the Petri net simulation model. The theory helps to find the contradictions in design automation rules and also helps to identify any missing design conditions. The research theory concept is proven by demonstrating the practical examples of the shipyard and finally an error free design logic was proposed by the author. The error free design logic was implemented in the 3D CAD application and a successful test was made which proved that the Petri net graph theory is very much suitable to resolve the automation problems.

CHAPTER 3

AUTOMATION FOR
SHIP DESIGN VERIFICAION

GODGHATE SUSHANT   **(Doctoral Thesis)**   **JANUARY 2014**

3 AUTOMATION FOR SHIP DESIGN VERIFICAION

3.1 Introduction

Design quality is always a major challenge in ship manufacturing industry. However, even today, design knowledge supported by experiences and know-how of designers plays an important role in the improvements of design quality. Some shipyards record their design know-how as the documents written in natural language (human language) called design criteria documents. Ship design is carried out based on the classification society rule, designer's know-how and design criteria documents to verify their design quality. However, generally it is difficult to fully verify the completeness and consistency of ship hull design using such a manual process. There is a possibility of human error like missing some design verifications by oversight etc.

Examples below describe various mandatory design quality checks which were performed manually before implementing automation rules in the shipyard industry. However now, using the automation techniques described in section 2 above shipyard could achieve automatic ship design verifications at all design stages as described below.

Example 1: Automation for Bracket Shift Verification

The automation rule for Bracket Shift Verification allows designer to check the bracket shift when the brackets supports are profile or plate edge or whatever is the bracket shift design condition requirements. Basically, the automation rule defines the shift automatically at the time of bracket placements, however, as the design progresses, some design changes are expected. There is no mechanism that the bracket shift can be re-evaluated after the design change of its connected objects. The mechanism is useful only at the time of placements of brackets. Hence the check manufacturability rule is used to validate the bracket shift and automatically repair it if the discrepancies are found in the design model before it goes for the production
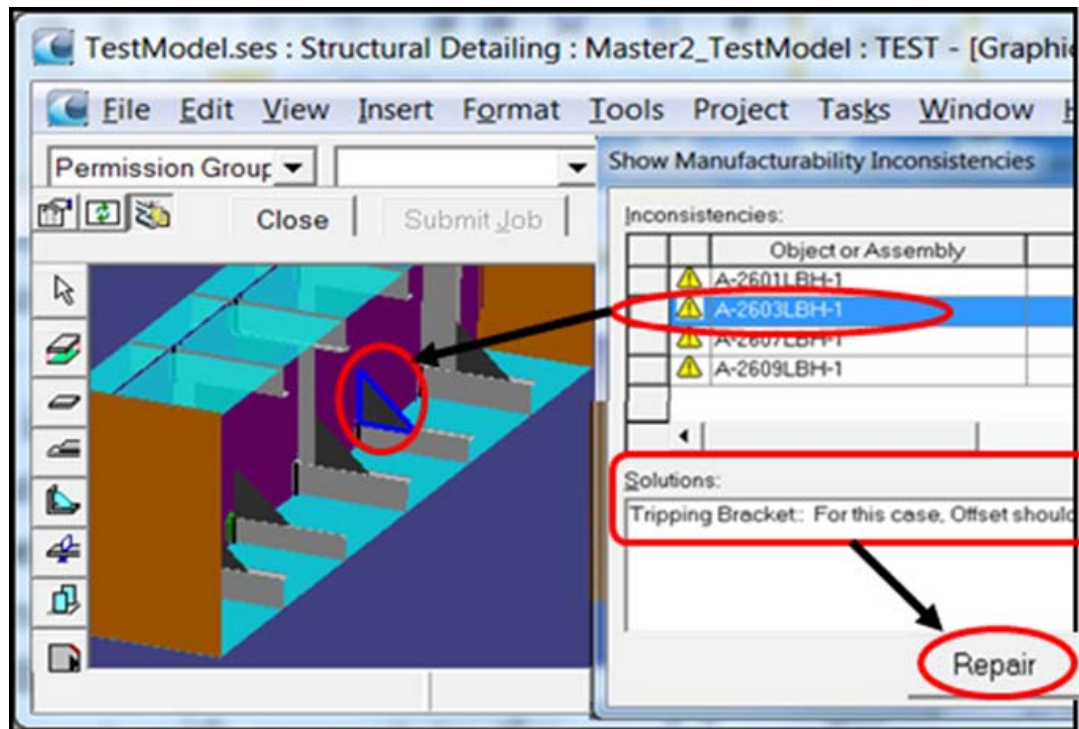
Fig. 3-1 Bracket Shift verification Rule

Fig. 3-1 shows the 3D CAD design model having brackets with shift applied for various design conditions. A check manufacturability automation rule is run on this model to verify if the shift applied to the brackets within the model is as per the design. The rule identifies some brackets having wrong shift applied and the bracket objects are listed in "Show Manufacturability Inconsistencies" graphical window as seen in the right hand side of the figure. The rule also provides the solution for these inconsistencies as described in the solutions section at the bottom of the graphical window. The problem of bracket shift can be automatically resolved by using the 'Repair" button which corrects the bracket shift as per the design condition using an automation rule for "Bracket Shift Verification".

Example 2: Verification of Distance between Edge Feature and Corner Feature

There are design regulations of individual shipyards and also from the classification society that the two features should not be close to certain predefined distance. However in a design model, while placing the manual features, there is no mechanism to control this condition and user is allowed to create the features wherever they need it. At the time of design decisions by the experts, the feature locations are decided based on theoretical imaginations. The distances can be verified

only when the design model is ready. To overcome this problem, as seen in Fig. 3-2 below, with the use of check manufacturability automation rule, the designer can now verify the distance between edge feature and corner feature.
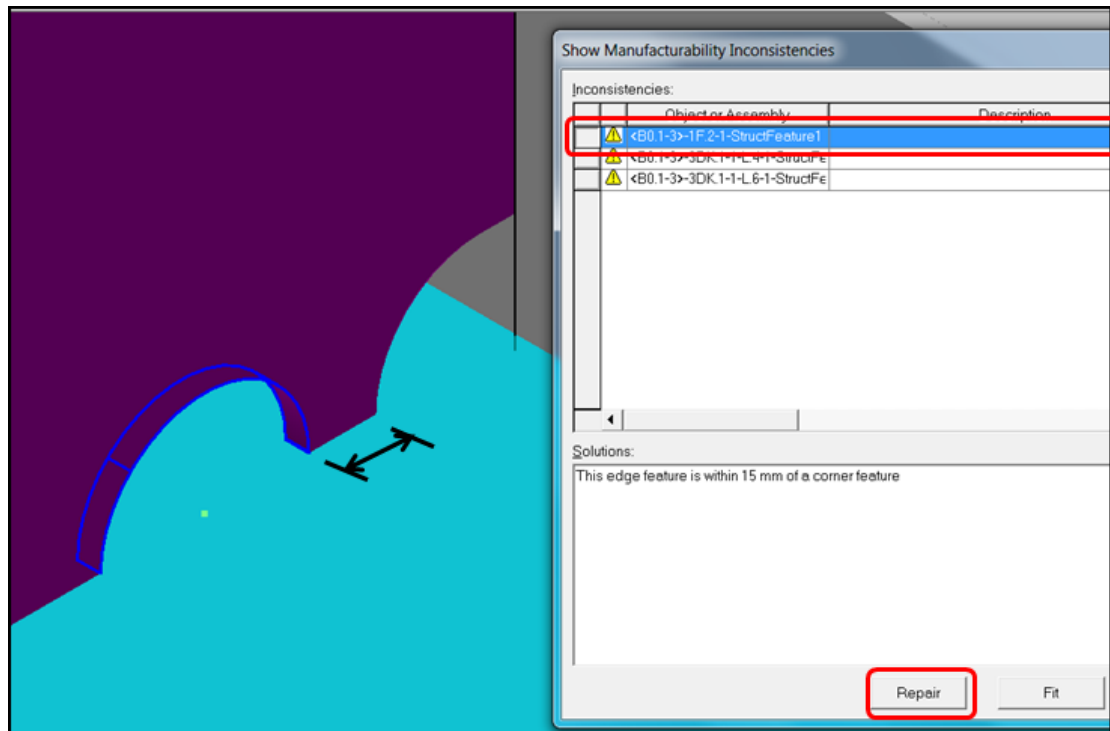

Fig. 3-2 Verification Rule for Distance between Edge Feature and Corner Feature

Fig. 3-2 shows the 3D CAD design model having edge feature and corner features on a bulkhead and are very close to each other. A check manufacturability automation rule is run on this model to verify if the minimum distance between edge feature and corner feature is maintained as per the shipyard and classification society rules. The rule identifies the features that are inconsistent and are listed in "Show Manufacturability Inconsistencies" graphical window as seen in the right hand side of the figure. The rule also provides the solution for these inconsistencies as described in the solutions section at the bottom of the graphical window. The problem of minimum distance between edge feature and corner feature is then automatically resolved by using the 'Repair' button. The repair rule for "Distance between Edge Feature and Corner Feature" corrects the distance between edge feature and corner feature to be maintained minimum as per the design regulation before the objects goes for production.
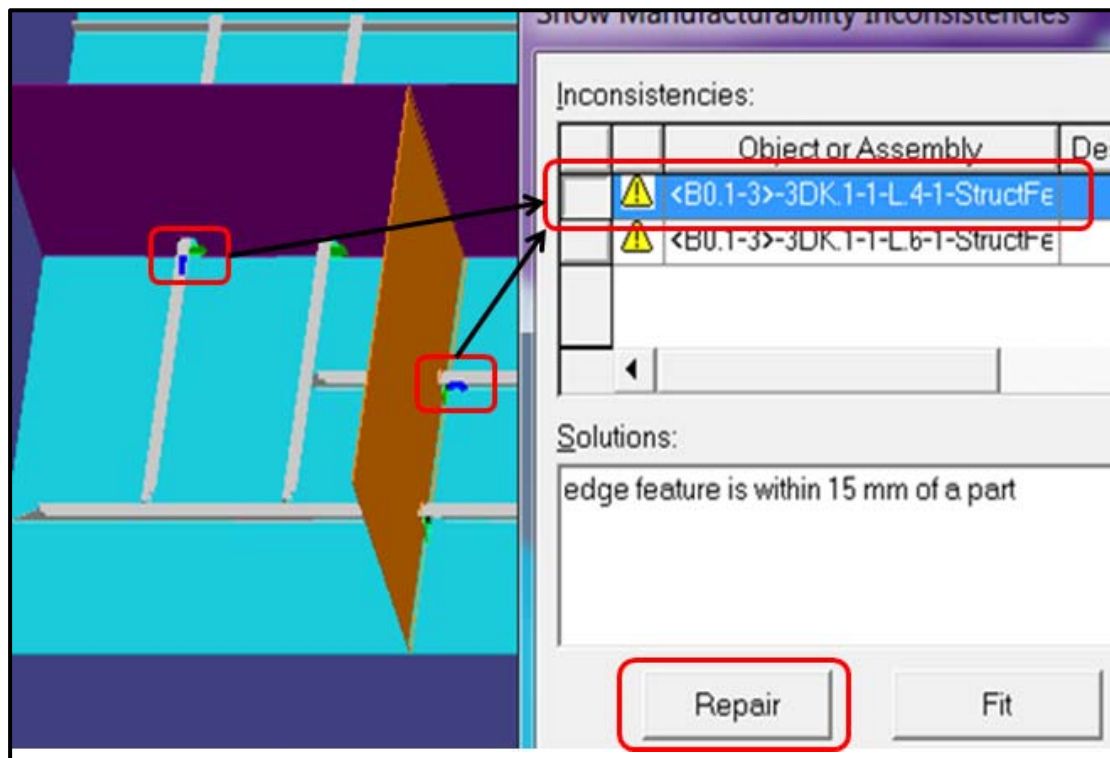
Example 3: Verification of Distance between Edge Feature and Collar Plate

Fig. 3-3 Verification Rule for Distance between Edge Feature and Collar Plate

This case is also very similar to the case above except that the distances are validated between the feature and the collar plates as shown in Fig. 3-3 above.

Example 4: Automation for Verification of Bracket Nose Adjustment for bevel

There is also a case that the standard bracket nose of 15 mm gets reduced due to the bevel cut for welding applied on bracket edge. However it is expected that the Nose should be maintained after the bevel cut. Since the bracket is created at basic design stage and welding information's are applied in detailed design phase, there is no mechanism that the basic design information updated automatically based on the detailed design result. Hence the automation rule for verification of bracket nose adjustment for bevel helps designer to find the brackets that need adjustments and automatically repair the nose on the bevel edge.
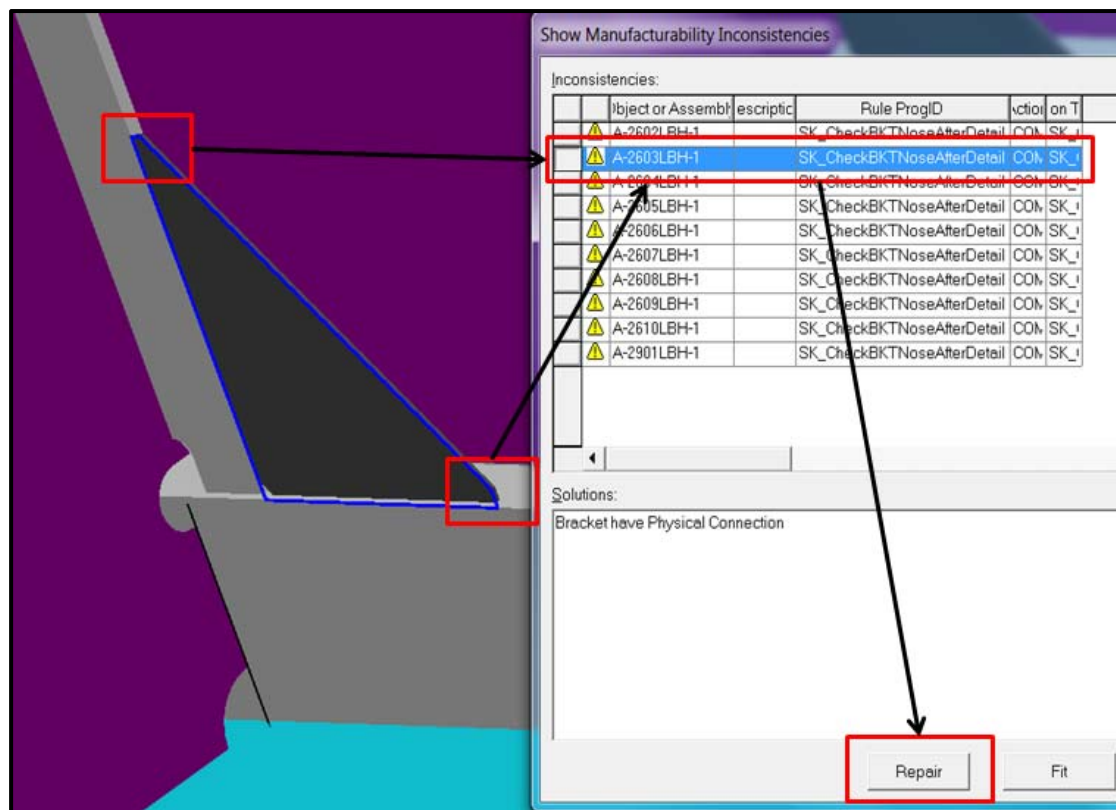
Fig. 3-4 End Cut Type Automatically Changed to "L" from "S".

Fig. 3-4 shows the 3D CAD design model having brackets with 15mm "Nose" and the based edge of the bracket to be welded to another object. In this test case, a check manufacturability automation rule is run to identify these inconsistent brackets. The rule finds the brackets that are inconsistent and are listed in "Show Manufacturability Inconsistencies" graphical window as seen in the right hand side of the figure. The rule also provides the solution for these inconsistencies as described in the solutions section at the bottom of the graphical window. The minimum 15mm "Nose" for the brackets is then automatically corrected by using the 'Repair" function of "Bracket Nose Adjustment for bevel" automation rule before it goes for production.

Example 5: Automation for Verification of Weight Lifting Capacity

This check manufacturability rule checks to see if the assembly weight is within the limits for assigned work center to the assembly. The work center is the physical location where the ship objects are assembled together. If the assembly weight exceeds the work center capacity, it marks the assembly in error and allows designer to update the assembly capacity.

On the similar lines, ship manufacturers also assure the safety of ship inspectors and crew members as per the regulations defined by the classification society. A mechanism to verify the ship design for classification society rule is also an equally important for the ship manufacturers. This section describes the ship design methodology using software system by applying classification society rule and systemized design knowledge based on past experiences. Various mandatory design verification rules are described using a specification description language in declarative manner, and then are translated into an executable program written in Java.

Author introduces one of the tools called "Access Path Verification Tool". In this tool, Classification society design rules and shipyard regulations are verified in 3D Data. Design which needs adjustments as per class society and shipyards regulations are highlighted in the 3D-viewer. Design quality is then can be improved back in the 3D CAD application by designer. Also, the commonly used classification society PrimeShip CAD XML in shipbuilding industry today created from 3D CAD data is used as the input to this newly developed system. The effects of this tool were confirmed by simulating the realistic access path in ballast tank. This achievement will help the shipbuilding industry to improve the access path design quality. Using this tool, the designers can quickly verify the classification society rules and designers know-how. Additionally, shipyards will achieve the design verification time reduction compared to existing manual process.

Ship design knowledge representation[17] and a systemization research on semantic web and workflow[18] for ship basic design was carried out by H. Yamato and his team. The purpose of this research is to automate the existing manual process of ballast tank access path verification to maintain the compliance with ship design rules and regulations. Hence it is necessary to

1. Analyze and systemize design knowledge.

2. Describe design knowledge using a formally defined description language.

3. Utilize the description as a design support system to verify design quality.

This research achievement will help to increase the ship design quality and skill growth of designers. This tool performs the access path design (for ship inspection) verifications in virtually designed ship. Ship designers can then improve the access

path design quality in the virtual model and repeat the same design verification cycle unless the design quality is verified successfully.

3.2 Concept and Method

3.2.1 Concept

Author selected an example of design criteria for access path of a tanker. This access path is considered as the safety for the crew members and ship inspectors while passing through the manholes within the access path. An interference check with other structural objects within the access path space volume is performed to verify if the path is clear for the access. The access path is defined based on the classification society rule, designers know-how and design criteria documents. Following concepts are used to finalize the systemization of ship hull design knowledge.
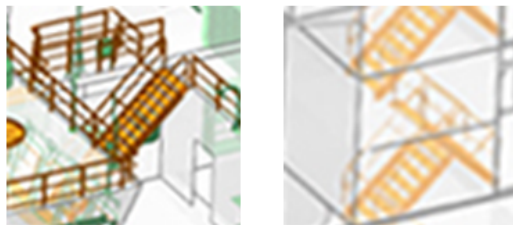

Design Standard (Hull Part)

Title.	Access path Usability			
Type.	Common		Date.	2002/06/10

Access path is designed as shown in image. It should be designed by considering the pedestrian's safety.

Ref. Problem occurred in construction ship. It corresponds by the request from assembly section in Yard.

Fig. 3-5 Design Criteria Document

To develop this "Access Path Verification Tool", it is important that the classification society rule and shipyard regulations for access path are gathered collectively. Rule refers to classification society rule here and shipyards regulation refers to the designers know-how and design criteria documents based on past experiences. Sample design criteria document is as shown in Fig. 3-5. This research was started by interviewing the skilled designers and verifying the guidelines on access path of existing design criteria documents. List of the access path design verification items are documented as described in section "3.4 Access Path Design

Verification Items" below which are used to systemize the skilled designer know-how into a design verification tool.

Based on the access path design verification item list created in knowledge gathering, the rules for access path verification based on classification society rule and shipyard regulations are clarified for the knowledge description. For the classification society rule, the logic as defined in the class rule is implemented as it is, however in some cases when a shipyard wanted to apply some strict conditions, a stringent rule is applied in the verification tool logic.

Designers experience and documents written in natural language are inappropriate for automated information processing because there may be some human errors and documents are often incomplete and inconsistent. Though formal description language is essential for utilizing design knowledge in CAD system, usual programming languages such as Java are not appropriate for this purpose. This is because it is necessary to convert structure and semantics of design knowledge into control flows and data structure. The description of design knowledge is conceptually possible in any conventional programming language. Nevertheless, if design knowledge is directly represented using a procedural language such as Java, it is quite difficult not only to describe design knowledge, but also to audit and maintain it. This is because the knowledge of an application domain is often large-scale and complicated, and each application domain has its own specific structures and semantics of knowledge. In particular, the audit and maintenance of written knowledge is a major issue in an information system involving expert knowledge, because such a system cannot easily be changed and the transfer of expert knowledge to succeeding generations is difficult. Therefore, knowledge representation methodology becomes very important to enable domain experts themselves to describe, audit, and maintain their knowledge included in an information system.

In this research, software specification description language DML is introduced for the description of design knowledge of ship hull. The language allows declarative description of structural and spatial concepts used in design knowledge and relationships between them.

3.2.2 Methodology

Following methodologies are adopted to develop this newly invented "Access Path Verification Tool"

3.2.2.1 3D CAD system

While adopting a methodology, lots of factors need to be considered e.g. the tools that are majorly used in the industry, impact of the change in design process, training of user etc. The tools that are in use cannot be replaced easily and it needs very huge efforts. Hence the criterion is to utilize the technology currently in place. Almost all shipyards use 3D CAD application as their design tool nowadays. And it is the only the tool which consists of complete ship data. Applying the design check on this 3D data will be convenient for the ship designers and manufacturers. Author used the Intergraph's Smart Marine 3D application to simulate this research concept.

3.2.2.2 3D viewer for virtual verification

To easily identify the access path design improvement areas, author developed a virtual verification tool. This helps the beginners, any designer though he/she is not an expertise, to quickly know the improvement area which does not satisfy rules and regulations. Since, the design verification will be applied on 3D CAD data; it is convenient for ship designers and manufacturers to use the 3D viewer of same 3D CAD application they are using. Most of the 3D CAD application vendors are already providing the 3D viewer. Author have used DXF viewer application in this research since it was easy to use in multiple CAD viewers.

3.2.2.3 XML scheme as a mediator

Since the viewer and design applications are finalized, it is now time to verify if the viewer can read ship design data as it is. Yes, it is possible in case of a similar 3D CAD application, but the "Access Path Verification Tool" is customized in CAD independent programming language. Hence it is a key to decide the mediator format. Due to the dependency on classification society access path verification rule, it is efficient that the classification society format is used as a mediator. A neutral XML-based schema[19] as shown in Fig. 3-6 below, available from CAD application, is utilized for the exchange of the early design information. Figure shows the standard neutral xml file created from the 3D CAD model. The xml has all necessary information e.g. plate thickness, material, contour information etc of the ship objects.

Fig. 3-6 3D CAD Application XML Data Format

        Since the global Ship manufacturers must use classification society access path rule, classification society XML scheme as shown in Fig. 3-7 below has been developed and used as the mediator between 3D CAD data and a newly invented "Access Path Verification Tool". By that, this supportive tool can be widely used by the global shipbuilding industries. This also helps to use the tool by any shipyards since the different design tools supports the classification society rule checking format. PrimeShip CAD XML Scheme of Nippon Kaiji Kyokai classification society is used in this research.
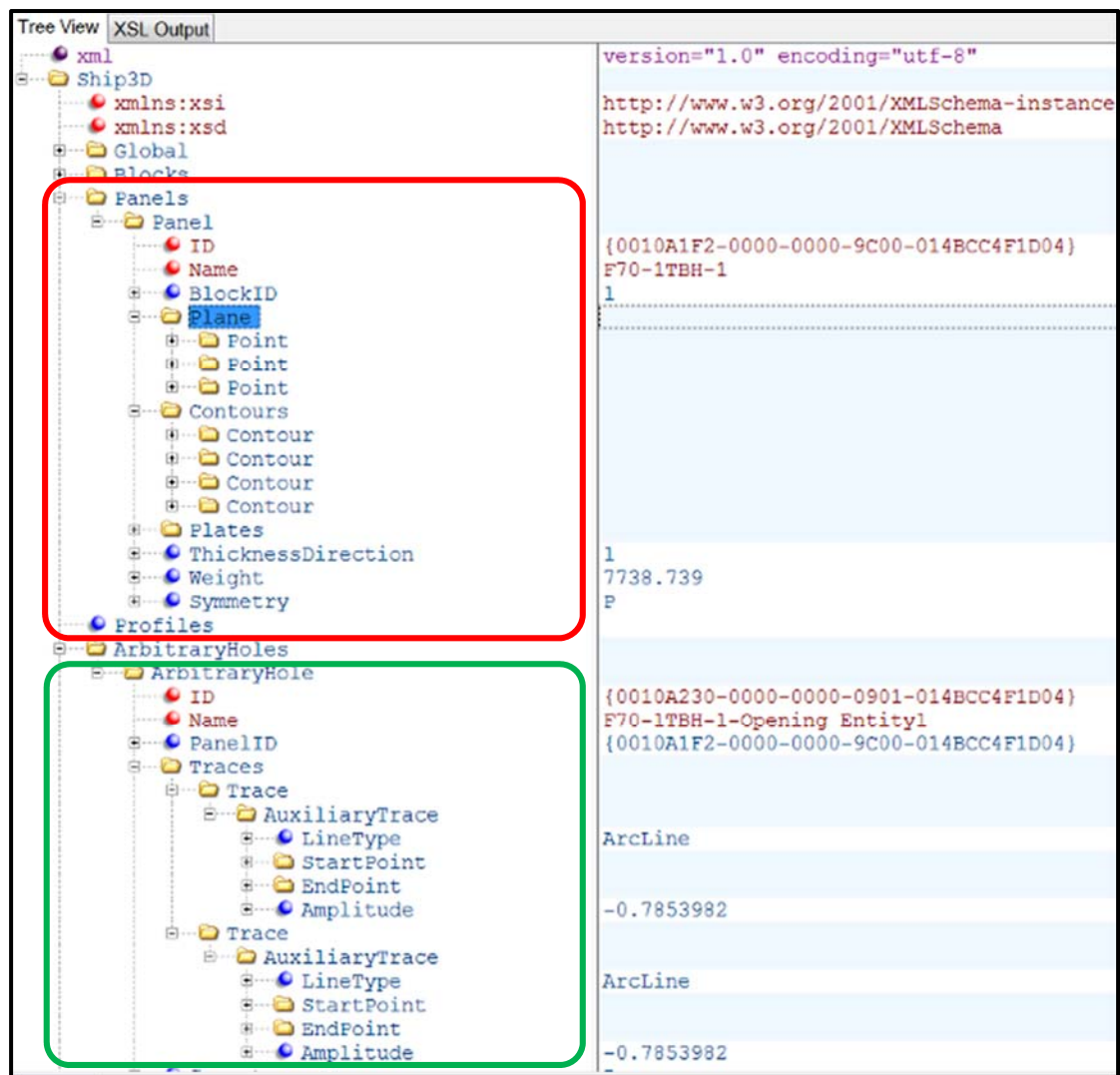
Fig. 3-7 Class Society XML Data Format

Figure shows the PrimeShip CAD XML data format that can be used in the "Access Path Verification Tool". As seen from the figure, the data are reflected differently in classification societies PrimeShip CAD XML and the original 3D CAD xml e.g. the plate systems information of 3D CAD xml is represented as the panel information in PrimeShip CAD XML. Similarly the opening in 3D CAD xml is represented as the "ArbitraryHoles – Traces" in PrimeShip CAD XML.

Additionally, it is required to know the access path in verification tool to perform the analysis of access path verification items. Fig. 3-8 below shows the access path defined in port side ballast tank represented by black color lines. Author used the point and path information as an input to this verification tool in addition to the above classification society XML file.
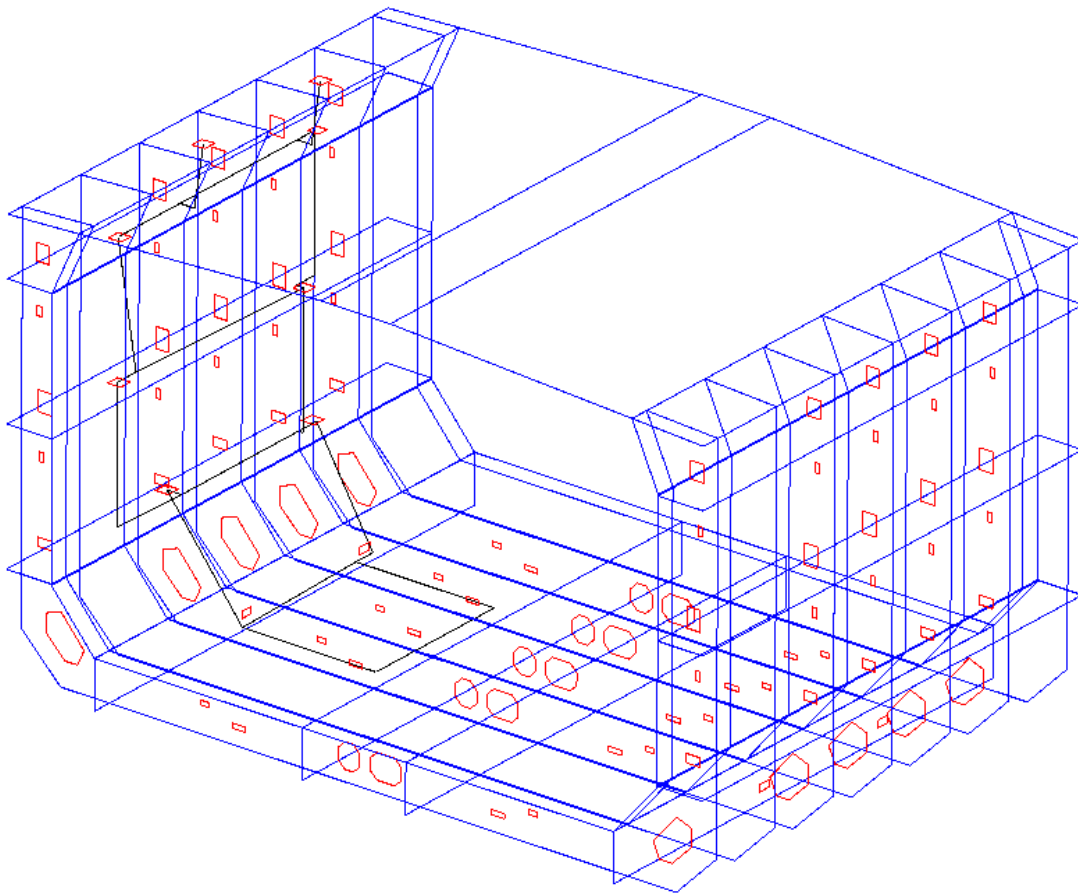
Fig. 3-8 Access Path for Design Verification.

Using these concepts and methodologies, finally author could successfully invent the "Access Path Verification Tool" by systemizing the classification society rule, designer's know-how and design criteria documents into an information system virtual verification tool.

3.3 Design Workflow

Shipyards are printing drawings to verify design regulation implementation once the design is completed. They use classification society rule, design criteria documents and designers own experiences/know-how to verify these design regulations manually. Author have introduced a new workflow with the use of "Access Path Verification Tool". Fig. 3-9 below describes the complete ship design workflow of a shipyard. Production ready data from master/type ship is copied to create a sister ship. Ship design is modified as per the design ordered for this sister ship. Because of the design change, it is necessary that the modified design is again verified for the classification society rule and ship manufacturers design criteria safety

standards. For this verification, the 3D CAD design data is exported in XML format. Verification of access path is performed in this newly invented "Access Path Verification Tool". Access path design quality Improvement areas are reviewed in 3D viewer by the design review team and these improvements can be done back in 3D CAD application again. This cycle continues until the design is fully verified. Finally the drawings are submitted to classification society for ship approval.
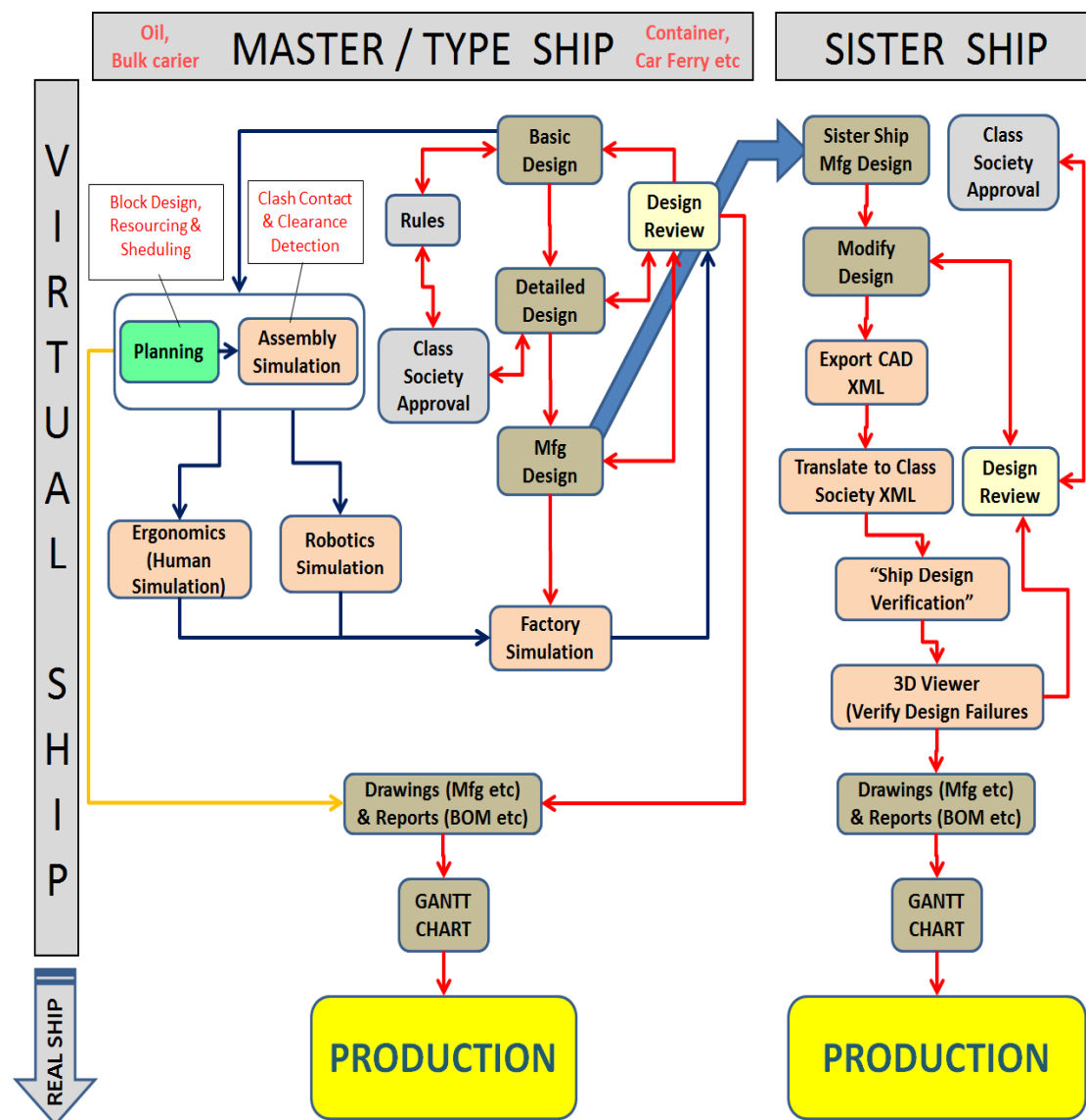

Fig. 3-9 Complete Ship Design Workflow.

3.4 Access path Design Verification Items

There are various ship access path design verification items for a tanker from classification society rule[20] and shipyards design standards. Fig. 3-10 below describes the access path design verification items used by the author in this research. Verification tool will highlight the area with color codes where these design standards are not maintained and will also report the warnings in output file.
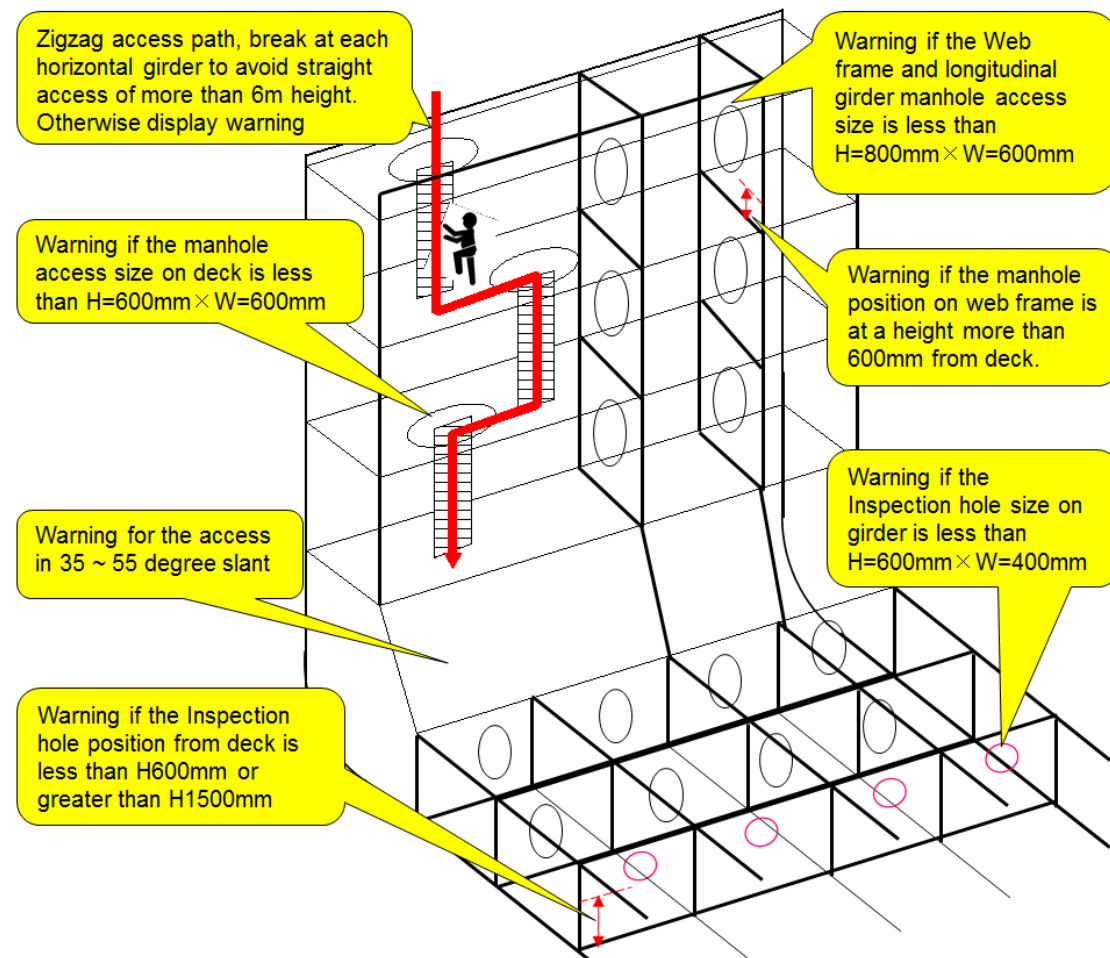
Fig. 3-10 Access Path Design Verification Items.

1. The Vertical Access

As per the classification society, classNK rule, the vertical access path stepping upward or downward should be maintained zigzag when access height is more than 6m.

2. The Manhole Size

Manhole size on web frames and longitudinal girders should be maintained as H=800mm×W=600mm and on deck as H=600mm×W=600mm.

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3. The Inspection Hole Size

Inspection hole size on web frames and longitudinal girders should be maintained as H=600mm×W=400mm.

4. The Manhole Position

As per the classification society rule, Manhole position on web frame or longitudinal girders for access in longitudinal or transversal direction should be maintained at a height less than 600mm from the deck. In this study it maintains this height less than 300mm.

5. The Inspection Hole Position

Inspection hole position on web frame or longitudinal girders for inspections should be maintained between H=600 and H=1500mm from the deck.

6. Slant Access

As per the classification society rule, the slant access path should be avoided for 45 degree inclination. This study avoids the inclination of 35 ~ 55 degree.

3.5 Application Development (Software Programing)

To achieve this research objective, it was necessary to develop a new software program for access path verification. Software specification description language DML is introduced for knowledge representation of ship hull design.

3.5.1 XML Convertor Tool

This tool is developed to translate the 3D CAD application data format into the classNK specific format. E.g. the 3D CAD data part contour need to be defined in classNK XML. Similarly, the CAD data opening NURBS (non-uniform rational basis spline is a mathematical model commonly used in computer graphics for generating and representing curves and surfaces) format need to be defined by the hole trace of classNK XML. Visual Basic programming language is used to develop the translation tool.

3.5.2 Knowledge Representation for Access Path

In this research, software specification description language DML is introduced for knowledge representation of ship hull design. DML is a non-procedural software specification description language based on entity-relationship model and object-oriented model. It is used to describe design object model and design rules of ship hulls, and DML descriptions are automatically translated into executable Java program by a DML compiler.

Specification description in DML mainly consists of two elements, programing class and association. Programing class is used to describe physical and conceptual objects constructing a ship hull structure, such as deck and access path, while association is used to describe relationships between classes. A class can have attributes which specialize itself, and unidirectional noncircular dependency can be defined between attributes as an expression designating an attribute value. An association defines a relationship between two classes with multiplicity. Class and association can also define dependency on others regarding their existence.

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```
class::part(
   attributes(
      [Point]::accessPath
   )).
class::partBoundarySurface(
   dependency(until(exist(surfacePart)));
   attributes(
      Point::point1;                        % First node point
      Point::point2;                        % Second node point
      Point::point3;                        % Third node point
      Point::edge12 := point2 - point1;     % Edge between 1 and 2
      Point::edge13 := point3 - point1;     % Edge between 1 and 3
      Point::normalVector :=
            normalize(outerProduct(edge12, edge13));
      [Point]::accessPathDirections :=
            vectorListSubtraction(surfacePart->accessPath, point1);
      [real]::innerProducts :=
            vectorListInnerProduct(accessPathDirections, normalVector);
      real::maximumInnerProduct :=
            if(innerProducts == [],     % No access path
               -1.0,                % Invisible
               max(innerProducts));
      boolean::surfaceVisibility := maximumInnerProduct >= 0.0
   )).
association::part_BoundarySurface(
   collections(
      part::surfacePart(multiplicity(1-1));
      partBoundarySurface:boundarySurface(multiplicity(0-n))
   )).
```

Fig. 3-11 Class and Association in DML.

The program in Fig. 3-11 above shows an example of class and association descriptions in DML, where class part defines a subdivision separated by web and girder of a tank and class "partBoundarySurface" defines a surface surrounding a part, while association "part_BoundarySurface" defines a one-to-many relationship between a part and its "partBoundarySurfaces".

Class "part" has attribute accessPath of Point type, which represents a list of 3-dimensional points of an access path of a part. Class "partBoundarySurface" has attributes point1 upto point3 which represent typical edge points of a surface, edge12 and edge13 which represent edges of a surface, and normalVector which represents a

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normal vector of a surface. Attribute "accessPathDirections" represents a list of directional vectors from point1 to all points of an access path of a part related to a surface. Attribute "innerProducts" represents a list of inner products of a directional vector and a normal vector of a surface. Attribute "maximumInnerProduct" represents maximum value of the inner products, and attribute "surfaceVisibility" is true if maximumInnerProduct is equal or greater than 0.0. Association "part_BoundarySurface" declares that a part can have multiple "partBoundarySurface" indicated by role name boundarySurface, and also a "partBoundarySurface" can have a single part indicated by role name surfacePart. Dependency description until(exist(surfacePart)) in class "partBoundarySurface" indicates that a "partBoundarySurface" can only exist while a part associated with it exits.

23 classes and 100 associations are described in DML for access path verification, and there are 5000 lines of code in total. Access Path Verification Tool written in Java is automatically generated from these descriptions.

3.6 Computation Results of Verification Tool

To prove the developed tools, author carried out a computation for the mid-ship block of oil tank in 3D CAD application. Design improvements are identified in "Access Path Verification Tool" as briefly described below.

3.6.1 Designing a Virtual Ship

Fig. 3-12 below shows the mid-ship block of a ballast tank to prove the usability of this access path design verification tool.
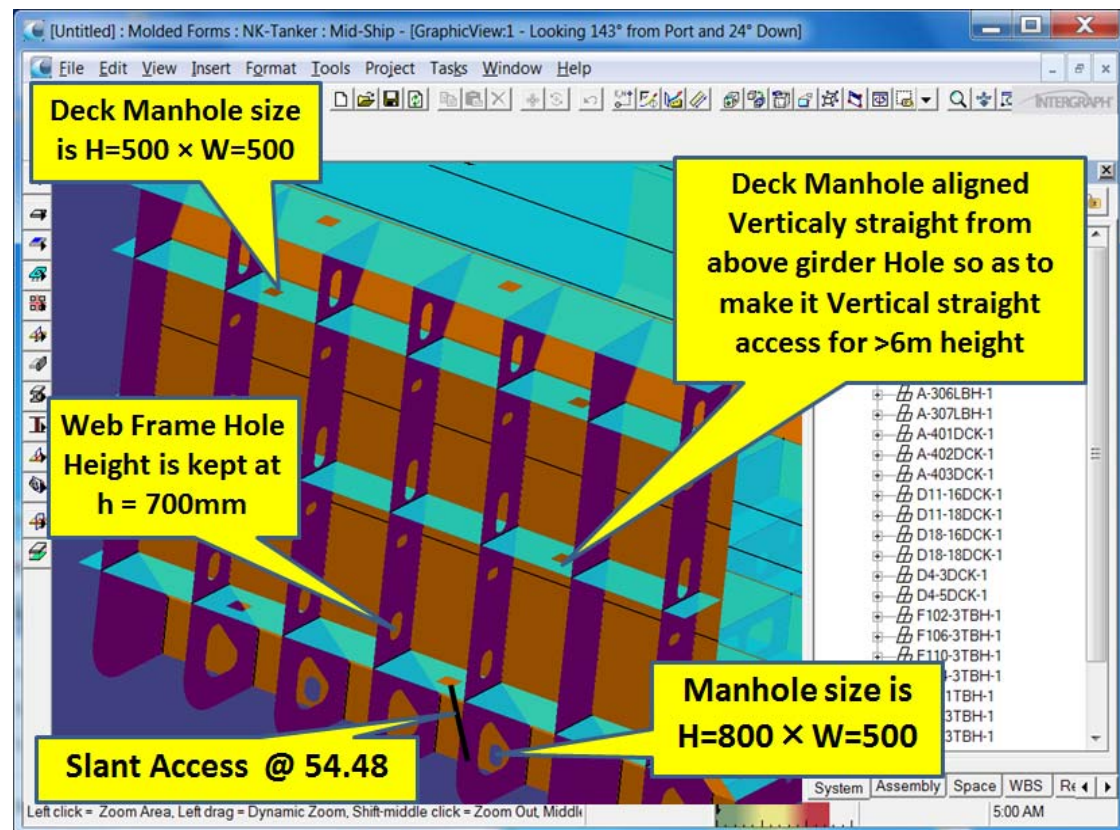
Fig. 3-12 Mid-Ship Block of a 3D Virtual Ship.

First the author created a wrong access path where the warnings will be highlighted for vertical access, size and position of manhole and inspection hole and also the slant access condition. The highlighted area in figure shows that the warnings should be displayed for improving these access path design quality.

3.6.2 Classification Society XML

To verify the access path design quality in verification tool, first of all, the 3D CAD data is translated to classification society, ClassNK XML format.

3.6.3 Access Path Verification Tool

The classification society XML, point and path data are used as the input in this Access Path Verification Tool. Interference check is performed on math data based on the access path defined in point and path data. All check condition logics that are defined in section "3.4. Access Path Design Verification Items" above are applied in this interference check. The warnings as shown in Fig. 3-13 below are highlighted in

the 3D viewer with specific color codes for the designer to quickly identify the area where the access path design quality needs improvements.
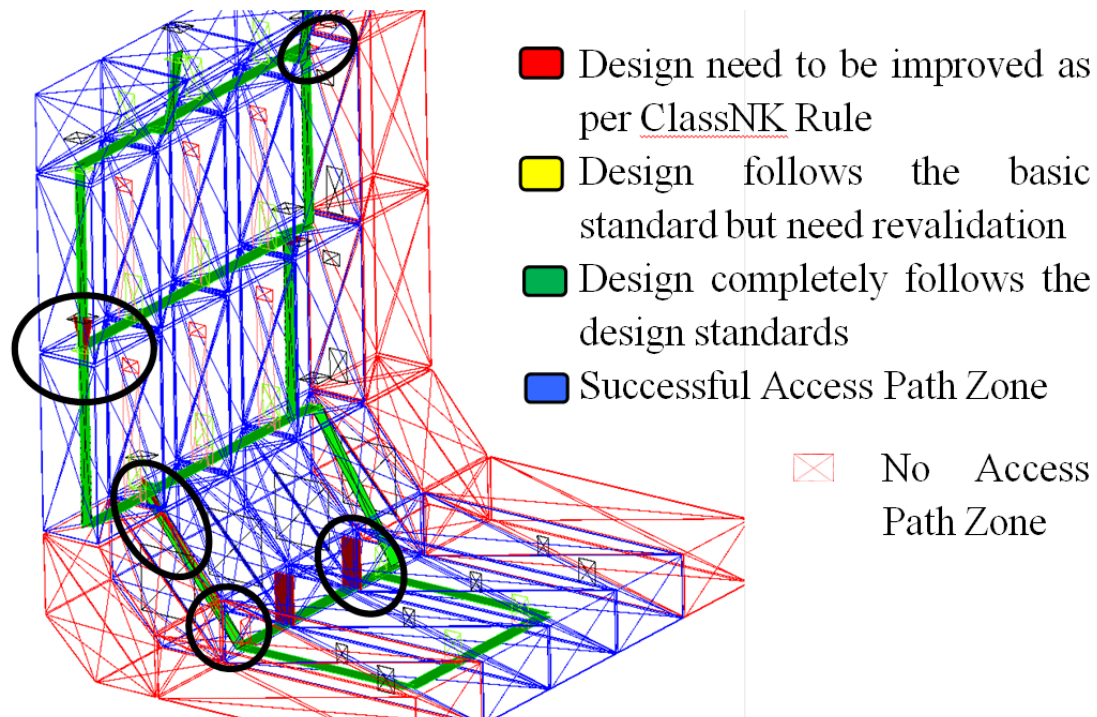

Fig. 3-13 Highlighting Area of Design Quality Improvements.

3.6.4 Improving Design Quality in 3D CAD application

Design quality improvements identified above are corrected back in 3D CAD application as shown in Fig. 3-14 below.
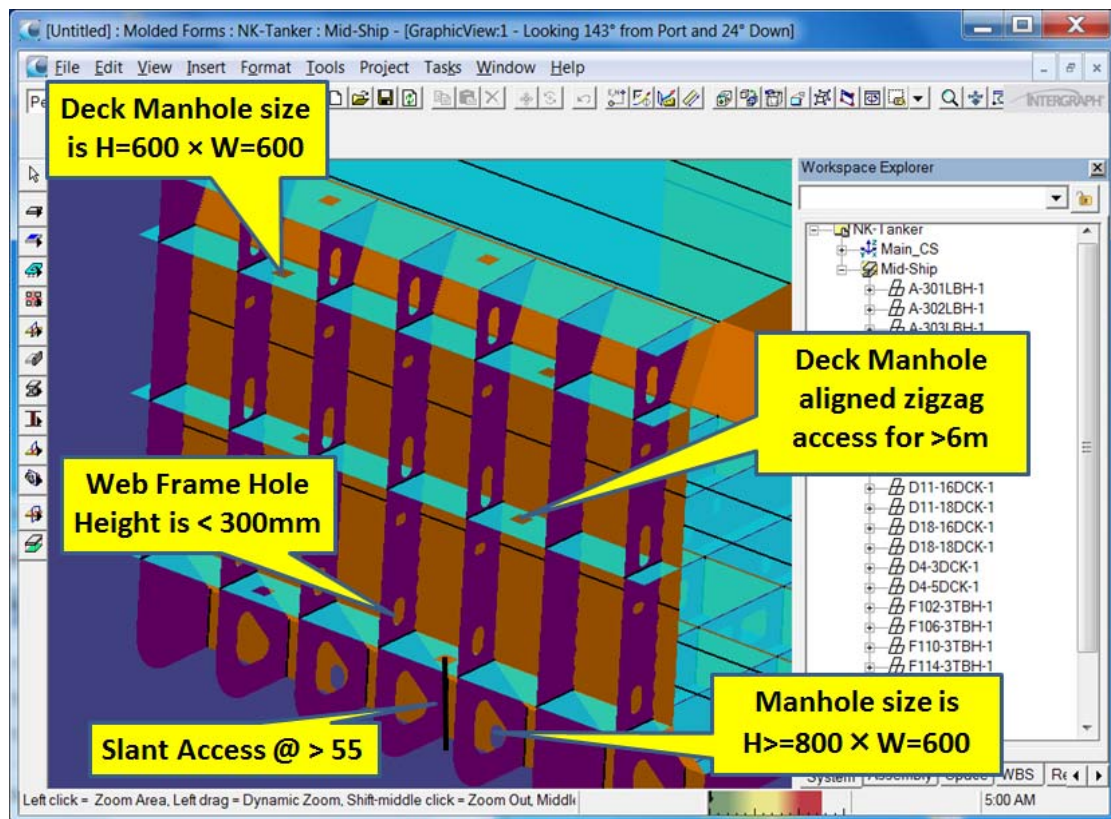
Fig. 3-14 Virtual Ship that fully follows Classification Society design standards.

The vertical access path is changed to zigzag access, size and position of manhole and inspection hole is changed to design standard size, slant access condition is improved by changing the slant access inclination angle to greater than 55 degree (other than 35~55 degree). Fig. 3-15 below shows the verification results after improving the design quality.
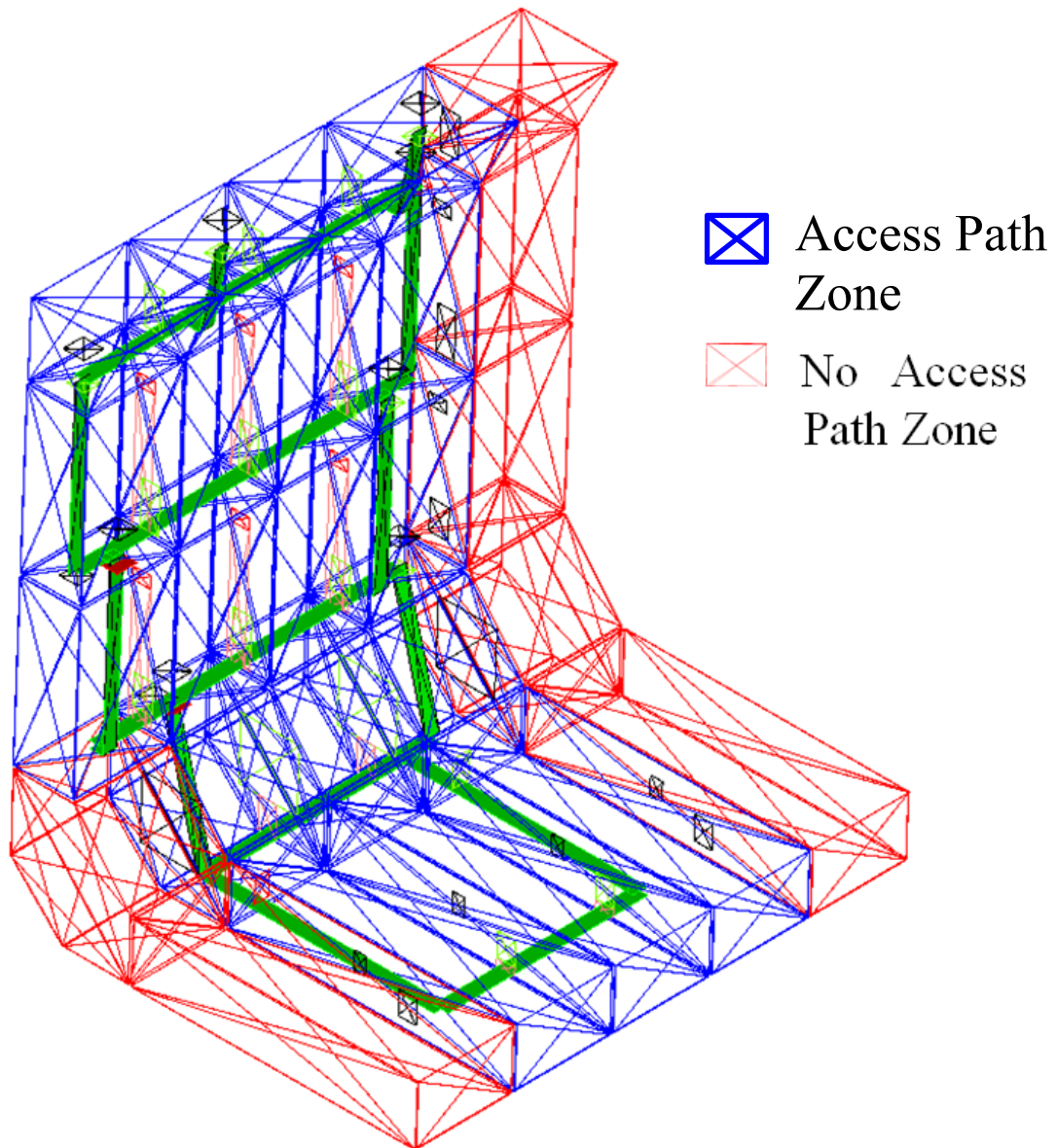
Fig. 3-15 Improved Design Quality Verification Results.

3.7 Summary

This chapter explained the extended application of Petri net graph theory for ship design automation. An example was taken from the mandatory class rule regulations together with the shipyards specific regulation that must be maintained in a ship design. The design regulation was to verify the design conditions of access path in a ballast tank for the ship inspectors and the crew members. The automation rule was proved by providing a practical example of ballast tank design in 3D CAD application integrated with the class rule prime ship CAD XML. Finally a visual verification of error-free access path can be done by applying the invented automation rule.

CHAPTER 4

AUTOMATION FOR
SHIP CONSTRUCTION ESTIMATION

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4 AUTOMATION FOR SHIP CONSTRUCTION ESTIMATION

As seen in section 2 and section 3 above, the virtual ship design concept using 3D CAD system with automation rule is very useful in shipbuilding industry. Extending the use of this virtual ship concept and automation rule, it will be remarkable if the prospect ship quotation can be estimated using this virtually designed ship. Accurate quotation is very crucial milestone of the shipyards to succeed commercially. This section describes a methodology that can be adopted to retrieve all necessary realistic data needed to estimate the realistic quotation of manufacturing a ship. The research will also open the doors for future research activities such as complete-automation for quotation, realistic manufacturing scheduler and inventory management of shipbuilding based on the virtual ship.

4.1 Introduction

Shipyards use various methodologies to estimate the prospect ship quotation. Based on the discussions with various shipyards in Japan, author realized that some shipyards estimates the quotation based on references to the drawings used in most closure designed ship going through all the design steps from basic design to the production design. Some of the shipyards estimate the quotation based on their Mid-Ship design by comparing the results with past experience ships data recorded. Author introduce a virtual ship concept using an existing 3D application with an add-on customizing tool in this application. The proven concept will help to retrieve the complete ship information's needed to estimate the shipbuilding quotation. Author have selected the major factors of quotation as described in "4.3 RESEARCH SCOPE" section. Customization of the application for recording man-hour data that is needed to manufacture a complete prospect ship is studied. All other factors are used from the original 3D CAD system functions with a minor customization. The research will prove that there are different kinds of fluctuations in estimation of a ship for any kind of design change occurs during manufacturing time. Fluctuations are studied based on the change in length of the hold and number of parts. This concept will also be useful to continue the research on creating manufacturing schedule as Gantt chart and

inventory management information's within the same 3D CAD application using the modeled virtual ship.

The purpose of this research is to provide a new concept in shipbuilding industry which will help shipbuilders to automatically create the realistic/accurate quotation from the virtually deigned complete prospect ship. Complete prospect ship is more important here since as described in the background, quotation's in today's world are based on references to the drawings[8] used in most closure designed ship or based only on Mid-Ship design which tends to be an assumption and trial and error method.

Author have selected a 3D CAD application method to prove this research concept. A limited set of realistic block and sub-assemblies of a Japanese shipyard is selected. A Mid-Ship block having plate parts, stiffeners, brackets and collar parts are designed virtually in 3D CAD system.

4.2 Concept and Method

The concept used in this research is a virtual ship that is mandatory to create all necessary required data for estimating the ship quotation. Fig. 3-9 above describes the prospect virtual ship design steps from its basic design[5] to receiving the final order from ship owner. The virtual ship is an exact replica of the real ship that needs to be manufactured. Before reaching to "receiving the final order" step, "drawings and reports"[8] step generates the necessary reports to estimate the complete ship quotation after going through classification society approval, planning, detailed and manufacturing design.

The shipyards who will newly adopt the 3D CAD applications for their ship design will need to build the complete virtual ship to utilize this newly introduced method for estimations in the beginning. However once a sample virtual ship is designed, that ship can be reused[9] as the reference for next generation ship orders as a sister ship. The only changes that need to apply are the blocks where design changes are needed for new orders. The shipyards those are already using 3D CAD application may already be having the virtual ships designed and can use sister ship concept as described in Fig. 4-1 for the new ordered ship. They can utilize this methodology for quotation estimations. Sister ship can be generated at any stage of the design like basic design, detailed design or manufacturing design based on the data reutilization.
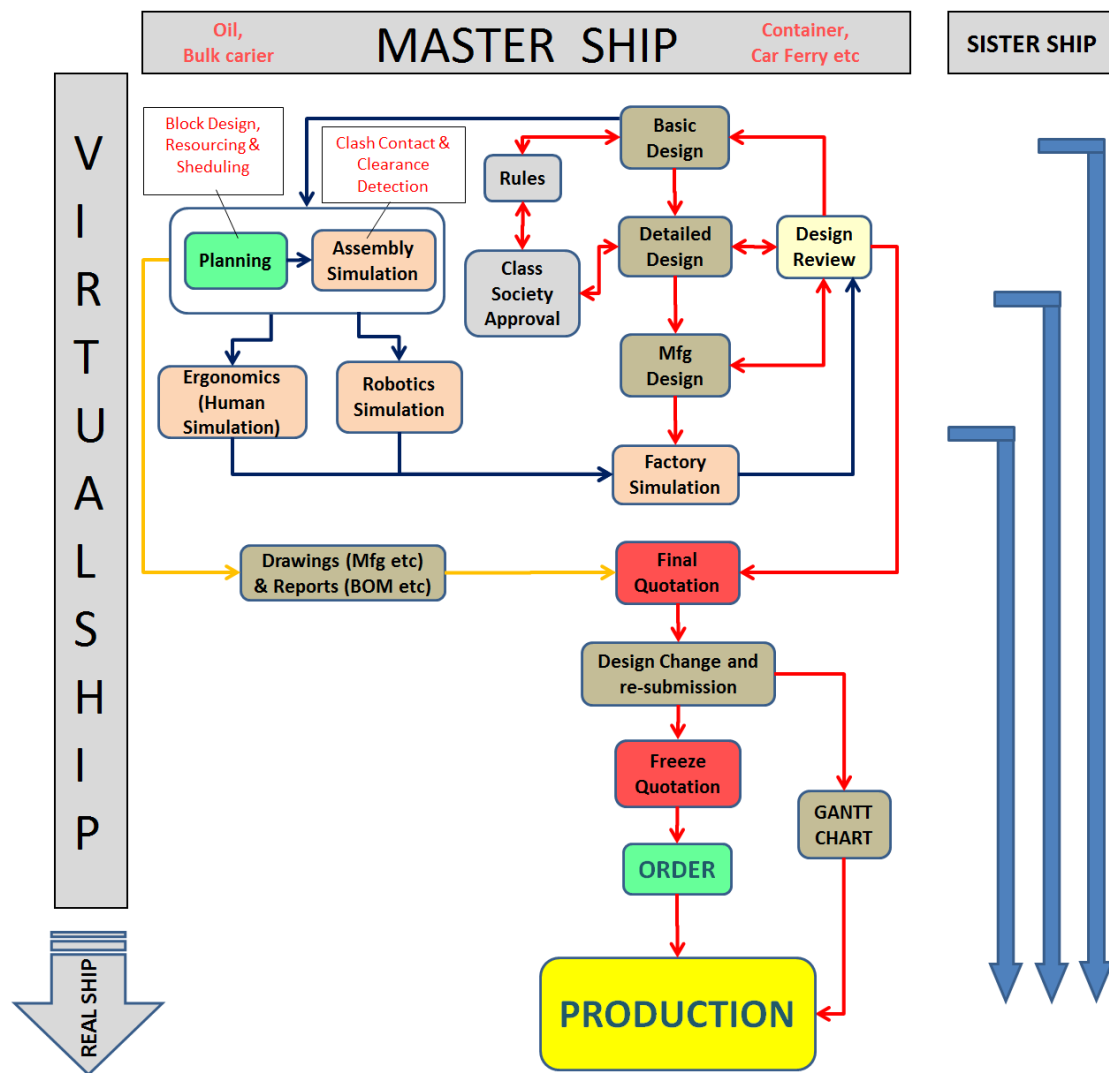
Fig. 4-1 Virtual ship and sister ship concept

Considering the time limitation and research scope, author selected the limited set of block as shown in Fig. 4-2 below and each individual assembly within the block of a bulk carrier.
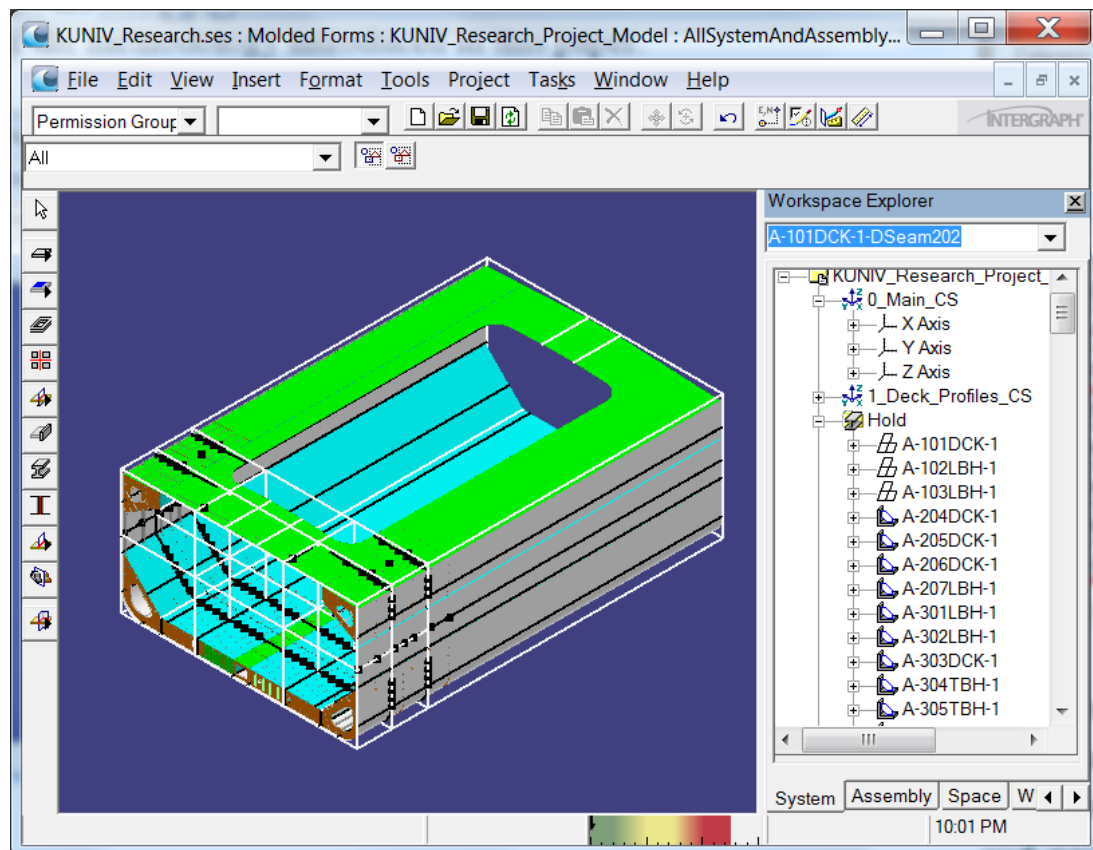
Fig. 4-2 Mid-Ship block used for concept proven

Various analyses like assembly simulation, robotics simulation, ergonomics and factory simulations as shown in Fig. 4-1 can be done on this 3D design to fully complete the virtual design as if it is manufactured in the yard. Similar method needs to be applied on all of the blocks of the prospect ship design to complete the full virtual ship design. This design information will be useful for creating quotation estimations using author methodology introduced in this paper.

4.3 Research Scope

There are various types of ship quotation estimations[21] to meet the needs of the user. Typical examples include.

- Construction (acquisition) quotation:-

  Shipyard labor and material estimation

- Life cycle estimation:-

This includes maintenance, operation, support, and modernization quotation on the top of construction estimation

- Total ownership quotation:-

This includes infrastructure estimation for training and other indirect estimation on the top of construction estimation and Life cycle estimation.

The scope of this paper is limited to construction (acquisition) quotation. There are many estimation factors while estimating the ship construction quotation[22]. The methodology proved from this research will be useful for each factor. Author have used the major factors mentioned below to prove this concept.

Weight of Material:

Research study will show the final "weight of material" report from the virtually designed ship which will help ship builders to finalize the quotation of material requirements.

Weld Length:

Similar to the "weight of material" report, the final weld report from the virtually designed ship will be created that will help ship builders to finalize the quotation of weld length requirements.

Paint Area:

Paint area report will be created from the virtually designed ship which will help the ship builders to finalize the quotation of paint area requirements for the prospect ship.

Manpower:

Manpower report will be created from the virtually designed ship which will help the ship builders to calculate the manpower budget of a company.

4.4 Designing a Virtual Ship

Virtual ship is designed in 3D CAD application and used to retrieve all necessary reports to estimate the prospect ship. Ship is designed from its basic design to the production design in following steps as described below.

4.4.1 Basic Design

Basic ship design in this CAD application is an early stage design for hull structure. Stiffened plate systems are defined with major openings, seam patterns, stiffener patterns, columns/beams, edge reinforcements, brackets, material thickness & grade. This data represents approximate (light weight) geometry.
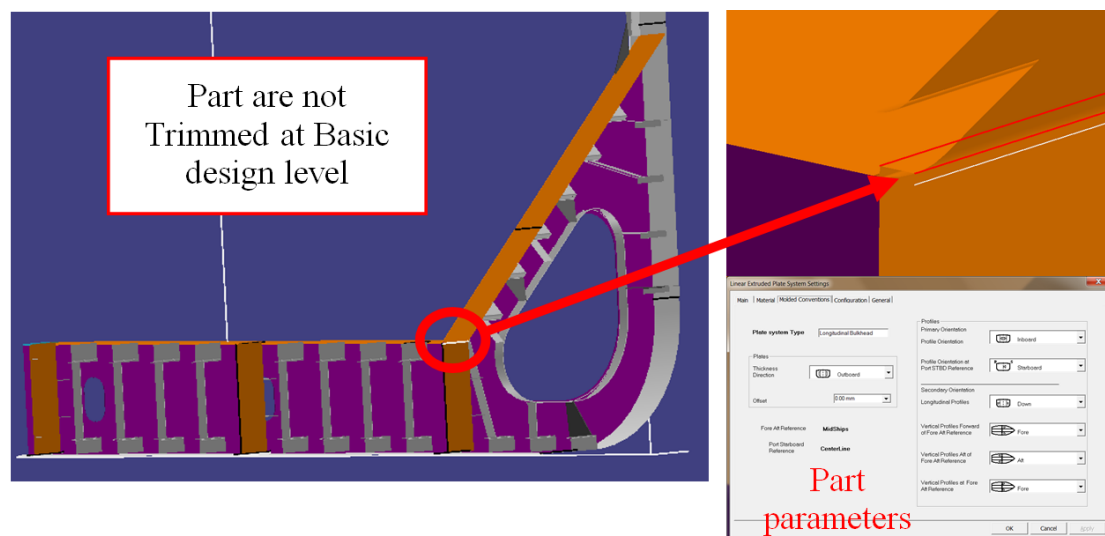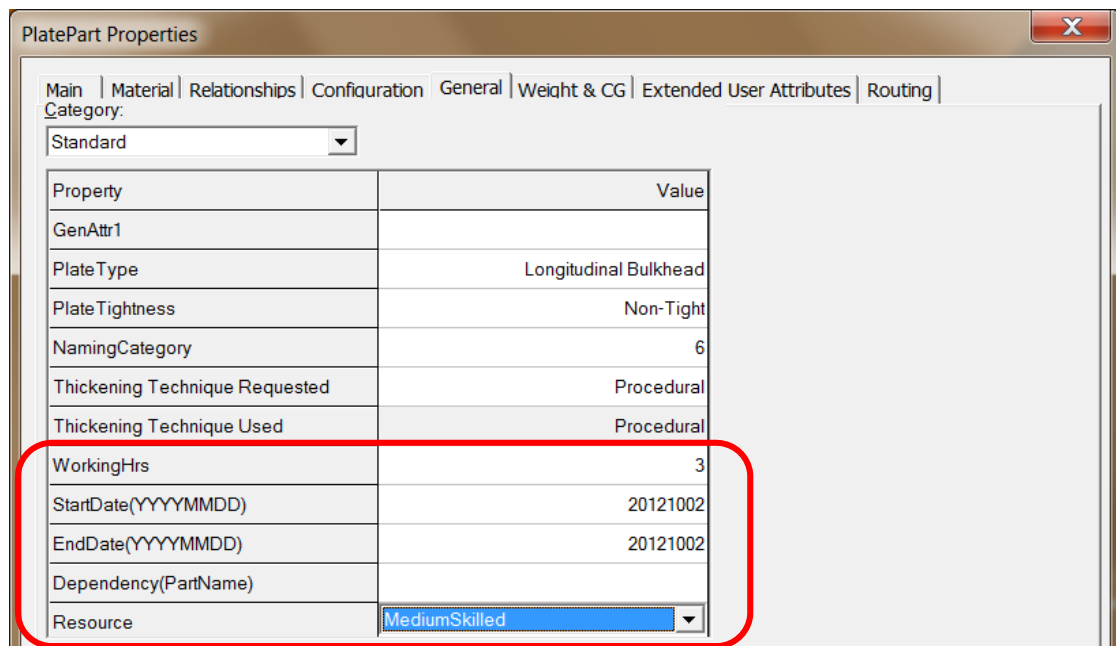

Fig. 4-3 Basic design of a virtual ship

Fig. 4-3 shows the basic design level 3D CAD model where the parts are not formed the exact 3D solid geometry; they are not trimmed with the bounded objects and represent the light weight geometry.

While designing the parts at basic level, it is made sure that the parts have assigned all necessary data as shown in Fig. 4-4 below like the plate thickness, material grade, profile section, resource skill level needed for manufacturing the part, start and end date, working hours required for manufacturing the part etc. It should be noted here that working hours is a very crucial attribute to drive the realistic quotation of the ship. Considering the research scope, author have assumed that this data will be based on the past experiences in factory workshop. However an automation rule can be created to drive the working hours estimation based on the predefined logic if any followed at the shipyards e.g. any fixed timing of operations of the machine etc.

Fig. 4-4 Manpower definition in a virtual model

The Data highlighted in Fig. 4-4 was made available in the application by customizing the catalog as described in next section "4.5 CUSTOMIZING CAD APPLICATION".

4.4.2 Planning

Planning design in this CAD application is a part-based "assembly" perspective. Planning information includes assembly content (parts that need to be assembled in the same assembly), Assembly sequencing (sequence of assembling the parts assigned within the same assembly), work center assignment (assigning the operational work center of the factory/yard), manufacturing or assembly orientation (assembly that need to be orientated in a particular direction in the shipyard while performing work operations like welding etc).
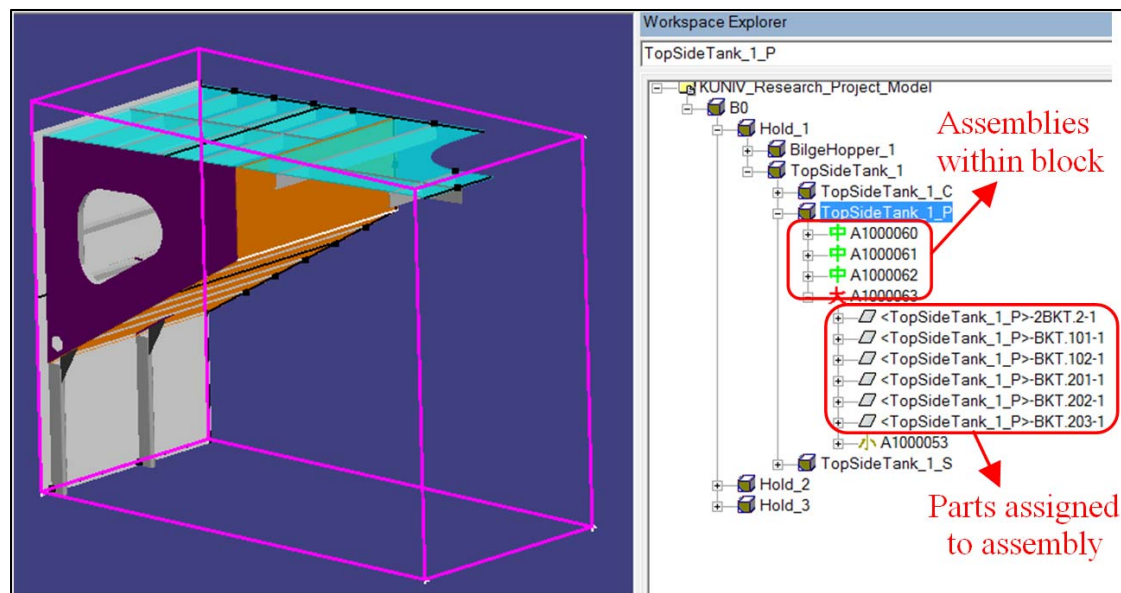
Fig. 4-5 Planning design of a virtual ship

Fig. 4-5 shows the virtual ship design with a highlighted planning block where the ship is divided into multiple blocks from production aspects. Each block then have the small, medium and high level assemblies within the block as shown in the figure. Parts those will be assembled at the same workstation are assigned within the same assembly.

4.4.3 Detailed Design

Detailed Design in this CAD application creates exact 3D solid geometry from the "approximate" light weight geometry created in basic design. Detailed design of a virtual ship fully depends on the rule based automation[5]. Detailed design features like slots and collars, profile end cuts, corner features & edge features (snipes & scallops), welds etc. are created using an automation rule.
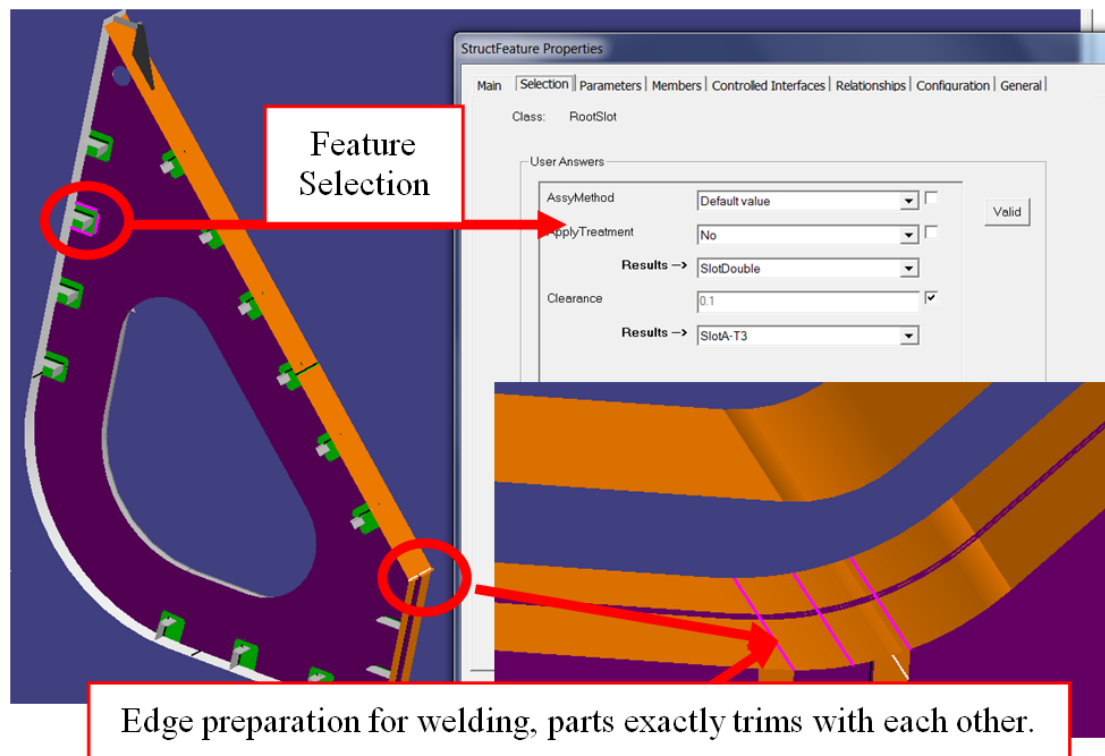
Fig. 4-6 Detailed design of a virtual ship

Fig. 4-6 shows the basic design level untrimmed girder plate part and detailed design of same frame in the hold. The part is exactly trimmed now by the double bottom plate after executing detailing. The figure also shows the new mandatory features like slot and collar, profile end cuts, edge features etc are created automatically using the predefined automation rules[16].

4.4.4 Manufacturing Design

Manufacturing plate and profile parts are generated as 2D line-arc representations from the 3D detailed parts. Manufacturing part generation is largely automatic and rule based. Fig. 4-7 below shows the manufacturing drawing 2D line arc representation of a 3D detailed and manufactured plate system having slot cut outs, profile landing on the plate, manhole, outfitting hole, fitting mark etc.
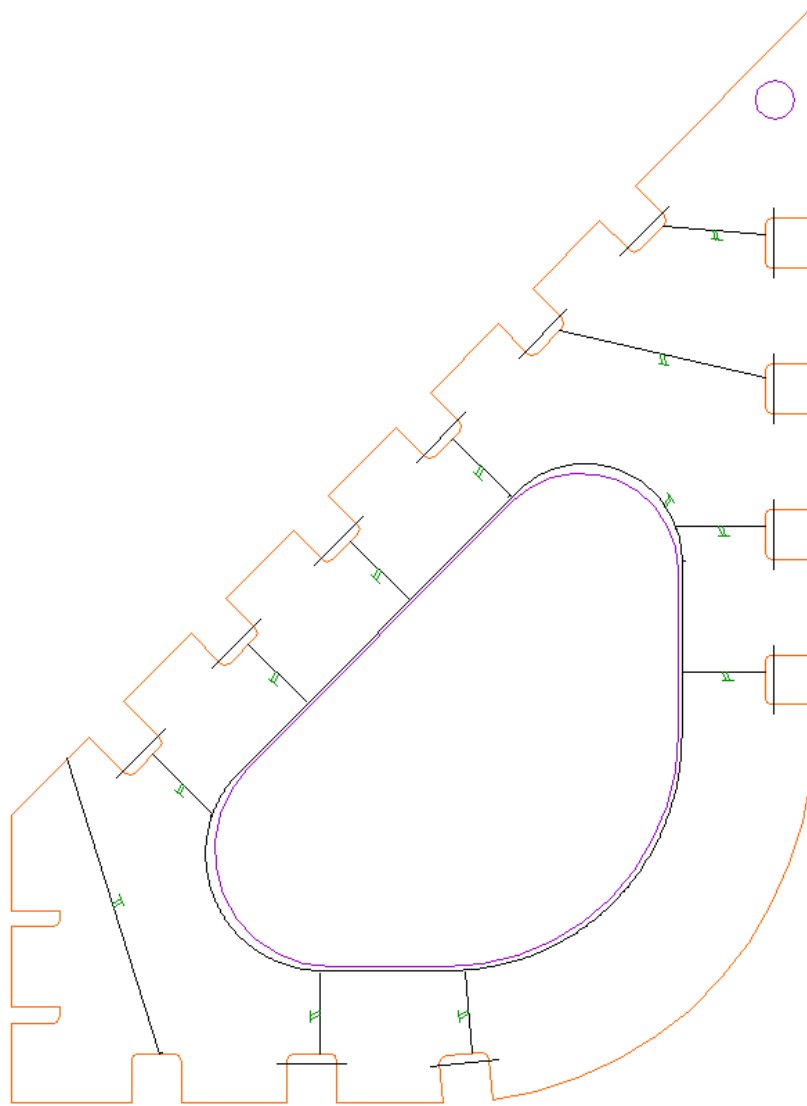
Fig. 4-7 Manufacturing drawing of a virtual ship

Manufacturing parts can be exported to XML data as shown in below Fig. 4-8. Line, arc, bevel etc information's are defined by the XML standard keywords as:

Line segment as <CVG_CURVE CURVE_TYPE="Line">,

Arc as <CVG_CURVE CURVE_TYPE="Arc">

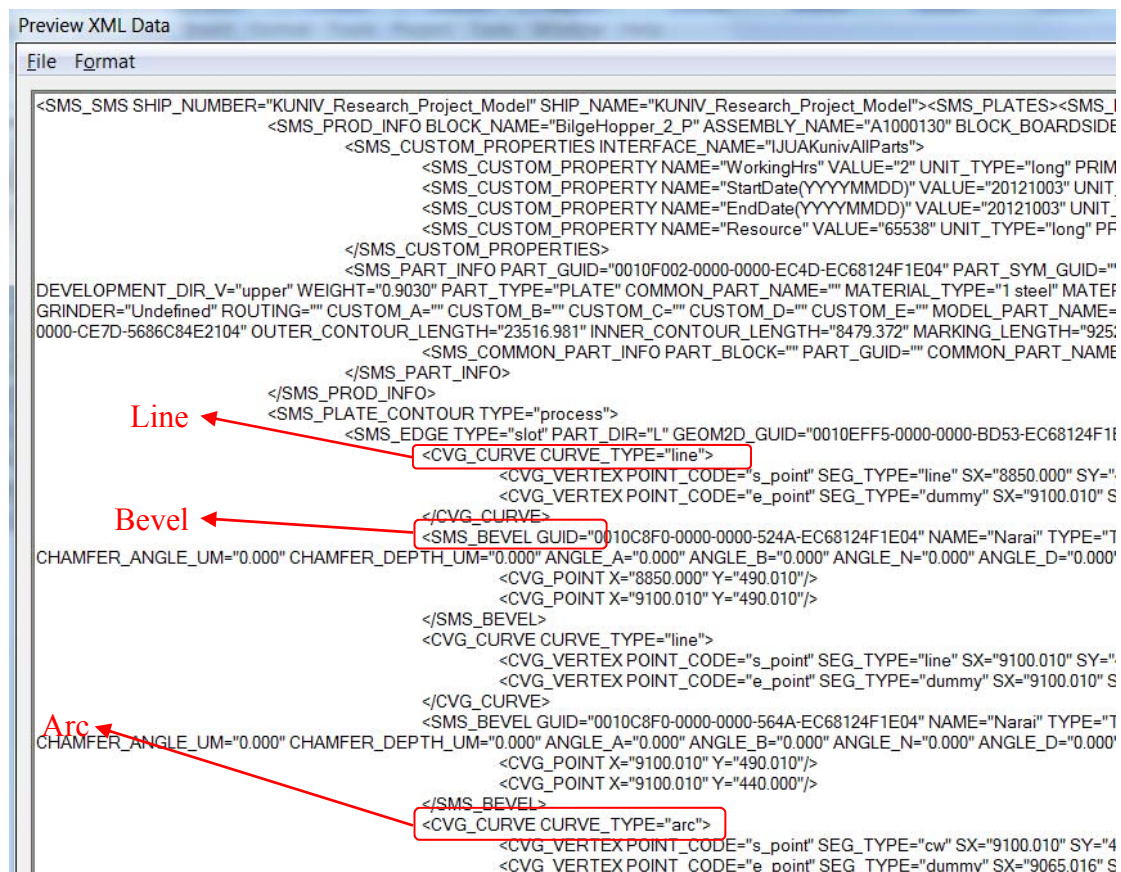Bevel as <SMS_Bevel Guide = "……….>

Fig. 4-8 Manufacturing XML of a virtual ship

The XML file will have all information like starting point, end point, length of the segment, angle etc related to each line, arc spline segments defined in the XML. This XML information can be exported to 3rd party nesting or other manufacturing systems.

4.5 CUSTOMIZING CAD APPLICATION

To retrieve the manpower details for estimating resource estimation of manufacturing a complete prospect ship, it is necessary to input the relevant manpower data at the basic design level on each part. To achieve this, the necessary manpower attributes need to be added in a simple table of this CAD application catalog. This will allow user to select the attribute in 3D model to define the necessary manpower data on each parts.

Table 4-1 Selection of 3D objects for basic manpower data

Head	ClassName	InterfaceName
Start		
	CPlatePart	IJUAKunivAllParts
	CStiffenerPart	IJUAKunivAllParts
	CEdgeReinforcementProfilePart	IJUAKunivAllParts
End		

Table 4-1 signifies that the manpower attributes that will be added in the table will be applicable to 3D objects like Plate, stiffener and edge reinforcement profile part. 3D objects are selected based on the research scope. To recognize the objects in the rule, an interface name is defined as shown in Table 4-1.

Table 4-2 below shows the attributes that are assigned to the interface name defined in Table 4-1. This way, 3D application recognizes which attribute names are applied to what type of 3D objects. Category name in the table is the 3D application task name which is same as basic design phase in this research meaning that the user will be able to define these attributes to the objects in 3D at basic design level. Codelist indicates that the user selection values have to be supplied in pull down selection for the end user. If no codelist is defined, the manual input need to be supplied by the end user.

Table 4-2 Attributes on selected 3D objects for basic manpower data

Head	InterfaceName	CategoryName	*AttributeName*	*AttributeUserName*	*CodeList*
Start					
	IJUAKunivAllParts	**MoldedForms**	ResourceName	**Resource**	ResourceTypeCodeList
			WorkingHours	WorkingHrs	
			StartDate	StartDate(YYYYMMDD)	
			EndDate	EndDate(YYYYMMDD)	
			Dependency	Dependency(PartName)	
End					

It should be noted here that the working hours attribute is set to be manual input for the end user. However it is also a crucial attribute to drive the realistic quotation of the ship. Considering the research scope, author have assumed that this data will be based on the past experiences in factory workshop. However a VB rule can be customized to drive the working hours estimation based on the predefined logic if any followed at the shipyards e.g. any fixed timing of operations of the machine etc.

Fig. 4-9 below shows the highlighted attributes that will be available for user selection and also the manual input by end user at basic design level after completing the customization

Fig. 4-9 User defined basic manpower data after customization

Table 4-3 below shows the values assigned to the attribute "Resource" added as described in Table 4-2 since a code list is defined for this attribute. All values shown in Table 4-3 will be selectable by the user on the properties page of relevant 3D objects as prescribed in Table 4-1. Values in this 3D CAD application are recognized by the codelist numbers. Manpower attributes are not available in the catalog for user definitions without these customizations as described in Table 4-1, Table 4-2 and Table 4-3. The resource codelists "HighSkilled", "Medium Skilled" and "LowSklled" are defined by the author for the simulation purpose. These codelist can be anything as per shipyard standards e.g. the names of the resources etc. These codelist values are user defined meaning that the user can select the values manually in 3D CAD model. Finally, when generating the manpower report, the total working hours per resource type can be analyzed.

Table 4-3 Attribute values for basic manpower data

HEAD	ResourceTypeCodeList ShortDescription	ResourceTypeCodeList LongDescription	Codelist Number	Sort Order
START				
	HighSkilled	HighSkilled	65536	
	MediumSkilled	MediumSkilled	65537	
	LowSkilled	LowSkilled	65538	
	Trainee	Trainee	65539	
END				

Table formats shown in Table 4-1, Table 4-2 and Table 4-3 is the standard format of this CAD application that need to be used to update the 3D objects information in database table of the catalog.

4.5.1   Major Factors for Reports Customization

Considering the research scope, Author has selected to prove the concept by generating 4 major reports namely "Weight of Material", "Weld Leg", "Paint Area" and "Manpower" reports.

$$\text{Quote of material} = \text{Total weight of material (KTons)} \times \text{Quote / KTons}$$

$$\text{Quote of weld leg} = \text{Total weld Leg (m)} \times \text{Quote / m}$$

$$\text{Quote of paint area} = \text{Total paint area (m}^3) \times \text{Quote / m}^3$$

$$\text{Quote of man work} = \text{Total man work (hours)} \times \text{Quote / hour}$$

$$\genfrac{}{}{0pt}{}{\text{Quotation}}{\text{Estimation}} = \genfrac{}{}{0pt}{}{\text{Quote of}}{\text{Material}} + \genfrac{}{}{0pt}{}{\text{Quote of}}{\text{Weld length}} + \genfrac{}{}{0pt}{}{\text{Quote of}}{\text{Paint area}} + \genfrac{}{}{0pt}{}{\text{Quote of}}{\text{Man work}} \quad (4\text{-}1)$$

Total quotation estimation is given by Equation (4-1). From the equation, total weight of material, weld leg, paint area and man work are automatically reported in the respective report outputs once the virtual ship is fully completed in 3D CAD application. To retrieve these information's in respective reports, it is necessary to customize the reports in virtual ship CAD application to generate the output as needed. Author customized the application as described below for generating the needful reports. Weld leg and paint area report are also delivered in the CAD application however all of these reports needs customization as per the needs of the shipyards. Author have customized the reports as per research scope. This paper describes one example of manpower report customization; all other reports follow the same customization process.

4.5.2 Retrieving Attributes for Manpower Reports

Reports customization can be started in drawings and reports environment in this CAD application. To start customizing the reports, as shown in Fig. 4-10 below, a basic blank report template delivered in this CAD application can be used to create a new report for manpower data output from 3D model.
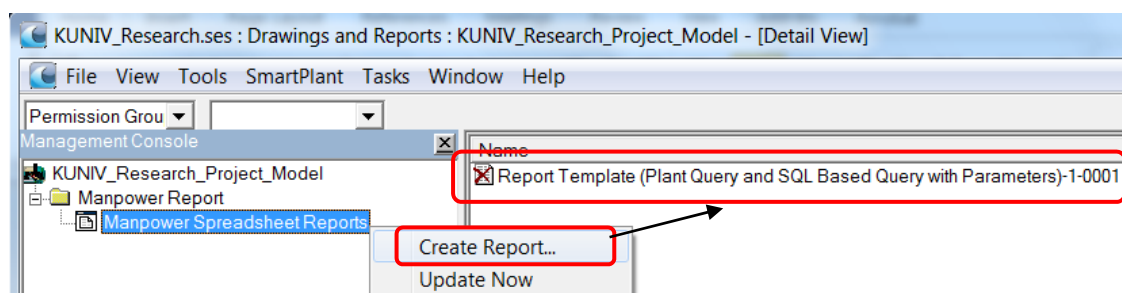

Fig. 4-10 Use of a CAD application delivered blank report template

Once a blank report is created, the template of this report can be edited to customize it as per the need of a new report, a manpower report in this case. As shown in Fig. 4-11a and Fig. 4-11b, a base template is already available in the

beginning from the blank report and author then keeps on adding the new necessary attributes needed for the manpower report.

Fig. 4-11a Base template from the blank report

Fig. 4-11b Newly added attributes for manpower report in blank template

These newly added attributes are already available in the 3D CAD application catalog. Some of them e.g. Name (part names, assembly names) are the standard attributes of the application and others (resource, start date, end date etc.) are the attributes added in the catalog as a Manpower Definition as described in section 4.4.1 "Basic Design". Access to these catalog attributes is available through the filter definitions in this CAD application. Following described filters are applied to these attributes.

4.5.2.1   Part name
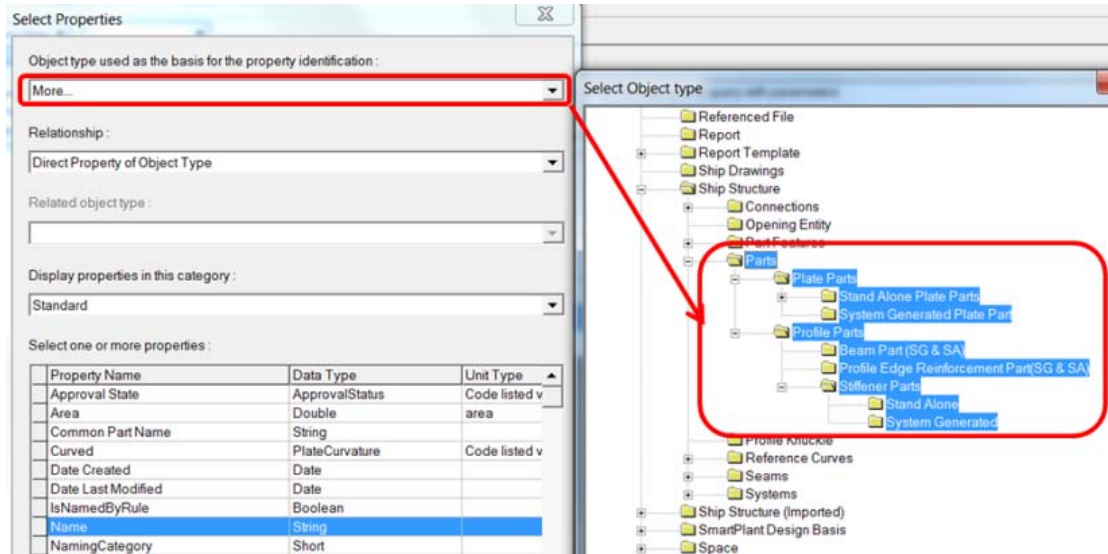
Fig. 4-12 Filter for part name definitions

Part name filter is defined as shown in Fig. 4-12 above where an object type selection is set to parts and relationship to the "direct properties of those selected parts". The property assigned for the selection in report is "name" which will retrieve the name of the selected part object.

4.5.2.2   Assembly name

Assembly name filter is defined as shown in Fig. 4-13 below where an object type selection is set to "parts" and relationship to the "assembly hierarchy-IsParentOf" meaning the assembly parent of selected parts. Defining a related object type in this case is mandatory and set to "planning hierarchy" since the assembly is defined in planning environment in this CAD application. The property assigned for the selection in report is "name" which will retrieve the name of the immediate assembly parent of selected part object.
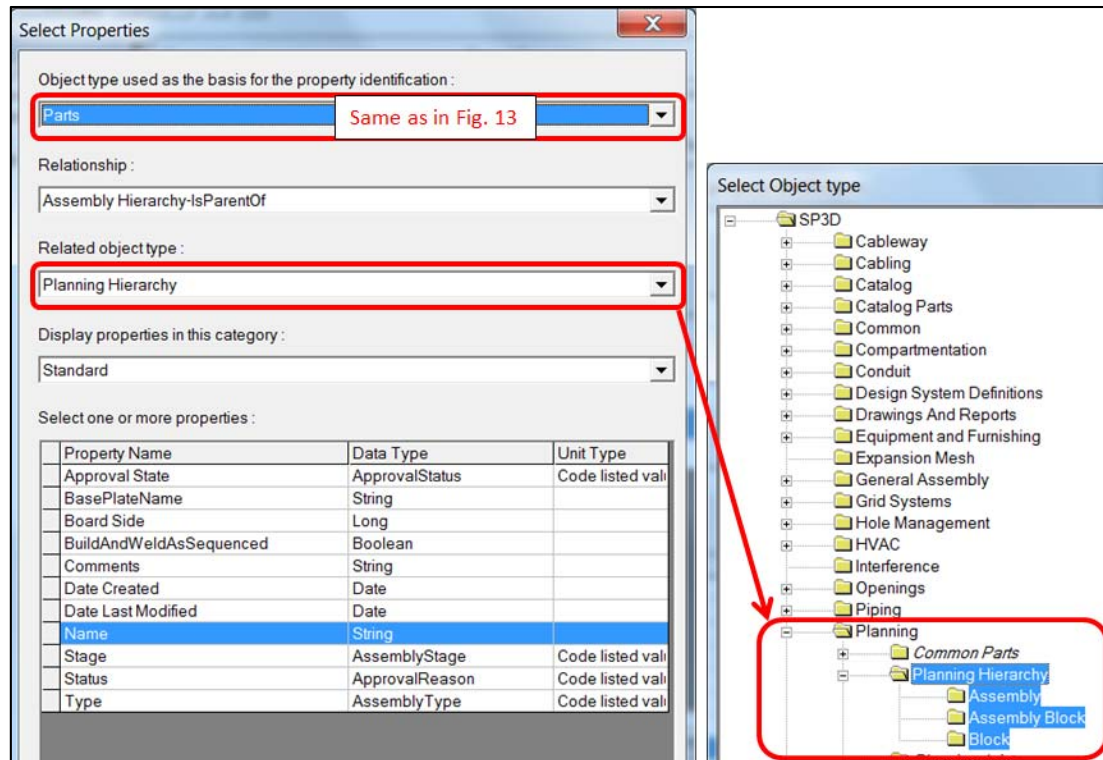
Fig. 4-13 Filter for assembly name definitions

4.5.2.3   Manpower attributes

Filter for manpower attributes is defined as shown in Fig. 4-14 below where an object type selection is set to "system generated plate parts" and relationship to the "direct properties of those selected parts". The property assigned for the selection in report is all manpower attributes like "resource", "start date", "end date", "working hours" which will retrieve the values assigned these attributes for the selected part object.
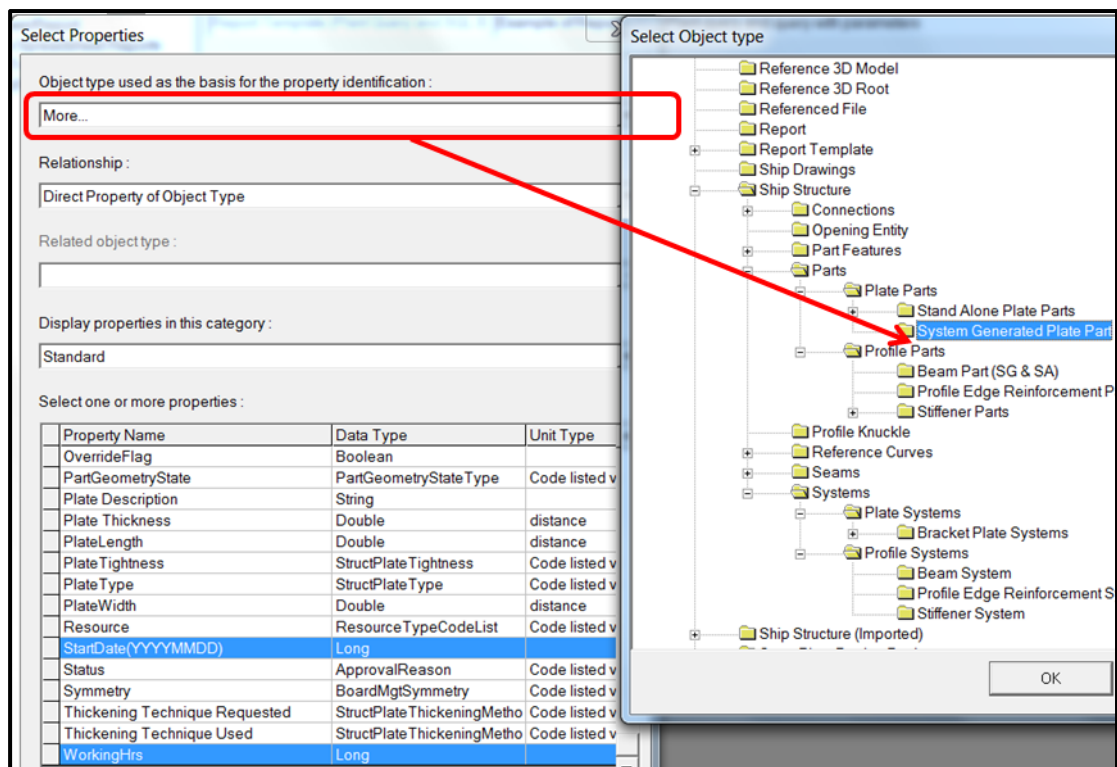
Fig. 4-14 Filter for manpower attributes definition

Thus all the attributes that are needed in manpower report output are now retrieved in the template and finally an excel output format need to be defined for the collection of all data.

4.5.3 Formatting Report Template for Excel output

Switch to "Formatting Report Template" tab in the template form as shown in Fig. 4-15a below and use "design layout" button to open the excel template file for formatting it in an expected manner. The excel file opened in the beginning Fig. 4-15b will be in a blank template format.
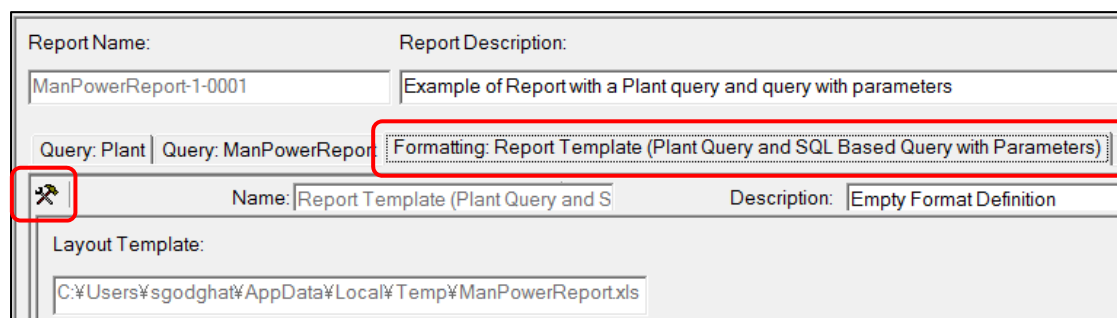
Fig. 4-15a Filter for manpower attributes definition
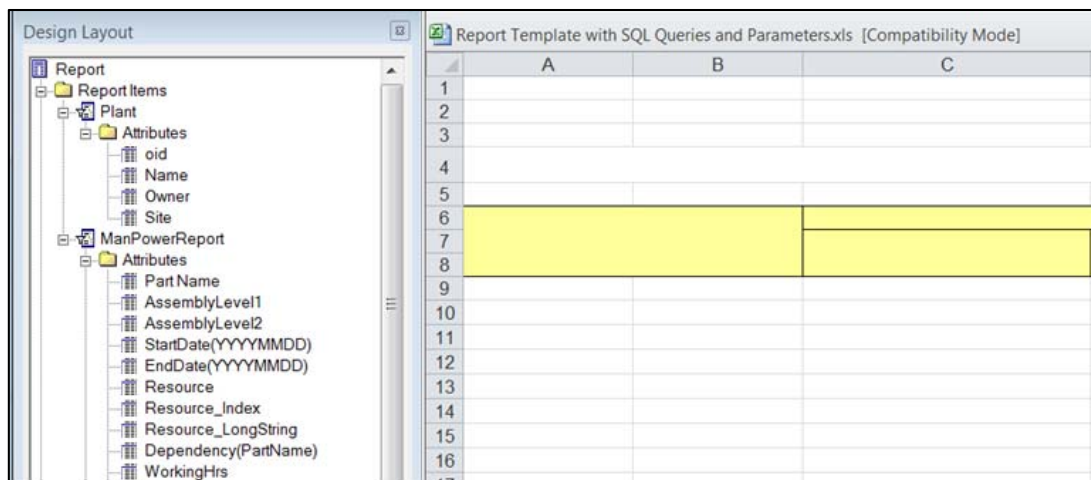
Fig. 4-15b Blank template of report format

Now, author have defined the excel format as shown in Table 4-4 below where the attributes that are needed in the output are defined in the excel cells and values of those attributes will be retrieved in the excel cells defined with the format "#......#". The format for values is defined just by drag and drop of the attribute (e.g. Part Name, Assembly Level etc) from "Design Layout" in left hand side of the Fig. 4-15b to the right hand side in the relevant excel cells.

Table 4-4 Manpower report output format

Report formatting is now completed and this customized report is now copied to the catalog as shown in Fig. 4-16. This creates a new folder with all customized files into the CAD applications target standard location. These custom files can be reused across the multiple catalogs.
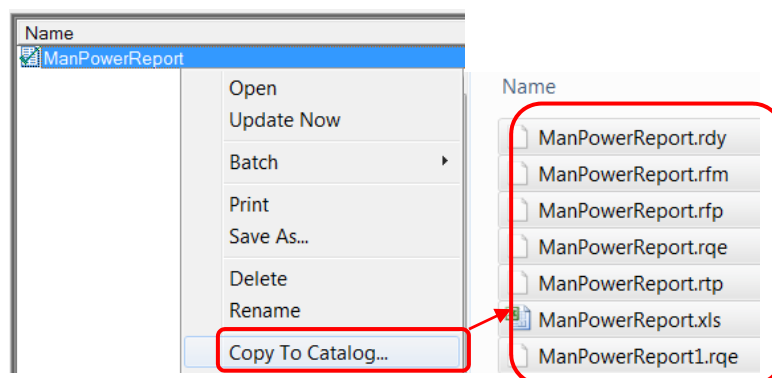
Fig. 4-16 Copy report to the catalog

When reusing the custom report data across multiple catalogs for sister ship designs, it is mandatory to add the new report template and its standard folder locations into the new catalogs which will avoid redoing all these customize steps as described in this section. System automatically formats the report generated files. A sample report template parametric file is as shown in Fig. 4-17 below. All other reports within the scope are customized in the similar manner.
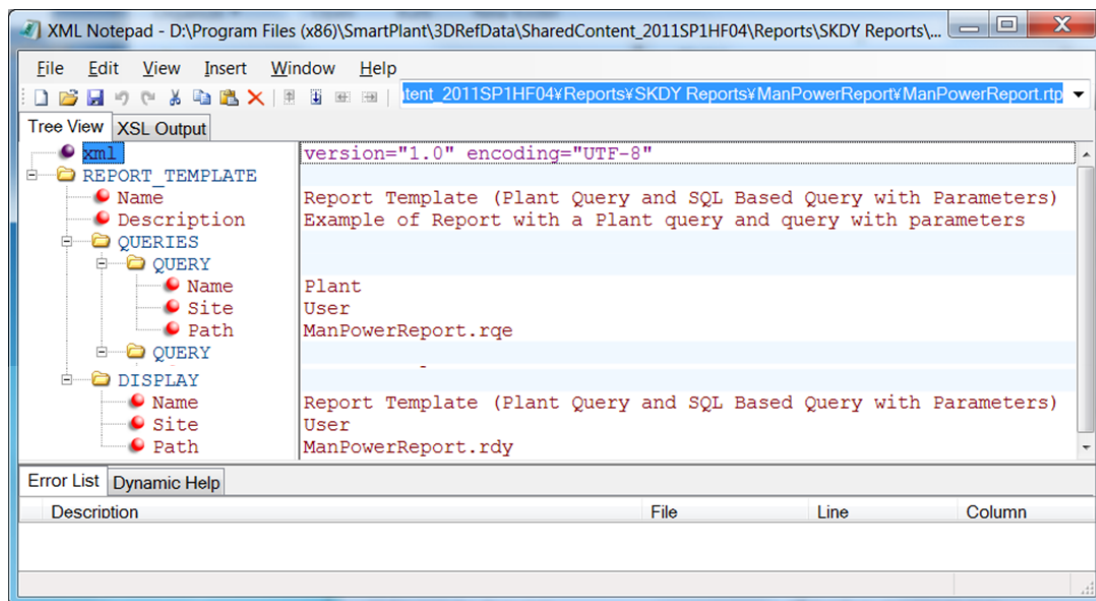
Fig. 4-17 Report Template File (*.rtp)

4.6 GENERATE REPORT OUTPUTS FOR FINAL QUOTATION

Now the Virtual Ship Model is completely ready at its production design stage. It is the time to generate all mandatory reports which can retrieve all necessary data from a virtual ship to estimate the prospect ship. This estimation will be a realistic estimation since all Engineering Design are already completed at virtual level considering all requirements of the Ship Owner. Shipyards now can submit their realistic quotation to the Ship Owner. It is important to note that the estimations using this virtual ship method is dynamic. Shipyard can quickly re-estimate the same if any design changes are implicated by the classification society or are requested by the Ship-Owner or any other unavoidable reasons. Changes need to be applied in the virtual model and re-estimations can be done based on the newly generated reporting's from the CAD application.

4.6.1   Weight of Material:

Weight of material report is useful for raw material procurement. Based on this report the complete ship raw material procurement as shown in Table 4-4 can be estimated at the virtual ship design level so as to account for complete ship raw material quotation.

Table 4-4 Weight of Material Report

Ship Number = 3				
Assembly Name = A10, Assembly Board = P				
Assembly or Part Name	Weight	X-Axis	Y-Axis	Z-Axis
<B0.1-7.1-4.1-2>-CL.201-1	0.16	21.995	4.402	6.968
A14	3094.08	23.021	5.758	6.996
A15	1193.49	17.607	2.351	4.396
Total	14885.16	22.52	5.34	5.31

4.6.2   Weld Leg:

Weld leg report is useful for weld leg procurement. Based on this report, the complete ship weld leg procurement as shown in Table 4-5 can be estimated at the virtual ship design level so as to account for complete ship weld leg quotation.

Table 4-5 Weld Leg Report

3rd Block	4th Block	Part Name	Plate Thickness	Weld Category	Weld Leg	Weld Position	Weld Length
		B0.1-7.1-4					
B0.1-7.1-4		<B0.1-7.1-4>-7D.A-1	12.0	N/A		H	5.073
B0.1-7.1-4		<B0.1-7.1-4>-7D.A-1	12.0	N/A		N/A	5.105
B0.1-7.1-4		<B0.1-7.1-4>-7D.A-1	12.0	FF	5	OO	3.024
B0.1-7.1-4		<B0.1-7.1-4>-7D.A-1	12.0	FF	5	OO	3.139
B0.1-7.1-4		<B0.1-7.1-4>-7D.A-1	12.0	FF	5	OO	2.91
B0.1-7.1-4		<B0.1-7.1-4>-7D.A-1	12.0	FF	5	OO	3.397
B0.1-7.1-4		<B0.1-7.1-4>-7D.A-1	12.0	FF	5	OO	3.826
B0.1-7.1-4		<B0.1-7.1-4>-7D.A-1	12.0	FF	5	N/A	7.853
B0.1-7.1-4		<B0.1-7.1-4>-7D.A-1	12.0	FF	5	OO	2.51
B0.1-7.1-4		<B0.1-7.1-4>-7D.A-1	12.0	FF	5	OO	3.024
B0.1-7.1-4		<B0.1-7.1-4>-7D.A-1	12.0	FF	5	OO	3.14
B0.1-7.1-4		<B0.1-7.1-4>-7D.A-1	12.0	FF	5	OO	2.91
B0.1-7.1-4		<B0.1-7.1-4>-7D.A-1	12.0	FF	5	OO	3.397
B0.1-7.1-4		<B0.1-7.1-4>-7D.A-1	12.0	FF	5	OO	3.826
B0.1-7.1-4		<B0.1-7.1-4>-7D.A-1	12.0	FF	5	OO	2.51
B0.1-7.1-4		<B0.1-7.1-4>-7D.A-1	12.0	FF	5	N/A	7.853
B0.1-7.1-4	B0.1-7.1-4.1-4	<B0.1-7.1-4.1-4>-CL.212-1	10.0	N/A	0	N/A	0.15
B0.1-7.1-4	B0.1-7.1-4.1-4	<B0.1-7.1-4.1-4>-CL.211-1	10.0	N/A	0	N/A	0.15
B0.1-7.1-4	B0.1-7.1-4.1-4	<B0.1-7.1-4.1-4>-CL.210-1	10.0	N/A	0	N/A	0.15
B0.1-7.1-4	B0.1-7.1-4.1-4	<B0.1-7.1-4.1-4>-CL.207-1	10.0	FF	5	N/A	0.343

4.6.3 Paint Area:

Paint area report is useful for paint procurement. Based on this report the Paint requirement for complete ship as shown in Table 4-6 can be estimated at the virtual ship design level so as to account for complete ship paint area quotation.

Table 4-6 Compartment based Paint Area Report

	Compartment Painting Area Report						
Compartment	Condition	Block Name	Part Name	Paint Area A	Paint Area B	Paint Area C
Cargo Volume	Overlapping	B0.1-5	<B0.1-5>-68BH.A-1	128.7		
Cargo Volume	Boundary-Overlapping	B0	<B0>-2LS.B-1	534.2		
Cargo Volume	Boundary-Overlapping	B0	<B0>-0LS.B-1	743.8		
Cargo Volume	Boundary-Overlapping	B0	<B0>-LS.3-1	795.0		
Cargo Volume	Overlapping	B0.1-5	<B0.1-5>-67BH.A-1	128.7		
Cargo Volume	Overlapping	B0.1-5	<B0.1-5>-70BH.A-1	128.7		
Cargo Volume	Overlapping	B0.1-5	<B0.1-5>-74BH.A-1	128.7		
Cargo Volume	Overlapping	B0.1-5	<B0.1-5>-66BH.A-1	128.7		
Cargo Volume	Overlapping	B0.1-5	<B0.1-5>-71BH.A-1	128.7		
Cargo Volume	Overlapping	B0.1-5	<B0.1-5>-73BH.A-1	128.7		
Cargo Volume	Overlapping	B0.1-5	<B0.1-5>-69BH.A-1	128.7		
Cargo Volume	Overlapping	B0.1-5	<B0.1-5>-72BH.A-1	128.7		
Cargo Volume	Boundary-OutsideAndTouchi	B0.1-5	<B0.1-5>-65BH.B-1	0.1		

4.6.4 Manpower:

Manpower report as shown in Table 4-7 is useful for working hour's estimations and manufacturing schedule planning. Based on this report the resource quote can be estimated at the virtual ship design level so as to account for complete ship resourcing quotation. The report is also useful to manage the inventory at the factory shop. Material arrival at the factory shop can be scheduled as per its manufacturing schedule.

Table 4-7 Manpower report output

Ship Name:				Manpower Report				Calendar					
Assembly level 2	Assembly level 1	Part Name	Dependency	Resource	Start Date	End Date	Working Hours	1	2	3	4	5	6
A1	A1-Mid	-C	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-E	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-H2-2-A	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-D	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-C	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-D1-2-A	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-B	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-H2-3-A	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-D1-1-A	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-F	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-D1-3-A	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-A	0	MediumSkilled	20121001	20121001	2						
A1	A1-Mid	-CL.14	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-CL.9	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-CL.4	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-CL.15	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-CL.10	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-CL.5	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-CL.11	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-CL.16	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-CL.1	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-CL.6	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-CL.12	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-CL.7	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-CL.2	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-CL.13	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-CL.8	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-CL.3	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-CL.21	0	LowSkilled	20121001	20121001	1						
A1	A1-Mid	-CL.23	0	LowSkilled	20121001	20121001	1						

4.7 IMPACT ON QUOTATION DUE TO CHANGE IN DESIGN

Author selected only the port side double bottom small assembly block of a mid-ship design under this research scope to study the impacts on quotation due to change in design.
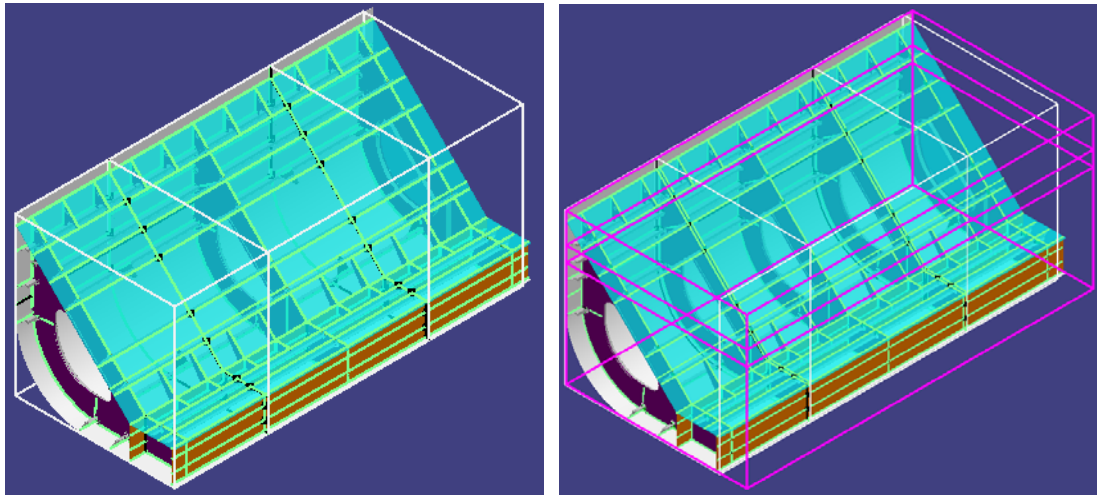

Fig. 4-18 Change in design of a prospect ship

In real ship manufacturing, there are many factors that affect design changes e.g. length, width, number of parts etc. Fig.59 shows the original design of double bottom hold in left hand side of the figure. And in right hand side, is the same double bottom hold with change in design after changing the length and additional number of parts for strengthening the hold. Author studied the variations of quotation for two independent factors.

4.7.1 Change in length of hold

Original design was studied for 11m length of hold and design variations are carried out on 11.2 m and 11.5 m length respectively.

4.7.2 Change in number of parts compared to the original design.

Author also studied the design variations by adding more strengthening parts like hull stiffener, two transverse frames with strengthening stiffeners and collar plate parts on the slots in 3 stages.

First Stage: The number of parts was increased from 168 to 194

$$\text{Increased number of parts} = 194 - 168 = 26 \text{ parts} \qquad (4\text{-}2)$$

Second Stage: The number of parts was increased from 194 to 220

$$\text{Increased number of parts} = 220 - 194 = 26 \text{ parts} \qquad (4\text{-}3)$$

Third Stage: The number of parts was increased from 220 to 228

$$\text{Increased number of parts} = 228 - 220 = 8 \text{ parts} \qquad (4\text{-}4)$$

From Equation (4-2) and Equation (4-3), you will observe that the same number of parts (26) were increased in first and second stage. This is due to the fact that an existing frame from original design was copied as similar shape[6] with all of its connecting parts strengthening stiffeners, brackets and collar parts due to the original penetrating hull stiffeners. However as per Equation (4-4) the 8 number of parts are added as described by Equation (4-5) and Equation (4-6).

$$\text{Child hull stiffeners} \qquad = 3 \text{ parts} \qquad (4\text{-}5)$$

$$\text{Collar Plates} \qquad = 5 \text{ parts} \qquad (4\text{-}6)$$

In fact only one additional hull stiffener was added in third stage but due to the mandatory design of split at transverse seams on the hull, this one stiffener was split into the 3 child parts. And due to the penetration of this additional hull stiffener through the 5 existing transverse frames created the 5 additional collar plate parts. Right hand side image in Fig. 4-17 above shows the difference in number of parts.

Table 4-8 Variations in quotation due to change in design

Quotation For Change in Design				Weight Of Material (ratio)	Weld Length (m)	Paint Area (m^2)			Manpower (Hrs)
						BLUE	RED	SILVER	
Length of Hold (m)	11 m	Number OF Parts	168	1.017	839.353	314.239	23.406	28.018	204
	11.2 m	Number OF Parts	168	1.034	840.028	319.32	23.782	28.501	204
	11.5 m	Number OF Parts	168	1.059	845.109	353.505	24.347	29.23	204
			194	1.085	909.796	372.741	25.282	29.741	234
			220	1.111	973.709	392.026	26.216	30.248	264
			228	1.118	1001.551	392.231	26.216	30.248	272

Table 4-8 shows the results of author study on impact on quotations due to change in length and number of parts. Values shown for the "Weight of Material" in this table represent only the ratio of actual values obtained in the simulation results. Results for 11.5 m length of hold shows the variations for different number of parts. Paint area are defined as BLUE, RED and SILVER colors. These colors are defined as 3 different zones in the 3D model as shown by 3 highlighted pink square boxes in

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Fig. 4-18 above. The results are for the area of the parts belonging to respective zones of the colors.

Following graphical representations shows the impacts on originally designed prospect ship when there was a change in length of hold from 11m to 11.2m and then to 11.5m. Fig. 4-19a to Fig. 4-19e below show the impact on "Weight of Material", "Weld Length", "Paint Area" and "Working Hours" versus length of hold and number of parts respectively.
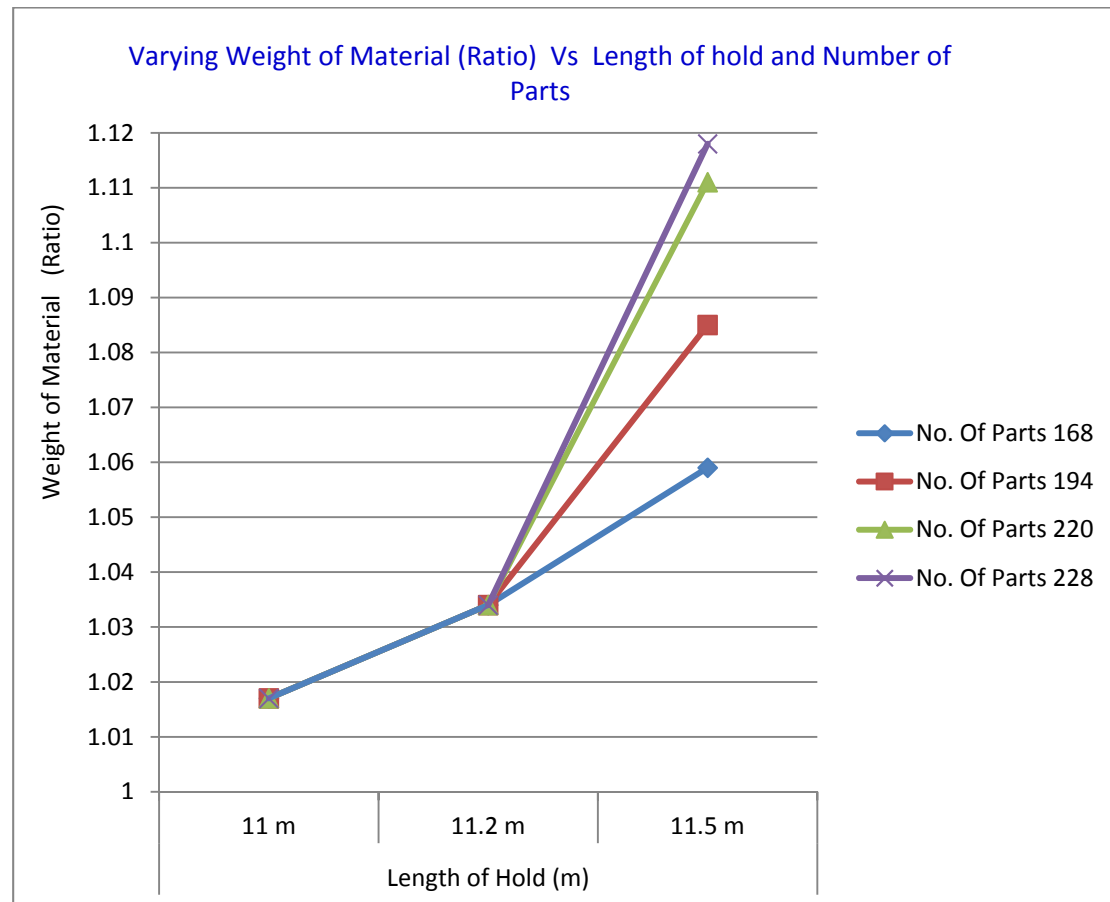

Fig. 4-19a Varying weight of material Vs length of hold and no. of parts
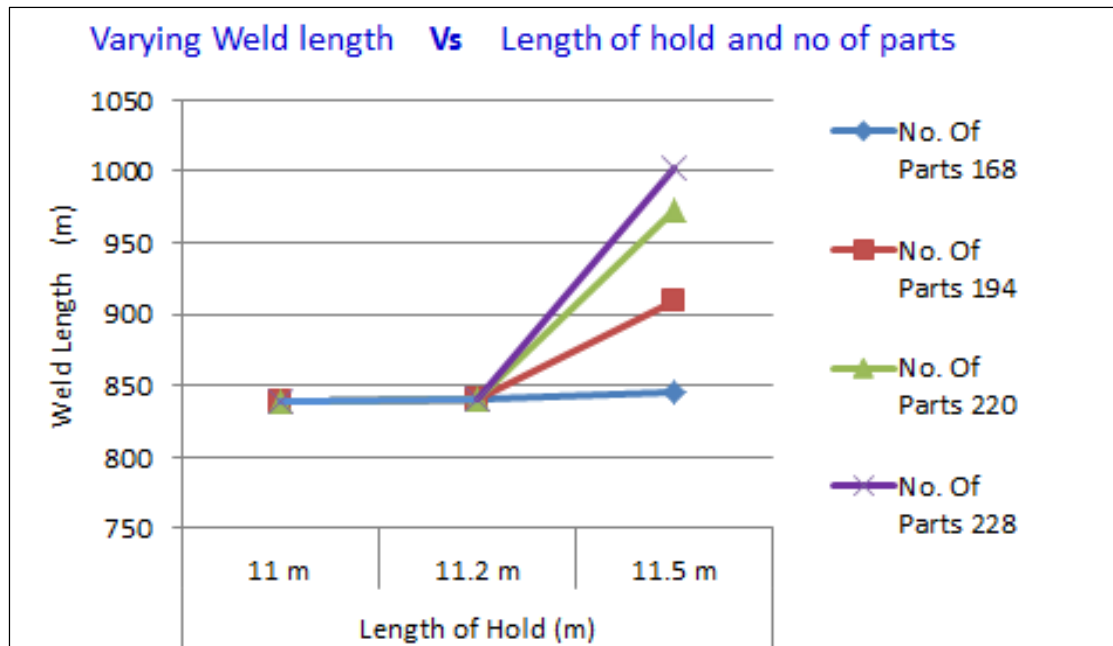
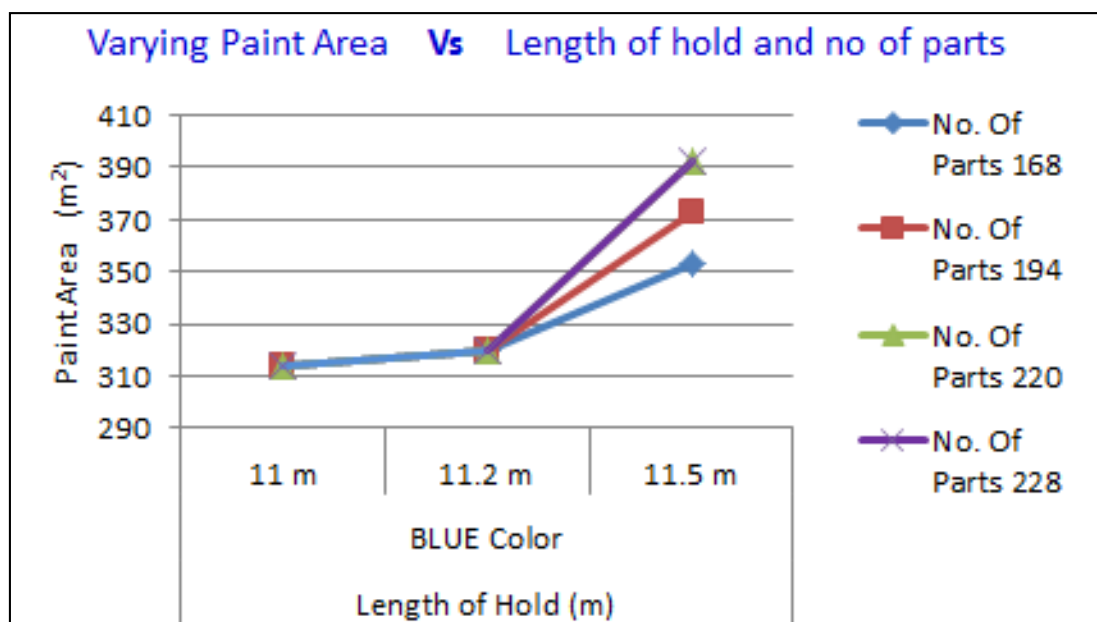Fig. 4-19b Varying weld length Vs length of hold and number of parts

Fig. 4-19c Varying paint area Vs length of hold and number of parts
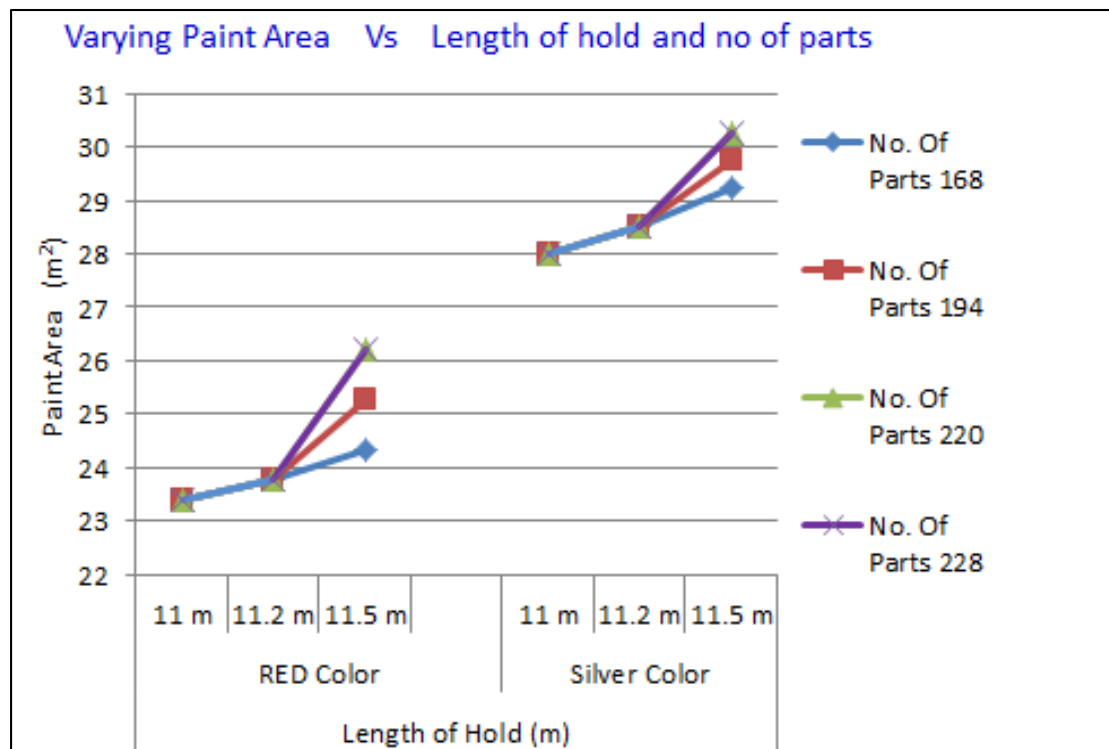
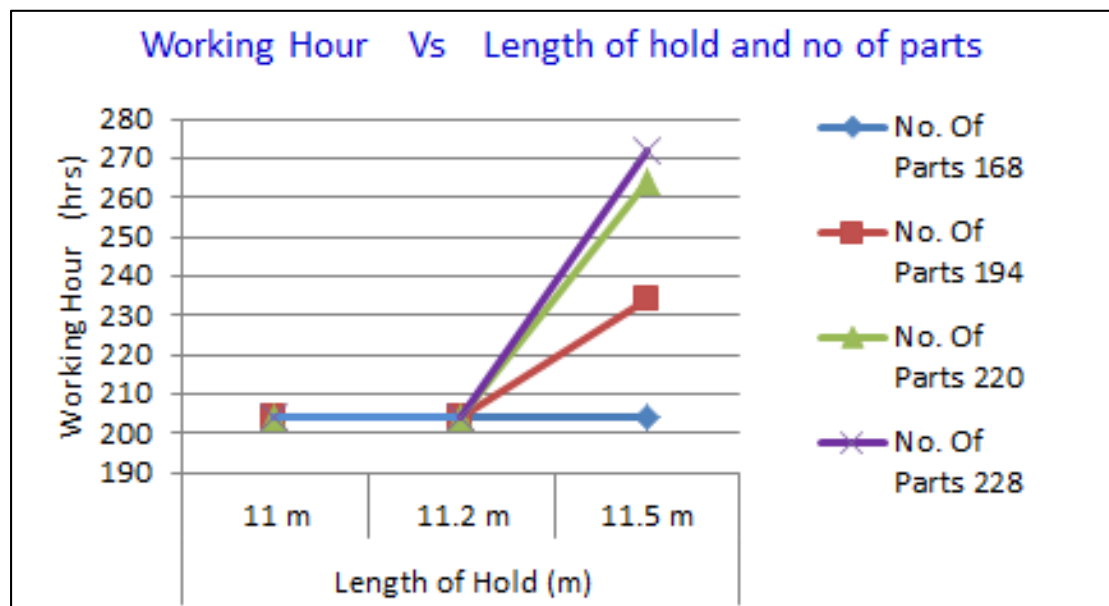Fig. 4-19d Varying paint area Vs length of hold and number of parts

Fig. 4-19e Varying working hours Vs length of hold and number of parts

Each results shows that the quotations increased by increase in length of the hold. Number of parts (168) was common when studying the results for change in length from 11 m to 11.5 meters. Only the blue color graphs for 168 no. of parts in each figures shows the variations due to change in length of the hold.

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Results also show the quotations increased by increase in number of parts in 3 stages at a constant hold length of 11.5m. Graphs are represented by dark red, light green and violet color lines. All of the graphical results show the trend in increase due to change in length or change in no. of parts fully depends on the mandatory modifications and increase in no. parts and their sizes. Similarly the trend in reduction will be seen when reducing the length of hold or no. of parts from the original designed ship.

In manpower study, it is found that there was no impact when changing only the hold length but found increase in working hours when adding new parts in the ship. This was due to reason that there was no change in time to perform labor operations on the updated parts that were updated due to change in length but additional time was needed to manufacture newly added parts. In the study, author added similar parts that were existing in original design and assigned the same working hours as that of original parts so that the realistic change can be seen in analysis.

Author also studied the variations in quotation only for the change in parts. Fig. 4-20a to Fig. 4-20c below shows the impact on "Weight of Material", "Weld Length", "Paint Area" and "Working Hours" versus number of parts respectively. Same results are used in this study too but this time the graphs are plotted independent of the hold length to study how the trend follows when there is change only in number of the parts.
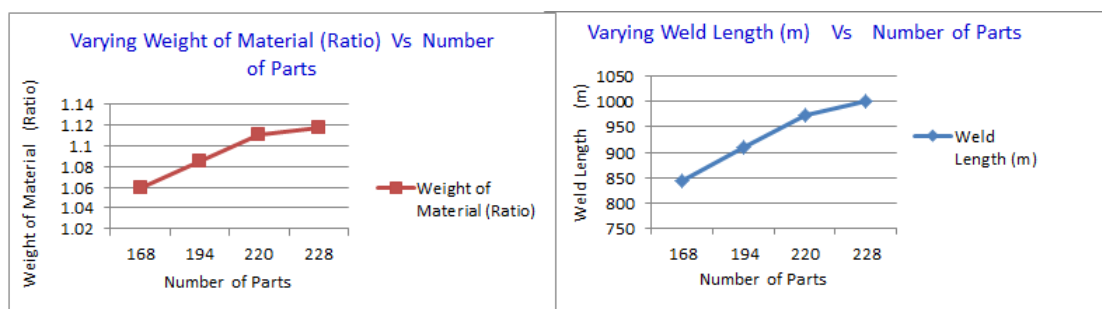

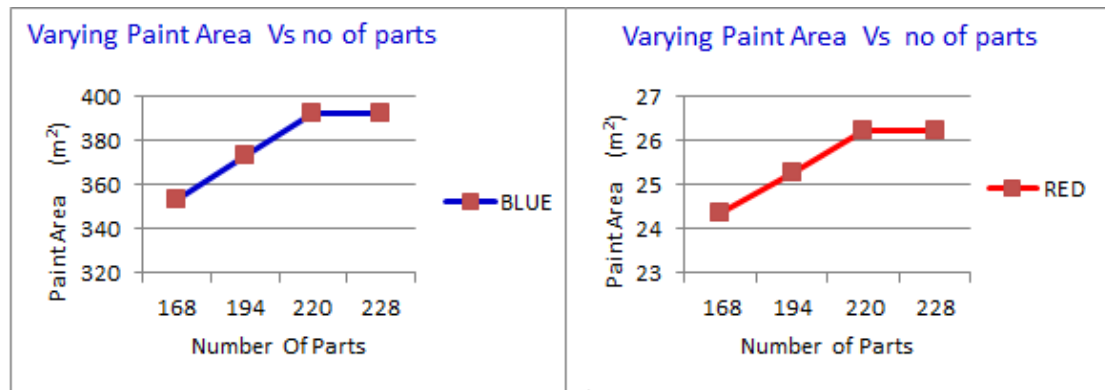Fig. 4-20a Varying weight of material and weld length Vs no. of parts

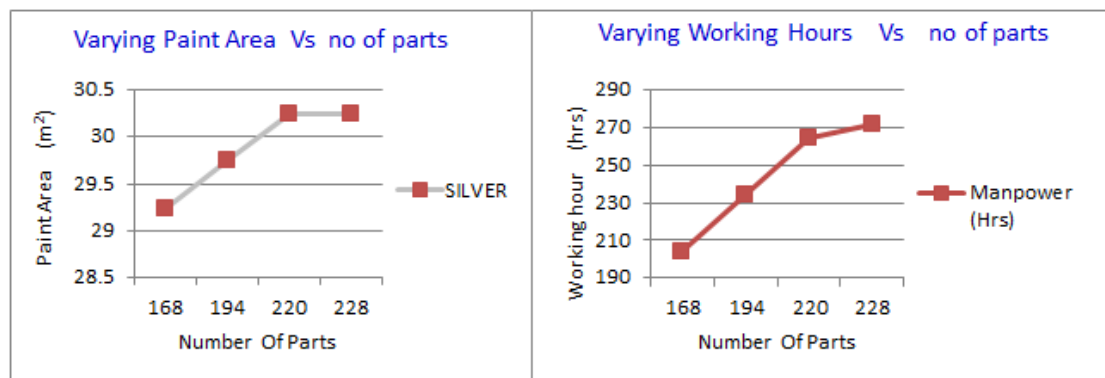Fig. 4-20b Varying paint area Vs number of parts

Fig. 4-20c Varying paint area and working hours Vs number of parts

Author observed that the results and trends in increase were same as the results that were observed for the combination of increase in length and number of parts as per Fig. 4-19a to Fig. 4-19e.

Author further extended the analysis for more detailed variations in ship design and tried to observe the impact on quotations. Table 4-9 below shows the brief explanation on design changes applied in a research model.

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Table 4-9 Design Variations to Analyze Impact on Quotation

Quotation For CHANGE in Design		Details of Parts Added
Length of Hold (m)	11.0 m (168 parts)	Standard Design
	11.2 m (171 parts)	1. Increased the section sizes of Hull and Bilge Hoper profiles from (UA 150 × 9) to (UA 200 × 9) 2. Increased the size of Brackets 3. Added a Hull Profile (Bilge Keel) and Brackets
	11.4 m (183 parts)	1. Added new Transverse bulkhead 2. Increased the section sizes of Hull and Bilge Hoper profiles from (UA 200 × 9) to (UA 250 × 9) 3. Increased the size of Brackets
	11.6 m (192 parts)	1. Increased Hull plate thickness 2. Increased the section sizes of Hull and Bilge Hoper profiles from (UA 250 × 9) to (UA 300 × 11) 3. Increased the size of Brackets 4. Added new Bilge Hoper Profile and Brackets
	11.8 m (208 parts)	1. Increased the section sizes of Hull and Bilge Hoper profiles from (UA 300 × 11) to (UA 350 × 11) 2. Increased the size of Brackets 3. Added two Hull Profiles and Brackets
	12.0 m (252 parts)	1. Added new Transverse bulkhead 2. Increased the section sizes of Hull and Bilge Hoper profiles from (UA 350 × 11) to (UA 400 × 12) 3. Increased the size of Brackets

This time, the variations of quotation is studied for change in length and change in number parts including its dimensions.

4.7.3 Change in length of hold

Original design was studied for 11m length of hold and design variations are carried out on 11.2 m, 11.4 m, 11.6 m, 11.8 m and 12.0 m length respectively.

4.7.4 Change in number of parts and section sizes compared to the original design.

Study on design variations by adding more strengthening parts like hull and bilge stiffener, two transverse frames with strengthening stiffeners, brackets and collar plate parts on the slots was carried out.

Table 4-9 shows the complete details of geometrical changes made at each change in hold length. When adding two transverse frames, existing frame from original design was copied as similar shape with all of its connecting parts

strengthening stiffeners, brackets and collar parts. Right hand side image in Fig. 4-18 above shows the differences.

Table 4-10 Quotation variation results due to change in design

Quotation For CHANGE in Design		Weight Of Material (Ratio)	Weld Length (m)	Paint Area (m²)			Manpower (Hrs)
				BLUE	RED	SILVER	
Length of Hold (m)	11.0 m (168 parts)	1.0171	839.353	314.239	23.406	28.018	204
	11.2 m (171 parts)	1.0574	867.848	337.358	24.05	29.287	207
	11.4 m (183 parts)	1.0957	929.906	384.659	23.396	29.763	220
	11.6 m (192 parts)	1.1777	984.713	379.579	23.435	30.279	229
	11.8 m (208 parts)	1.2536	1071.445	441.946	23.836	30.764	245
	12.0 m (252 parts)	1.3406	1214.21	458.599	25.972	31.445	295

Table 4-10 shows the results of the study on impact on quotations due to change in length and number of parts. Values shown for the "weight of material" in this table represent only the ratio of actual values obtained in the simulation results. Paint areas are defined as blue, red and silver colors. These colors are defined as 3 different zones in the 3D model as shown by 3 highlighted pink square boxes in Fig. 4-18 above.

Fig. 4-21 below shows the graphical representations for the impacts on originally designed prospect ship when there was a change in length of hold from 11.0 m to 12.0 m. Figure shows the impact on "weight of material", "weld length", "paint area" and "working hours" versus length of hold and number of parts respectively. Each results shows that the quotations increased by increase in length of the hold. Graph also shows that, the ratio of increased in the quotation for one factor differs with the other factors for the same change in length of hold e.g. at length 12 meters, the ratio of increased in the quotation for manpower and red paint area is more compared to the other factors. This is because, the time required for manufacturing and painting red color for the additional number of parts that are added at 12 meters length of the hold is more compared to the time required for other factors.
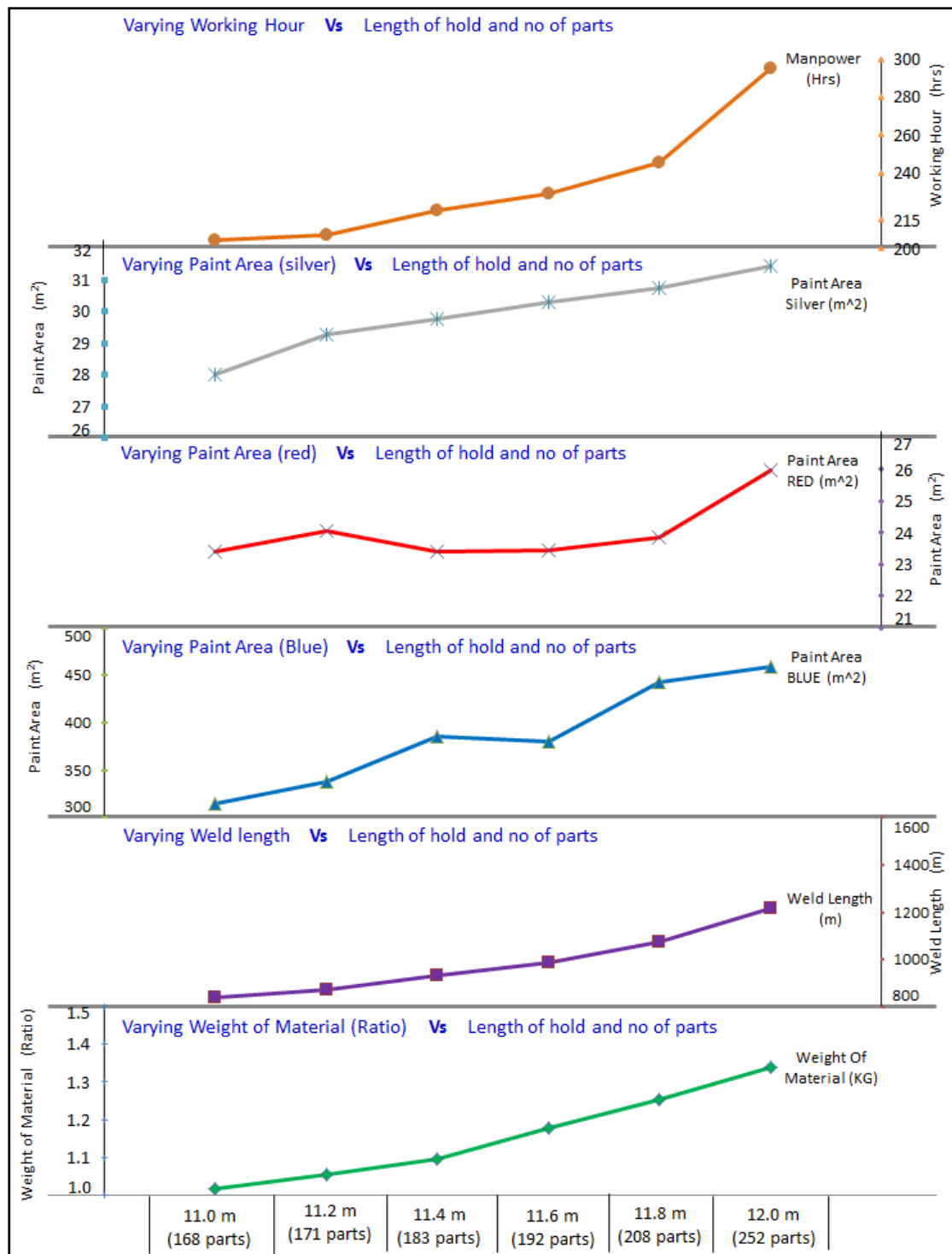
Fig. 4-21 Impact on quotation due to change in design

All of the graphical results show the trend in increase due to change in length or change in number of parts fully depends on the mandatory modifications and increase in number of parts and their sizes. Similarly the trend in reduction will be seen when reducing the length of hold or number of parts from the original designed ship. In the study, author added similar parts that were existing in original design and assigned the

same working hours as that of original parts so that the realistic change can be seen in analysis. Thus the graphical result proves that, the quotation estimation variations is not standard and varies for any kind of design changes during manufacturing lifecycle. This variation enforces the shipbuilders for a need of dynamic and real time estimation methodology. The customization tool used in this research helps the ship manufactures to estimate the ship construction quotation dynamically and in real time.

4.8 Summary

The application of Petri net graph theory was further extended to automate the ship construction estimation. This chapter has provided the details of major estimation factors that area ready to use from 3D CAD application data. The chapter explains that, how the major factors are impacted by a change in design parameters affecting the original estimations. Further a dynamic realistic estimation method is provided which can be used at any design or production time so that the stake holders are kept up-to-date with the change in original plans and financial impacts to take the preventive actions before it becomes too late.

CHAPTER 5

CONCLUSIONS

5 CONCLUSIONS

This research study is conducted in three different phases. In first phase, which is the key innovation of this research study, proves that the automation rules for an expert system written in any programming languages can be analyzed using the Petri net graph theory. In second phase, author provided an automation tool that can be used to quickly identify the design errors in the virtual ship model created using automation rules. In third phase, author provided a tool for the estimation of ship construction quotation. The tools introduced in second and third phase of the research study are the additional examples of the automation rule which can also be analyzed using the Petri net graph theory before developing the logics in any software development programming languages.

This research study proves that the Petri net theory is very useful to analyze extremely complex graphs created from the complex logic of any automation rule. Similar analysis can also be performed on each individual functions like only slot and collar rule or profile end cut rule or profile end scallop rule etc. It is fully depending on the available inputs and driven or expected outputs. This concept is fully applicable for any expert systems.

The analysis results and resolution of the design failure condition by Petri net theory proves that the shipyards can now rely on their automation rules created using Petri net automation concept and increase the quality of their production. It also helps to reduce the design time since design features are now automatically created with complete reliability. Manual verification is not needed anymore for the automation rules achieved using this analysis.

Research is done on a real ship model of a Japanese shipyard. Automation rules are applied in this ship model from its basic design to production design. Ship design automation rules are analyzed using Petri net graph theory. This theory helped to identify the contradictions and missing logics in the original automation rule. To resolve this problem, new logic has been analyzed in the original graph and the resolution of the problem is verified by mathematical analysis results with newly introduced graph. Additional logic for visual basic program is recommended to avoid the unexpected design. Finally a test is performed on the virtual ship model to confirm

that unexpected design does not occur by automation rules created using Petri net automation concept.

Although the research study is applied on ship design automation rule, the theory is fully applicable for any kind systemization using the reachability concept applied on one or more regions in a Petri net. Following conclusions of author's research on additional systemization explains the benefits of using Petri net automation concept.

As described in section "3 AUTOMATION FOR SHIP DESIGN VERIFICAION", shipyards prints the A3 size drawings to verify access path rules and ship regulations. Designers need to spend almost about 10 minutes per drawing to verify if all rules and regulations are followed. There are almost 40 such drawings that need to be verified. This means shipyards spend almost 400 minutes (6.5 hrs) for this verification. This is also a tiresome job for a designer to verify minute details manually in a drawing.

Author could able to reduce this verification time just to 5 minutes by inventing this Access Path Verification Tool. The tool is also user friendly since the areas of improvement are identified visually in a tool.

The computation results of this research could also help to assure the access path quality in a ship design since the results computed using this tool are highly accurate since they are computed using an information system. Moreover, using this tool, the designers can quickly verify the classification society rules and designers know-how.

The research and analysis results described in section "4 AUTOMATION FOR SHIP CONSTRUCTION ESTIMATION" shows that the ship manufacturing goes through various financial fluctuations right from the design stage through the manufacturing and final delivery stage due to various changes in the ship design, ship owners requirements and also may be due the change in market situations. This study proves that the dynamic/real time quotation estimations are achieved right at the time of change in requirements/ship design etc. This achievement will help all stake holders to maintain complete financial satisfactions. This achievement also helps to maintain the financial balance between the shipbuilding industries in today imbalance market situation.

As seen in all of the reports output in this section, author could able to retrieve the major factors (Weigh of Material, Weld Length, Paint Area and Manpower) details

for estimation of a prospect ship based on the customization done in the virtual ship design CAD application. Based on these reports, the ship raw material, welding rod procurement, paint requirement and resource quote can be estimated at the virtual ship design level. The similar customization can be extended for retrieving the details of all other factors that are necessary for completing the prospect ship quotation. The graphical results for these factors proved that there is no particular standard in trend in increase or decrease of the quotation however it all depends on what kind of design changes are occurred. Hence it is very crucial for each stake holders that these variations are managed dynamically in real time of the prospect ship life cycle time so as to avoid wrong decisions.

Based on the analysis results in this research, it will also be possible to customize the application for creating realistic Production Schedule (Gantt Chart) and Inventory Management reports using the manpower and dependencies information in virtual model. An automated rule can be written in virtual ship CAD application which can retrieve the production schedule from the start of production date to end of the production date and dependencies can be used to identify if the part that scheduled to manufacture has any dependency on other parts and if the manufacturing process of dependent part is already finished. Uncertainty in the business situations, changes requested by the Ship Owner or any other consequences may impact the scheduled plan. The customized automation rule for production schedule will help to react dynamically and in real time to the uncertain changes in various conditions. Automation can also be done to manage the inventory at manufacturing shop. Based on the production schedule, the material arrival at the factory shop can be scheduled for Just-In-Time arrival. Similar to the impacts on production schedule due to various uncertainty, the inventory management can also be updated and material arrival at the factory can be rescheduled using the automation done based on manpower data in virtual ship CAD application. All of these achievements in a single 3D CAD application will help in efficient end to end capital lifecycle management.

Following are the conclusive summary of this research:

1. A Virtual Ship is designed in 3D CAD application.

2. Ship Design automation rule for slot-collar combination is analyzed using Petri net graph theory

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3. Theory helped to identify the contradictions and missing logics in automation rule

4. A region has been defined in the Petri net graph.

5. A new logical test condition for all input group utilization is introduced.

6. New logic has been analyzed in the graph to help resolving the problems analyzed in the design rule.

7. Resolution of a problem is verified by mathematical analysis results from newly introduced graph.

8. Additional logic for visual basic program is recommended to avoid the nonstandard design.

9. Realistic ship model is tested again with the new logical condition and it is verified that the unexpected design is avoided with the new concept.

10. Petri net automation concept is applied on ship design verification rules.

11. ClassNK XML is created from 3D CAD application.

12. Access Path Verification Tool is developed using DML.

13. Translation tool is developed using visual basic programming language.

14. The ship design verification rule helped in reduction for design verification time compared to existing manual verification.

15. The safety of crew members and ship inspectors are assured by increasing the quality of access path.

16. Design improvements are verified visually in Access Path Verification Tool.

17. Ship drawings could be generated automatically from a virtual ship for ship owners and classification society approvals.

18. Estimate the ship construction quotation using rule based estimation method.

19. The reports generated from ship construction estimation can be utilized for the realistic Production schedule (Gantt Chart) using the dependencies and resource utilization information from virtual model.

20. Customized automation rule can also be applied to manage the inventory at manufacturing shop. Based on the production schedule, the material arrival at the factory shop can be scheduled for Just-In-Time arrival.

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APPENDIX

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APPENDIX A

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"Rule Based Ship Design Automation - Research, analysis and achievements using Petri Nets Theory", the Journal of the Japan Society of Naval Architects and Ocean Engineers", December 2013, pp. 199-206.

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NOMENCLATURE

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NOMENCLATURE

Abbreviation	Nomenclature
ΔM	Marking State
2D	Two Dimenssional
3D	Three Dimenssional
A	Incidence Matrix of Petri net Graph
A^-	Weight of the Arc to Transition from its Input Place
A^+	Weight of the Arc from Transition to its Output Place
A1	Slot Type 1 for Penetrating Profile IA
A_{11}	Nonsingular Matrix
A1-1	Slot Type 1 and Collar Type 1 for Penetrating Profile IA
A_{12}	Nonsingular Square Matrix
A1-2	Slot Type 1 and Collar Type 2 for Penetrating Profile IA
A1-3	Slot Type 1 and Collar Type 3 for Penetrating Profile IA
A2	Slot Type 2 for Penetrating Profile IA
A2-1	Slot Type 2 and Collar Type 1 for Penetrating Profile IA
A2-2	Slot Type 2 and Collar Type 2 for Penetrating Profile IA
A2-3	Slot Type 2 and Collar Type 3 for Penetrating Profile IA
A4	Slot Type 4 for Penetrating Profile IA
A5	Slot Type 5 for Penetrating Profile IA
A5-3	Slot Type 5 and Collar Type 3 for Penetrating Profile IA
B1	Slot Type 1 for Penetrating Profile BP
B1-1	Slot Type 1 and Collar Type 1 for Penetrating Profile BP
B1-2	Slot Type 1 and Collar Type 2 for Penetrating Profile BP
B1-3	Slot Type 1 and Collar Type 3 for Penetrating Profile BP
B2	Slot Type 2 for Penetrating Profile BP
B2-1	Slot Type 2 and Collar Type 1 for Penetrating Profile BP
B2-2	Slot Type 2 and Collar Type 2 for Penetrating Profile BP
B2-3	Slot Type 2 and Collar Type 3 for Penetrating Profile BP
B4	Slot Type 4 for Penetrating Profile BP
B5	Slot Type 5 for Penetrating Profile BP
B_f	Fundamental Circuit Matrix
$B_f \Delta M$	Reachability of Petri net Graph

CAD	Computer Aided Design
classNK	Nippon Kaiji Kyokai Classification Society
DaNAMiCS	DaNAMiCS is a simulation tool for Petri net model
dll	Dynamic Link Library
DML	Data Manipulation Language
DXF	Drawing Exchange Format
H	Height
IG1	Input Group 1
IG12	Input Group from Region 1 to 2
IG12P	Total Number of Places Input Group from Region 1 to 2
IG1P	Total Number of Places in Input Group 1
IG2	Input Group 2
IG23	Input Group from Region 2 to 3
IG23P	Total Number of Places Input Group from Region 2 to 3
IG2P	Total Number of Places in Input Group 2
IG3	Input Group 3
IG3P	Total Number of Places in Input Group 3
IG4	Input Group 4
IG4P	Total Number of Places in Input Group 4
IT	Information Technology
I_μ	Identity Matrix
L	Lag Touch on Profile End
L21	Slot Type 1 for Penetrating Profile Built Up L2
L31	Slot Type 1 for Penetrating Profile Built Up L3
LS	Lag Touch and Snip Cut on Profile End
M_0	Initial Marking State
M_d	Destination Marking State
NURBS	Non-uniform Rational Basis Spline
P	Finite Set of Places
PIPE	Platform Independent Petri net Editor
PLM	Product Lifecycle Management.
PNK	Petri Net Kernel

PrimeShip	PrimeShip consists of a range of software applications and supplementary services which offers an approach to enhancing safety throughout the life of ships.
r	Rank of Incidence Matrix of Petri net Graph
R	Radius
R1	Region 1
R2	Region 2
R3	Region 3
RFP	Request For Proposal.
RFQ	Request For Quotation.
RT1n	Total Number of Immediate Transitions in Region 1
RT2n	Total Number of Immediate Transitions in Region 2
RT3n	Total Number of Immediate Transitions in Region 3
S	Snip Type Cut on Profile End
S1	Slot Type 1 for Penetrating Profile FB
S2	Slot Type 2 for Penetrating Profile FB
S4	Slot Type 4 for Penetrating Profile FB
S5	Slot Type 5 for Penetrating Profile FB
Silos	A management system incapable of reciprocal operation with other, related information systems.
T	Finite Set of Transitions
T1	Slot Type 1 for Penetrating Profile Built Up T
T2	Slot Type 2 for Penetrating Profile Built Up T
T4	Slot Type 4 for Penetrating Profile Built Up T
T5	Slot Type 5 for Penetrating Profile Built Up T
TDL	To Do List
W	Width
XML	Extensible Markup Language

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