THE APPLICATION OF MODULAR ELEMENTS IN THE DESIGN AND CONSTRUCTION OF SEMI-SUBMERSIBLE PLATFORMS

BY

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door de promotoren

Prof.Dr.Ing. C. Gallin   Prof.Ir. S. Hengst

Contents

Chapter 1

Introduction

1.1 Background

In the strive for reduction of building costs in the construction of marine structures, two main approaches have been suggested /1.1-10/ :

1. Through the design, by reducing (steel) material costs through increased efficiency of (steel) material usage and ever improving methods of structural strength/reliability analysis.

2. Through the construction, by reducing production costs through matching more closely design requirements with production capacity; this was termed "design-for-production".

In both approaches, one seeks for the relation between design parameters and cost price, but a different basis has been suggested :

- In the first approach, the emphasis has been laid on steel weight as a measure of merit for the cost price; the results of the reviewed studies indicate :
  - . steel weight optimization gives cost savings for certain types of vessels such as tankers, bulk-carriers, etc.
  - . for volume controlled ships such as containerships and car-carriers, weight optimization is not of primary importance and steel weight alone cannot be used as a measure of merit for the cost price.

- In the second approach, the emphasis has been laid on the interaction between the structural design system and the (steel) production system. The combined effect of steel materials and production costs is used as a measure of merit for the cost price. Hereby, local, yard-related factors such as the cost of labour, production performance, etc. are introduced. An important aspect here is the flow of information between the two systems. The following havebeen suggested as necessary conditions for design-for-production approach :

- the possibility to determine the work content of the structure o the basis of design information and the procedures and methods b which the structure is constructed at the particular building (yard) location.
- the availability of production cost data in a form which enables the production costs to be determined directly from the (structural) design information on the basis of the determined structure work content; hereby, the relation between design parameters and production costs, for the particular yard, is established.

An example on design-for-production is the attempt to reduce cost-price by simplifying the external shipform geometry /1.11-13/. Prefabricated flat panels instead of double curvature panels were used to achieve the required ship characteristics.

The above studies have increased the ability of designers to generat more efficient structures in terms of material usage as well as thei consciousness towards the various aspects of production, resulting i a better control of the cost-price. It seems, however, that the achieved improvements have reached a threshold and that the current concepts used in the design and construction of marine structures hold no potentials for further breakthrough in cost-price reduction.

In the strive for a breakthrough in the above situation, much can be learned from other enterprises where an industrial approach to the production process has led to rationalization of design and production in terms of :

1. Design simplification by using series of pre-determined, standardized components and structural patterns.
2. Advanced mechanization and automation in manufacturing of components and assembly of the final product.
3. Increased efficiency in the entire production process due to "learning effects" associated to the use of standardized components and structural patterns.

The possibility to apply the above in marine constructions may hold the key for further breakthrough in cost-price reductions.

If such is to be achieved, a different approach towards design and construction of marine structures is required. In the line of considerations regarding such a possibility, the following characteristics regarding the marine product should be taken into account :

- The product is physically complex and of sizeable dimensions.
- The design is tailored to a specific and often unique set of requirements.
- Work preparation and production procedures are design-tailored to a high degree.
- The nature of the market (capital goods) limits deliveries, with few exceptions, to a one-off basis or small batches.

1.2 A new approach

This investigation deals with a new approach in design and construction of marine products which aims to achieve a further breakthrough in cost-price reduction, in particular with respect to the steel structure. Within this approach, a concept will be developed which incorporates elements (1) and (3) above (other enterprises) and uses series of standardized structural components to generate a more complex structure; this concept is termed "modular concept".

In general, the proposed modular concept will address the above-suggested approach in design-for-production with respect to the conditions of information transfer and the availability of data. Newly introduced is the industrial approach to the production process which will be based on the following :

- A standardization of structural patterns throughout the entire steel structure, at levels beyond the most elementary components such as plates and rolled sections.
- A series-wise production process which, if applied in the construction of the steel structure of marine products, create conditions for the introduction of learning effects in cost calculations regarding a single final product.

Two additional conditions are imposed :

1. The modular concept must enable to generate design solutions technically comparable with solutions obtained by conventional design methods.
2. The obtained reduction in cost-price must be in excess of the possibilities contained in the current design-for-production methods, with due regard for eventual increase of capital investments necessary for the realization, in practice, of the modular concept.

The above implicate comparison with the existing practice in design and construction of marine structures and, thus, the choice of a reference product and a reference production facility. With respect to the former, a semi-submersible drilling platform was chosen to represent the inventory of marine structures (ships and offshore structures) on the basis of the following requirements :

- Commercial functioning such as transport of dry/liquid cargo, exploitation of marine resources, support of offshore activities.
- Structural composition in terms of complexity, patterns and components.
- Sufficient interest for which a world-wide market can be found.
- Sufficient available data.

See also Chapter 2, par. 2.2.1.

With respect to the reference production facility, comparison with the current practice relies on data regarding activities, facilities, methods, performances, cost factors, etc. With a view to possible applications of the modular concept, current practice in Dutch marine construction yards is maintained as a basis for comparison.

1.3 Investigation scheme

To obtain insight in matters regarding the realization of marine products, the investigation is initiated by an analysis of the current practice with respect to :

1. Design and construction of the steel structure.
2. Calculation of building costs for the above.
3. The activities and relations between the parties involved.

A schematic representation of the above set-up is given in Fig. 1.1. By introducing the new elements of modular concept and learning, a new set-up is obtained (Fig. 1.2) which forms the basis for the further scheme of investigation. The obtained insight will be used, at a later stage, in the implementation of the modular concept.

The requirements, functions and technical characteristics of the reference product, the semi-submersible drilling platform, are analysed in order to obtain insight in :

- Design aspects; this is necessary for the later establishing of a design procedure following the modular concept.
- Structural composition; this is necessary for the establishing of components' liability to modular construction and the implementation within the semi-submersible structure.

(Chapter 3)

The actual implementation of the modular concept in design, construction and calculation of building costs is done in Chapters 4 and 5 in accordance with the flow diagram from Fig. 1.3.
Chapter 4 deals with the design. Methodology and models are briefly discussed with respect to the conventional approach to semi-submersible platform design. A procedure for the preliminary design of semi-submersible drilling platforms is developed on the basis of the following :

1. Requirements usually involved in conventional design practice with regard to adequate technical characteristics in matters of

operability and safety. For the former, the measure of merit is motion characteristics; for the latter, the stability and structural strength characteristics in conformity with the requirements of a classification society /1.14/.

2. Requirements specifically related to the proposed modular approach and concerning :
   - liability to modular-wise construction on the basis of a limited number of standardized series of structural components; will be later used to develop a modular-wise building procedure.
   - provide information for the later development of a cost-calculation model which fulfills the conditions of design-for-production.

The developed design procedure is demonstrated by calculations and comparison with an existing, conventionally performed design /1.16/. The outcome will indicate to what extent the condition of technical comparability has been met.

An industrial approach to the building of the reference marine product involves also the organization of the reference construction yard in terms of activities, facilities, methods, performances, etc. Considering the already-taken decision on the maintenance of the current practice in Dutch marine construction yards, the implementation of the industrial approach will be done on the basis of this practice. On the other hand, a more systematic production process will be introduced by :

- Considering the product as a limited assortment of structure series, at various levels of complexity.
- Differentiating between :
  - . the type of connections effectuated in the course of the various assembly stages.
  - . the type of activities performed with respect to these connections.

This approach is used for the development of a building procedure and a calculation model for structure's work concent, both fulfilling the conditions of design-for-production. This is necessary for the

calculation of labour effort and costs. The cost-calculation procedure follows in general the guidelines set by the Netherlands Shipbuilding Industry Foundation N.S.N.I. /1.15/.
The calculation model is meant for comparison between alternatives and involves, in addition to steel material costs, only those costs of labour and overheads which are directly related to the building of the steel structure.

The developed models are demonstrated by calculating labour effort and production costs for simple and complex parts of the steel structure of the semi-submersible platform.

The element of learning is introduced in Chapter 6 with respect to the fabrication of structure series within the building process of complex parts of the semi-submersible platform. First, factors and conditions necessary for the realization of learning in industrial production processes are discussed with the purpose of determining a set of principles for introducing learning effects. Then, a parallel is drawn with the practice in (modular) marine constructions in order to establish the extent to which the above factors and conditions are met and the liability of (building) activities to learning. The obtained conclusions are implemented, in accordance with the established principles, in the cost-calculation model developed in Chapter 5. Hereby, first insight in the effects of learning on labour effort and costs is obtained.

The impact on the building facility itself is addressed with respect to the following :
- The organization, through changes in the level of activity due to reduction of labour effort and becoming available of production capacity.
- The economical side with respect to the sensitivity of the obtained financial room to eventual capital investments.

The condition on the reduction of building costs, in excess of the possibilities contained in current design-for-production practice, is handled in Chapter 7 with respect to the complete steel structure of the semi-submersible platform. The relation between design parameters and cost-price is demonstrated for a limited range of design solutions. In addition, the sensitivity of the modular concept is investigated with respect to variations of :

- Yard set-up, in terms of cost variables such as capital investments and wages.
- Learning.

A summary of the most important conclusions and new aspects which emerged in the course of this work are presented in Chapter 8.

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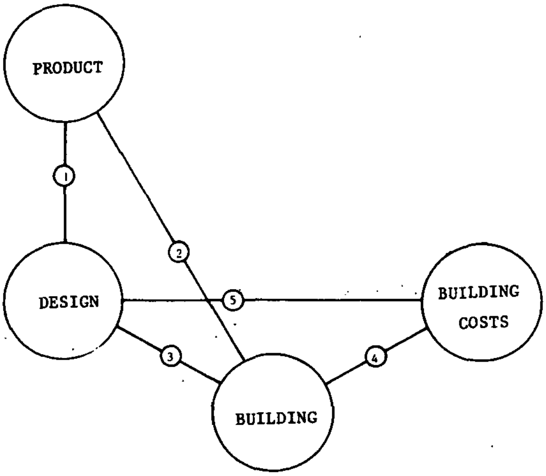

Fig.1.1 : Notions and relations in current marine construction practice

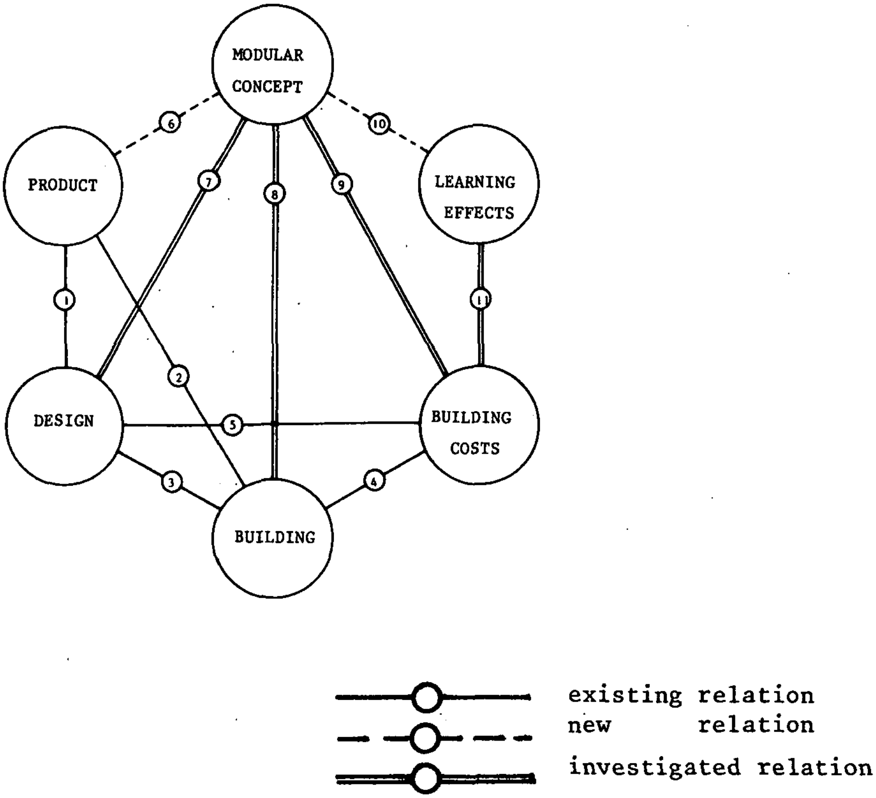

Fig.1.2 : Notions and relations in the new approach

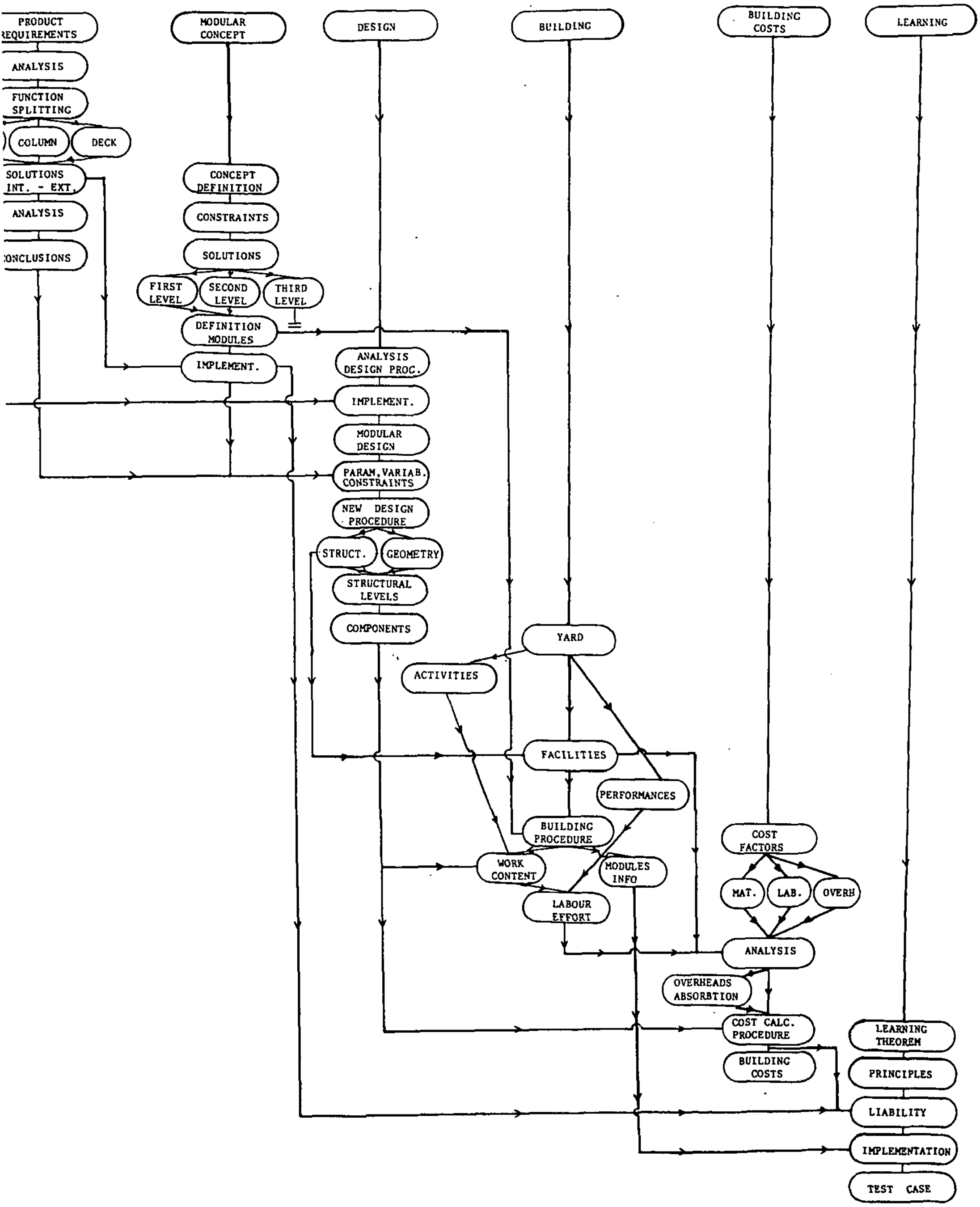

Fig.1.3 : Work scheme

Chapter 2

Current practice in the marine industry

2.1 Introduction

To investigate the matter of cost-price reduction, one needs to know :

1. The nature of the involved costs.
2. The way the costs are incurred.
3. The necessary information on (1) and (2), its transfer and use during the realization of the marine product.

Details on the above are found in the current practice with respec to the realization of the product :

- Design and construction.
- The cost calculation procedure.
- The activities and relationships between the parties involved.

All these are confined within the notions and relationships shown in Fig. 1.1; the necessary information is transferred through the design notion (relations 2 and 4), the construction (relations 2 and 5) and the coupling relation 3.

A more detailed representation of the above is given in Fig. 2.1. The notions of the design and construction and their respective relations form the sources of two main streams of information in the calculation of building costs. Design and building represent also the two main phases in the realization of the marine product.

The following investigation of the current practice in marine constructions is meant to provide insight in the realization of marine products, in particular with respect to matters of interest in the calculation of the cost price.

2.2 The marine product

2.2.1 Definition

The marine product belongs to the group of capital goods; a suggested definition is that of a system which fulfills one or more functions either independently or within a larger system.
Possible functions are :

- Transport of goods, raw materials, passengers.
- Fishing and/or other industrial activities (exploration and/or exploitation of hydrocarbons, minerals, etc.).
- Support for the above (storage, construction, maintenance).
- Survey and security, etc.

The inventory of the existing marine products comprises a large variety of structures which may be grouped on the basis of their functions, size, operational area, etc. A meaningful representation of this inventory, by one single product, has to rely on the largest possible combination of group characteristics.

A possible division into groups is based on the relation between product functions and its structure. The following distinction is made :

1. All functions are housed within a single main structure (monohull), which has a caisson-type structural configuration. This group comprises mostly floating structures and includes all types and sizes of ships for transport of goods, passengers, research, industrial activities and warfare.
2. Functions are divided over two or more main structures or function-dedicated structures; the structural diversification is larger and includes caisson-types, lattice-types or combinations hereof. This group comprises some floating structures such as catamaran hulls, push-barge combinations, etc. but also all types of gravity structures, self-elevating structures, jackets, semi-fixed structures, etc.

The chosen reference product, the semi-submersible platform, combines the characteristics of the above groups with respect to :

1. Separation of functions which are housed within separate structural bodies.
2. Structural configuration combining caisson-type and lattice-type structures.

2.2.2 The design

In the broad sense, the aim of the design is to provide a technical/economical solution to a specific set of requirements within a specified set of constraints. The solution consists of the following :

a. An external geometrical form given by dimensions and shapes, hereafter the geometrical design solution.
b. An internal geometrical form given by the arrangement of structural patterns which fulfil functional and strength requirements, hereafter the structural design solution.

In addition, an arrangement of machinery, equipment, systems and controlls concerning the functions and the safety of the marine product. The quality of the solution is judged by technical/economical characteristics such as resistance, propulsion, stability, behaviour in a sea-way, storage volumes and areas, cost-price, etc.
The relation with the geometrical and structural design solutions and some relevant aspects are given below.

2.2.2.1 The geometric design

The geometrical design solution is of importance for the determination of the following :

- Resistance
- Stability against overturning
- Behaviour in a sea-way; motions and other phenomena such as the shipping of green water, slamming, etc.
- Hold volume
- The generated environmental loads serving as input for the determination of strength characteristics
- Mass and mass distribution.

Some approaches, methods and means to establish the geometrical design are discussed in /2.1-7/. For some marine products, it has been common practice to link cost-price to parameters related to the external geometrical form /2.8/.

2.2.2.2 The structural design

In the broad sense, the structural design is concerned with the (structural) safety of the marine product as well as the provision of local support for light and dead-weight items.
The structural arrangement or composition of marine structures consists of various elements which can be divided into three levels of structural complexity /2.9/ :

- The primary level which refers to the characteristics of major elements of the complete structure such as hull, decks, etc.
- The secondary level which refers to the structural composition (pattern) of primary elements and consists mainly of an assortment of stiffened panels.
- The tertiary level which refers to the structural composition of secondary-level structures such as plates and stiffening elements, but also other simple structural components such as brackets, face flats, etc.

The primary level

Elements of construction belonging to the primary level are related to the external geometrical form and therefore concerned with the functions of the latter. Because of this, the primary level is oriented mainly towards efficient external geometrical form rather than efficient internal structural form.

The secondary level

At this level, a distinction is made between curved and flat panels. Flat panels take an important share out of the total steel weight; some examples are :
- Containerships and medium-sized product carriers, about 30%
- Large tankers and ore carriers, about 60%

/2.9/.
For various other marine products such as barges, floating docks, etc., this percentage is even higher.

Flat panels have been also the subject of various weight and cost-price optimization studies. Unlike elements of the primary level, the number of variables involved is small, whereas loads and constraints can explicitely be defined /2.9-13/. These studies provided useful information on building cost aspects which have been used in cost-reduction measures, either within the approach of weight minimization or within the approach of design-for-production.

The tertiary level

This level is concerned with the most elementary structural components either ready-made or yard-fabricated. The variation in the geometrical dimensions is large and yard policy with respect to standardization of components will depend on the capacity of the equipment and the characteristics of the contracted structure.
The adoption of standards such as plate length/width, form and size of stiffening elements, dimensions of webs and flanges, etc. are weighted against possible adverse results such as unefficient, heavy structures.

2.2.3 The construction

The construction (building) of the steel structure is related to the following aspects within the construction yard :

1. The performed activities.
2. The production facilities
3. The production performances.

The nature of these aspects is discussed below; the obtained information is necessary for the calculation of building costs (par. 2.2.3) and will also be used in the implementation of the modular concept in design, construction and calculation of building costs.

2.2.3.1 Activities

The construction (building) of the steel structure is mostly an assembly process where the central activity is the connection, by welding, of structural components at all levels of complexity; the complete overview is :

1. Activities concerning the preparation of parts.
2. Activities concerning the effectuation of connections.
3. Activities concerning the finishing.

With respect to the type of activity, a distinction is made between :

1. Activities concerning technological processes (flame cutting, machining, shaping, welding, etc.).
2. Activities concerning supporting operations (transport, positioning, aligning, fairing, cleaning).

The main difference between the above lies in the nature of the constraints involved in the performance of these activities; technological processes are mainly constrained by the employed technology, supporting operations by the employed equipment.

The extent of the above activities and their relative contribution to the building process differ at different structural levels. This has resulted in a concentration of these activities within specific areas of the construction yard, termed work-stations. A work-station is hereby defined as a sub-system production facility concerned with specific combinations of activities related to a structural level. The distribution of the above activities over work-stations is hereby defined as a building procedure. A simplified building procedure and work-station set-up is discussed below.

2.2.3.2 Production facilities

Yard production facilities are represented here by a set-up of work-stations, according to the main phases of the building process; these are shown in Fig. 2.2, with reference to the relevant structural levels and comprise :

- work-station 0 : preparation of third-level components
- work-station 1 : sub-assembly of components
- work-station 2 : panel assembly
- work-station 3 : unit blocks assembly
- work-station 4 : erection.

Since work-station 0 is not directly involved in the assembly process, the further evaluation of the building process of the steel structure will concern only activities performed at work-stations 1 - 4.

The distribution of work over the various work-stations depends on the following factors :

- The type of structure to be produced
- The type and capacity of production equipment and other facilities at the work stations, such as lifting capacities, dimensions of components which can be handled, etc.

- The fitting of machinery, equipment, systems, etc. which is a contemporary activity with the building of the steel structure and occurs mainly at the unit assembly and erection work-stations.

Some examples on the distribution of work over the work-stations are shown in table 2.1/2.9, 2.15-17/ ; the displayed data indicate that for the type of products shown here, most of the work is performed at work-station 3.

2.2.3.3 Production performance

Production performance is a measure of merit for the accomplishment of a production facility, given by the ratio :

$T_p = T_1/U_p$, where : (2.1)

T_p = production performance, per unit of production

T_1 = input of labour effort

U_p = units of production

For the industry under consideration, labour effort input is given in manhours. On the other hand, no definite units exist for the production output at work station level. Presently used quantifiers for production output are hereby divided into two groups :

1. Those related to some physical measure such as weight of steel, panel area, etc. In these cases, production performance is given by respectively manhours/tonne (steel weight) and manhours/m squared (panel area).

2. Those related to performed activities such as the amount of connections, the number of components, etc. In these cases. production performance is given by respectively manhours/unit of connection, manhours/tonne (steel weight) for certain types and numbers of components.
   (See also table 2.2).

An inherent term to the above is the amount of labour required to assemble a structure or the work content of the structure; the work content is given by the amount of production units for which table 2.2 is applicable.

2.3 Calculation of building costs

The combination of information from design and construction for purpose of building cost calculations in marine constructions is shown in Fig. 2.1; in general, building costs are given by :

$C_T = C_M + C_L + C_O$, where :

C_T = total building costs

C_M = material costs

C_L = (direct) labour costs

C_O = overhead costs

Material costs concern the costs of all purchased materials which are worked up in the final product.

Direct labour costs are defined as costs directly related to man-hours expended during the operating of production facilities within a work-station.

Overhead costs are defined as costs directly or indirectly related to the existing and functioning of the construction yard.

The sequence in which the above factors are determined is given by a calculation model; a necessary characteristic of this model is the possibility to provide insight in the relation between design parameters and cost factors. The necessary elements in the calculation model are :

- Suitable quantifiers for the cost factors.
- Methods to determine the total amount of these quantifiers for given design and building facility.
- Methods to determine the money-value of each quantifier for given building facilities.

All costs are given in some monetary unit; for this investigation the monetary unit used as reference is the Dutch guilder (fl.). The obtaining of the necessary information for calculation of building costs will now be discussed, starting at the bottom of Fig. 2.1.

2.3.1 Calculation of material costs

Material costs are given by :

$$C_M = \sum_1^i W_i \times P_{mi} \text{ , where} \qquad (2.3)$$

W_i = weight of i-type (steel) material

P_{mi} = unit price of i-type (steel) material

W_i is derived from the internal structural arrangement by means of breakdown to second and third-level components.
P_{mi} is the (steel) material market price for plate, sections, etc

2.3.2 Direct labour costs

Direct labour costs of the steel structure stand for the money value of the amount of labour effort necessary to accomplish the activities mentioned in par. 2.2.4; this is done on a work-station basis following the building procedure. Direct labour costs are :

$$C_L = \sum_1^j T_{1j} \times R_j \text{ , where} \qquad (2.4)$$

C_L = direct labour costs

T_{1j} = labour effort, in manhours, at work-station j

R_j = hourly rate at work-station j, in fl/manhour.

The work-station labour effort is given by :

$T_{1j} = W_{1j} \times T_{pj}$, where (2.5)

W_{1j} = work content at work-station j (see table 2.2)

T_{pj} = production performance at work-station j.

The determination of work-station work content is based on activities concerning the assembly of structures at the particular work-station and it is here that a coupling between the notions design and construction is effectuated (Fig. 2.1). The quantification of activities is derived from (design) information on the internal structural arrangement at the second and first levels; this is, in fact, a simulation of the assembly process at the particular work-station and a most labourious task. The current practice is to determine the work content by comparison with similar structures assembled, at the particular work-station, in the past (post-calculation data). The basis for comparison is the structural level and the physical characteristics of the structure (length, width, volume, weight). The fact that the internal structural arrangement is not involved in the comparison is a shortcoming of this practice; the calculation model based on the above lacks sensitivity for variations in the structural pattern of the internal geometry and, thus, does not fulfil the conditions of design-for-production mentioned in Chapter 1.

In general, the obtained results are yard-dependent and related to a specific type of marine product (tanker, containership, offshore platform), but without distinction between various designs of the same product.

Following the current practice, once work content has been determined, work-station labour effort is calculated by means of the (work-station) relevant production performance data. If work content and production performance data are given by compatible

quantifiers, the final result is given by manhours.
Hourly rates consist of the following :

- basic wages;
- social schemes;
- additionals.

The latter involves different categories of overheads; the allocation procedure of overheads is not universal and depends on the accounting method. The differences between types of overheads are discussed below.

2.3.3 Overhead costs

The integration of overhead costs within any calculation model requires clear insight and knowledge of the expenditures at the building yard (app. 2.1, /2.18/). The elements of importance are :

- The causative factors
- The absorption procedure.

/2.20/

In general, overhead costs are divided into two groups :

1. Fixed costs, i.e. independent on the level of activity.
2. Variable costs, i.e. dependent on the level of activity.

A primary causative factor for the first category is capital investment; for the second category, production throughput. /2.9/

The absorption procedures used in the marine construction industries are :

1. Absorption on the basis of labour costs (Fig. 2.3.a)
2. Absorption on the basis of hourly rates (Fig. 2.3.b)
3. Direct absorption (Fig. 2.3.c)

Absorption on the basis of labour costs in the form of percentage addition does not account for variations in the rate of manhours/ machine hours. As the level of investment in a certain work-station increases, the associated manhours usually decrease and so, according to this method, the overhead allocated to that work-station will also decrease.

Absorption on the basis of hourly rates, the so-called tariff method, is commonly used in marine constructions; tariffs are calculated for each work-station and include :

- the costs of human labour (hourly rates),
- the costs of the operating facility (overheads).

Following a procedure proposed by the Netherlands Shipbuilding Industry Foundation /2.18/, overheads' contribution to work-station tariffs is achieved on the basis of normal and planned production levels :

$$\text{contribution/manhour} = Cov_j / PP_j + Cof_j / NP_j \text{ , where} \qquad (2.6)$$

Cov_j = variable overheads at work-station j

Cof_j = fixed overheads at work-station j

PP_j = a variable level of production, at work-station j, corresponding with the planned activities at that work-station and termed planned production.

NP_j = a fixed level of production, at work-station j, determined at the initiation of the facility and termed normal production.

Overheads related to a production cost-centre (work-station) are directly accounted for; overheads initially related to a general cost centre are allocated to production cost centres (work-stations) according to a distribution key based on local, work-station related, production capacity.

Direct absorption of overhead costs has been suggested as a part of a cost calculation procedure based on work-station-related levels of production; this is given, at each work-station, by the length, in metres, of the effectuated connections (joints) /2.9/.

According to this procedure, overhead costs are allocated to work-stations in proportion with the share of each work station out of the total yard overheads; a distinction is made between four causative factors :

1. Labour force
2. Capital investment
3. Production level
4. Area.

The general expression is :

$x_i = X_t\ (R_1f_1 + R_2f_2 + R_3f_3 + R_4f_4)$ where : (2.7)

x_i = allocated overhead costs at work-station i

X_t = total yard overhead costs/year

R_1 = ratio work-station labour force to total yard labour force

R_2 = ratio work-station capital investment to total yard capital investment

R_3 = ratio work-station production to total yard production

R_4 = ratio work-station area to total yard area

$f_1 - f_4$ = proportion of overheads related to the causative factors

The calculated x_i values are allocated to the respective production levels as follows :

$C_o = x_i\ /(H_o \times P_h)$, where (2.8)

C_o = overhead costs/joint length (m)

x_i = allocated overhead costs/year

H_o = the amount of operating hours/year

P_h = production performance in metres joint length/hour

In both methods (2) and (3) there is a relation between the structure (structural pattern) and the overhead costs :

- In method (2) through the contribution of variable overheads, thus the ratio variable overheads/planned production; the latter corresponds with the work content at the work-station and, thus, with the structure which is assembled at the work-station.
- In method (3) all overheads are related to the product $H_o \times P_h$ which is, in fact, the work content at the respective work-station i.

In both cases, the determination of the work content and its relation with the real structure forms the basis for overheads' absorption.

2.3.4 Summary

The calculation of building costs was discussed on the basis of three main cost factors, namely material, labour and overhead costs. The necessary information for the determination of these cost factors is derived :

- For the design notion, with respect to the calculation of material costs, the labour costs and the variable part in overhead costs.
- For the construction notion, with respect to the calculation of labour costs and the fixed part in overhead costs.

The determination of labour and variable overheads requires the knowledge of work content, at each work-station; the necessary (ideal) transfer of information is hereby defined. The real transfer is, however, determined by the activities and relationships between the involved parties.

2.4 The involved parties

The information required for the calculation of building costs was discussed in par. 2.3. In the current paragraph, the origin of this information and its transfer during the realization of the marine product are being discussed with regard to the directly involved parties. Relationships and behaviour of the following parties are being considered with the aim to characterize their influence on design and production :

- The client
- The builder
- The authorities.

A fourth party is the designer which can either act independently or within the organization of the client or the builder (Fig. 2.4.a).

A representation of characteristic activities based on the current practice is shown in Fig. 2.4.b. For designer and builder a distinction is made between activities of main and secondary importance with respect to the tasks fulfilled by these parties.
All activities are divided over a design phase, a construction phase and an intermediate contract phase (Fig. 2.4.c).

With regard to the information necessary for calculation of building costs, two sources of information are observed :

1. The designer
2. The builder

(see also Fig. 2.1).

Considering the steel structure only, designer information concerns the external geometrical form and internal structural arrangement. These are laid down in drawings and specifications concerning the quality of steel materials, preparation, the type and quality of connections, etc.

The above design information has to be "translated" into working information, the working drawings, by the builder. This is done on the basis of specific, yard-related information concerning the local facilities, methods, procedures, etc. The final amount of labour required to accomplish the work content is determined by yard production performance (par. 2.3.2). Following the current practice, one design is offered for tendering to several yards. Hereby, design information reaches the builders at a stage of completion where both geometry and internal structural arrangement are already established (see Fig. 2.1). In this way :

- builder information on cost-effective structures is not involved in the design.
- the conditions at any particular construction yard, both advantages and disadvantages, are not included in the design.

The relationship between all four parties and their activities in accordance with Fig. 2.4.c are shown in Fig. 2.4.d; the thick lines stand for the main flow of information regarding the realization of the marine product. On the basis of the above the following is concluded :

- The active parties which determine the realization of the product are designer and builder.
- Each active party dominates in his respective phase, thus the designer in the design phase and the builder in the building phase.
- Each active party performs his main characteristic activities, in the respective dominated phase, with little or no interaction with the other party.
- Consequently, each party has developed specific systems and tools to perform his characteristic activities; the designer with the aim of determining the design solution(s), the builder with the aim of building it.

It seems that while the designer has based his system mainly on parameters related to the external geometrical form, the builder uses the internal geometry, thus the structural composition, as a basis for his specific system.

2.5 Summary

In general, the current practice does not fulfil the conditions of design-for-production. In the first place, the lack of interaction between designer and builder deprives both parties of necessary information for efficiently performing of their respective tasks.
This is characterized, in the design phase, by a passive role of the builder which deprives the designer of information on cost-effective structural patterns; the lack of information transfer has led to the development of different executive systems by designer and builder where calculation models with identical purposes, such as weight and cost-price, use different parameters.

In the second place, the consideration of cost-calculation methods indicates an inadequacy in the cost calculation models to deal with variations in the internal structural arrangement and patterns; the determination of work content is usually not based on the real structure, whereas the used quantifiers are related to physical characteristics such as weight or area.

The above lead to the following conclusions :

- The information available to the builder cannot be used in its current presentation to achieve insight in the relation between structural patterns and production costs.
- The current practice in the transfer of information does not enable to include, in an early design stage, builder data on cost-effective structures.
- Calculation models used by designer and builder are not compatible.

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Table 2.1 : Distribution of work over work stations

type of structure	amount of work at workstation		
	sub + panel assembly	unit assembly	erection
.250000 TDW tanker	18 %	61 %	21 %
.container ship	19 %	55 %	27 %
.15000 TDW cargo ship	18 %	54 %	28 %
. small cargo ship	26 %	55 %	18 %

Table 2.1 : Work content quantifiers

characteristic	parameter
. geometrical dimensions	manhours/unit of area
. steel weight	manhours/unit of weight
. structural pattern and number and and types of components	manhours/unit of weight
. quantity of connections	amount of connections/ unit of weight

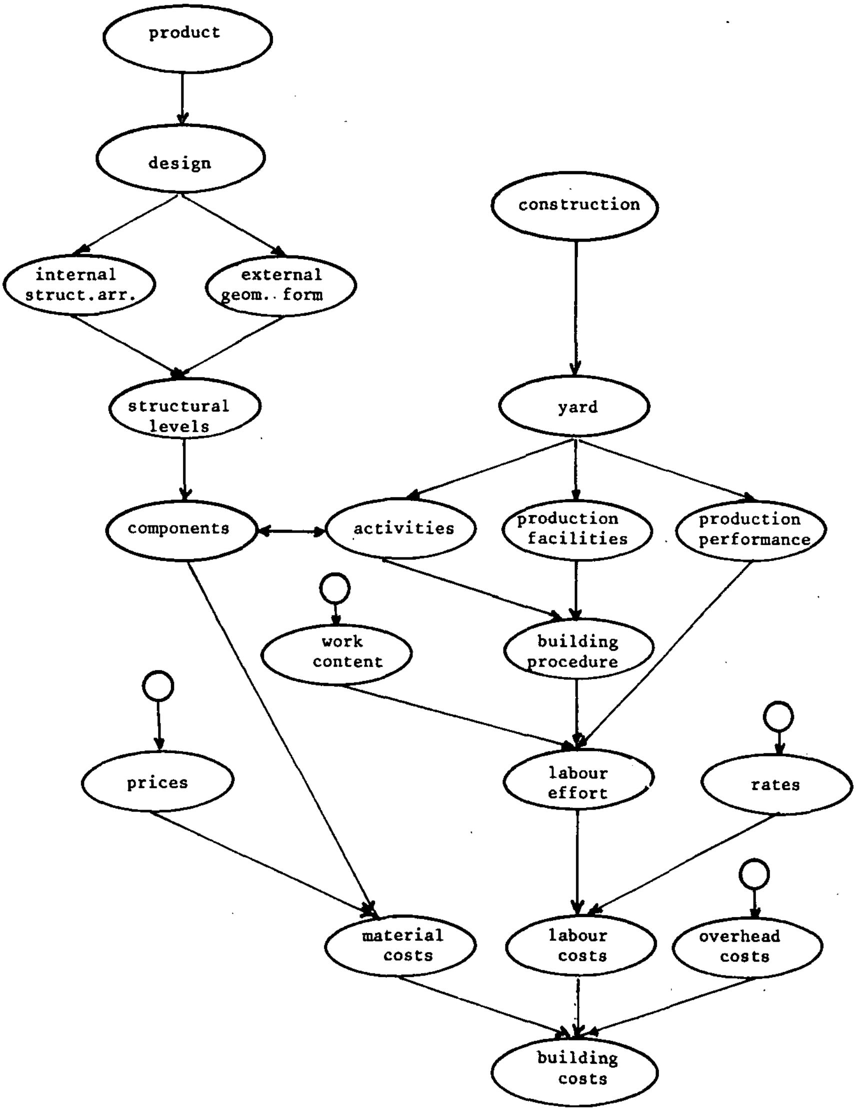

Fig.2.1 : Information flow in current marine construction practice

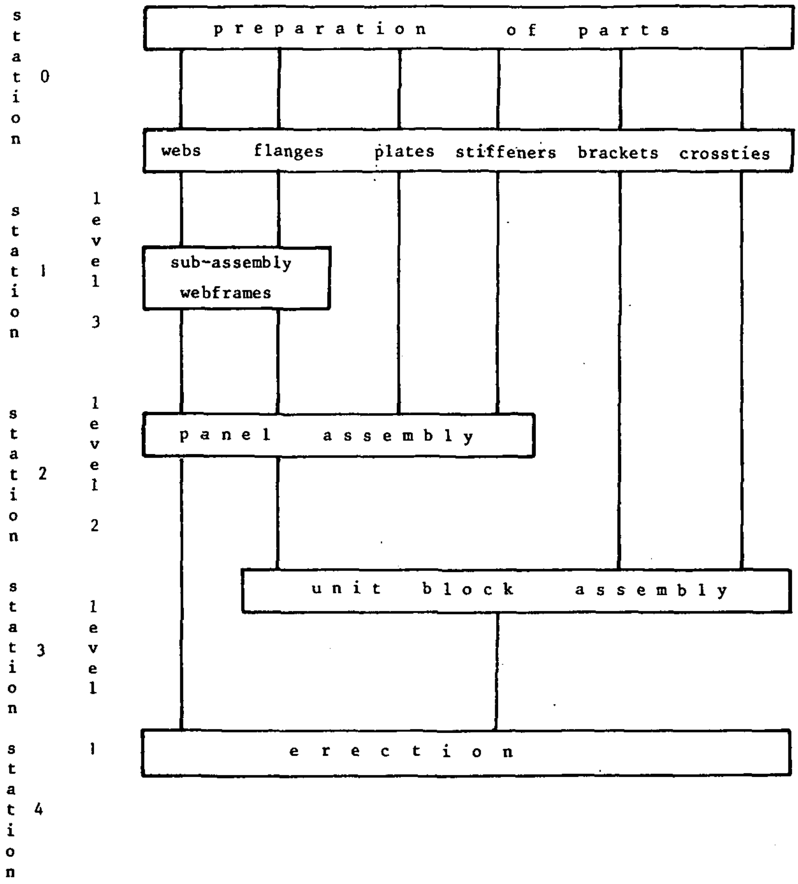

Fig.2.2 : Relations between work stations and structural levels

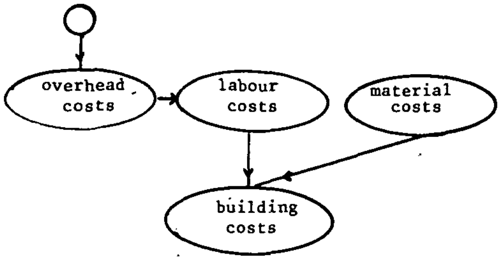

Fig.2.3-a : Overheads absorption on the basis of labour costs

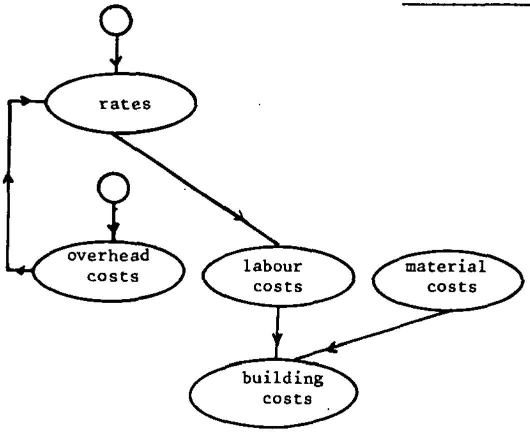

Fig.2.3-b : Overheads absorption on the basis of hourly rates

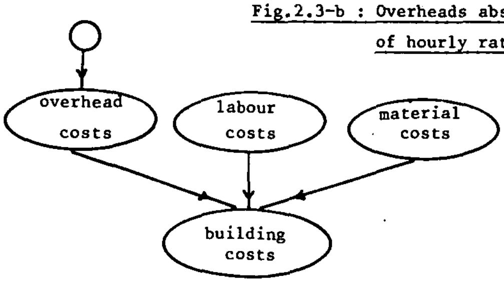

Fig.2.3-c : Direct absorption

Fig.2.3 : Overhead costs absorption

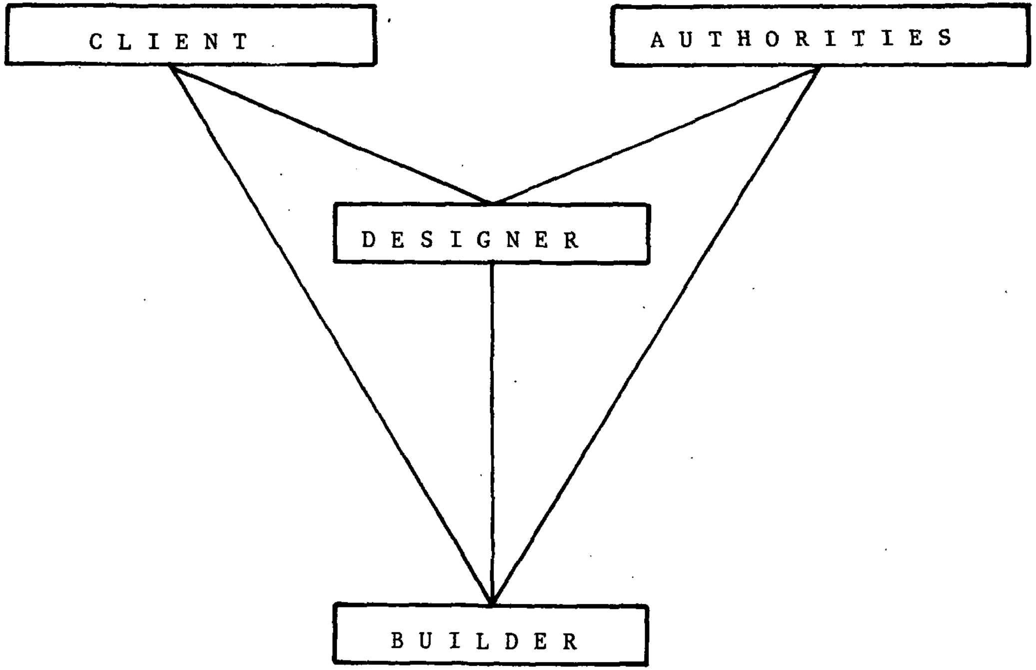

Fig.2.4.a : Inter-action between the involved parties in the realization of the marine product

PARTY	CHARACTERISTIC ACTIVITIES
1. CLIENT	1.1 Determines general requirements
	1.2 Co-operates with designer
	1.3 Issues tender
	1.4 Receives/selects bids, negotiates contract
	1.5 Supervises realization and tests
2. DESIGNER	Main Activities
	2.1 Determines economical/technical requirements and constraints
	2.2 Translates technical requirements/constraints into technical solution, hereby defining the product
	Secondary Activities
	2.3 Consults with authorities, manufacturers
	2.4 Support (technical) client activities
3. BUILDER	Main Activities
	3.1 Translates technical solution into : . material lists . production (labour) effort . cost price for the above
	3.2 Engineering, planning
	3.3 Purchases materials, services
	3.4 Processes materials, assembly final product
	Secondary Activities
	3.5 Prepares offer, negotiates contract
	3.6 Tests product, commissioning, delivery
	3.7 Consults authorities
4. AUTHORITIES	4.1 Issue regulations on quality and performance of materials, systems and final product
	4.2 Evaluate compliance of design with respect to 4.1
	4.3 Supervises realization and tests
	4.4 Issues documents

Fig.2.4.b : Characteristic activities of involved parties in the realization of the marine product

PHASE	SEQUENCE OF ACTIVITES	INVOLVED PARTIES	DOMINANT ACTIVITY BY
1. DESIGN	1.1	1 , 2 , 4	2
	2.1		
	2.2 , 4.2		
	2.3		
	1.3		
2. CONTRACT	3.1 , 3.7 , 4.2	1 , 2 , 3 , 4	1 and 4
	3.5		
	1.4		
3. CONSTRUCTION	3.2 , 3.7	1 , 2 , 3 , 4	3
	3.3		
	3.4 , 1.5 , 4.3		
	3.5 , 1.5 , 4.3		
	4.4		

Fig.2.4.c : Main phases in the realization of the marine product

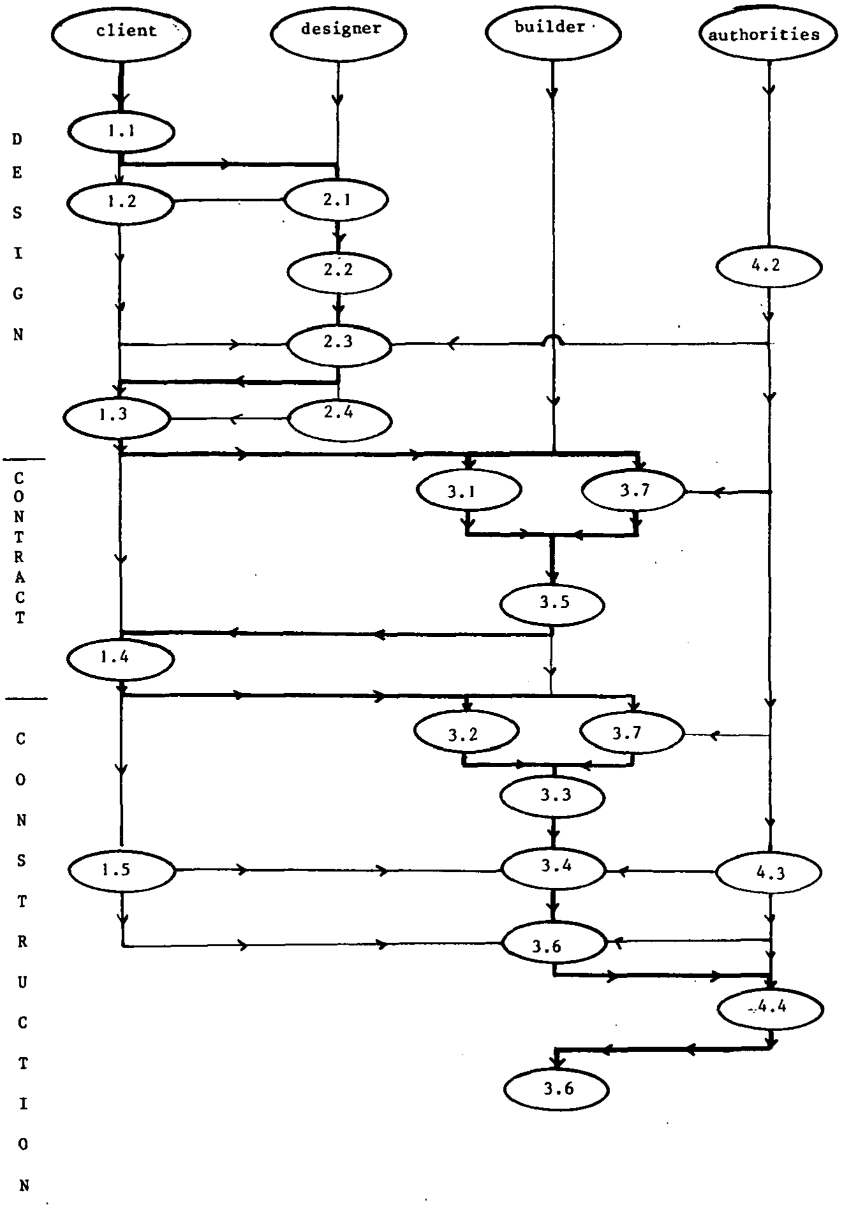

Fig.2.4.d : Information flow between the involved parties in the realization of the marine product

Appendix 2.1

Overhead Costs at a Marine Construction Yard

Overhead costs at a marine construction yard are associated with so-called cost-centres and divided into two groups :

1. General cost-centres
2. Production cost-centres.

General cost-centres

1.1 General Management and Draftrooms
  - management
  - sales and costing
  - research and development
  - administration
  - personnel administration
  - draftrooms

1.2 Accommodation and Maintenance

1.3 Materials Management
  - purchasing
  - stores, expediting
  - plate/section stores
  - laboratory and quality control
  - transport

1.4 Services
  - energy
  - tooling
  - medical care and social services
  - canteen/washrooms
  - protective clothing
  - training
  - reproduction

1.5 Exploitation of launchways, cranage on/offshore, wharfs, etc

Production cost-centres

2.1 Material Preparation

2.2 Sub-assembly

2.3 Panel Assembly

2.4 Unit Assembly

2.5 Erection.

Chapter 3

The semi-submersible platform

3.1 Introduction

The semi-submersible platform concept emerged in answer to an increasing demand from the side of the Offshore Industry for mobile, deep-water/rough weather work-platforms with low motion response to wave action and a large work-deck area.
Initially used for exploration drilling only, the semi-submersible platforms have been introduced over the past 15 years in other offshore activities such as :

- pipe-laying
- installation/construction work
- general support activities
- accommodation
- production

Designs for other applications such as dredging have been prepared.

The current semi-submersible fleet comprises some 200 units of which 90% are employed in exploration drilling, the rest in other activities /3.1/.

In general, a semi-submersible platform consists of the following component groups :

1. One or more buoyant bodies or lower hulls.
2. A deck structure
3. A number of vertical columns or slender walls supporting the deck-structure and connected to the lower hulls.
4. A configuration of slender vertical/horizontal bracing elements (see Fig. 3.1 and 3.2).

An important feature of the concept is the possibility to operate at various draught conditions due to a ballasting system with a capacity up to 30-50% of the maximum operating displacement. In general, a distinction is made between :

a. Shallow draught; this is a condition when the buoyant bodies are partly submerged. This condition is of importance for sea-voyages (transit), either under tow or under own propulsion.
b. Deep draught or submerged; this is a condition when the buoyant bodies are completely submerged, well below the sea-level, whereas the vertical columns or walls pierce the sea-level. This is the operational condition characterized by reduced motions with respect to the shallow draught condition

Within the above concept, each of the component groups fulfils one or more functions :

a. A group of desired functions, i.e. functions which positively contribute to the existing and operating of the semi-submersible platform.
b. A group of undesired functions, i.e. functions which are a necessary consequence of the existing and functioning of the platform but exert a negative, disturbing influence on the desired functions.

(see table 3.1)

In search for an adequate balance between the above groups of functions, numerous geometrical and structural (design) solutions were developed. The former concern the number, shape and configuration of buoyant bodies and supporting columns, the latter concern the configuration of braces and the role of the deck structure in the structural strength.

The geometrical solutions are grouped into :

a. A configuration of columns spread around a circle with each column being connected to a separate buoyant body (Fig. 3.1.a).
b. A configuration of two or more parallel floaters, each supporting a row of vertical columns (Fig. 3.1.b).

The structural solutions are grouped as follows :

a. General stiffening is provided by an extensive configuration of braces with little participation from the (un-rigid) deck structure (Fig. 3.2.a).
b. General stiffening is provided by a reduced configuration of braces and a rigid, box-shaped deck structure (Fig. 3.2.b).

Following the accumulated experience in design, construction and operation of semi-submersible platforms over the past years, a preference has arisen for the following geometrical/structural solution :

- A catamaran-geometry with two parallel floaters, each supporting 2-4 columns.
- A rigid box-shaped deck structure with buoyancy capability and a simplified configuration of braces.

This investigation will refer to the above geometrical/structural solution, in particular the exploration drilling version. The various aspects of this type of platform will now be reviewed with respect to two points of interest :

- Operability of the platform
- Safety of the platform.

3.2 Conventional concept

3.2.1 Introduction

Operability and safety are the main points of interest in the discussion of the various aspects of the semi-submersible platform. Operability is the capability to maintain an efficient level of (drilling) operations under environmental conditions at the work location; the capability is given by either of the following terms :

1. Workability, defined as the ratio of efficient operating time to the total time spent at the work location

$$\text{workability} = \frac{\text{operating time}}{\text{time at location}} \times 100\%$$

2. Down-time is the complement of workability :

   down-time = 100% - workability.

In principle, determination of workability/downtime implies an investigation on the occurrence of conditions under which drilling operations cannot efficiently be maintained due to excessive excursions in the vertical/horizontal planes. The necessary information comprises the following :

1. The spectrum of drilling operations in terms of time spent at each type of operation and the hereto related limitations; an example is shown in table 3.2.
2. Platform characteristics.
3. The characteristics of environmental phenomena at the work location in terms of magnitude and distribution over the period of operations; usually, this concerns the regimes of wind, waves and currents.

Methods and techniques developed to deal with the determination of workability, in particular point (3) above, are given in /3.2-4/.

Platform characteristics concern the response to exciting forces where a distinction is made between :

1. Phenomena of cyclic nature such as first order response to waves, in particular the heave motion; the latter is derived from the under-water geometry of the platform.
2. Phenomena of steady-state nature such as response to mean wind, current and wave drift forces; these are derived from the under & above geometry as well as from the arrangement of deck superstructures and equipment.

The heave motion addresses the capability of equipment to compensate for vertical displacements. Displacements in excess of this capability will cause interruption of drilling operations (see table 3.2).

The second group above addresses the capability of the mooring system to compensate for (horizontal) displacements. The mooring system does not compensate for cyclic displacements caused by second order phenomenae, wind gusts, etc.

The discussion on operability will be limited to minimization of the heave motion by means of design solutions addressing the under-water geometry of the platform.

The safety of the platform concerns, in the broad sense, the preserving of buoyancy capability on the basis of the following conditions :

1. The capability to return, after being heeled to an angle under environmental circumstances, to its normal upright or operational position in a short duration, without sustaining damage, ceasing to perform its intended functions or endangering the personnel on board. This capability is commonly known as stability /3.14/.
2. The capability to withstand combinations of loads occuring during its lifetime without sustaining damage which affects structural integrity to a degree leading to loss of capability (1) above. This is commonly known as structural strength.

The exact circumstances under which the above conditions are to be met as well as the measures by which the fulfilling of the conditions are judged, have been traditionally determined by regulatory bodies. In the discussion on the safety point of interest, reference to Rules for Classification of Mobile Offshore Units issued by Det Norske Veritas will be made /3.5/.

3.2.2 Operability

3.2.2.1 The heave motion

Basic insight in phenomena related to the heave motion of the semi-submersible platform can be obtained by observing the behaviour of a vertical cylinder in a train of regular sinusoidal waves (Fig. 3.3). The amplitude z_a of the vertical motion of the cylinder is given by :

$$z_a = \frac{F_a / C}{((1 - (\frac{\omega}{\omega_n})^2)^2 + (2d_c \frac{\omega}{\omega_n})^2)^{0.5}} \text{, where} \qquad (3.1)$$

F_a = vertical wave exciting force

C = force per unit relative vertical displacement from still water position

ω = wave frequency

ω_n = natural frequency of the vertical motion of the cylinder

d_c = dimensionless critical damping coefficient

/3.6, 3.7/

Considering expression (3.1), the values of d_c for floating structures is less than 1, usually less than 0.2 /3.7/. Furthermore it was shown that for values of ω away from the natural frequency ω_n, the behaviour of z_a is mainly governed by the first term in the denominator of expression (3.1) /3.6/.

The possibilities to reduce the amplitude of motion z_a in expression (3.1) are found by controlling the values of numerator and denominator, respectively :

1. By minimizing the exciting forces in expression (3.1), hereby reducing the numerator and, consequently, the amplitude of motion z_a.

2. By choosing the natural heave frequency ω_n below most wave frequencies, hereby maintaining a large denominator value and, consequently, reducing the amplitude of motion z_a. This has been termed the de-tuning method.

On the basis of the above, two main approaches towards reduction of the heave motion were developed where the principles (1) and (2) are achieved by suitable under-water geometry.

3.2.2.2 Minimization of exciting forces

The minimization of exciting forces on the submerged parts of the semi-submersible platform has been investigated /3.6, 3.8-13/. Calculation methods, confirmed by model tests, were developed on the basis of the following conditions :

1. The motion amplitudes for the platform and waves are small.
2. The platform is composed of a configuration of slender cylindrical elements whose cross-dimensions are small compared with the wave lengths.
3. The forces are computed for an individual element of the structure as though other elements were not present, i.e. no hydrodynamic interference between elements.

/3.10/

According to the studies performed, the governing contribution from wave excitation is attributed to :

1. The variation in pressure due to the passage of the wave, the so-called Froude-Krylov force.
2. The inertia forces due to accelerations of the particles withi the wave on the added mass.

/3.8, 3.10, 3.12/

In the total exciting force, contributions from all submerged parts of the semi-submersible platform are included. Minimization of the total force is possible by adjusting the geometry of the submerged parts of the platform in such a way that the contributions from pressure and inertia forces cancel each other at a chosen wave frequency ω. This is demonstrated by an example from /3.10/. This example concerns a simple configuration of one horizontal cylinder with cross section A_h and length 1 and two vertical cylinders with cross section A_v and immersed length h (see Fig. 3.4). Cancellation of forces occurs when :

$$\frac{A_v}{A_h} = 2 \times tg \left(\frac{\omega^2}{g} \times \frac{1}{2} \right), \text{ where :} \tag{3.2}$$

ω = frequency of the exciting wave.

Expression (3.2) implicates that cancellation of forces can be obtained at any wave frequency ω for which the ratio A_v / A_h fulfills the condition given by this expression. Two alternatives have been suggested /3.8, 3.10/ :

1. Minimization of the total exciting force at the resonance frequency. In this case, cancellation occurs at a wave frequency equal to the natural heave frequency ω_n :
   $\omega = \omega_n$
   The outcome for the example from Fig. 3.4 is :

$$\frac{A_v}{A_h} = 2 \times tg \left(\frac{A_v \times 1}{2 (A_v \times h + A_h \times 1)} \right) \tag{3.3}$$

2. Minimization of the total exciting force at the frequency of maximum wave energy ω_p. The outcome for the example from Fig. 3.4 is :

$$\frac{A_v}{A_h} = 2 \times tg \left(\frac{C^2 \times A_v \times 1}{2 (A_v \times h + A_h \times 1)} \right) \text{ , where :} \tag{3.4}$$

$C = \omega_p/\omega_n$

3.2.2.3 The de-tuning method

The principle of de-tuning is explained on the basis of expression (3.1). By choosing a low value for the natural heave frequency ω_n, the denominator is large over a range of wave frequencies (see Fig. 3.5). For example, the natural heave frequency ω_n for the configuration from Fig. 3.4 is :

$$\omega_n = \left(\frac{g \times A_v}{A_v h + A_h 1} \right)^{0.5} \tag{3.5}$$

or

$$\omega_n = \left(\frac{g}{h(1 + \alpha \times \beta)} \right)^{0.5} \text{, where :} \tag{3.6}$$

$\alpha = A_h / A_v$

$\beta = 1/h$

By choosing a certain (low) value for ω_n, for example 0.3 (period 21 sec), various geometrical solutions in terms of α, 1 and h can be provided (see table 3.3).
In practice, additional aspects such as stability, etc. are also considered.

3.2.2.4 Summary

Two approaches towards minimization of the heave motion were presented and demonstrated by means of a simple semi-submersible configuration. The implementation of these approaches in real and more complex semi-submersible structures must also consider other factors such as roll/pitch motions, functional aspects, structural strength, building costs, etc.

Semi-submersible drilling platforms are usually designed for world-wide operations. A particular approach to minimization of the heave motion which is suitable for certain environmental conditions, may provide less satisfactory results elsewhere. In this respect, the de-tuning method is regarded as the more general approach towards reduction of the heave motion whereas the force cancellation approach is better geared for particular applications. A comparison between these approaches for purpose of design is only meaningful when design requirements and operating conditions are well established /3.10/.

Since present work is not related to some specific operating area, the de-tuning approach will be followed.

3.2.3 Safety

The definition of safety involves certain ambiguities with regard to its quantification. In this discussion, safety is considered as a characteristic which is measured against standards determine by an acceptable level of risk. The latter is subject to continuous adjustments due to the state of the art of technology, public opinion, the protection of environment, etc. Structures which were designed and built in compliance with official standards several years ago may, today, be declared unfit for service or require significant adjustments.

In general, safety standards or criteria are related to circumstances under which the particular structure must perform. In thi respect, a distinction is made between various operating conditions. An operating condition is hereby defined as a specific combination of activities which can be carried on up to certain limits imposed by external factors or own limitations. In the broad sense it concerns :

1. The activities which must be performed
2. The way in which (1) must be performed
3. The circumstances under which (1) must be performed.

(1) and (2) are directly related to the design requirements.
(3) is a basis for the various constraints related to the applicable safety criteria.

The operating condition or conditions which determine the upper limits of the structure in terms of design requirements and constraints is termed design condition. These definitions are applicable to the entire structure as well as to any part of it. For example, the design condition for the complete structure differs from the design condition for a particular bulkhead.

Finally, the term loading condition is introduced. This is defined as a specific combination of loads which may occur in a design condition.

Each combination of loading/design conditions is related to safety criteria.

The semi-submersible platform operates in two principal conditions (par. 3.1) :

1. A deep draught condition for :
   - normal operating condition for purpose of drilling operations where the combined loadings, environmental and otherwise, are within the appropriate design limits for such operations.
   - survival condition during which the platform may be subjected to the most severe environmental conditions for which it is designed and where drilling operations are suspended.

2. A shallow draught condition for movements from one geographical location to another.

/3.5/

In the following discussion, criteria for stability and structural strength will be involved.

3.2.3.2 Stability

This discussion is limited to that approach to stability which has been adopted as a basis for an internationally recognized stability criterion for floating structures. This criterion, known as the "weather criterion", compares the potential energy generated by the structure through its restoring moment, at some heeled position, with the wind induced energy. The basis for this ap-approach was established by Moseley in 1850 by means of the following :

$$\frac{\displaystyle\int_{\varphi_0}^{\varphi_f} M_r\ (\varphi)\ d\varphi}{\displaystyle\int_{\varphi_0}^{\varphi_f} M_h\ (\varphi)\ d\varphi} \geqslant 1 + C_s \text{ , where :} \qquad (3.7)$$

$M_r\ (\varphi)$ = restoring moment

$M_h\ (\varphi)$ = heeling moment

φ = heeling angle, subscripts 0 and f indicate the initial and final or maximum angles of heel.

C_s = safety factor accounting for phenomena which are not included in expression (3.7), such as the impact of waves on platform's restoring moment, etc. /3.14-15/.

The weather criterion forms the basis for stability assessment in all operating conditions. The difference between the conditions is given by the values for parameters and factors involved in expression (3.7) which are laid down by regulatory bodies. An additional element here is the distinction between stability in intact or damaged condition for which, again, different values for parameters and factors are used. Hereby, the principle of different levels of risk acceptance is a central matter.

Fig. 3.6 represents a schematic approach to stability assessment. Considering this representation and expression (3.7), the following points are of interest :

- The determination of the restoring moment $M_r\ (\varphi)$.
- The determination of the heeling moment $M_h\ (\varphi)$.
- The determination of the initial and final (maximum allowable) angles of heel.
- The stability criteria and the safety factor C_s.

3.2.3.2.1 The restoring moment

Considering the terminology used in stability matters (Fig. 3.7.a), the restoring moment M_r of a floating structure is given by :

$M_r(\varphi) = \rho \times g \times V \times GZ(\varphi)$, where (3.8)

GZ = restoring or righting arm and a function of the heeling angle a; GZ is given as :

$GZ(\varphi) = GN(\varphi) \sin(\varphi)$, where : (3.9)

GN : the false metacentre height above the centre of gravity

For small angles, i.e. $a \sim 8^o - 9^o$, GN reduces to the metacentric height GM; for larger angles, the so-called Scribanti formula can be used :

$GZ = (GM + 0.5 \times BM \times tg^2(\varphi)) \times \sin(\varphi)$, under the (3.10) conditions shown in Fig. 3.7.b (see also Fig. 3.7.a).

The necessary data are derived from platform's underwater geometry and mass distribution for the considered operational condition. With respect to the former, the axis of heel is important, since the second water line area moment depends on it. With respect to the latter, mass distribution, even at a given operating condition, is not constant; this is caused by a continuous shifting of items and the consuming of fuel, water, chemicals, etc. in the course of drilling operations.

3.2.3.2.2 The heeling moment

The heeling moment consists of the influence of the steady wind o the above-water part of the platform; the definition of the wind heeling moment is based on principles shown in Fig. 3.8 and involves :

1. Determination of wind forces on the above water part of the platform
2. Determination of the above-water wind-force centre
3. Determination of the under-water reaction centre.

Two main approaches to the above are :

1. By calculations; in this approach, the platform is considered as an assembly of individual elements and bodies whereas the total force is given by summation of all individual forces. The basic expression is :

$$F_{wi} = 0.5 \text{ x } \rho \text{ x } V_h^2 \text{ x } A_i \text{ x } C_{wi} \text{ , where} \qquad (3.11)$$

F_{wi} = wind force on element i

V_h = wind velocity at height h above sea-level

A_i = reference area for element i

C_{wi} = wind force coefficient for element i

The centre of the total wind force h_a is obtained from :

$$h_a = \frac{\sum_i F_{wi} \text{ x } h_i}{\sum_i F_i} \qquad (3.12)$$

Corrections for element shielding, blockage and other interference between elements are recommended /3.5/. Additional complications arise from the fact that calculations are to be performed at various angles of heel and wind attack, where the effects of such interference are not well understood /3.14/.

2. By means of model tests in wind tunnels.
   This approach deals with the entire platform configuration, modelled to a scale suitable for existing laboratory facilities.

Studies performed for the purpose of comparison between the two methods indicate /3.16-17/ :

- The calculation approach may lead to over-estimation of wind heeling moments by as much as 20%.
- Lift effects at angles of heel a > 0 are important and may have a restoring (stabilizing) effect on the semi-submersible platform, hereby reducing the influence of the wind-heeling moment.

3.2.3.2.3 Initial and final angles of heel

With respect to the values for the initial and final (maximum allowable) angles of heel, two main approaches are followed :

1. The initial angle of heel has a negative value, thus leeward. In this case, the safety coefficient C_s is zero (Fig.3.9.a and /3.18/). This approach considers to some degree dynamic influences caused by wave action and platform motions.

2. The initial angle of heel is zero. In this case, the safety coefficient C_s is established at 0.3 (fig. 3.9.b and /3.5/).

For further discussion, approach 2 above will be considered.

The final, maximum allowable angle of heel for which the weather criterion is calculated, is given by the intersection between restoring and heeling moments. It is customary to represent these moments by their arms, defined as :

$$\text{arm} = \frac{\text{moment}}{\text{platform displacement}} ,$$

so that the final heeling angle is defined as the angle beyond which the restoring arm is less than the heeling arm. This is also known as the second interception point, the first interception point being the point where the restoring arm equals, for the first time, the heeling arm (Fig. 3.9.c).

Additional requirements concern :
- The maximum value of the first interception point
- The minimum value of the second interception point

/3.5/.

3.2.3.2.4 Summary and remarks

The principles of stability assessment are summarized as follows:

1. Operating conditions :
   - 1.1 Normal working condition
   - 1.2 Survival condition
   - 1.3 Transit condition
   - 1.4 Transient condition, i.e. change of draught between 1.1/2 and 1.3.

2. Levels of risk :
   - 2.1 Intact stability
   - 2.2 Damage stability

3. Criteria :
   - 3.1 Minimum metacentric height
   - 3.2 Maximum heeling angle under steady wind pressure
   - 3.3 Minimum heeling angle for calculation of the coefficient C_s
   - 3.4 The value of C_s

4. Conditions :
   - 4.1 Most critical angle of heel obtained from combinations of $M_r(\varphi)$ and $M_h(\varphi)$

4.2 Minimum wind velocity for each mode of operation and level of risk.

4.3 The determined values for draught and centre of gravity KG at which criteria under 3 and conditions 4.1 and 4.2 are met (see also Fig. 3.9 and /3.5/).

Remarks

The aspects of stability discussed above are derived from the approach basically developed for ship structures. The application of this approach to stability assessment of semi-submersible structures has been subject to criticism due to its shortcomings on the following :

- The influence of waves on restoring moments
- The neglecting of platform's dynamic behaviour, including the influence of waves, currents and mooring forces

/3.14, 3.19/.

Discussion of these aspects goes beyond the purpose of this investigation. The above discussion is meant to provide insight in stability assessment following officially recognized criteria and for the purpose of establishing the necessary factors which will be involved in the modular approach to the design of semi-submersible platforms. These are :

1. The definition of the under-water geometry (value KB and BM)
2. The determination of mass distribution (the value KG)
3. The determination of the wind heeling arm curve.

3.2.3.3 Structural strength

3.2.3.3.1 Introduction

In principle, the assessment of structural strength follows a similar approach to this outlined for stability matters (Fig.3.10) A distinction is made between operating conditions whereas the levels of risk are given by loading conditions (par. 3.2.3.1). An additional factor here is the distinction between structural components on the basis of their importance with respect to :

- The local strength; this concerns components of minor (secondary) importance whose failure are unlikely to affect the overall structural integrity of the platform;
- The overall strength; this concerns components of either :
  - . essential (primary) importance to the overall structural integrity of the platform
  - . special (critical) importance; these are components which are critical for load transfer and stress concentrations

(see Fig. 3.11 and /3.5/).

The distinction on the basis of importance addresses (strength) criteria, quality of materials, the effectuation of connections. Loading conditions for the semi-submersible platform are shown in table 3.4; relevant combinations of operating and loading conditions are shown in table 3.5.

Criteria for assessment of structural strength are :

1. Yielding
2. Buckling
3. Fatigue

The measure of merit is a (usage) factor η, which gives the ratio between a reference measure and the actual measure derived from the loading. The maximum permissible value of η is related to the importance of the considered component and the loading condition; for example, yielding :

$$\eta_y = \frac{\sigma_a}{\sigma_y}$$, where :

η_y = usage factor for yielding

σ_y = reference measure, material yield stress

σ_a = actual measure, von Mises equivalent stress

The assessment of structural strength assumes the existance of a (preliminary) structural design solution obtained by comparison with similar structures or on the basis of a simplified calculation model (see hereafter and Chapter 4).

Considering the approach from Fig. 3.10, once the loading condition, the type of structure and the type/nature of loads are determined, the level of risk is established and the process of assessment of structural strenth is initiated. In the course of this process, one needs to represent the structure and its components by an analogy, the structural model. It is also necessary to represent the loads by mathematical expressions, the load model. The points of interest here are :

- The type/nature of loads and the modelling
- The impact on the structural strength
- The structural modelling.

3.2.3.3.2 The loads

The principle distinction here concerns the type and the nature of the loads /3.5/. Load type establishes the relation between loads and structural components :

- Loads acting directly on a particular component generate local forces. For example, the hydrodynamic pressure on the submerged part of the platform.
- Loads which are not directly acting on a particular component

but generate (overall) forces which are transferred to this component through the structural continuity of the platform. For example, horizontal hydrodynamic mass loading on floaters and columns generate forces and moments which affect the deck structure.

With respect to the nature of the loads, the following distinction is made :

- Functional loads which are a necessary consequence of platform's existance and functioning in each operating condition, but without the influence of the environment; for example :
  . static gravity loads
  . working loads
  Also included are the reactions to these loads, such as buoyancy

- Loads related to environmental phenomena such as :
  . wind, wave and current loads,
  and the reaction of the platform to these loads :
  . inertia
  . mooring

- Accidental loads which occur as a result of exceptional conditions such as :
  . collision
  . explosion
  . fire

(See also table 3.4 and /3.5/).

The modelling of loads addresses the representation of phenomena by mathematical expressions. A distinction is made between :

- Static modelling, i.e. loads are time independent;
- Dynamic modelling, i.e. loads are time dependent.

The static approach to load representation is a commonly used method in the determination of the (preliminary) structural design solution for secondary and primary-importance components in floaters, columns and deck structure (thus, not for critical components) /3.21-24/. Used criteria are yielding and buckling. Loads are represented by a single-valued number; this (maximum) value is used to determine the design value of the force, the design force.

Design values do not necessarily represent real phenomena in nature and magnitude. The reason for this is the need for safeguards which account for uncertainities concerning the real value of loads as well as for practicle reasons related to the process of structural strength assessment.

The dynamic approach to load representation is used for confirmation of the (preliminary) design solution and assessment of components of critical importance subject to cyclic loading. Examples are the connections floater-column, column-deck structure and all brace connections. Used criteria are yielding, buckling and fatigue. /3.21-22/

3.2.3.3.2 Impact on the structural strength

The structural integrity of the semi-submersible platform is determined by the overall strength. The acting loads concern phenomena of local and overall type. In principle, the assessment of structural strength involves all combinations of operating/loading conditions since there is no one single combination by which the assessment, for the entire structure, can be performed. Correspondingly, loads which are critical for the assessment of a particular part of the structure are of lesser importance for other parts. An example based on /3.22, 3.25-26/ is given in App. 3.1. This example represents the general approach to assessment of overall strengh and involves combinations of functional and environmental loads. Of the latter loads, wave loads are the most important.

3.2.3.3.4 Real structures and modelling

Structural applications for semi-submersible platforms are shown in Fig. 3.14. Fig. 3.14.a shows a floater cross section. Longitudinal (and transverse) bulkheads divide the floater volume in a number of spaces and tanks. The structural pattern consists of longitudinal stiffeners and transverse web-elements where span reduction is obtained by horizontal and vertical cross-ties.

A similar pattern is used in columns with either longitudinal or transverse framing (Fig. 3.14.b).

An example of a complete box-type deck structure is shown in Fig. 3.14.c; the deck structure is divided by longitudinal and transverse bulkheads meant for :
- structural strength
- division in compartments
- support of deck superstructures.

The association of the above with the various levels of structura complexity (par. 2.2.2.2) is shown in table 3.6. The relations between these levels and components of the structures from Fig. 3.14 are shown in table 3.7.

Structure modelling concerns, in principle :
- participation of components in the structural strength
- representation of the real structure by its (model) analogy.

The former concerns the inclusion of components in the model, in relation with their participation in the particular loading case. An important aspect here is the smooth transition and proper alignment of components in connections /3.5/. The latter concerns the dimensions of the model representing the structure and those of the elements representing individual components; for example :
- the dimensions of the model : 2 or 3-dimensional
- the dimensions of the element : beam, plate or volume elements.

Fig. 3.15.a is a 2-dimensional model of beam elements representing a floater section for assessment of local strength or transverse framing (web-frames); included are the participation of plating and transverse web-frames. The load model is static; the floater is considered in a stationary position and subjected to :

- A design pressure load, along its circumference, given by the design wave crest above the floater (see Fig. 3.15.b).
- A vertical balancing load equal to the pressure-difference between the floater upper (deck) and lower (bottom) planes.

By considering various configurations with empty/full tanks (Fig. 3.13.c-d), the assessment of transverse web-frame strength is performed.

Fig. 3.16 shows a 3-dimensional model of beam elements representing a complete semi-submersible platform structure, commonly used in the assessment of overall structural strength /3.22, 3.24/. Floaters, columns and deck structure are represented by beam elements whose sectional area and moduli characteristics involve those components which participate in the overall structural strength; for example, plating only or plating and stiffening elements. The considered loads include :

- Weight of structure, equipment, supllies and ballast
- Buoyancy
- Hydrodynamic forces
- Wind and current forces
- Reaction forces such as inertia and mooring.

Loads are applied in distributed and/or lumped form. This model is used for assessment of overall structural strength for the conditions a-c from Appendix 3.1.

The above models are sufficient for the assessment of secondary and primary components which account for the structural weight of the semi-submersible platform. For special components where stress concentrations are critical with regard to fatigue, finite element modelling is necessary; these components form a minor part of the structural weight /3.22/.

3.2.3.3.5 Summary and remarks

The principles of structural strength assessment are summarized as follows :

1. Operating conditions
   - 1.1 Normal operating condition
   - 1.2 Survival condition
   - 1.3 Transit condition

2. Levels of risk
   - 2.1 Combinations of operating and loading conditions (table 3.5)
   - 2.2 Participation in local or structural strength

3. Criteria
   - 3.1 Yielding
   - 3.2 Buckling
   - 3.3 Fatigue

4. Conditions
   - 4.1 Most critical combinations of operating and loading conditions for parts of the structure which are essential to the overall structural integrity.
   - 4.2 Minimum values for environmental phenomenae associated with 4.1.

Remarks

The assessment of structural strength is derived from the principle of risk acceptance associated with combinations of operating and loading conditions. The necessary elements are :

1. Determination of load combinations which are critical to the structural integrity of the platform
2. The modelling of the loads
3. The modelling of the structure.

For purpose of assessment of secondary and most primary structural components, an adequate approach is :

1. The beam-wave attack (case a. of Appendix 3.1)
2. Static modelling of loads
3. Frame models with beam elements
4. Yield and buckling criteria.

3.3 Modular concept

3.3.1 Introduction

In principle, the modular approach in design and construction of semi-submersible platforms is directed towards phases in the building process prior to the final erection of the structure, thus towards assembly activities which concern the assortment of second and first-level structures. In the conventional approach, this assortment is characterized by a large variation of geometries and structural patterns. The ordering of this assortment on the basis of a limited number of geometries and structural patterns forms the basis of the modular approach. In other words, the design solution of the complete structure is obtained by combining several series of standardized components at the second and first level of complexity which, according to table 3.7, correspond with stiffened panels and floater/column/deck elements, respectively.

Considering the definition of the design solution given in Chapter 2.2, the internal structural arrangement is derived from panels' structural pattern, whereas the external geometrical form is derived from the characteristics of first-level structures in terms of shape and dimensions (see Fig. 3.17).

The implementation of the modular approach in the design solution implies :

1. Standardization of (structural) patterns in second-level structures.
2. Standardization of (geometrical) form in first-level structures

The obtained standard structures are termed second and first-level modules, respectively.

3.3.2 Standardization of structural components

3.3.2.1 Second level structures

Standardization of second level structures (panels) involves the following aspects :

1. The structural pattern
2. The dimensions of the panel.

The structural pattern concerns the configuration of structural components, i.e. longitudinal and transverse stiffening elements, which is given by the spacing s and S, respectively (Fig. 3.18.a). Standardization implies the adopting of identical values for s and S throughout the entire structure.

An important aspect here is the transition and alignment of (structural) components in connections which are responsible for the distribution of loads throughout the structure (see /3.5/ and par. 3.2.3.3.4). Effective use of the structural pattern is achieved if it brings the components in-line, regardless of panel spacial orientation (see Fig. 3.18.b). This can be obtained if the ratio S/s observes the following rule :

$\frac{S}{s} = k$ (k = 1, 2, 3, ...), throughout the entire semi-submersible structure (Fig. 3.18.c).

The value of k, in combination with s (or S) will affect the matters of structural design solution and cost of production; the choice for a particular k-value will be done once insight in the latter matters is obtained.

Panel dimensions concern length and width which depend on the following factors :

- The production facilities (par. 2.2.3.2)
- The dimensions of first level structures, i.e. floaters, columns and deck.

Standardization of these dimensions throughout the entire semi-submersible platform implicates the breakdown of first-level structures in a manner which yields the minimum possible variation in dimensions. By doing so, the internal arrangement of vertical/horizontal bulkheads has to be considered in addition to the factors mentioned above. The various aspects related herewith will be handled in the course of design and building processes.

3.3.2.2 First structural level

Standardization of first level structures involves the following aspects :

1. The (external) geometrical form of floaters, columns and deck structures,
2. The dimensions of the above structures.

Data contained in table 3.1 show a similarity between floaters and columns in terms of :

1. Form (shape), circular or rectangular cylinders,
2. Dimensions, the cross-sectional areas.

The deck structure bears no resemblance to the above. Though, considering the arrangement of longitudinal/transverse bulkheads within a box-type construction (Fig. 3.14.c), the deck structure can be broken down into an assortmentof complete or partial circumference cylindrical elements of rectangular cross section and lengths corresponding to deck dimensions from table 3.1 (see Fig. 3.19). Hereby, a common basis between floater, column and deck structures is found in terms of a single, rectangular cylinder shape. By choosing a suitable cylinder length, standardization at the first structural level is achieved throughout the entire semi-submersible structure. The necessary dimensions of floater, column and deck structures are obtained by combining a number of such standard cylinders.

3.3.2.3 Summary

A second level module is a stiffened flat panel built according to a standard structural pattern established by the ratio S/s = k (k = 1, 2, 3 ...) between longitudinal and transverse stiffening elements (Fig. 3.18.c).

The variation in panel length and width dimensions is limited; the modules are used for the external geometrical form of first level modules as well as for the internal structural division of same (bulkhead arrangement).

A first level module is a cylinder of rectangular shape. Cylinder width and height dimensions are obtained by combining the width of second level modules in horizontal and vertical directions (Fig. 3.20). Hereby, the orientation of longitudinal stiffening elements corresponds with the length direction of first-level modules of which the width b and height h are multiples of the spacing s (see Fig. 3.20).

The lengths of second and first level modules are set equal and are obtained through the design solution and the building facilities; in principle, this length is too a multiple of the spacing s.

Floater and column structures are obtained by combining the lengths of several first level modules. The deck structure consists of a more complex arrangement of first level modules. In addition to the structural complexity, the deck structure comprises the bulk of equipment, machinery, outfit, etc. In present work, the arrangement of these items is not included.

3.3.3 Implementation in the semi-submersible structure

The dimensions of floater, column and deck structures are obtained by combining first level modules. In principle, these dimensions are all multiples of the standard spacing s and are expressed in the following form :

$\text{dimension}_i = n_i \times s$, where

dimension_i = platform dimension i

n_i = the number of (equal) spacings s to obtain dimension_i

All these are considered as continuous variables which may take on a continuous range of values within practicle limits. The notation of the various dimensions and properties derived from these dimensions will be used in design, construction and building cost calculations. Some of the most important dimensions and hydrostatic properties are given below (Fig. 3.21).

Floaters

- L_f : length floater = $n_3 \times s$, parallel to platform X axis
- B_f : width floater = $n_1 \times s$, parallel to platform Y axis
- H_f : height floater = $n_2 \times s$, parallel to platform Z axis
- $V_f=V_2$: volume floaters = $2\, n_1 n_2 n_3 s^3$
- A_f : floater cross sectional area = $n_1 n_2 s^2$
- A_{fwl} : floater water line area = $n_2 n_3 s^2$

Columns

- L_c : length column = $n_1 \times s$, parallel to platform X axis
- B_c : width column = $n_2 \times s$, parallel to platform Y axis
- H_c : height column = $n_4 \times s$, parallel to platform Z axis
- h_1 : immersed column height
- $V_c=V_1$: volume columns = $mn_1 n_2 n_4 s^3$
- V_{h1} : immersed column volume $n_1 n_2 h_1 s^2$

- A_{cwl} : column cross sectional area = $n_1 n_2 s^2$
- A_{wl} : water line area = $mn_1 n_2 s^2$
- m : total number of columns

<u>Deck</u>

- L_d : length deck = $n_5 \times s$, parallel to platform X axis
- B_d : width deck = $n_6 \times s$, parallel to platform Y axis
- H_d : height deck = $n_2 \times s$, parallel to platform Z axis
- X : longitudinal distance between centres of corner columns
- Y_c : transverse distance between centres of opposite columns

$L_d = X + n_2 s$

$B_d = Y + n_1 s$

<u>Complete model</u>

- V : platform displacement = $2s^2 n_1 n_2 (n_3 s + mh_1/2)$
- ratio $\frac{V_2}{V_1} = \frac{2sn_3}{mh_1}$

<u>Hydrostatic data</u>

- Centre of buoyancy KB : $\dfrac{2s^3 n_1 n_2 n_3 \times 0.5\, n_2 s + ms^2 n_1 n_2 \times h_1 (h_1/2 + n_2 s)}{2s^2 n_1 n_2 (n_3 s + mh_1/2)}$

- Metacentric height BM : $\dfrac{\frac{1}{12}\, mn_1 s \times (n_2 s)^3 + mn_1 n_2 s^2\, (Y/2)^2}{2s^2 n_1 n_2 (n_3 s + mh_1/2)}$

- Draught : $n_2 s + h_1$

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Table 3.1: Functions and characteristics of semi-submersible platforms

ITEM	FUNCTIONS			GEOMETRY			
	DESIRED FUNCTIONS		UNDESIRED FUNCTIONS	FORM CROSS-SECTION		DIMENSIONS	
	PRIMARY	SECONDARY		CIRCULAR	RECTANGULAR	AREA (m^2)	LENGTH (m)
FLOATER	buoyancy ($\pm$ 70 %)	storage of : . ballast . fuel . drill water, etc accommodation of : . propulsion . pumps	generate : . hydrodynamic exciting forces . drift forces	yes	yes	75 - 100	80 - 110
COLUMNS	stability support of deck structure	buoyancy ($\pm$ 30 %) storage	generate : . hydrodynamic exciting forces drift forces wind heeling moments	yes	yes	25 - 100	25 - 35
DECK STRUCTURE	work area/space accommodation of machinery, etc storage structural strength	eventually, reserve buoyancy	generate : . wind forces and heeling moments . negative impact on stability due to top-location	yes	---	length 60 - 90 m. width 50 - 80 m.	

Table 3.2: Spectrum of activities and heave motion limitations

ACTIVITY	DURATION %	LIMITING HEAVE	
		max (m)	sign (m)
DRILLING	55	3.6	2.4
RUNNING CASING	7	3.6	2.4
LANDING CASING	1	1.5	0.9
LOGGING	2	3.6	2.4
SUBSEA HANDLING	9	3.6	2.4
SUBSEA HANDLING	2	1.5	0.9
ANCHOR HANDLING	3	3 m. max.wave	
TRANSIT	11	UNLIMITED	
VARIOUS	10	3.6	2.4
TOTAL	100		

Table 3.3: Value of h at combinations of α,β according to fig.3.1 (in metres)

β α	1	2	3
1	54.5	36.3	27.2
2	36.3	21.8	15.6
3	27.2	15.6	10.9

Table 3.4 : Loading conditions for semi-submersible platforms

LOADING CONDITION	DESCRIPTION OF LOADS
a	only functional loads
b	environmental loads and associated functional loads
c	accidental loads and associated functional loads
d	environmental loads and associated functional loads after credible failure or after accidental events
e	environmental loads ans associated functional loads in a heeled condition corresponding to accidental flooding

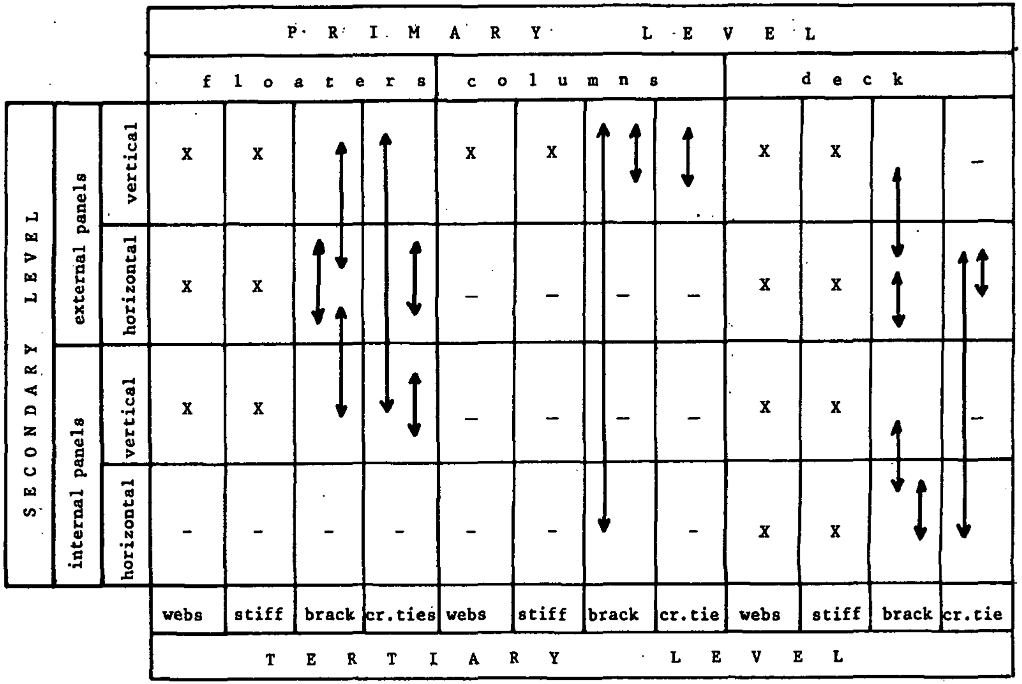
Table 3.5 : Combinations of operating and loading conditions

DESIGN CONDITION	LOADING CONDITION				
	a	b	c	d	e
normal operating	X	X	X	X	X
transit	X	X	-	-	X
survival	X	X	-	-	X

Table 3.6: Structural levels in semi-submersible platform structures

STRUCTURAL LEVEL	COMPONENTS
PRIMAY	. floater structure . column structure . deck structure
SECONDARY	. external (shell) panels : - horizontal (decks, bottoms) - vertical (side shell) . internal panels : - horizontal (decks) - vertical (bulkheads)
TERTIARY	. web-frames . stiffeners . brackets . cross ties

Table 3.7: Relations between structural levels and structural components



		PRIMARY LEVEL											
		floaters				columns				deck			
SECONDARY LEVEL	external panels vertical	X	X			X	X			X	X		–
	external panels horizontal	X	X			–	–	–	–	X	X		
	internal panels vertical	X	X			–	–	–	–	X	X		–
	internal panels horizontal	-	-	-	-	-	-		-	X	X		
		webs	stiff	brack	cr.ties	webs	stiff	brack	cr.tie	webs	stiff	brack	cr.tie
		TERTIARY LEVEL											

X : existing component

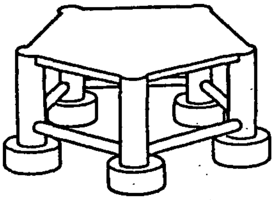
↕ : connection between similar types

↕ : connection between different types

Table 3.8 : Wave data for loading cases used in overall strength assessment

	WAVE DATA		
CASE	DIRECTION	LENGTH	LOADED STRUCTURAL ELEMENT
a	beam seas	approx. twice the breadth over the floaters	horizontal braces ; if not applied, connection columns/deck structure
b	diagonal seas	approx. equal to diagonal over opposite corner columns	deck structure , braces , columns
c_1	head seas	approx. equal the floater length	connection vert.braces/deck structure connection columns/deck structure
c_2	beam seas	approx. equal to breadth over floaters	connection vert.braces/deck structure connection columns/deck structure
c_3	head seas	approx.twice the floater length	connection vert.braces/deck structure connection columns deck structure

Fig.3.1.a Caison configuration



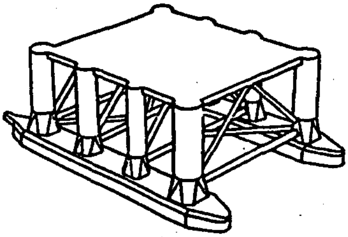
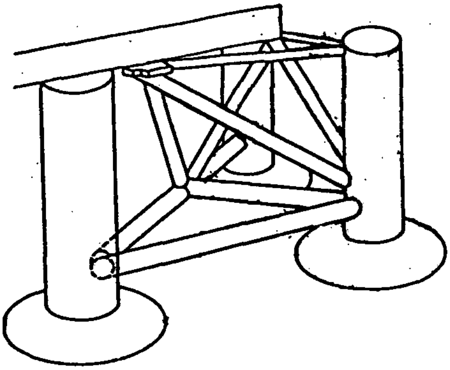


Fig.3.1.b : Hulls configuration

Fig.3.2.a : Extensive bracing



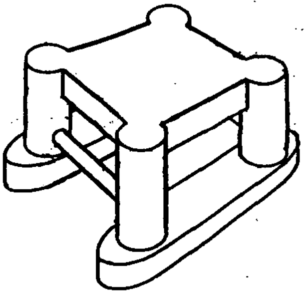


Fig.3.2.b : Reduced bracing,
box - deck structure

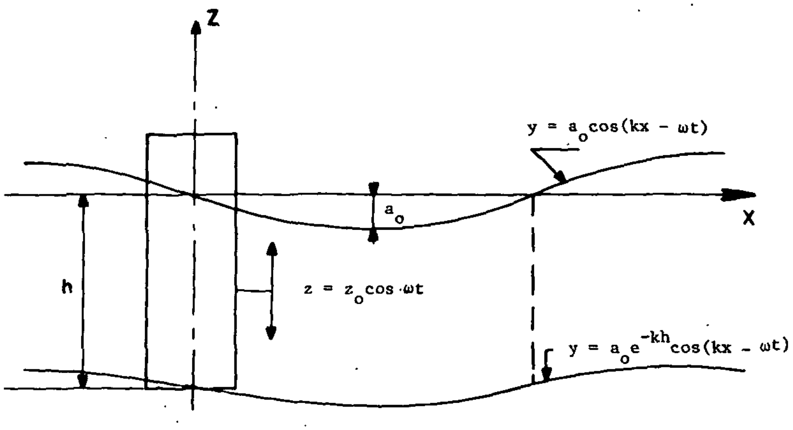


Fig.3.3: Vertical cylinder in sinusoidal waves

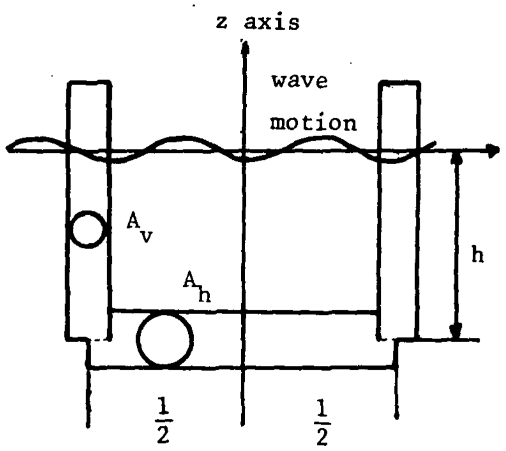


Fig.3.4: Semi-submersible configuration

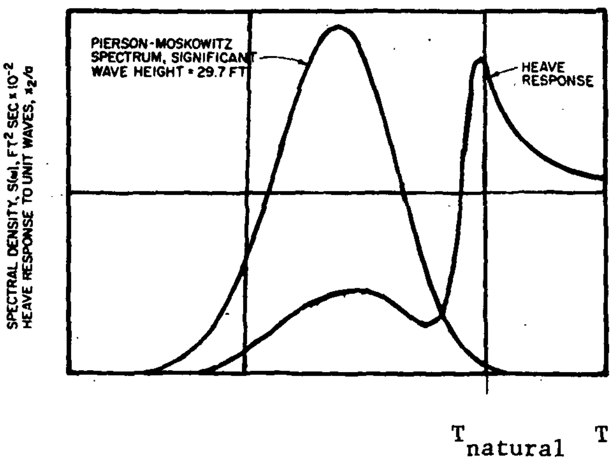


Fig.3.5: De - tuning principle

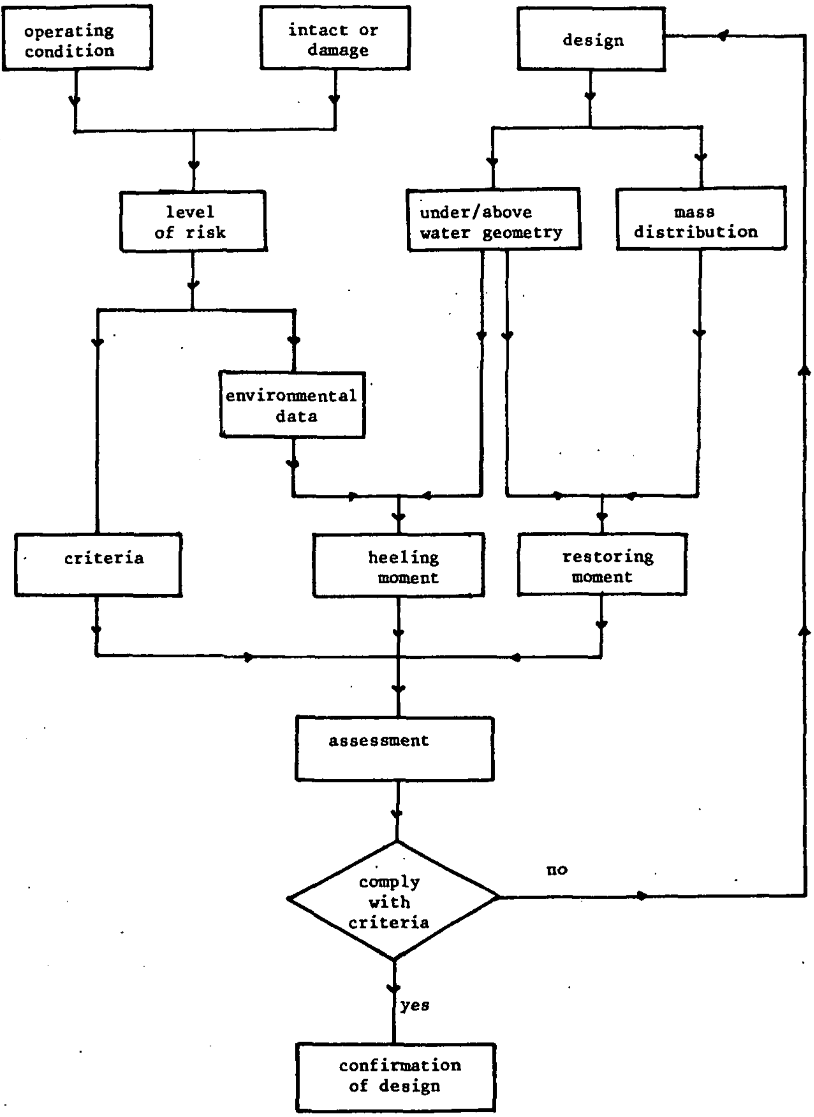
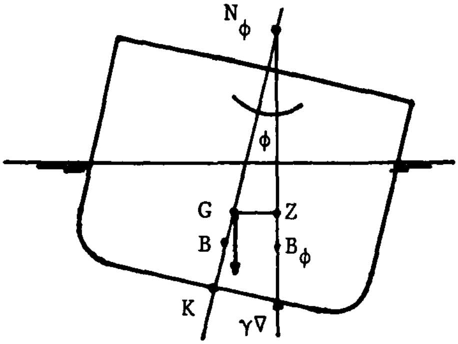


Fig.3.6 : Schematic approach to stability assessment

Fig.3.7.a : Used terminology

K : keel point
B : centre of buoyancy
G : centre of gravity
N (ϕ) : "false metacentre"
GZ (ϕ) : restoring arm
ϕ : heeling angle



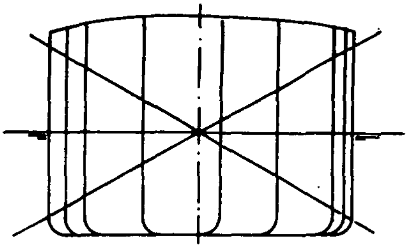


Fig.3.7.b : "Scribanti" ship

Fig.3.8 : Wind influence

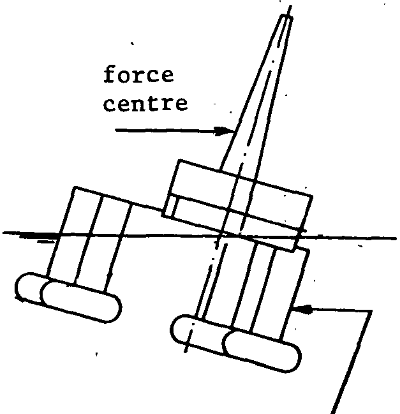


Fig.3.9.a: Weather criterion in waves

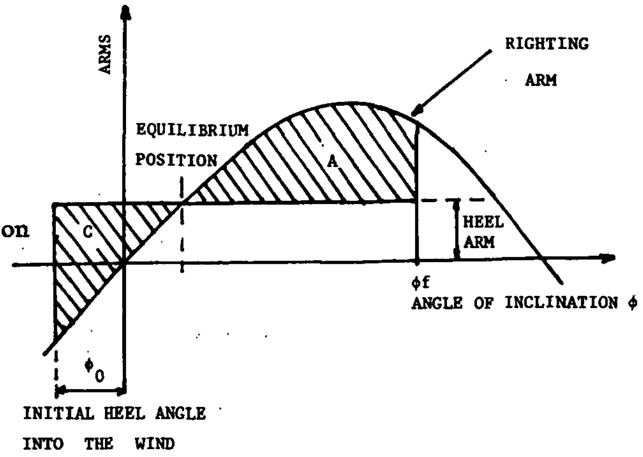


Fig.3.9.b: Weather criterion in still water

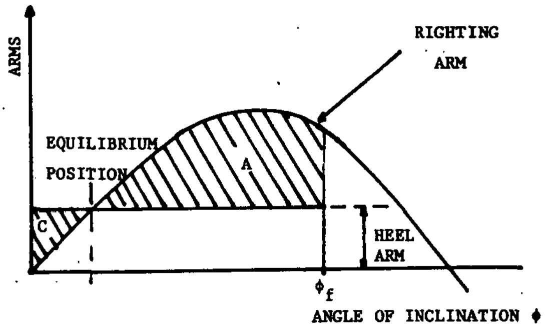
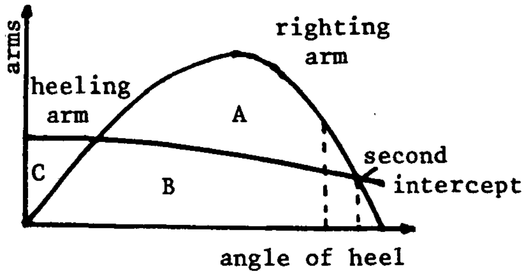


Fig.3.9.c: Interception points



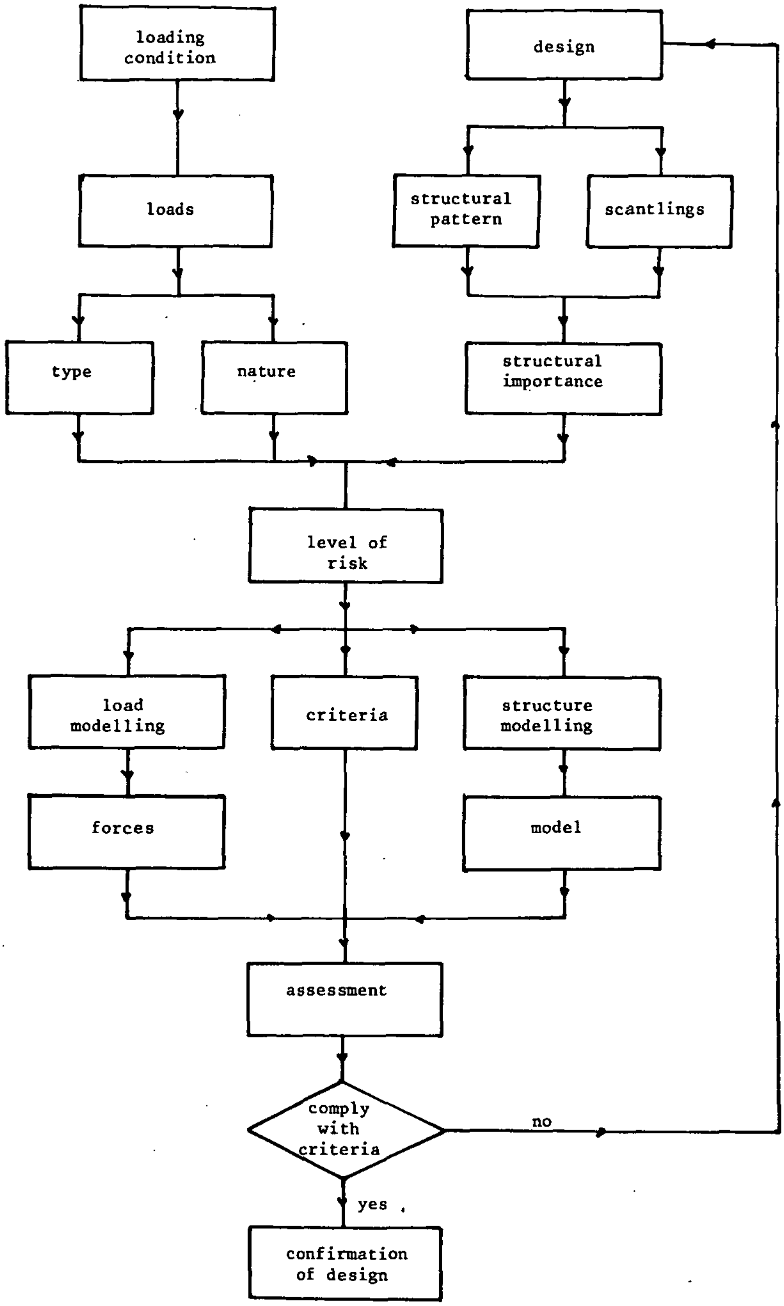


Fig.3.10 : Schematic approach to assessment of structural strength

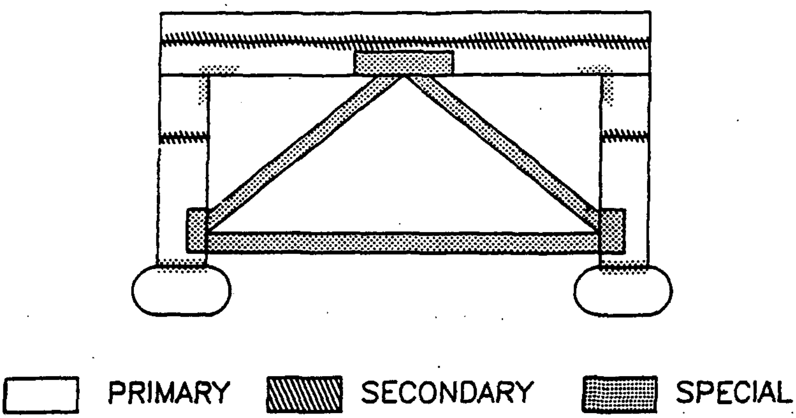


Fig.3.11 : Participation (importance) of structural components to overall strength

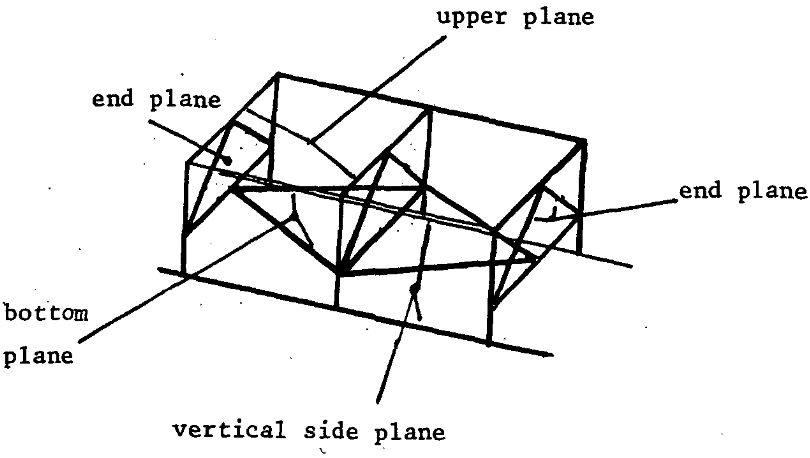


Fig.3.12 : Representation of planes in semi-submersible structure

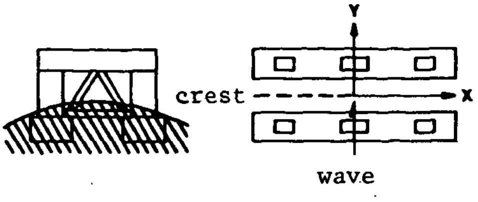


Fig.3.13.a: Loading case a: beam seas, wave length twice the breadth over floaters

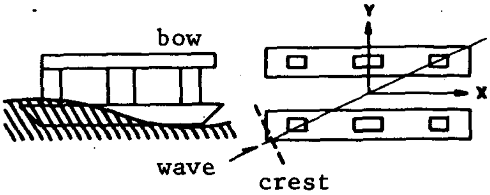


Fig.3.13.b: Loading case b: diagonal seas, wave length equal to diagonal over floaters

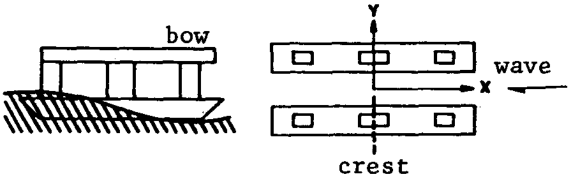


Fig.3.13.c: Loading case c_1: head seas, wave length equal to floater length

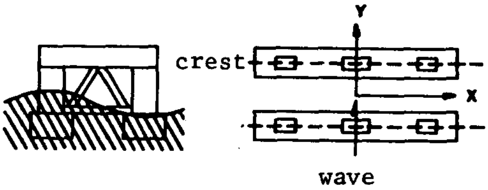


Fig.3.13.d: Loading case c_2: beam seas, wave length equal to breadth over floaters

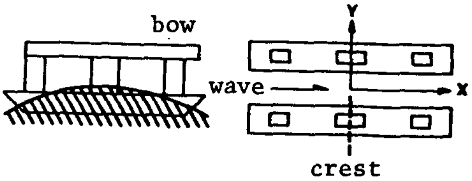


Fig.3.13.e: Loading case c_3: head seas, wave length equal twice the floater length

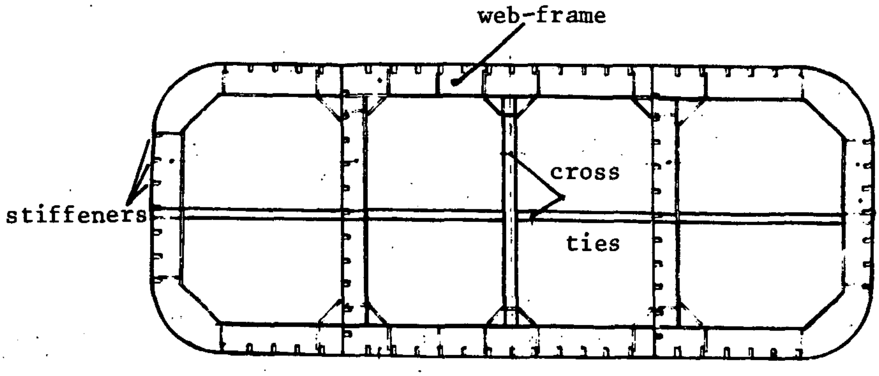


Fig.3.14.a: Cross-section over floater

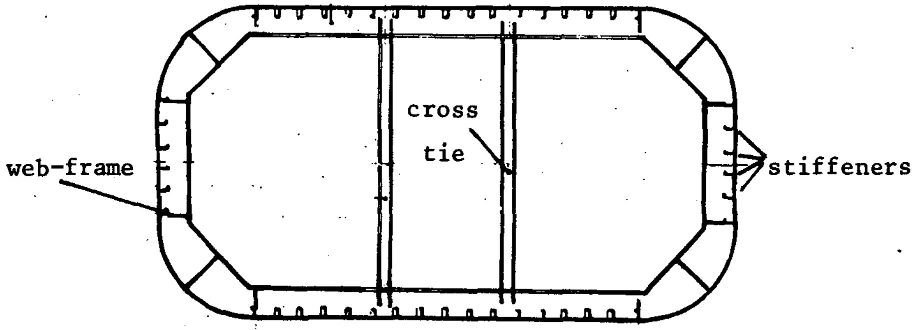


Fig.3.14.b: Cross-section over column

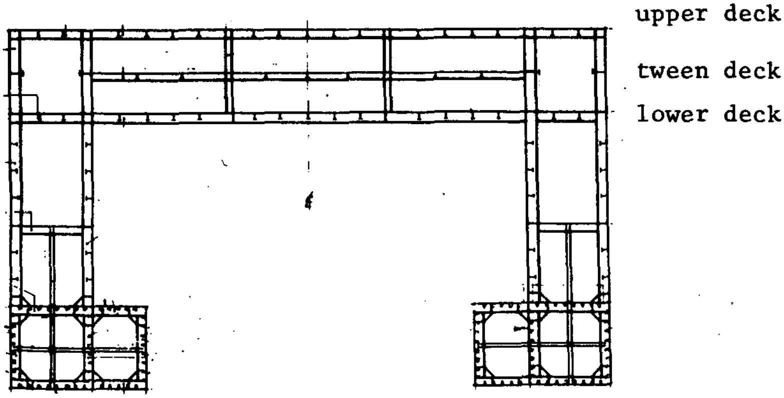


Fig.3.14.c: Cross-section over box-type deck structure

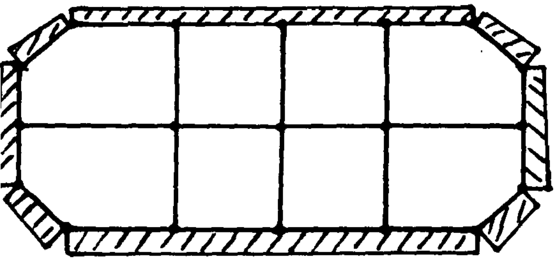


Fig.3.15.a: 2-D beam model of floater section ; external pressure, all tanks empty

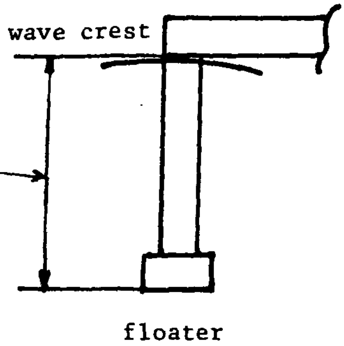


Fig.3.15.b: Design pressure column

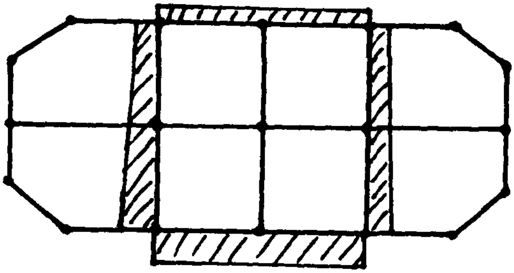


Fig.3.15.c: Floater model, side tanks full

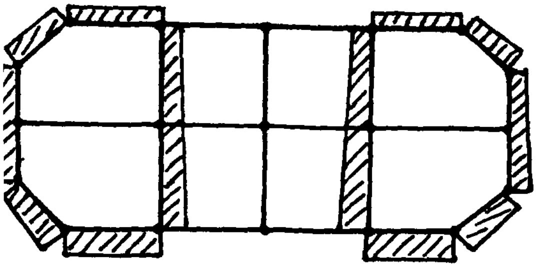


Fig.3.15.d: Floater model, centre tank full

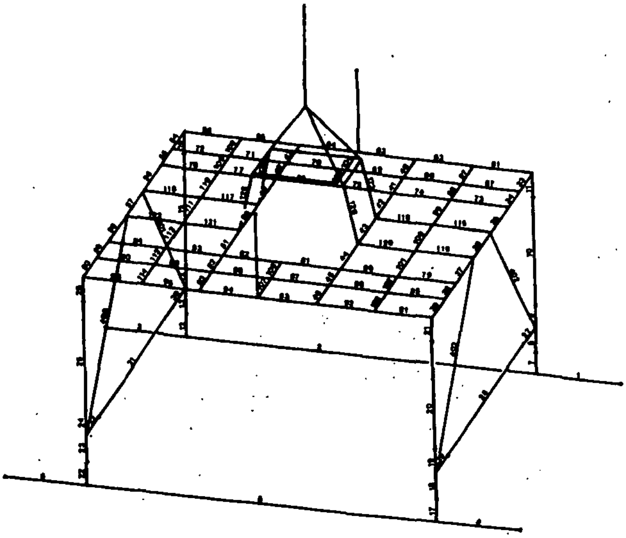


Fig.3.16: 3-D beam model, complete structure, for assessment of overall strength

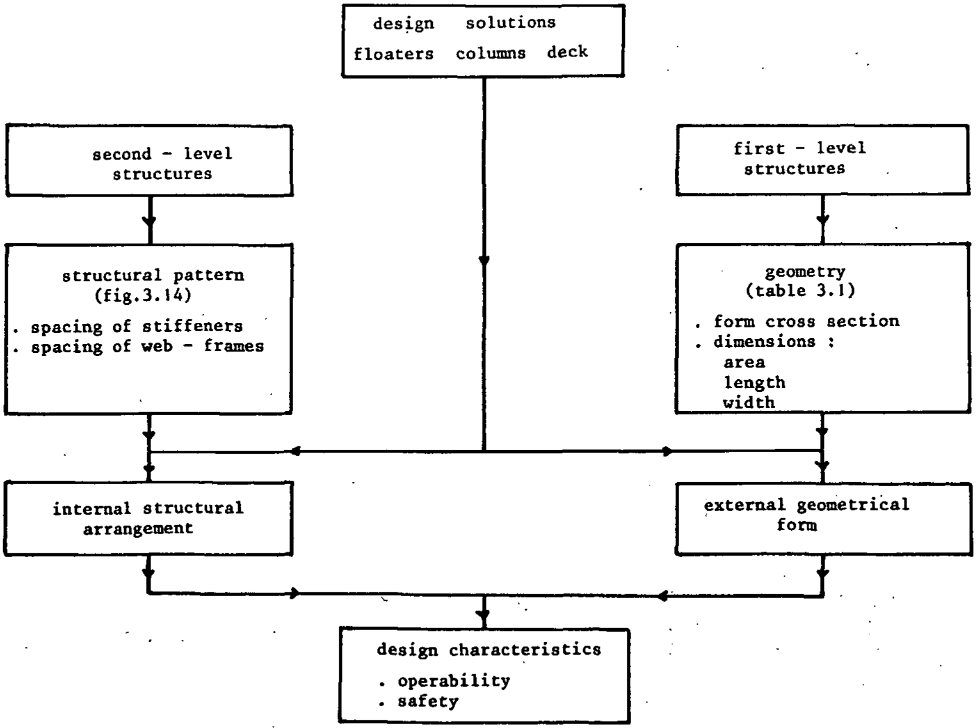


Fig.3.17: Relations between notions in the design process

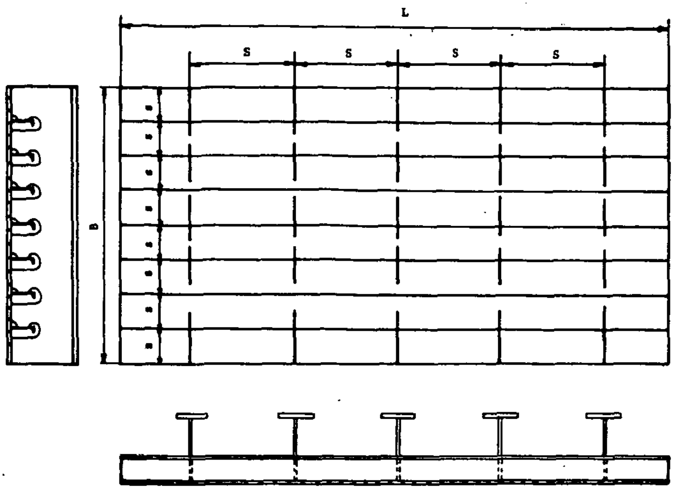


Fig.3.18.a: Structural pattern in flat panels

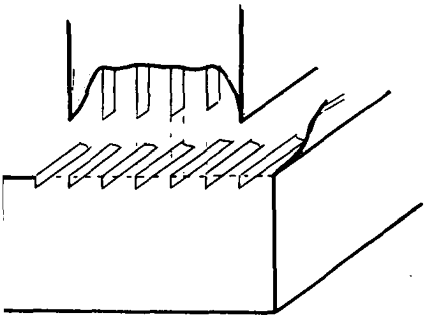


Fig.3.18.b: Alignment of structural components in connections

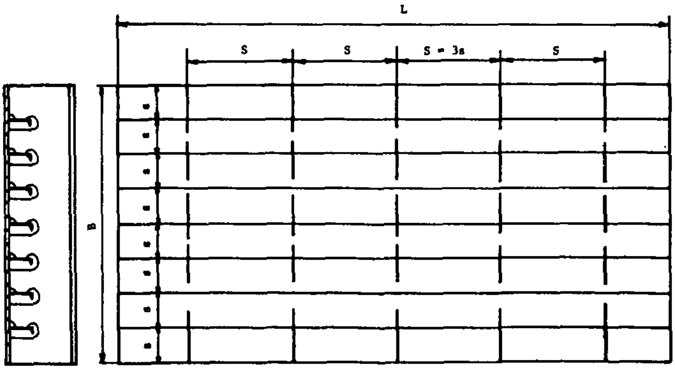


Fig.3.18.c: Structural pattern in modular flat panels

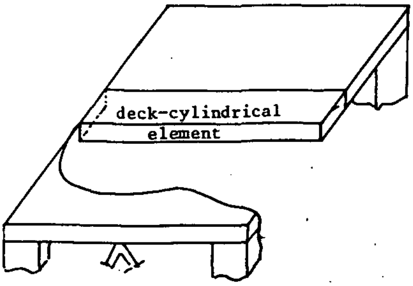


Fig.3.19: Break-down of deck structure into cylindrical components

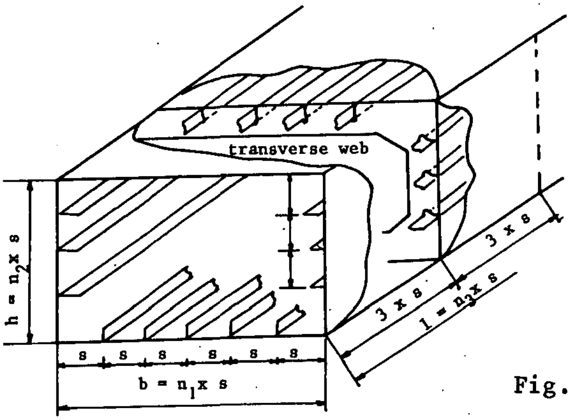


Fig.3.20: First-level module external geometry and internal structural arrangement

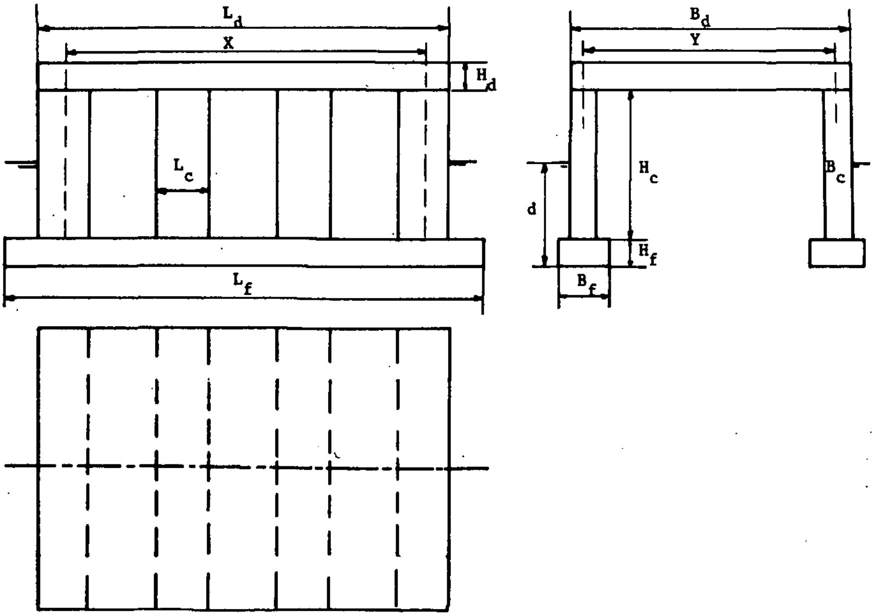


Fig.3.21: Complete modular semi-submersible platform

Appendix 3.1

Assessment of Overall Strength Based on ref. 3.22, 3.25-6.

The platform is considered in principle as a box-structure subjected to wave action and consisting of the following (Fig.3.12):

- an upper plane, i.e. the deck structure,
- two vertical side planes; starting from the deck structure downwards, it includes the columns and the floaters,
- eventually, a lower plane consisting of a configuration of horizontal braces between columns and floaters,
- eventually, vertical planes at the ends and in-between formed by a configuration of vertical braces.

Regular, sinusoidal waves, deep water condition and zero speed of advance are assumed.

Depending on wave direction and length, the box structure is subjected to :

a. Opposite-horizontal hydrodynamic mass forces acting on floaters and columns; this is termed splitting condition (fig. 3.13.a).

b. Torsion due to out-of-phase vertical hydrodynamic forces acting at the ends of the diagonal over floaters and opposite corner columns (Fig. 3.13.b).

c. Inertia forces acting on the deck structure in :
   1. horizontal direction ==> transverse racking (Fig. 3.13.c)
   2. vertical direction (Fig. 3.13.d)
   3. horizontal direction ==> longitudinal racking (Fig. 3.13.e)

The corresponding critical wave length, direction and the critically loaded structure parts are given in table 3.8.

A commonly used method for the calculation of hydrodynamic forces on the submerged parts of the platform, the so-called Morison formula; denoting F_m and F_d as the mass, respectively drag hydrodynamic forces :

$F_m = \rho \times V \times C_m \times a$, where :

C_m = mass coefficient

V = reference volume

a = horizontal acceleration of water particles in the incoming wave, at cylinder's axis

ρ = fluid density

$F_d = 0.5 \times \rho \times d \times l \times C_d \times v \times |v|$, where :

d = reference cross-sectional dimension

l = cylinder length

C_d = drag coefficient

v = horizontal velocity of water particles in the incoming wave at cylinder's axis

ρ = fluid density

The above approach is a simplification of wave load phenomena. In a more realistic approach, a combination of wave components of various lengths (frequencies) are considered, the wave spectrum. Correspondingly, the loads associated with the various wave components from a load spectrum /3.6-7/.

A commonly used technique is to associate the peak period of the wave spectrum with the period of a sinusoidal wave for cases a-c above /3.22/.

Chapter 4

The design

4.1 Introduction

4.1.1 General

Design is a creative activity where the designer generates and provides one or more solutions to a given set of requirements within imposed limitations.

In general, the design of marine structures has been discussed with respect to particular marine products. Special emphasis has been laid on merchant ships /4.1-5/, though sufficient attention has been paid to other products, including semi-submersible drilling platforms /4.7-11/.

In spite of essential differences between the nature of the various marine products, there is a common general approach towards design activities. Some definitions, methods and models used in the design of marine products, in particular floating structures, are reviewed below.

4.1.2 Definitions

The design of floating marine structures is an iterative process where a concept solution is gradually worked out by performing several cycles of calculations, with increasing accuracy, until all technical/economical requirements have been satisfied within limitations imposed by :

- The laws of physics
- The applicable rules, regulations and conventions
- The technical capabilities of builder and suppliers.

/4.6/

The discussion on ship design involves the following definitions :

4.1.2.1 Design process

The total of activities with the aim of generating a design. Thes activities are divided into a number of phases. A division based on /4.6/ consists of the following phases :

- An analysis phase, which is the taking-in of information with th purpose of defining boundary conditions for and conceptualizatio of design solutions.
- A synthesis phase, where one concept is chosen and developed int a fully feasible technical solution, the preliminary design.
- An evaluation phase which deals with the evaluation, improvement and detailing of the preliminary design.

(Fig. 4.1)

4.1.2.2 Parameters, variables, constraints

The information used in the course of the above and the obtained solutions are expressed by a number of items which determine the required characteristics of the design and the imposed limitations these are :

Input parameters or data

Numerical values of (design) characteristics which need to be realized in the course of the design process, usually imposed by the owner. These may include :

- pay-load, cargo volume
- sailing speed
- endurance at sea.

Design variables

Numerical values of (design) characteristics which need to be esta blished in the course of the design process. A distinction is mad between independent or free variables and dependent variables.

Free variables are chosen by the designer on various grounds such as experience or imposed restrictions.

Dependent variables are calculated by means of expressions of physical or empirical nature between these and free variables.

There is no clear distinction between the types of variables, the choice depends on the design and directing models.

Design variables are considered as deterministic and may take on a continuous range of values within practical limits. Some examples are :

- Main hull dimensions such as length, width, height;
- Displacement, draught and form coefficients;
- Hydrostatic properties;
- Mass and mass distribution.

Inequality/equality constraints

Inequality constraints are used to express limitations associated with the numerical values of design variables. Some examples are :

- Draught or width restrictions;
- Minimum metacentric height.

Equality constraints express relations between design variables on empirical or physical grounds. The dead weight/displacement ratio and Archimedes' law are examples for the former, respectively latter. Equality constraints can also be derived from inequality constraints. For example, by setting ship draught equal to the maximum allowable draught. Equality constraints are used to eliminate design variables.

Specific design data

Specific design data concerns the total of information extracted from previous designs and concerning various aspects such as :

- Data on specific structures, equipment, machinery, outfit, etc. with respect to mass and mass distribution.
- Data on aerodynamic and hydrodynamic properties necessary for the calculation of resistance, motions, drift, etc.
- Data on power take-off of various systems.
- Data on efficiency of propulsion systems, etc.

The nature of all the above as well as the associated numerical values depend on the type of the required floating marine product.

4.1.2.3 Design method

The approach or technique used to initiate the iteration process. Usually, it depends on the type of structure and the extent/quality of available information. Though no definite distinction can be made, the following general design methods are used :

1. Design following similar structures
2. Design by the coefficient method
3. Step-by-step iteration.

/4.6/

4.1.2.4 Design and directing models

Design model

Design model is the procedure (sequence) by which the various calculations are performed, depending on the type of ship and/or the directing model.

Directing model

Directing model is the technique used to steer the iteration process which leads to the concept solution in the synthesis phase of the design process.

The steering can be entirely controlled by the designer (open directing model) or pre-determined through a set of equality constraints (closed directing model).

The choice of the directing model depends on the amount and the quality of information available to the designer. An increase of these two items will limit the interference (steering) by the designer and lead to a more closed directing model.

4.1.2.5 Operating and design conditions

These terms were already discussed in chapter 3, par. 2 with respect to the semi-submersible platform. The principles are applicable to all floating structures, with due consideration to the operating aspects of each type of structure.

4.2 Conventional design concept

4.2.1 Introduction

In general, the conventional approach to the design of semi-submersible platforms is handled along lines similar to those in the design of floating marine structures, as long as due attention is paid to the particular characteristics of the former product.

In the first place, there is a separation of functions such as buoyancy, stability, structural strength, etc. which are divided over several structures.

In the second place, the differences between operating conditions have an impact on various design aspects. In particular, the buoyancy aspect, where a large share of the available buoyancy (30 - 50%) is "destroyed" by taking-in of liquid ballast to achieve the deep draught condition.

The above leads to a different system of relations with respect to:
- Inter-action and dependence between design parameters and variables.
- Corrective measures applied to a particular part of the structure and the impact on the entire platform.

A simplified design scheme is shown in Fig. 4.2 where analysis, synthesis and evaluation phases are clearly recognizable. Design methods, models and directing models are also applicable.

On the other hand, the identification of design parameters and variables as well as equality constraints are defined within the aspects of the semi-submersible platform design. The identification of these items and their integration and, eventual, redefinition within the reference structure will be handled in this chapter. A brief review of all design phases with regard to the semi-submersible platform is given below.

4.2.2 Phase 1 : Analysis

The basis for the analysis is given by owner's requirements which are presented as follows :

1. Operating area and season
2. Technical performances
3. Applicable rules, regulations and conventions.

4.2.2.1 Operating area and season

These are used to establish the nature and magnitude of environmental phenomena during all design conditions and concern :

- water depth;
- the regimes of winds, waves and currents;
- atmospheric and water conditions such as temperature, humidity, ice forming, etc.

The derived information is used as follows :

- To establish environmental design and operating conditions for the platform and its systems.
- To establish, in combination with other loads and relevant safety criteria imposed by (3) above, loading conditions for the structure and its systems.
- To evaluate the safety of the platform in terms of stability and structural strength.
- To evaluate the operability aspects of the platform.

4.2.2.2 Technical performance

This involves several items :

1. Job specification; for drilling platforms, this is given by the depth of the drill hole.

2. Endurance at sea, i.e. the duration of the time or the number of holes which must be accomplished without re-supplying.
3. The efficiency of the design, usually expressed by the workability or down-time (see Chapter 3 par. 2).

Items (1) and (2) are used to determine :

- The specifications of systems, i.e. machinery, outfit, etc. related to the drilling function of the platform.
- The pay-load (P.L.), which is the amount of supplies which can be stored on the platform.
- The variable deck-load (V.D.L.), which is the amount of supplies or loads which can be accommodated on/within the deck structure, eventually in the upper column parts.

Both pay-load and variable deck load are design parameters.

Item (3) is usually given as an inequality constraint :

$T_{downtime} < X \% \text{ or } T_{workability} \geq (100 - X) \%$

Unlike pay-load and variable deck load, down time or workability are not directly related to a particular design parameter, but are derived from platform dynamic behaviour in waves, thus from design variables, in particular those determining the heave motion (chap. 3 par.2). If, for example, the de-tuning method is used for reduction of the heave motion, platform operability can be related to an inequality constraint concerning the natural period in heave :

$T_{heave} > T_{heave\ min.}$

4.2.2.3 Applicable rules, regulations and conventions

The general approach to assessment of platform safety was discussed in chapter 3 par. 2. The applicable criteria, based on the Classification Rules were also presented.

4.2.2.4 Design variables

Design variables are divided into two groups :

1. Those related to the external geometry of the platform :
   - displacement and draught in all operating conditions
   - main dimensions of floaters, columns and deck
   - hydrostatic properties
   - the number of columns.

2. Those related to the internal structural arrangement :
   - spacing of longitudinal and transverse stiffening elements
   - unsupported spans of stiffeners, webframes, etc.
   - components' scantling such as plate thickness, cross-sectional areas of sections, etc.

An additional distinction is made between continuous and discrete variables. The former can take on a continuous range of values within practical limits (dimensions, cross-sectional areas, etc.), the latter are limited to discrete values (plate thickness) (see also table 4.1).

4.2.3 Phase 2 : Synthesis

In the synthesis phase, the design concept is established to a satisfactory feasibility level. The sequence of activities involved are presented in the following design model (Fig. 4.3) :

4.2.3.1 Geometrical design solution

The geometrical design solution concerns the external geometry :

- The arrangement of floaters, columns and deck-structure, including the number and location of columns;
- The dimensions and shaping of the above.

The geometrical design solution determines the hydrostatic and hydrodynamic characteristics of the semi-submersible platform. The coefficient design method and a partly closed directing model are indicated; all these with respect to the amount and quality of available information / 4.6/.

4.2.3.2 General arrangement

The arrangement of all machinery, equipment, accommodation and storage spaces is the second step in this phase. In general, the location of the above is related to particular parts of the platform (see chapter 3 table 1).

4.2.3.3 Structural design solution

Unlike the practice for some floating marine structures (ships) there is no overall strength parameter in the form of a design section modulus or design bending moment for the midship section. Structural design solutions and dimensioning of scantlings are based on direct calculations. The general approach to the assessment of structural strength was discussed in chapter 3, par. 2. Some important aspects were :

- The determination of relevant load combinations and the modelling of loads.
- The modelling of the structure for purpose of calculations.
- The relevant criteria for structural strength assessment.

4.2.3.4 Sizing of major systems

The sizing of major systems is related to platform systems and involves :
- positioning
- propulsion

- domestic services such as ballast, fuel, etc.

Drilling equipment, auxiliaries, accommodation, etc. are already established.

The above information is used to perform electrical load analysis and determine :

- the required installed power
- the configuration of power generating machinery, auxiliaries, etc.
- the amount of fuel.

4.2.3.5 Feasibility

The feasibility of the design is assessed, for the first time, with respect to the entire platform. The matters of response to wave action, stability and structural strength are investigated. The performed activities are divided into two groups :

1. Calculation of :
   - capacities
   - light and dead weights
   - mass distribution and centres of gravity.

2. Calculation of :
   - stability in intact and damage condition
   - motions
   - structural strength, eventually with inclusion of dynamic effects.

In addition to the eventual involvement of time dependent loads, a complete model of the platform is considered; usually this is a 3-dimensional model with beam elements (chapt. 3 par.2 and Fig. 3.16).

The obtained information is used, in the first place, to confirm the feasibility of the initial geometrical and structural solutions. If the results are satisfactory, the activities concerning the preliminary design are hereby ended.

4.2.4 Phase 3 : Evaluation/final design and engineering

4.2.4.1 Detailed structural analysis

If dynamic effects were already included in the synthesis phase, the detailed structural analysis here deals with :

- vibration and fatigue phenomena
- joint design, for example braces connections, column-deck connection.

Input information for the above is derived from the dynamic strength calculation. More refined structure modelling such as finite elements are used.

4.2.4.2 Detailed design and engineering

Detailed drawings are prepared on the following :

- machinery
- crew accommodation
- piping and cabling
- steel structure.

4.2.4.3 Confirmation of feasibility

Various calculations from the synthesis phases are repeated with inclusion of new available information on mass and mass distribution, etc. Eventually, model tests are performed to confirm platform response to waves.

4.2.4.4 Specifications

Technical specifications form a document which includes all the information acquired in the course of the design process :

- design requirements
- physical description
  - geometry
  - arrangement
  - capacities
- information on the following :
  - steel structure
  - drilling equipment
  - machinery
  - positioning and propulsion
  - accommodation
  - all piping and cabling systems
  - etc.

Where applicable, technical specifications include :

- required system performance
- materials
- conservation

4.2.4.5 Cost price

The economical aspects, in particular platform cost-price, form an integral part of the design. In general, the accuracy of the cost-price calculation depends on the amount and quality of information available. It seems, thus, logical to perform this calculation at the end of the design process, using information derived from detailed drawings and technical specifications. The cost-price is, thus, regarded as a consequence of the design solution.

This practice deprives, however, the designer of the possibility to consider alternative and, possibly, cheaper solutions at an earlier design stage, for example before the elaborate evaluation phase. The question is at what stage should the calculation of cost-price be performed. A major point here is the relation between design variables and cost-price. Some aspects of this relation, centred around the steel structure, were discussed in chapter 2 par. 3; the impact of other items such as machinery, outfit, etc. on this relation was not included.

Following the above design procedure, a distinction can be made between :

1. A group of items related to drilling operations, i.e. drilling and auxiliary systems, machinery, accommodation, etc.
2. A group of items concerning platform systems, such as positioning, propulsion, ballasting, etc.

The main difference between the two groups is that group 1 is independent of the values assumed by design variables concerning the geometrical form and the internal structural arrangement. In othe words, group 1 is not involved in the relation design variables - cost price.

An overview of the relation and dependence between cost factors an design is given in table 4.2. Only material and labour costs are considered, with a more detailed break down of the various items. Following table 4.2, once the external geometry and general arrangement are determined, the cost of materials remain, with exceptio of steel, unchanged. This holds, to a lesser extent, also for material processing, assembly, installation, etc.; here again, steel material offers possibilities for alternative solutions. In fact, steel material/processing costs can only be established afte the determination of the structural design solution so that the relation between cost-price and design variables is established in two steps :

1. <u>Step 1</u> : cost-price of machinery, equipment, outfit, etc. in relation with geometrical design variables (dimensions, form, etc.) of floaters, columns and deck structure.
2. <u>Step 2</u> : cost-price of the steel hull structure in relation wit internal structural design variables (spacing of stiffeners, unsupported spans).

The cost-price of items within group 1 above is established before the first step.

To eliminate unfeasible solutions before the final step in cost-price calculations, the design model from Fig. 4.4 is proposed. The feasibility is assessed, at each geometrical solution, for all structural alternatives. This proposal concerns an open directing model.

If, however, a design model can be developed so that the geometrical solutions are already within feasible boundaries (Fig. 4.5), several iteration loops can be spared. This can be done if the feasibility of the design solution is established in the relation between design parameters and variables by means of equality constraints; thus, a closed directing model.

4.2.5 Summary

The cost-price is an important item in the economical evaluation of the final design solution. By establishing a link between this item and the design variables, cost-price becomes an active factor in the definition of the design solution.

In the above discussion, it was shown that such a link exists and that it is related to the geometrical and, in particular, to structural design variables in the synthesis phase. Furthermore, it was shown that this link concerns mainly the steel structure; items related to drilling operations do not depend on design variables whereas items related to platform systems depend only on external geometrical variables.

Cost-price evaluations are limited to feasible geometrical/ structural design solutions only if the former are established through equality constraints concerning aspects of stability and motions.

4.3 Modular design concept

4.3.1 Introduction

The evaluation of the conventional design concept has indicated that the relation design variables - cost price is mainly concerne with the steel structure. In this section, a design concept will be developed which uses the modular approach to provide a preliminary, feasible design solution for the steel structure. This will consist of :

- A geometrical design, i.e. shape, configuration and dimensions of platform's external geometry.
- A structural design, i.e. dimensions of structural components throughout the entire platform.

The degree of accuracy at this stage must be sufficient to prove the feasibility of the design and provide the necessary informatio for the calculation of (steel) material and labour costs.

The design procedure is based on Fig. 4.5 and steered by a closed directing model. This implies the use of equality constraints to eliminate free variables. The equality constraints are obtained b using limit values given in inequality constraints; for example :

$T_{heave} \geqslant T_{heave\ min.}$ becomes $T_{heave} = T_{heave\ min.}$

The design model deals separately with the geometrical and structural design, using relevant variables and derived equality constraints. To ensure the feasibility of the solution, the various constraints will be used to determine the numerical values of design variables.

4.3.2 Geometrical design

Fig. 4.6 shows a schematic approach to the geometrical design. The involved design parameters and variables are :

Design parameters

- The variable deck load V.D.L. This is used in a way similar to the deadweight/displacement ratio in ship design for the first estimate of the underwater volume for deep draught condition /4.6, 4.16/.
- The minimum natural heave period T_h.

Design variables

The design variables involved in the geometrical design are :

- The underwater volume V of the platform.
- The ratio V_2/V_1, where V_2 and V_1 are the respective floater and column displaced volumes.
- The number of columns m.
- The aspect ratio α between floater width b and height h, which is the first-level module aspect ratio. This ratio is the same for all floater, column and a part of the deck modules.
- The total and submerged column height, H_c and h_1 respectively.
- The longitudinal and transverse distance between corner columns, X and Y respectively.
- The vertical position of the centre of gravity KG.
- The moment heeling arm a_h.
- The metacentric height above the centres of buoyancy and gravity, respectively BM and GM.

A total of twelve (12) design variables.

The geometrical design is performed in two phases (Fig. 4.6) :

Phase 1

This phase concerns the determination of the underwater geometry of the platform, without the configuration of columns. This is done on the basis of heave motion constraints.

Phase 2

This phase concerns the determination of columns' configuration on the basis of intact and damage stability constraints.

4.3.2.2 The heave motion

The involved variables are :

- the underwater volume V
- the ratio V_2/V_1
- the aspect ratio α
- column immersion h_1
- the number of columns m

In total, there are five (5) design variables.

The available relations and constraints are :

- the ratio variable deck load to underwater volume V.D.L./V
- the inequality constraint $T_h \geqslant T_{h\ min}$

A total of two (2) relations.

First, the underwater volume V is estimated from the V.D.L./V ratio. Then, the underwater geometry is determined through the inequality constraint regarding the natural heave period; this is given by /4.15/ :

$$T_h = 2\ \pi\ x\ \left(\frac{M_{own} + M_{add}}{\rho\ x\ g\ x\ A_{wl}}\right)^{0.5} \quad \text{, where} \qquad (4.1)$$

M_{own} : own mass

M_{add} : hydrodynamic added mass

ρ : water density

g : gravity constant

A_{wl} : water line area

If T_h is set equal to the minimum value $T_{h\ min}$, above the peak period of waves regime in the operating area, then T_h is further regarded as a design parameter and expression (4.1) as an equality constraint.

By substituting the expressions for M_{own} and M_{add} and A_{wl}, the following relation is established :

$$\frac{V_2}{V_1} = \frac{T_h^2 \times g}{4 \times \pi^2 \times h_1 \; (C_v + 1)} - \frac{1}{C_v + 1} \quad , \text{ where :} \qquad (4.2)$$

$C_v = \pi \times C_m \times \alpha / 4$ is the added mass coefficient, depending on α (see appendix 4.1).

Expression (4.2) contains the free variables V_2/V_1, h_1 and C_v ; the latter can be derived from α.

By choosing values for α and h_1, V_2/V_1 becomes dependent and can be calculated. If, in addition, the number of columns m is chosen, the underwater geometry can be determined for any given displacement.

The final results contain :
- floater length, width and height, respectively L_f, B_f and H_f.
- column length, width and height, respectively L_c, B_c and H_c.
- the number of columns m and column submerged height h_1.
- the centre of buoyancy KB.

(see appendix 4.1 and /4.24/)

4.3.2.3 Stability

In the synthesis (preliminary) design phase, stability constraints are initially met by geometrical form only /4.15/. Columns' configuration is determined to meet stability criteria from /4.12/, whereafter the maximum allowable value for the vertical position of the centre of gravity KG is established. This is compared, at a later stage, with the calculated KG-value. The final value of KG is determined through an inclining test.

An early estimate of the KG value will shorten the design process by approaching the feasible geometrical solution at an early design stage. The followed procedure here is shown in Fig. 4.6. First, the KG value is estimated from data on mass distribution of a number of platforms /4.16-18/. The mass distribution is related to the geometrical form of the platform; in this case, to the geometrical form of the modular platform. Then, the maximum allowable KG value for an assumed column configuration is determined. This is done by using stability constraints based on intact and damage conditions, on the basis of an assumed heeling moment arm for these conditions. In other works, the obtained geometrical design solution possesses a restoring capability corresponding with the assumed value for the moment heeling arm (/4.15, 4.19-21/ and appendix 4.1).

The involved variables are :

- the vertical centre of gravity KG
- column height H_c
- the variables X and Y
- the moment heeling arm a_h for which the platform is designed
- the metacentric height above the centres of buoyancy and gravity, respectively BM and GM

A total of seven (7) variables.

The available relations and constraints are :

- platform mass distribution based on platform geometry
- the relation H_c/h_1
- the relation X/Y which is derived from the requirement for equal stability around the longitudinal and transverse platform axes
- four intact and two damage stability criteria from /4.12/.

First, the vertical centre of gravity KG is estimated from the generalized mass distribution (KG_{est}). Then, a restoring capability is assumed by choosing a value for the moment heeling arm a_h.

For this moment heeling arm, values of BM and GM are established on the basis of intact and damage stability constraints (app.4.1). These values and the already calculated value of the centre of buoyancy KB are used to determine the maximum allowable vertical position of the centre of gravity KG_{max}, for which :

$$KG_{max} \geq KG_{est}$$

The values of BM abd GM are adjusted so that the obtained KG_{max}-value complies with the inequality above.

The finally established value of the metacentric height BM is used to determine the configuration of columns and the values of X and Y. For the transverse direction :

$$Y^2 = \frac{12 \times BM \times V - m \times b \times h^3}{3 \times m \times b \times h} \qquad (4.3)$$

If the contribution of the column own moment is neglected (less than 1%) :

$$Y = 2 \times \left(\frac{BM \times V}{m \times b \times h}\right)^{0.5} = 2 \times \left(\frac{BM \times V}{A_{wl}}\right)^{0.5} \qquad (4.4)$$

For operational reasons it is desired to have equal stability characteristics for all heeling axes. This can be approached by equal second waterline area moments about the longitudinal and transverse axes /4.15/ :

$$Y = X \times \left(\frac{m + 2}{3(m-2)}\right)^{0.5} \qquad (4.5)$$

Hereafter, deck dimensions are established (app. 4.1 and /4.24/).

4.3.3 Structural design

4.3.3.1 Introduction

The structural design solution comprises three elements :

1. The configuration (pattern) of components.
2. The role of each component in the overall/local strength and the relevant criteria.
3. The scantlings.

The structural pattern follows the modular arrangement from chapter 3, par. 3.

The role (participation) of each component in the local/overall strength determines the criteria by which the component is assessed (chapter 3 par. 2 and /4.12/).

For the initial (preliminary) determination of scantlings in floater, column and deck structures, a static approach to load modelling is customary. Since the final dimensioning of scantlings involves dynamic effects, an inherent question here is the validity (feasibility) of the static approach with respect to the dynamic approach. Under-estimating of scantlings in the initial phase will result in an un-feasible design solution whereas over-estimating will result in an unnecessary heavy structure.

In general, local strength requirements form the basis for the determination of scantlings of most primary components in floaters, columns and deck. The acting loads concern lateral pressure :

- Hydrostatic pressure due to tank overflow, maximum (design) wave or damage water line.
- Own gravity load and working pressure load.

/4.22/.

The practice of pressure-related structural design is applicable to floater modules and the lower part of the columns. For column upper part and deck structure modules, overall strength considerations must be included.

With regard to the deck structure, it does not consist, like floater and column elements, of one rectangular cylinder. A break-down in a number of such cylinders, as suggested in chapter 3 par. 3, must consider the local/functional and overall strength aspects of the deck structure.
The functional aspects involve the arrangement of machinery, equipment, stores, etc. and the activities performed in the course of (drilling) operations. All these are a source of functional loads,

located and distributed in accordance with the arrangement of machinery, equipment, etc. The arrangement of bulkheads and local supports (vertical cross-ties, webframes) are meant to meet the requirements imposed by the functional loads. In this respect it should be mentioned that the arrangement of the deck structure is more complex than the arrangement of floater and column structures. This is caused by the large amount of machinery, equipment, etc. items related to drilling and domestic functions. Furthermore, the arrangement of the deck structure is often subject to changes in the course of the building process. In present work, it is assumed that the arrangement of machinery, equipment, etc. is determined within the frame of the internal structural arrangement of the deck structure with respect to bulkheads, cross-ties, etc.

The overall strength was discussed in chapter 3 (app. 3.1, cases a-c). Wave loads are transferred, by means of the columns, to the deck structure in the form of shear forces, bending and torsional moments. A solution to the above is to connect all column-tops by box girders in the longitudinal and transverse directions /4.13/. The suggestion to construct these box girders in a form identical to floater and column modules and connect them by rectangular cylinders of incomplete circumference (thus only deck and bottom panels, Fig. 4.7), will result in an efficient deck-structure for withstanding bending and torsional loading /4.17-18/.

Furthermore, it was found that the scantlings of a box-type deck structure which satisfy strength criteria for a combination of functional and environmental loads corresponding to case (a) (that is "splitting force" loading), form a good basis for the combinations of functional and environmental loads corresponding to other loading cases (see table 3.8 and Fig. 3.14.a-e).

On the basis of the above, the following procedure for determination of scantlings in floater, column and deck modules will be used (Fig. 4.8) :

- Scantlings in floaters will be determined on the basis of local pressure. An assessment of the obtained results will be done by

2-dimension frame modelling with beam elements under various configurations of external and internal pressure loads.

- Scantling in columns and deck modules will be determined on the basis of combined local and overall loading.
  First, the scantlings will be determined for columns and deck independently. Then, the overall strength will be assessed by means of transverse vertical frames comprising the following beam elements :
  - An upper, horizontal, transverse rectangular cylinder representing a transverse deck module. The external geometry and internal structural arrangement are identical to first-level floater/column modules. The cylinder is located in the vertical plane formed by two opposite columns (Fig. 4.9).
  - Two vertical, rectangular cylinders representing two opposite columns (Fig. 4.9).
  - A lower, horizontal, transverse brace which closes the vertical frame at the under side of the columns (Fig. 4.9).
- The used criteria will be yielding, by means of the equivalent stress which is limited to a maximum permissible value, dependin on the participation of components in the strength and the loading condition (see chapter 3 par. 2 and /4.12/).
  Usage factors for determination of maximum permissible stress are given in table 4.3

The free variables involved in the structural design are :

- The spacing s between longitudinal stiffening elements.
- The ratio k between the spacing of transverse webframes S and s.
- Unsupported spans of webframes, struts, etc.

Dependent variables are all component scantlings, such as :

- Plate thickness t.
- Cross sectional areas of stiffeners, webs, flanges, cross-ties.
- Bracket dimensions, thickness.

Available relations and constraints are :

- stress conditions from /4.12/
- minimum scantling conditions from /4.12/.

Furthermore, by assuming a certain ratio k and an arrangement of internal bulkheads, cross-ties, bracket connections, etc, boundary conditions for all components can be established and the dependent variables calculated (see Fig. 4.8).

A brief review of the considered loading cases, load modelling and other considerations is given below; in general, the followed procedure is based on /4.17-18, 4.24/.

4.3.3.2 Design of floater modules

A typical cross section of a floater module is shown on Fig.4.10.

Design condition

Survival condition, loading case b (table 4.3).

Design loads

Design pressure determined on the basis of a design wave-crest located above the floater, at the underside of the deck.

Participation in the local/overall strength

Plating and other longitudinal material is considered to participate in the overall strength (see table 4.4). The permissible stress is, however, determined on the basis of local pressure only /4.12/.

Assessment

The investigated loading condition with respect to combinations of external/internal pressure loads are shown in Fig. 4.11.a-c.

4.3.3.3 Design of column modules

A typical cross section of a column module is shown in Fig. 4.12.

Design condition

The most severe of the following combinations of loads :

1. Survival condition, loading cases b, environmental and functional loads.
2. Normal operating condition, loading cases b, environmental and functional loads.

Design loads

For combinations 1 and 2 above, respectively :

1. Design wave-pressure, identical to floater module design, in combination with axial loading due to deck structure and own gravity.
2. The combined effect of :

2.1 A representative share of the maximum hydrodynamic horizontal mass force on the floater and the same type of force on the considered column (case (a), chapter 3, par. 3).

2.2 Axial loading due to the deck structure and own gravity.

2.3 Lateral pressure due to column immersion corresponding with 2.1 above.

Participation in the local/overall strength

Plating and stiffeners are considered to participate in the local and the overall strength (see table 4.5). Permissible stress determined on the basis of local and overall strength considerations /4.12/.

Assessment

The initial scantlings are determined by means of design combination 1. The final assessment occurs in combination with the deck structure and will be handled in the following paragraph.

4.3.3.4 Design of deck modules

A typical cross section of a deck module is shown in Fig. 4.13.a.

Design condition

The most severe of the following combinations of loads :

1. Normal operating condition, loading cases a, functional loads.
2. Accidental flooding (loading case (e)), causing immersion of the deck structure up to the upper deck-level, in still water (Fig. 4.13.b).
3. Normal operating condition, loading case b.

Design loads

For combinations 1-3 above, respectively :

1. Only functional loads, comprising :
   - 1.1 Overall loading due to a proportional share of the deck structure gravity load.
   - 1.2 Local pressure due to local, own gravity.
   - 1.3 Local pressure due to live loads.
2. Hydrostatic pressure on the lower and vertical panels of the deck module (Fig. 4.13.b).
3. Combined functional and environmental loads; the latter derived from the horizontal hydrodynamic mass force corresponding to a wave length twice the distance over floaters. For this combination, the complete 2-dimensional frame analysis comprising vertical columns and the lower horizontal brace are involved.

Participation in the local/overall strength

Plating is considered to participate in the local/overall strength. Stiffeners and web-frames only in the local strength (table 4.6).

Assessment

Initially, the scantlings of the upper beam element, the deck module, are determined independently on the basis functional or accidental loads only. The complete frame analysis considers functional and environmental loads.

4.4 Calculations and results

4.4.1 Geometrical design

On the basis of the geometrical design procedure from par.4.3.2, a calculation model was developed.
Input data consist of :

- platform displacement V
- the natural heave period T_h
- the metacentric height GM; this was based on an restoring capability sufficient to comply with safety requirements following the influence of a heeling moment arm of 0.8 m.

Free variables are :

- the number of columns m
- module aspect ratio α
- column immersed height h_1

For every assumed combination of values of m, α and h_1, the output consists of :

- platform geometry and dimensions
- hydrostatic properties
- the vertical position of the centre of gravity, following the generalized mass distribution from appendix 4.1.

A sample of the obtained results is shown in table 4.7.

To fulfil the condition of comparable operability with respect to a conventional design, platform motions in waves were calculated /4.25/. Results concerning response curves of the heave motion in regular and irregular waves of both modular and conventional design are shown in Fig. 4.14.a-b.

4.4.2 Structural design

On the basis of the structural design procedure from par. 4.3.3, calculation models were developed for :

1. Floater modules following par. 4.3.3.2.
2. Column modules following par. 4.3.3.3, load combination 1.
3. Deck modules following par. 4.3.3.4, load combinations 1 and 2.

Input data consist of :

- platform geometry, corresponding with the platform used in par. 4.4.1 for purpose of comparison with the conventionally designed platform.
- strength criteria, i.e. :
  - . maximum permissible stress levels in plating, stiffeners and webframes
  - . end conditions
  - . buckling criteria for cross ties

  (see also tables 4.4-6)
- dimensions of plates
- minimum plate thickness for :
  - . column outer shell (8 mm) and internal bulkheads (6 mm)
  - . deck-structure plating, internal and external (6 mm).

Free variables are :

- the spacing s between longitudinal stiffeners; the factor k, i.e. the ratio S/s (chapter 3 par.3), was taken equal to 3.

Output data consist of :

- scantlings of :
  - . plating thickness, given in whole mm
  - . stiffener section area
  - . web height, thickness and flange area
  - . crosstie sectional area and length
  - . bracket circumference and thickness.

- additional information such as :
  - . the number of third-level structural components
  - . steel weight, specified :
    1. per type of component, i.e. plating, stiffeners, webframes brackets and cross ties.
    2. per type of module, i.e. floater, column and deck.

Assessment of the obtained results was performed :

1. For floater modules, following par. 4.3.3.2 and Fig. 4.11.a-c.
2. For column/deck modules, following par. 4.3.3.3-4, load combinations 2 and 3, respectively (Fig. 4.12.b-c).

/4.26-27/.

The obtained results show that the followed procedure for determination of scantlings, on the basis of local loads, provided satisfactory results with regard to strength criteria concerning the maximum permissible equivalent stress /4.12, 4.24/.

4.5 Conclusions

Design procedures were developed for the semi-submersible platform following a modular approach.

Realization of this approach with respect to the external geometry was obtained in the geometrical design procedure; a range of solutions were calculated, each fulfilling the requirements on :

- operability, by means of the natural heavy period;
- stability, by complying with the necessary stability criteria.

The general condition of comparable heave motion response with respect to a conventionally designed platform of similar size is also fulfilled.

Realization of the modular approach with respect to the internal structural arrangement was obtained in the structural design procedure. Flat panels throughout the entire structure were designed according to an identical structural pattern. The size of the pattern was considered as a free variable (the spacing s).

Additional information on the amount, weight and characteristics of structural components, up to the third level, was made available.

Hereby, the feasibility of the modular concept in geometrical and structural design has been proven.

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Table 4.1 : Design parameters, variables and constraints for semi-submersible platforms

I T E M	SYMBOL	UNIT	DESIGN PARAMETER	DESIGN VARIABLE				CONSTRAINTS
				GEOMETRICAL		STRUCTURAL		
				FREE	DEP.	FREE	DEP.	
payload	Pload	T	x	-	-	-	-	-
deckload	Dload	T	x	-	-	-	-	-
displaced volume, total	V	m^3	-	x	-	-	-	-
displaced volume, columns	V_1	m^3	-	x	-	-	-	-
displaced volume, floaters	V_2	m^3	-	-	x	-	-	-
total column height	H_c	m	-	-	x	-	-	positive airgap
immersed column height	h_1	m	-	x	-	-	-	-
aspect ratio module	α	-	-	x	-	-	-	-
draught	d	m	-	-	x	-	-	-
number of columns	m	-	-	x	-	-	-	-
spacing between stiffeners	s	m	-	-	-	x	-	practicle
spacing between webframes	S	m	-	-	-	-	x	-
unsupported span	l	m	-	-	-	x	-	-
plate thickness	t	mm	-	-	-	-	x	min. rule value
section moduli	SM	cm^3	-	-	-	-	x	min. rule value
sectional area	A	cm^2	-	-	-	-	x	min. rule area
natural heave period	T_h	sec	x	-	-	-	-	min. value
metacentric height	GM	m	-	-	x	-	-	min. rule value
stability range		degrees	-	-	-	-	-	min. rule range
max. heeling angles	ϕ	degress	-	-	-	-	-	max. rule value

Table 4.2: Relations and dependence between design and cost factors

	cost group	external geometry			general arrange.	internal stuctural arrangement	
		dimensions	form	config.		geometry	scantlings
materials	1	+	+	+	-	+	+
	2	+	-	+	+	-	-
	3	-	-	+	-	-	-
	4	- (1)	-(1)	-(1)	-	-	-
	5	-	-	-	-	-	-
	6	+	+	+	-	-	-
	7	+	-	+	+	-	-
labour	1	+	+	+	-	+	+
	2	-	-	-	+	-	-
	3	+	-	+	+	-	-
	4	-	-	-	-	-	-
	5	-	-	-	-	-	-
	6	-	-	-	-	-	-
	7	+	-	+	+	-	-

1 : hull steel
2 : steel outfitting
3 : outfitting hardware/furnishings
4 : machinery/electrical
5 : drilling equipment
6 : positioning/propulsion equipment
7 : piping, ventilation, cabling

+ : dependence/relation
- : no dependence/relation
(1) : excluding items related to platform systems, propulsion, positioning, etc.

Table 4.3 : Usage factors for stress criteria in % of yield stress

	loading conditions				
	a	b	c	d	e
usage factor	60 %	80 %	80 %	100 %	100 %

Table 4.4: Design considerations for floater modules

element	variables	design forces	load point	participat. in structur strength	constraints	
					stress N/mm^2	boundary conditions
Plating						
- External						
.hor. panel	thickness (discrete)	local	midpoint plate field	overall	σ_p = 105	clamped
.vert. panel, long	thickness (discrete)	local	lower edge of panel or plate	overall	σ_p = 115	clamped
.vert.panel, trans	thickness (discrete)	local	lower edge of panel or plate	local	σ_p = 190	clamped
- Internal						
. vert. panel,long	thickness (discrete)	local	lower edge of panel or plate	overall	σ_p = 115	clamped
. vert. panel,tran	thickness (discrete)	local	lower edge of panel or plate	local	σ_p = 190	clamped
Stiffeners						
- External Panels						
. horizontal	area (continuous)	local, incl. forces on assoc. plating	midpoint of span	overall	σ_p = 110	clamped
. vert. longitud.	area (continuous)	local, incl.forces on assoc. plating	midpoint of span	overall	σ_p = 110	clamped
. vert. transverse	area (continuous)	local, incl.forces on assoc. plating	midpoint of span	local	σ_p = 190	clamped
- Internal Panels						
. vert. longitud.	area (continuous)	local, incl. forces on assoc. plating	midpoint of span	overall	σ_p = 110	clamped
. vert. transverse	area (continuous)	local, incl. forces on assoc. plating	midpoint of span	local	σ_p = 190	clamped

Table 4.4, Continuation

element	variables	design forces	load point	particip. in struct. strength	constraints	
					stress N/mm^2	boundary conditions
- Web-Frame, hor.						
. web	thickness (discrete)	local, incl.forces on assoc. plating	midpoint of load area	local	σ_p = 170	clamped
. flange	area (continuous)	local, incl.forces on assoc. plating	midpoint of load area	local	τ_p = 95	clamped
- Web-Frame,vertical						
. web	thickness(discrete)	local. incl. forces on assoc. plating	midpoint of load area	local	σ_p = 170	clamped
. flange	area (continuous)	local, incl. forces on assoc. plating	midpoint of load area	local	τ_p = 95	clamped
- Brackets	thickness (discrete) sides (continuous)	related to web-frame forces	related to web-frame	local		
- Cross-ties	area (continuous)	local forces	in axis-line	local	min. area	clamped

Table 4.5: Design considerations for column modules

element	variables	design forces	load point	participat. in struct. strength	constraints	
					stress N/mm^2	boundary conditions
Plating						
- External						
. vert. panel	thickness (discrete)	local, overall	lower edge of panel or plate	overall	σ_p = 190	clamped
- Internal						
. hor. panel	thickness (discrete)	local	midpoint of plate field	local	σ_p = 240	clamped
Stiffeners						
- External Panels						
. vertical	area(continuous)	local, incl. forces on assoc. plating	midpoint of span	overall	σ_p = 190	clamped
- Internal Panels						
. horizontal	area (continuous)	local, incl. forces on assoc. plating	midpoint of load area	local	σ_p = 190	clamped
Web-Frame, vert. panel						
. web	thickness (discrete)	local, incl. forces on assoc. plating	midpoint of load area	local	σ_p = 170	clamped
. flange	area (continuous)	local, incl. forces on assoc. plating	midpoint of load area	local	τ_p = 95	clamped
Web-Frame, hor. panel						
. web	thickness (discrete)	local, incl. forces on assoc. plating	midpoint of load area	local	σ_p = 170	clamped
. flange	area (continuous)	local, incl. forces on assoc. plating	midpoint of load area	local	τ_p = 95	clamped
- Cross-ties	area (continuous)	local	in axis-line	local	min.area	clamped

Table 4.6: Design considerations for deck modules

element	variables	design forces	load point	participat. in struc. strength	constraints	
					stress N/mm^2	boundary conditions
Plating						
- External						
. hor. panels	thickness (discrete)	local, overall	midpoint of plate field	overall	σ_p = 190	clamped
. vert. panels	thickness (discrete)	local, overall	lower edge of panel or plate	overall	σ_p = 115	clamped
- Internal						
. hor. panels	thickness (discrete)	local	midpoint of plate field	local	σ_p = 145	clamped
. vert. panel	thickness (discrete)	local, overall	lower edge of panel or plate	overall	σ_p = 115	clamped
Stiffeners						
- External panels						
. horizontal top	area (continuous)	local, incl. forces on assoc. plating	midpoint of span	local	σ_p = 145	clamped
. horizontal bott.	area (continuous)		midpoint of span	local	σ_p = 190	
. vertical	area (continuous)	local, incl. forces on assoc. plating	midpoint of span	local	σ_p = 190	clamped
- Internal panels						
. horizontal	area (continuous)	local, incl. forces on assoc. plating	midpoint of span	local	σ_p = 145	clamped
. vertical	area (continuous)	local, incl. forces on assoc. plating	midpoint of span	local	σ_p = 190	clamped
Web-frame, hor. panel						
. web	thickness (discrete)	local, overall	midpoint of load area	local,overall	σ_p = 125	clamped
. flange	area (continuous)	local,overall	midpoint of load area	local,overall	τ_p = 70	clamped
Web-frame, vert. panel						
. web	thickness(discrete)	local	midpoint of load area	local	σ_p = 125	clamped
. flange	area (continuous)	local	midpoint of load area	local	τ_p = 70	clamped

Table 4.7: Sample output for geometrical design

```
NUMBER OF COLUMNS

 6

MODULE WIDTH/HEIGHT RATIO

 1.75

HCOLS   VRATIO  VFLO      VCOL     BMOD     HMOD   LFLO      LDECK    BDECK     ACOL    AWLINE  XDIST  YDIST     TIMOM      KB      BM     KG

 13.00  2.834  16262.3   5737.7 11.346   6.483 110.537   75.534   58.892   73.560 441.362 64.188 52.409   303072.2  5.782 13.776 16.558
 14.00  2.607  15901.3   6098.7 11.272   6.441 109.508   76.954   60.070   72.604 435.622 65.682 53.629   313219.9  6.054 14.237 17.291
 15.00  2.411  15549.6   6450.4 11.199   6.400 108.478   78.344   61.223   71.671 430.028 67.145 54.824   323127.1  6.337 14.688 18.025
MODULE WIDTH/HEIGHT RATIO

 2.00

HCOLS   VRATIO  VFLO      VCOL     BMOD     HMOD   LFLO      LDECK    BDECK     ACOL    AWLINE  XDIST  YDIST     TIMOM      KB      BM     KG

 13.00  2.621  15925.0   6075.0 12.481   6.240 102.234   74.321   56.733   77.885 467.308 61.841 50.493   297851.2  5.777 13.539 16.315
 14.00  2.411  15551.2   6448.8 12.391   6.196 101.282   75.703   57.890   76.771 460.629 63.312 51.694   307732.7  6.058 13.988 17.046
 15.00  2.230  15187.9   6812.1 12.304   6.152 100.330   77.058   59.024   75.690 454.137 64.754 52.872   317376.1  6.351 14.426 17.777
MODULE WIDTH/HEIGHT RATIO

 2.25

HCOLS   VRATIO  VFLO      VCOL     BMOD     HMOD   LFLO      LDECK    BDECK     ACOL    AWLINE  XDIST  YDIST     TIMOM      KB      BM     KG

 13.00  2.445  15614.2   6385.8 13.572   6.032  95.361   73.420   54.898   81.869 491.215 59.848 46.865   293235.2  5.778 13.329 16.107
 14.00  2.249  15229.4   6770.6 13.467   5.985  94.473   74.767   56.037   80.602 483.613 61.300 50.052   302881.6  6.068 13.767 16.835
 15.00  2.053  14856.4   7143.6 13.364   5.939  93.585   76.089   57.154   79.374 476.243 62.725 51.215   312291.8  6.369 14.195 17.564
MODULE WIDTH/HEIGHT RATIO

 2.50
```

Input Data

Variable deckload : 3000 T

Displacement : 22000 m^3

Variables

HCOLS : submerged column height

VRATIO : ratio VFLO/VCOL

VCOL : volume columns

VFLO : volume floaters

BMOD : width module

HMOD : height module

LFLO : length floater

LDECK : length deck

BDECK : width deck

ACOL : crossarea column

AWLINE : waterline area

X/YDIST : values X and Y

Table 4.8: Sample output structural design

```
                    STIFFENER SPACING(M) =    0.600

                    TABLE 2 : DATA FLOATER PANELS



         PAN.TYPE        TPL  STAREA  WEDW   WETW   WEAF   PLMAT WEMAT STMAT PANO
                          MM    CM2    CM     CM    CM2     T     T     T     T

         C.T.BOTTOM   16.00  52.46  65.36  0.90 24.41   9.35  2.37  4.62 16.80
         C.T.DECK     15.00  47.10  59.13  0.90 22.18   8.77  2.14  4.15 16.80
         W.T.BOTTOM   16.00  52.46  65.36  0.90 24.41   4.68  1.18  2.06 33.60
         W.T.DECK     15.00  47.10  59.13  0.90 22.18   4.38  1.07  1.85 33.60
         W.T.L.BLHD   14.26  49.08  54.91  0.90 20.67   8.33  1.64  0.09 33.60
         W.T.SH.PAN   14.97  51.96  57.96  0.90 21.69   8.75  1.71  0.09 33.60
         TR.BHD CT    11.00  36.38 114.24  1.00 60.94   3.33  2.09  1.66 12.00
         TR.BHD WT    11.00  36.38  60.21  0.90 25.04   1.66  0.47  0.74 24.00
         END BHD CT   11.97  38.54 120.70  1.00 62.97   3.62  2.19  1.75  4.00
         END BHD WT   11.97  38.54  63.62  0.90 25.92   1.81  0.50  0.78  8.00


                            STEEL WEIGHT DATA

      PLATE MAT      WEE MAT      STIFF MAT     BRACK MAT    C.TIE MAT    TOT FLOATERS

     1291.697       313.034       335.488        23.484      130.726      2094.428
```

<u>Input Data</u>

Design water column : 34.2 m.

<u>Variables</u>

TPL : plate thickness

STAREA : stiffener area

WEDW : web height

WETW : web thickness

WEAF : flange area

PLMAT : plate material

WEMAT : webframe material

STMAT : stiffener material

PANO : panel mass

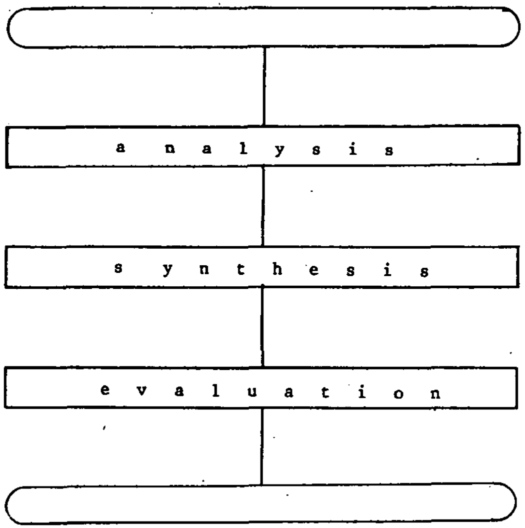


Fig.4.1: Main phases in the design process

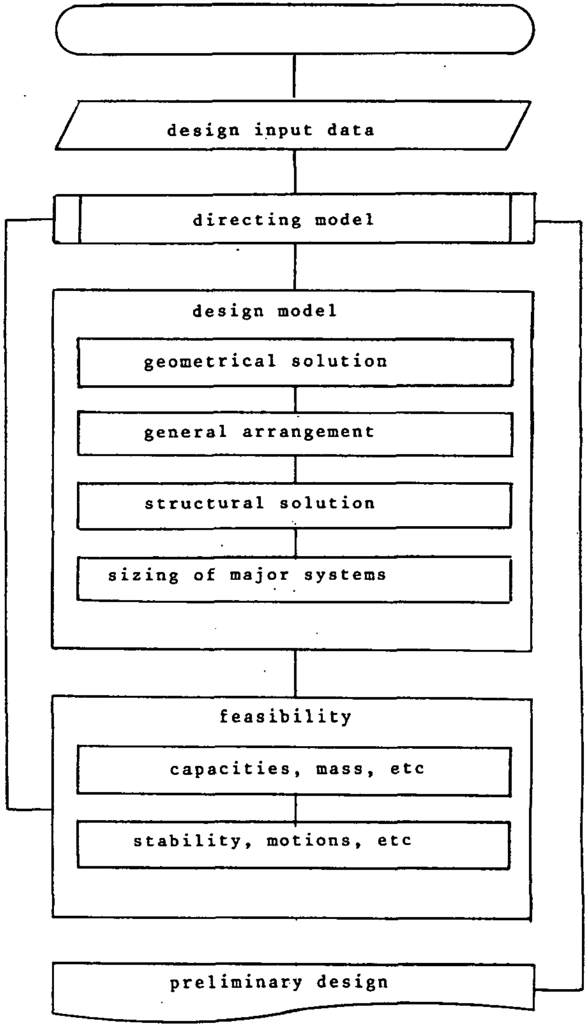


Fig.4.3: The synthesis phase

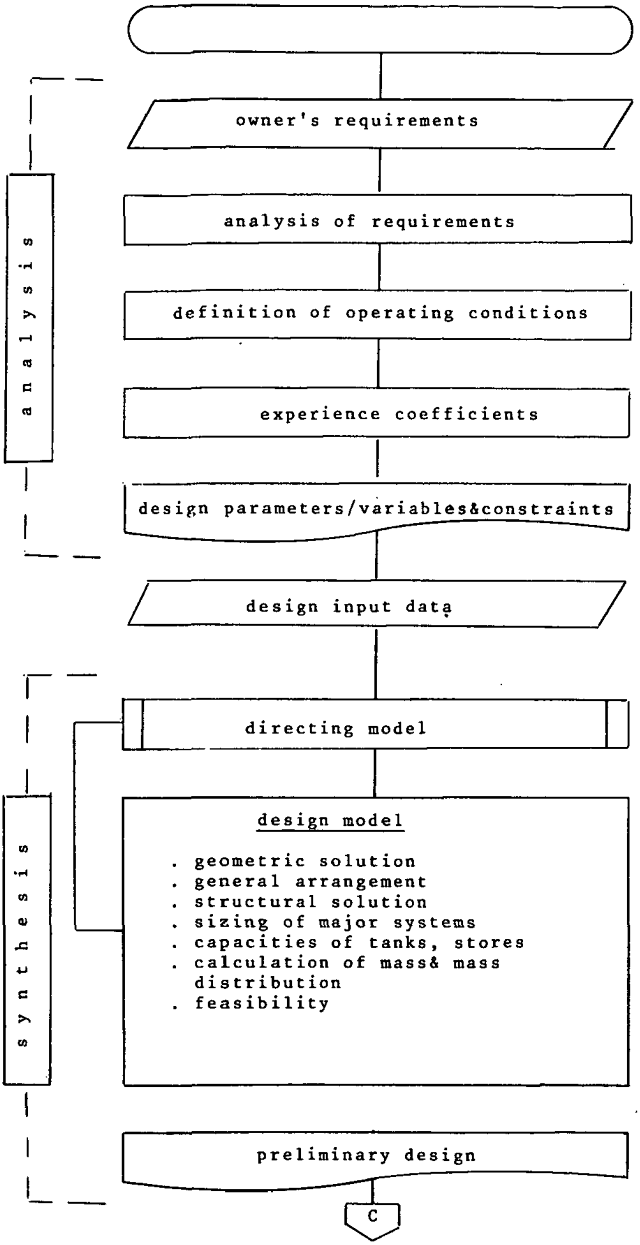


Fig.4.2: Design process for semi-submersible platforms

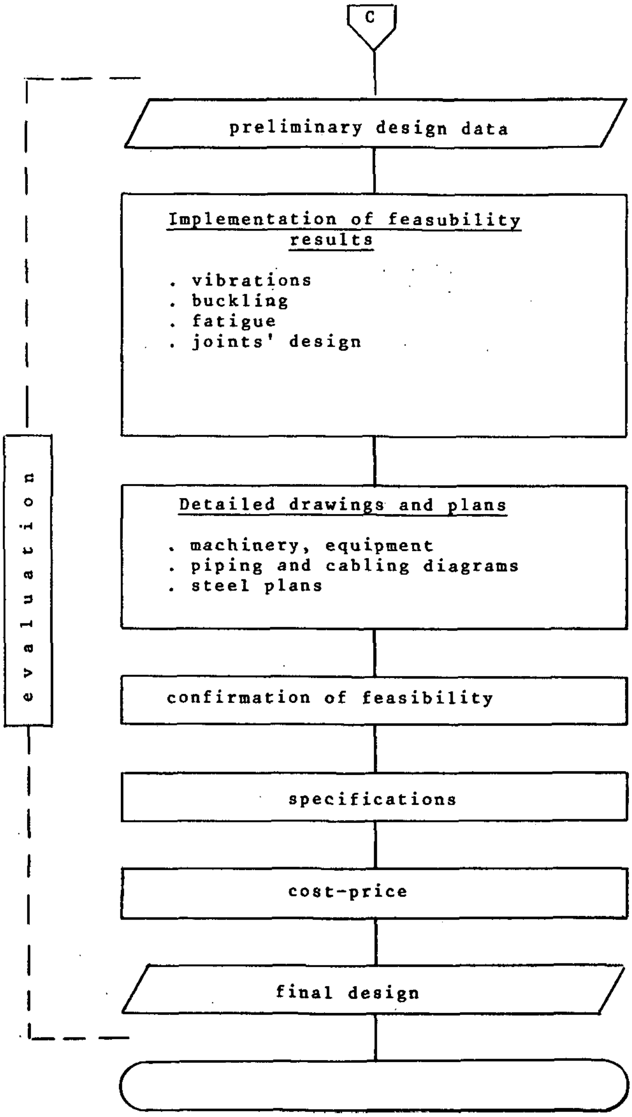


Fig.4.2, Continuation

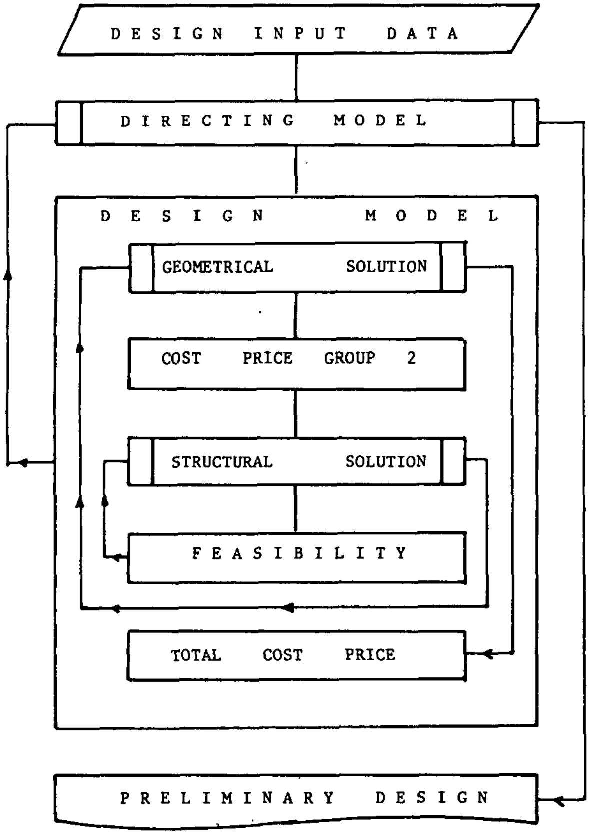


Fig.4.4 : Cost price evaluation in two steps

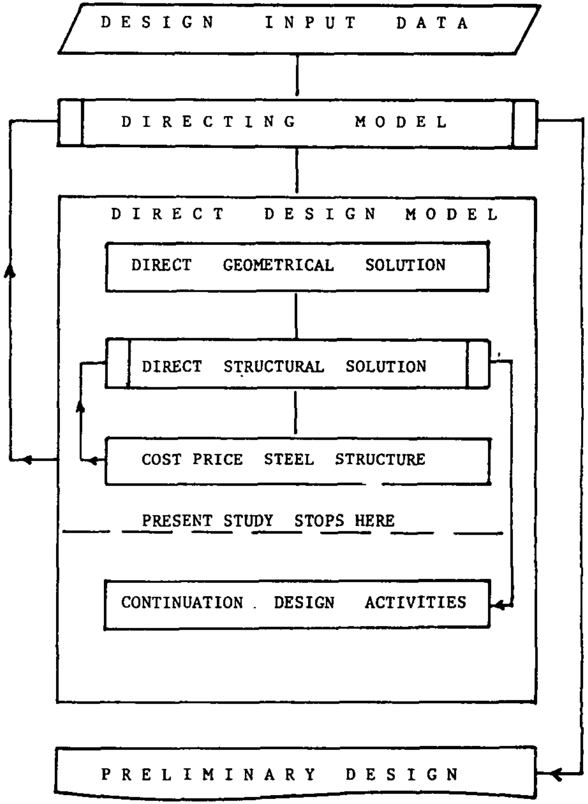


Fig.4.5 : Design model with cost price calculation for feasible design solution

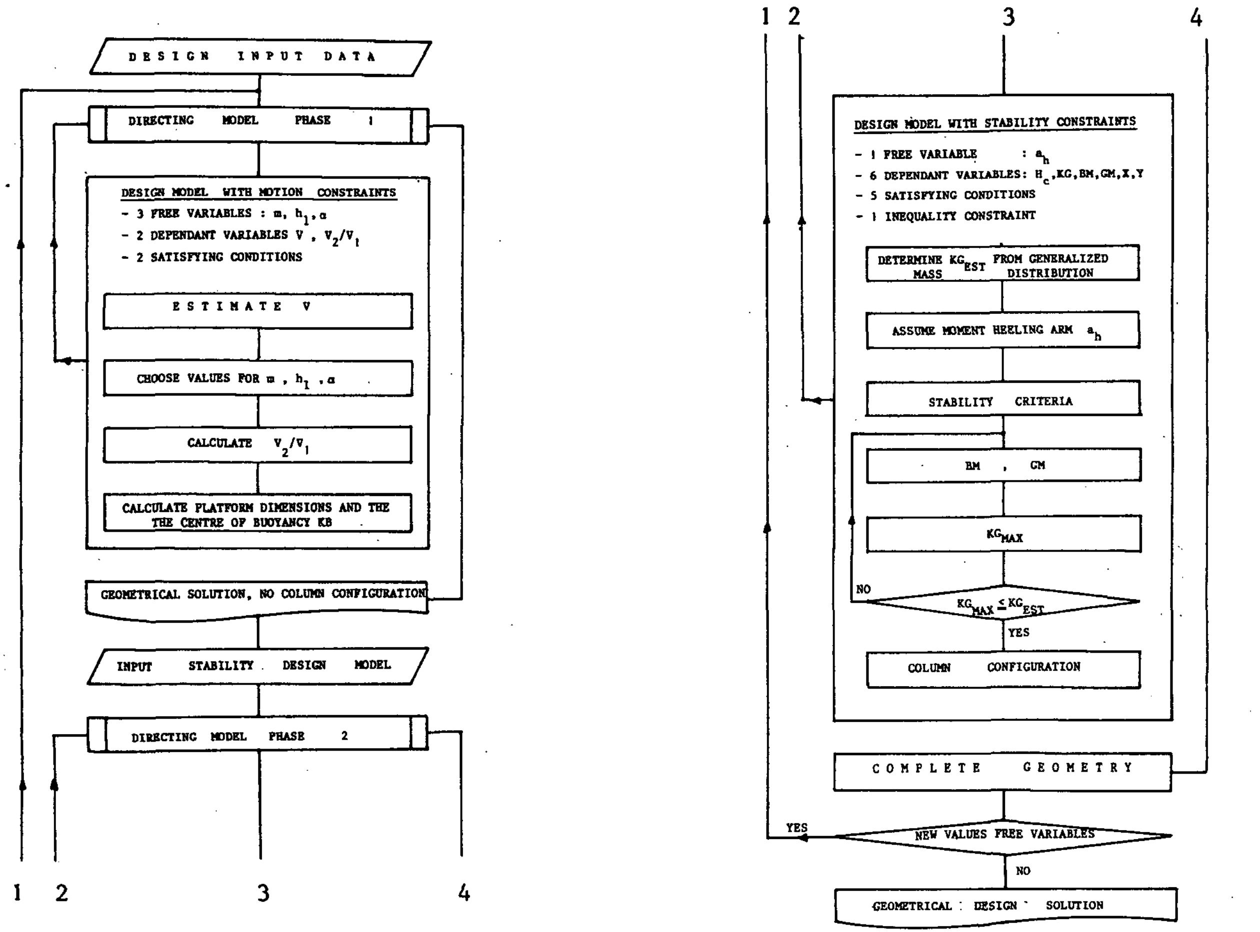
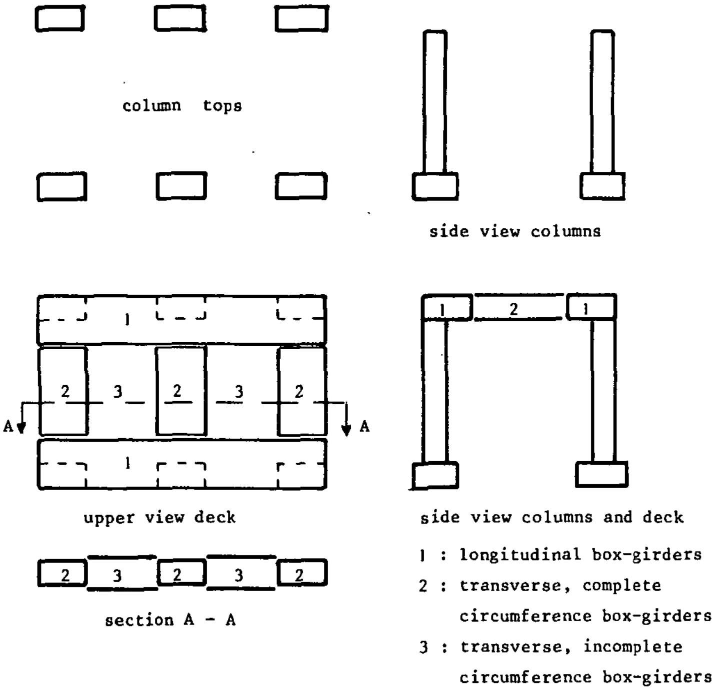


Fig.4.6: Geometrical design model



1 : longitudinal box-girders

2 : transverse, complete circumference box-girders

3 : transverse, incomplete circumference box-girders

Fig.4.7 : Box-type deck structure

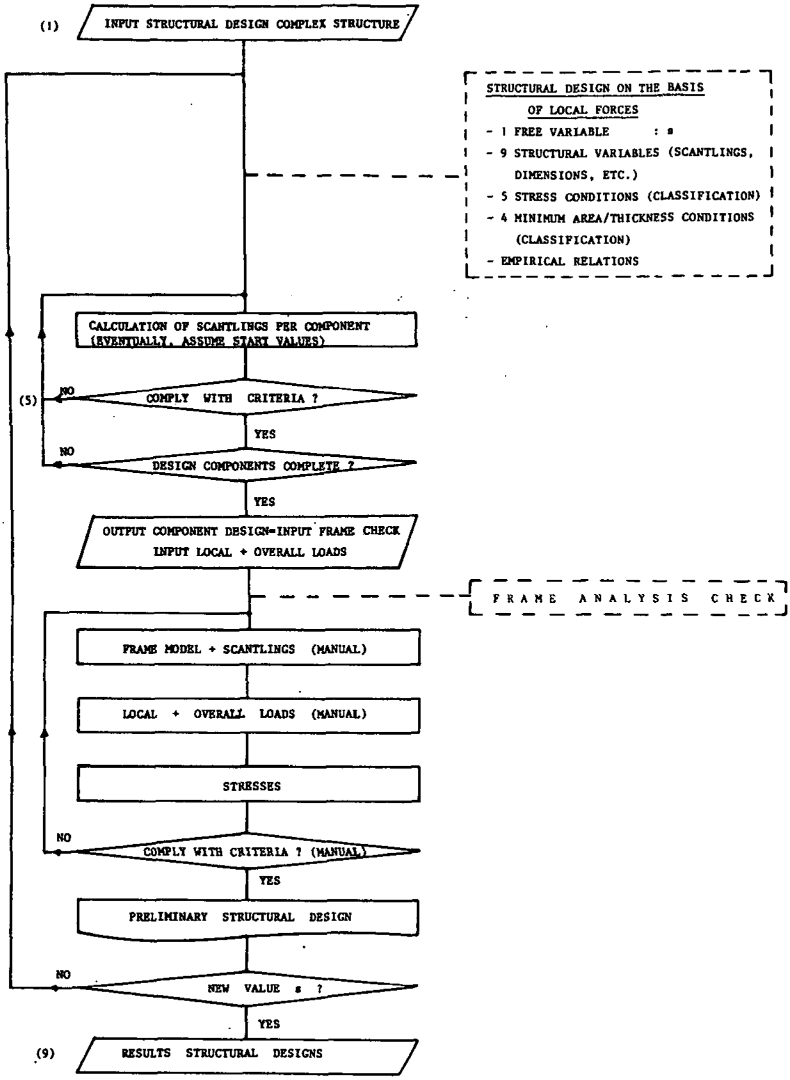
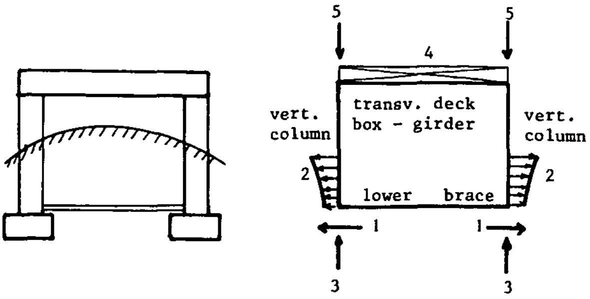


Fig.4.8 : Structural design model; numbers in brackets refer to the complete calculation model from fig.5.23.a



1 : horizontal mass force on floaters
2 : horizontal mass force on columns
3 : buoyancy force floaters
4 : own, distributed weight of deck structure
5 : own weight columns

transverse wave attack

Fig.4.9: Transverse frame model for structural design, overall strength

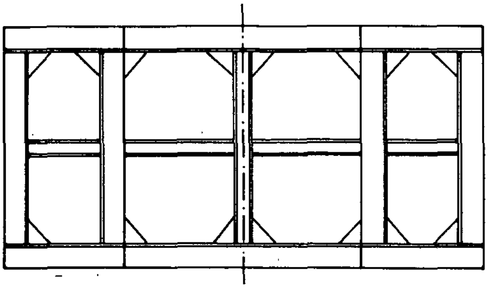


Fig.4.10 : Typical floater section

Fig.4.11.a : Transverse floater frame loading, external pressure, all tanks empty

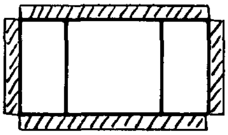


Fig.4.11.b : Transverse floater frame loading, external pressure, wing tanks full

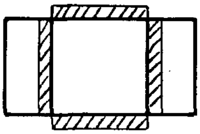


Fig.4.11.c : Transverse floater frame loading, external pressure, centre tank full

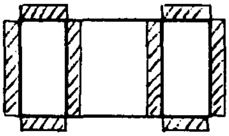
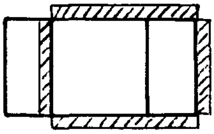


Fig.4.11.d : Transverse floater frame loading, external pressure, one wing tank empty



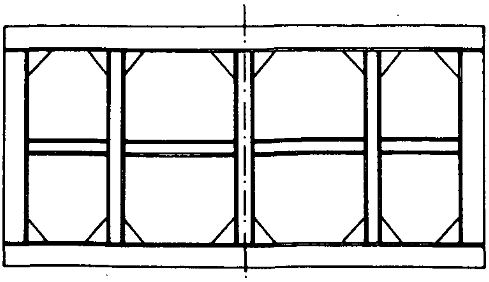


Fig.4.12 : Typical column section

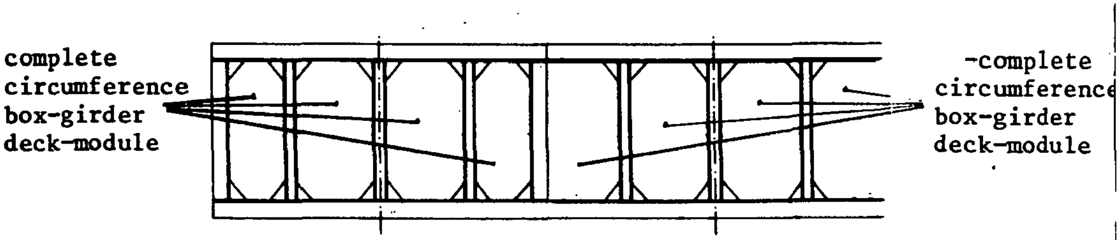


Fig.4.13.a : Typical cross section over deck structure

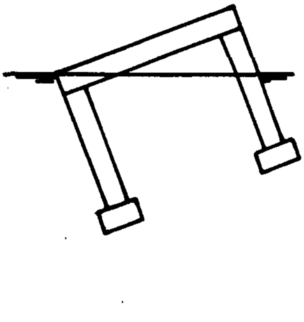


Fig.4.13.b : Design condition for deck panels following accidental flooding to deck-level

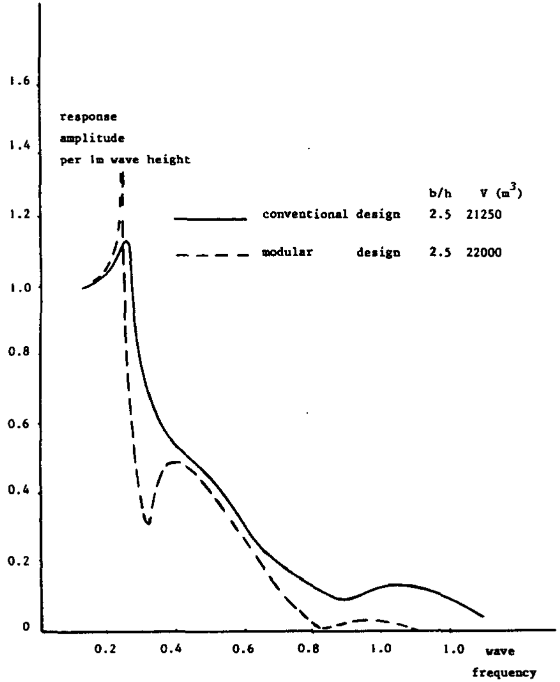


Fig.4.14.a: Heave response, conventional and modular design

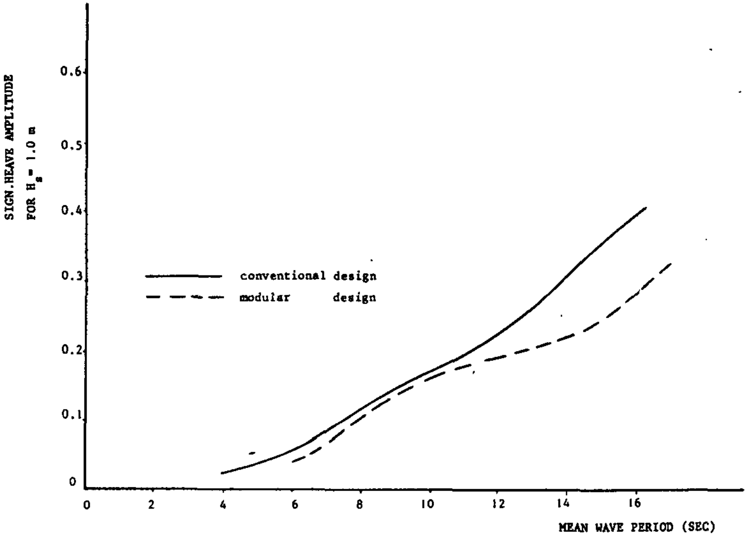


Fig.4.14.b: Heave motion in irregular waves per 1.0 m. wave height

Appendix 4.1

Geometrical Design

Derivation of expression (4.2)

$$T_h = \left(\frac{M_{own} + M_{add}}{\rho \times g \times A_{wl}} \right)^{0.5} \times 2 \times \pi \qquad (1)$$

$$M_{own} = V \times \rho = (V_1 + V_2) \times \rho \qquad (2)$$

$M_{add} = C_m \times \pi \times (\frac{b}{2})^2 \times L_{fl}$, L_{fl} is total floaters' length (3)

C_m = added mass coefficient

$$V_2 = b \times h \times L_{fl} \qquad (4)$$

$$L_{fl} = \frac{V_2}{b \times h} , \; L_f = L_{fl}/2 \qquad (5)$$

$$A_{wl} = \frac{V_1}{h_1} \qquad (6)$$

$$b/h = \alpha \qquad (7)$$

(5) and (7) in (3) :

$$M_{add} = \rho \times \frac{\pi \times C_m}{4} \times \alpha \times V_2 \qquad (8)$$

$$\frac{\pi \times C_m \times \alpha}{4} = C_v \qquad (9)$$

(2), (6) and (9) in (1) :

$$T_h = 2 \times \pi \left(\frac{\rho \times (V_1 + V_2) + \rho \times C_v \times V_2}{\rho \times g \times \frac{V_1}{h_1}} \right)^{0.5} \tag{10}$$

$$\frac{V_2}{V_1} = \frac{T_h^{\,2} \times g}{4 \times \pi^2 \times (C_v + 1)} - \frac{1}{C_v + 1} \tag{11}$$

By assuming values for α, m and h_1, platform underwater geometry can be calculated as follows :

$$V_2 = V - V_1 = V - \frac{V_2}{V_2/V_1} = V \times \frac{V_2/V_1}{V_2/V_1 + 1} \tag{12}$$

$$L_f = V_2/V_1 \times h_1 \times m/2 \tag{13}$$

$$b \times h = \frac{V_1}{m \times h_1} \tag{14}$$

$$h = \left(\frac{b \times h}{\alpha} \right)^{0.5} \tag{15}$$

$$b = h \times \alpha \tag{16}$$

$$KB = \frac{2 \times L_f \times h + m \times h_1 \times (h_1 + 2h)}{4\,(L_f + m \times h_1 /2)} \tag{17}$$

Stability constraints in geometrical design solution

Estimate of the vertical centre of gravity KG

The position of the centre of gravity is based on the following generalized mass distribution /4.16-18/ :

group	mass in % of total mass	vertical centre of gravity
floaters	50 - 60	at 0.5 floater height
columns	10 - 15	at 0.5 column height
deck	30 - 35	at upper side deck

Using platform dimensions from chapter 3 par. 3.3 and the relation $H_c = 2h_1$, the estimated value of the vertical centre of gravity is

$$KG_{est} = 0.5 \times 0.55 \times h + 0.125 \, (h + h_1) + 0.325 \, (2h + 2h_1) \quad (18)$$

$$KG_{est} = 1.05 \times h + 0.775 \times h_1 \quad (19)$$

Intact stability criteria

Stability criteria from /4.12/ are :

1. A reserve in the uprighting capability of the platform in excess (30%) of the capability required to withstand the action of a wind overturning moment before a critical heeling angle is achieved.
2. A maximum sustained heeling angle due to wind action of 15^o.
3. A minimum range of positive stability arms of 30^o before the above critical angle is achieved.
4. A minimum GM value of 1.0 metres in all operating conditions.

1. Maximum heel angle criterion

Under the influence of a wind heeling moment M_w, the restoring moment M_r is defined by :

$$M_r = V \times GN \sin(\varphi),\ \varphi \text{ is the heeling angle} \tag{20}$$

Using Scribanti's formula for vertical sided floating structures :

$$GN = GM + 0.5 \times BM \times tg^2(\varphi) \tag{21}$$

$$\frac{M_w}{V} = (GM + 0.5 \times BMxtg^2(\varphi))x \sin(\varphi) \tag{22}$$

$\frac{M_w}{V}$ is the wind lever arm, $\varphi_{max} = 15^o$

For various combinations of the wind lever arm and BM values, the minimum required GM can be determined :

$$\frac{M_w}{V} = C_1 \times GM + C_2 \times BM \tag{23}$$

$C_1 = 0.25882 \qquad C_2 = 0.00929$

2. Area ratio criterion

The area A_w under the wind moment curve M_w is :

$$A_w = \int_0^{\varphi} M_w(\varphi)\, d(\varphi) \tag{24}$$

The area A_r under the restoring moment curve is :

$$A_r = \int_0^{\varphi} GN(\varphi) \times V \times \sin(\varphi)\, d(\varphi) \tag{25}$$

To comply with the stability criterion :

$$1.3 \times \int_0^{\varphi} M_w(\varphi)\, d(\varphi) = \int_0^{\varphi} GN(\varphi) \times V \times \sin(\varphi)\, d(\varphi) \qquad (26)$$

Using Scribanti's formula and assuming M_w constant, independent of φ :

$$1.3 \times \int_0^{\pi/6} M_w(\varphi)\, d(\varphi) = V \times \int_0^{\pi/6} (GM + 0.5 \times BM\, tg^2(\varphi))\sin(\varphi)d(\varphi \qquad (27)$$

Dividing by V and integrating both sides yields :

$$\frac{M_w}{V} = C_3 \times GM + C_4 \times BM, \quad C_3 = 0.1968351 \quad C_4 = 0.0152201 \qquad (28)$$

For various wind level arms and BM values, the minimum required GM value can be determined.

A comparison of results using expressions (4) and (10) was performed for BM-values between 10 - 16 m; the results are given in table 1 below :

Table 1 : GM-values at various heeling angles and BM values

heeling arm (m)	max. heel angle, crit.(1)				area ratio, crit. (2)			
	BM:10m	12m	14m	16m	BM:10m	12m	14m	16m
0.1	0.027	--	--	--	--	--	--	--
0.2	0.41	0.34	0.27	0.20	0.24	0.09	--	--
0.3	0.80	0.73	0.66	0.58	0.75	0.60	0.44	0.29
0.4	1.19	1.11	1.04	0.97	1.26	1.10	0.95	0.80
0.5	1.60	1.50	1.43	1.36	1.77	1.61	1.46	1.31
0.6	1.96	1.89	1.82	1.75	2.28	2.12	1.97	1.82
0.7	2.35	2.27	2.20	2.13	2.78	2.63	2.48	2.32
0.8	2.73	2.66	2.59	2.52	3.29	3.14	2.98	2.83
0.9	3.12	3.15	2.97	2.90	3.80	3.64	3.49	2.83
1.0	3.50	3.43	3.36	3.29	4.31	4.15	4.00	3.84
1.1	3.89	3.82	3.75	3.68	4.82	4.66	4.51	4.35

A value for the heeling arm can now be chosen from table 1 above, on the basis of experience with comparable designs. The chosen value must now be evaluated with respect to damage stability criteria from /4.12/; these are :

1. The final equilibrium waterline after flooding, taking into account the effect of wind, shall be below the lower edge of any opening through which progressive flooding of assumed buoyant spaces may take place.
2. In the above equilibrium condition, the angle of heel is not to exceed 15° in any direction.
3. The area under the righting moment curve is to be at least equal to the area under the heeling moment curve. Both areas are to be calculated from the static angle of heel, without wind, to the second intercept, or any lesser angle.

These criteria can be handled in a way similar to intact stability criteria in order to obtain combinations of BM and GM values for various heeling arms. The heeling angle and are are considered to comprise the contribution from :

1. A wind heeling moment corresponding to a wind velocity half the value in intact condition, respectively 50 and 100 kn /4.12/.
2. A heeling moment caused by flooding water in one of the floaters. The amount of flooding water can be estimated by considering floater volume and the arrangement of bulkheads. In general, there will be at least one longitudinal and six transverse bulkheads in each floater, so that the flooded volume represents about 2 - 2.5% of the total underwater volume /4.16-18/.

Damage criterion 1 is given by an expression identical to expression (22) from intact stability :

$$GM = \frac{1}{\sin(\varphi)} \times \text{heeling arm} - 0.5 \times BM \times tg^2(\varphi)$$

Criterion 2 is given by an expression similar to expression (26) from intact stability. The difference consists of the following:

- The initial and final angles of heel differ from the intact stability condition.
- The ratio of areas under the curves of heeling and restoring arms differs from intact stability condition.

By assuming a constant value for BM with respect to the intact condition, combinations of BM and GM values can be calculated for various heeling arms in damage condition. The results for intact condition can be compared with the results for damage condition. In the first place, heeling arms are compared. For the larger heeling arm, the values of GM, at an assumed value of BM, are compared; the higher GM-value will prevail.

Chapter 5

Building and cost calculation

5.1 Introduction

Following the realization of the modular approach in design of semi-submersible platforms, this concept will now be implemented in the construction of same with the purpose of :

- developing of a building procedure;
- developing of a cost calculation procedure.

The basis for the former will be derived from the outcome of the design, i.e. the external geometrical form and the standard structural pattern of panels throughout the entire platform. The building procedure will deal with the breaking-down of platform's geometry into series of second and first-level structures (chapter 3, par. 3) and the assembly of these series into a final product.

The main factors involved in cost-price calculation and their relationship with the structure and the building yard have been briefly discussed in chapter 2, par. 2 (see also Fig. 5.1). Following the implementation of the modular concept in the structural design, the relation structure-material and, thus, structural variables-material costs is well established and understood.

The relation yard-overhead costs is known though the determination of the latter and its absorption in the cost-price depends on the particular yard practice with regard to the used accountacy method /5.1/. In this respect, the distinction between fixed and variable overheads is noteworthy since the former depend mainly on capital investments (chapter 2, par.3.3). Since the level of capital investments is linked with the production facilities, a relation between these investments and the building of the structure is hereby established. This relation and its impact on building costs will be evaluated at a later stage (chapter 6).

The relation structure and yard - direct labour costs is understood but not well defined. Fig. 5.2 represents this relation; given a certain building procedure, the required labour effort will depend on the work content and the production performance of the building facilities, at each work-station (chapter 2, par. 3.3). For the determination of the building procedure, information on yard activities and facilities is necessary but not sufficient; the particulars of the structure itself (geometry, dimensions, structural arrangement) are also necessary. In other words, the distribution of building actitivies over work-stations establishes a relation between the structure and the building procedure.

The determination of work content is not yet established; a relation with the structure by means of geometrical and structural design information is indicated, but the nature of this relation and the quantification of work content is not yet established.

According to the concept of design-for-production (chapter 1), the relation structure-building is determined in such a way that any changes in the (structural) design is directly "translated" in labour effort and costs. The point of interest here will be the transfer of information between design and building so that the realization of this condition can be achieved through the modular approach.

A further point of interest concerns the possibility to improve production performance due to learning effects associated with structure series' production; this too relies on a clearly defined relation between structure and direct labour effort.

Following the above, the relation structure and yard - direct labour costs can now be fully established. Structure data is transferred along two lines of information :

1. Through the building process.
2. Through the work content.

The work content contains only information from design drawings; this information is considered to have an universal character (see further par. 2 of this chapter).

The building procedure combines structure data with the possibilities of the construction yard; for example :
- the location of seams within plate fields (second-level structures);
- the location of seams within first-level structures (unit blocks).

By combining information from structure's work content and building procedure, the amount of work, per work-station, is hereby established.

A schematic representation of the above relation is shown in Fig. 5.3; the necessary information is divided into four groups:

- three groups are derived from yard data and concern production associated processes and handlings, production performance and labour unit prices.
- the fourth group, structure's work content, is derived from structure data; this is basically a yard-independent factor of universal character.

The determination of the above is the main concern of this chapter. The aspects related to work content and processes & handlings will be discussed in par. 5.2 below : the obtained insight will be used to establish the building procedure (par. 5.3). The matter of labour unit prices will be discussed within the cost calculation procedure (par. 5.4).
Following the determination of production performance data (par. 5.5), the established relation between structure and direct costs will be demonstrated by means of examples (par. 5.6-7).

5.2 Work content and yard activities

5.2.1 The work content

The determination of an universal structure work content can be achieved if the latter is associated with parameters derived from structure's own characteristics, independent of the building facilities. In other works, structure work content is considered to be a constant measure which has to be realized by any suitable building facility, at the cost of a labour effort proportional with the local production performance.

Structure characteristics are derived from design results by means of the external geometry and internal structural arrangement. Some commonly used characteristics to determine work content and the corresponding quantifiers were mentioned in chapter 2 (table 2.2).

Yard production performance has been traditionally related to the processed steel weight /5.2/; this method, however, distinguishes only partly between differences in the structural patterns and is therefore not suitable for the purpose of this investigation.

A different approach towards quantification of production performance is derived from the central activity within the building process, namely the effectuation of connections. Production performance is expressed by the amount of connections per unit of time, which are effectuated at a particular workstation whereas the associated labour effort is quantified by a necessary amount of manhours. The relation between production performance and labour effort is established by means of time measurements (chapter 2, par. 2 and /5.3-6/).

Following the above, it becomes clear that the quantifier connection is a compatible measure for work content and production performance, whereas the relation between this quantifier and the required amount of manhours is a compatible measure for the relevant labour effort. Since the amount of connections is derived from the structure itself, the quantification of work content following the above approach can be considered to have an universal character.

Finally, if the distribution of connections over the various work-stations and the costs of the respective labour effort (man-hours) are known, the total direct labour costs are determined. The additionally necessary information comprises the following :

- Definition of structure's building process which establishes the distribution of work content and associated labour effort over work-stations.
- The costs per manhour at each work-station.

The above approach establishes a direct relation between structure and labour effort, thus between structural variables and labour costs, since any changes in the structural pattern is converted in a change in the amount of connections.

5.2.2 The connections

Considering the assortment of connections applied in the marine construction industry, a classification is made on the basis of:

- The involved structural components; this is termed primary classification.
- The type of connection and the related physical circumstances; this is termed secondary classification.

5.2.2.1 Primary classification

The distinction concerns :

1. A group of long, uninterrupted connections between the plane of two structural components performed :
   - in-plane : plate/plate connections within a plate pane
   - orthogonally : stiffener/plate connection
     vertical/horizontal panel connection

   (Fig. 5.4.a-b)

2. A group of connections involving two or more strutural components of relatively small sectional areas :
   - in-plane and in-line : stiffener/stiffener connection
   - in-plane, orthogonally : horizontal/vertical web connectio
   - orthogonal : stiffener/girder connection

   (Fig. 5.5.a-c)

   In addition, all bracket connections from Fig. 5.6.a-f.

Choosing the geometrical characteristics of the above groups as a basis for distinction between these groups, the terms line-connections and point-connections are introduced. These terms will be later related to the type of connection and the possible techniques employed for its effectuation.

5.2.2.2 Secondary classification

The distinction here concerns :

1. The weld type
2. The positional mode.

These are two basic types of welds :
- butt welds
- tee (T) or cross-type welds.

Butt welds concern in-plane connections between structural components, of which the most common is the line connection between plate elements (Fig. 5.7.a).

Tee or cross welds concern various orthogonal line and point-type connections, of which the so-called fillet weld is the most common (Fig. 5.7.b).

The positional mode is related to the spacial orientation of the connection or its location with respect to the welder; the following positional modes are defined :
- down-hand
- over-head
- vertical

(Fig.5.8.a-c).

5.2.2.3 Connection parameters

Each type of connection is further characterized by a number of parameters related to the structural components involved. These parameters are divided into two categories :

1. Characteristic dimensions
2. Main dimensions.

Characteristic dimensions are related to matters addressing the structural strength characteristics of the components, such as :
- thickness of plating, brackets, webs
- sectional areas and height of stiffening elements.

Main dimensions are related to the overall size of structural components such as :
- length and width of plates
- length of stiffening elements.

A review of the various types of connections following the above classification and parameters is given in table 5.1. This classification will be involved in the determination of the relation between connections and the required labour effort.

5.2.3 Yard activities : processes and handlings

5.2.3.1 General description

The total of processes and handlings applied in marine constructions are grouped as follows :

1. Preparation
2. Connection
3. Finishing.

The above grouping is related to the chronological order of activities in the course of the building process; a review is given in table 5.2.

Following a different line of approach, the processes and handlings from table 5.2 are grouped as follows :

1. Activities related to the fabrication of components
2. Activities related to the effectuation of connections
3. Activities of a general nature.

When considering the role of these groups in the relation structure & yard - direct labour costs, the following are observed:

- Group 1 addresses the added value of third-level components in the course of their fabrication. These activities are not directly related to the assembly process concerning the workstations 1 - 4 (see chapter 2, par. 2). Due to this aspect and the common practice to perform some of these activities outside the construction yard (straightening, shot-blasting, priming), this group can be considered to have an effect of secondary importance on building costs and will not be involved in this study.

- Group 3 is associated with materials' handling between work-stations and other supporting activities of general nature at the work-stations (table 5.2). The contribution of the former to the final building costs is not negligible /5.17/. However, these activities are not involved in the effectuation of connections as a part of the assembly process but concern general yard organization and operation which are not included in this investigation. Supporting activities are connected to the effectuation of connections and will be taken into account.
- Group 2 is directly related to the work content of the structure as well as the distribution of same over the work-stations, hereby affecting direct labour effort and costs. The relation between activities within this group and connections' parameters (par. 5.2.2.3) is a point of interest here and will be discussed below.

5.2.3.2 Welding processes and rest handlings

Following a more detailed consideration of the group of processes and handlings associated with the effectuation of connections, the following distinction is made :

1. Preparatory activities, hereafter rest-activities; this concerns groups 2.1 and 3.1 from table 5.2.
2. The actual welding; this concerns groups 2.3 from table 5.2.

The distinction is derived from the following basic difference between the above :

- The actual welding concerns the melting and depositing of welding consumables (electrodes) which is, within certain boundaries, a technology-related process. This implicates that once the choice of technology and facilities has been made, production performance is determined by the process itself.

- Rest activities are basically handlings and subject to the influence of human skills and co-ordination between individuals in cases where more than one worker at a time is required. This implicates a potential for improvement of efficiency and production performance.

The above difference has further impacts on the possibility to apply mechanization/automation and robotical aids as well as on the benefit of repetitive activities resulting in learning effect A major point of interest here is the relation between production performance and rest activities/welding processes and the connection parameters from par. 5.2.2.3.

5.2.3.2.1 Welding processes

Welding rate is defined as the amount of time required to effectuate a unit line-connection; this depends on the following parameters :

a. Weld size
b. Seam form
c. Positional mode
d. Operating environment
e. Melting rate, determined by the type/size of the rod and the used current.

a. Weld size

The weld size depends on the characteristic parameters of the involved structural components. For butt-type connections, this parameter is the thickness of plating, for cross-type connections this parameter is the thickness of the perpendicular structural component which determines the throat-thickness (see Fig. 5.7.a-b).

b. Seam Form

The form of the seam is determined by components' edge preparation (Fig. 5.8). Parameters (a) and (b) together determine the weld groove, i.e. the cross-sectional area which has to be filled with weld material.

c. Positional mode

See par. 5.2.2.2.

d. Operating environment

The operating environment indicates restrictions imposed on the operator/welder by either obstructions and confinement of his movement or the possibility to use certain welding processes.

e. Melting rate

The melting rate is determined by the strength of the used current. The latter depends on components' characteristic parameters, such as plate thickness, which determines the allowable amount of heat with regard to the possibility of grain coarsening. Rod thickness and type are also limiting factors in the determination of the maximum allowable current strength /5.18/. This implicates that the amount of weld material deposited at one time is limited and that large weld grooves require a number of passes.

Of the above factors, (a) and (b) are mainly determined by the involved structural components, though the choice of the welding process plays an important role in the preparation of edges /5.19/.

Factors (c) and (d) are of importance in the choice of the welding process and equipment.

Factor (e) is a result of the choice of the welding process; following a certain choice, the welding rate and, consequently, the production performance are mainly determined by melting rate and the number of passes. In other words, the choice of technology dominates the welding process and this is the main reason for increasing application of mechanical/automatic and robotical aids in welding operations /5.12, 5.21/. The degree of automation concerns :

1. The feeding of the electrode
2. The manipulation of the electrode

/5.16/.

The application and choice of welding processes within this investigation is included in the building procedure.

Some points of interest regarding the automation of welding processes in marine construction are :

- semi-automatic and automatic welding are applied almost solely in line connections;
- semi-automatic and automatic welding are applied mainly at low structural levels, at the sub-assembly and panel assembly workstations /5.12, 5.20-21/.

5.2.3.2.2 Rest handlings

The main purpose of rest handlings is to provide the necessary conditions for the actual welding; these are :

a. Correct positioning of structural components following the determined structural pattern;
b. Accurate alignment of components to ensure the quality of the weld and production performance;
c. Clean environment at the weld groove;
d. Correct positioning and adjustment of welding gear.

Factors (a) and (b) are related to the involved structural components and depend on its main dimensions. In addition, alignment operations deal with deformations and rigidity of components of which the latter depend on the characteristic parameters such as plate thickness. A point of interest here is that while the final location and condition of components is accurately determined by the structural pattern, it is difficult to determine the initial state of deformation and dis-alignment. In other words, the lack of uniformity in the initial condition of components requires specific, component-related judgement in the performing of rest activities. This is an important cause for the reduced level of automation in rest activities.

Furthermore, the advance in the phase of building and structural complexity increases deformation and dis-alignment which result in an even lower level of automation in rest activities. It is therefore that mechanization and automation of rest activities is found mainly at the lower structural levels, at the sub-assembly and panel assembly work-stations and concern mainly line-connections. This is analogue to the practice in welding operations /5.13, 5.20, 5.22/.

5.2.3.3 Summary

The relation structure & yard - direct labour costs is attributed to a group of processes and handlings directly related to the effectuation of line and point connections. Hereby, the condition of compatible parameters for quantification of structure's work content and labour effort from par. 5.1 is fulfilled.

The whole processes and handlings are divided into two categories:

1. Welding processes which are technology-related.
2. Rest activities (handlings) which are subject to human skills and judgement.

The main differences here concern :

- The possibility to improve the production efficiency due to learning effects associated with repetitive activities; this is found mainly in rest activities where human judgement and skills are necessary.

A main conclusion here is that the magnitude of eventual gains in production performance depends on the share of point connections, respectively rest activities, out of the total labour effor In this respect, the distinction between line and point connections is a new elements in the building process.

5.3 The building process

5.3.1 Introduction

The building process has been described as a sequence of assembly operations, at increasing levels of structural complexity, which are performed according to a pre-determined procedure.

In a different approach, the building process is seen as a scheme for the effectuation of connections distributed over several work-stations; the following points are of interest :

1. The realization of such a scheme following the modular concept (see chapter 3, par. 3).
2. Optimization of the scheme with regard to the size of modules, the structural patterns, the distribution of assembly operations over work-stations, etc. This is a subject of investigation in its own rights and will not be included in this work.

The realization of the scheme will be based on the following principles :

- Limitations imposed by building facilities;
- Strive to maximum uniformity of components at the second and first structural levels with the aim of obtaining the smallest possible number of series in inter-action with the design solution;
- Break-down of the structure into natural blocks.

5.3.2 Principles in the building process

5.3.2.1 Work-station limitations

The fabrication of largest, in particular longest possible structures is a basic principle in marine constructions. The reasons are :

- Maximum benefit of mechanization/automation of welding operatio
- Reduction of the number of transverse connections, in particula point connections, at the highest structural levels which reduc leadtime at the erection work-station /5.5, 5.18/.

The limitations imposed by work-station facilities are :

- The crane capacity
- The maximum physical dimensions of first/second/third-level structures which can be processed and handled.

Possible combinations of the above are shown in table 5.3 :

- In case (1), both length and crane capacity are limited; either limitation constrains the physical dimensions of the structure, hereby not enabling efficient use of facilities.
- In case (2), only crane capacity is constrained; light construction will result in long structures, whereas heavy construction will result in short structures.
- In case (3), only length is constrained; this situation favours heavy structures.
- In case (4), no limitations are imposed; this is an un-economic facility though such may happen if limitations are imposed by previous or following work-stations.

Case (1) is the most common practice since building facilities are designed in accordance with the building procedure and the types c products which are expected to be contracted.

The choice for the purpose of this investigation will be made at a later stage.

5.3.2.2 Maximum uniformity

The following distinction is made with respect to the uniformity of structural components :

a. Geometry
b. Structural patterns

Geometrical uniformity addresses :

- The external geometrical form of first-level structures; this was already obtained through the geometrical design (chapter 4,par.4).
- The main dimensions of first and second-level modules; the former concerns the lengths of the modules, the latter length and width of flat panels throughout the entire platform. Both have to be realized in the course of the building process.
- Characteristic dimensions of components; these concern the third structural level and are determined on the basis of structural strength requirements. Standardization with respect to characteristic dimensions is not included in this study.

Uniformity of structural patterns was already obtained in the structural design.

Following the above, the uniformity which has to be obtained in the course of the building procedure concerns length dimensions of first-level structures and length/width dimensions of second-level structures.

5.3.2.3 Natural blocks

This term concerns an approach to assembly of unit blocks characterized by the following :

a. Minimum possible stages of final assembly;
b. Self-supporting in the construction stage with minimum shoring and other temporary supports;
c. Quick and accurate positioning at the construction stage;
d. Size and shape take the best advantage of advanced outfitting;
e. Accurate dimensions.

Items (a) - (c) implicate :

1. The use of few but large, preferably long panel components.
2. Components rigidity must be sufficient to prevent deformations during handling which might hamper positioning and aligning activities.

Item (d) is related to the sequence of assembly operations which must enable advanced outfitting implicating :

3. Easy access into the block.

Item (e) is related to the final stage of assembly, the erection; this condition is inherent to the modular approach where standardization of components promotes the obtaining of accurate dimensions of second and first-level modules /5.20/.

5.3.2.4 Conclusions

Following the considerations from the proceeding paragraphs, the building procedure for floater, column and deck modules will be based on the following principles :

- Longitudinal dimensions of first and second level structures are to be kept equal. The length will be determined by the maximum plate length which can be made available and kept as much as possible constant over all floater, column and deck modules.

- The variation in the main dimensions of panel elements is to be limited. Since identical length has already been required, the point of interest here will be to achieve the maximum possible number of panels of identical width.

- Standardization of main dimensions of third-level components wil be effectuated with respect to plate length and width dimensions

- Standardization of characteristic dimensions of third-level components will not be included. Discrete values for plate thickness and continuous values for all other characteristic dimensions will be used.

- Crane capacities will not be limited; the capacity necessary for the heaviest structure, at the maximum length, will be considered available.

- The building procedure concerns only the construction of the steel hull, without outfitting. However, due consideration to the latter will be given by observing the conditions of "natural blocks" from par. 5.3.2.3.

5.3.3 The building procedure

5.3.3.1 Work-station 1 : Sub-assembly

The activities performed at this work-station are shown in table 5.4 and concern the assembly of web-frame elements. The activities are divided over rest and welding; the parameters of importance and the welding processes are also mentioned.

5.3.3.2 Work-station 2 : Panel assembly

The activities performed at this work-station are shown in table 5.5; in addition to rest and welding activities related to assembly operations, panel circumference is marked and flame-cut (see also Fig. 5.9).

5.3.3.3 Work-station 3 : Unit block assembly

The activities performed at this work-station are shown in tables 5.6-7. In principle, the assembly scheme is the same for floater, column and deck modules, but due to the differences in the internal structural configuration, a distinction will be made between the various modules.

Assembly of floater modules

The assembly procedure for floater modules is divided into two main phases :

1. Assembly of wing blocks (see Fig. 5.10.a)
2. Assembly of floater blocks (see Fig. 5.10.b)

A total of 10 panels is involved, comprising two various series :

1. One series of six (6) panels
   - 4 x vertical panels
   - 2 x horizontal panels

   All panels have equal width but the webframes in the vertical panels are shorter than those in the horizontal panels.

2. One series of four (4) horizontal panels of identical width and length of the webframe elements.

See also tables 5.6-7.

Assembly of transverse bulkheads

In principle, the fitting of transverse and end bulkheads follows the same assembly scheme :

- wing tank bulkheads are fitted in phase 1
- centre tank bulkheads are fitted in phase 2.

Assembly of column modules

The assembly procedure for column modules is similar to the one for floater modules. The main difference is that the longitudinal bulkheads are replaced each by a row of cross-ties (see Fig.5.11.a) In addition, the connection of transverse bulkheads between wing and centre sections is done by butt welds (Fig. 5.11.b; see also tables 5.6-7).

Assembly of deck modules

An arrangement of deck modules is shown in Fig. 5.12; there are two different types :

1. A complete circumference module, identical in its external geometry with floater and column modules (Fig. 5.12.a).
2. An incomplete circumference module consisting only of deck and bottom panels (Fig. 5.12.b). The width of these panels is derived from deck's and type (1) module dimensions (see also Fig. 4.8).

Type (1) comprises two deck elements of a length equal to structure's deck length and a number of transverse elements which depends on the number and configuration of the columns. The internal configuration corresponds to floater configuration, with the omitting of horizontal cross ties and longitudinal bulkheads which are replaced by vertical cross ties; the practice from table 5.7 is applicable.

Type (2) concerns intermediate deck areas between transverse and longitudinal complete-circumference deck modules. The assembly of these modules is shown in Fig. 5.13; line butt-connections for horizontal panels and double fillet connections for vertical panels are analogue to the practice from table 5.7. Point connection number(5)(Fig. 5.6) for vertical cross ties and number (3) for the bulkheads are also analogue to table 5.7

5.3.3.4 Work-station 4 : Erection

The distinction between floater, column and deck structures concerns the position and location at which the erection of these structures is performed.

Floater elements

Floater elements are assembled in horizontal position on launching ways or in building dock. The followed procedure is shown in Fig. 5.14.a. The performed activities are given in table 5.8.

Column elements

Column elements are assembled in vertical position, which coincides with their location in the final structure. The followed procedure is shown in Fig. 5.14.b. The performed activities are given in table 5.9.

Deck structure

The assembly procedure for the deck structure is shown in Fig. 5.14.c. First, complete circumference modules in longitudinal and transverse direction are connected; hereafter, intermediate deck modules are placed. The proposed procedure may require some temporary supporting of the intermediate deck modules. The performed activities are given in table 5.10.

5.3.4 Summary

To initiate the building procedure outlined above, the structure was first broken down in several series of first and second-level structures. In principle, there is an infinite number of alternatives for breaking down the structure. The chosen alternative was based on the following :

1. The principles outlined in par. 5.3.2.4.
2. The relation with the design.

With respect to the former, particular attention was paid to matters concerning the natural block approach to the building process (par. 5.3.2.3).

With respect to the latter, a principle starting point was the internal structural configuration of the floaters regarding the longitudinal bulkheads which divide the floater module in one centre and two wing tanks. Should a different internal configuration be required, the break-down of floater modules and, consequently column and deck modules, would have been performed differently, resulting in a different building procedure. The building procedure outlined above is, thus, one of several possible solutions. However, this study is concerned, in the first place, with the differences between two concepts, i.e. the modular one and the conventional one. For purpose of comparison, general practice in conventional marine constructions has been followed; a further differentiation concerning alternative building procedures is not included in this study.

An overview of component series is given in table 5.11.

5.4 Cost calculation procedure

5.4.1 Introduction

The purpose of cost calculations within this study is directed towards the evaluation of economical merits of the modular concept with respect to the conventional concept. The primary interest goes to the comparison of results rather than their absolute value which implicates, on the first sight, that only costs which are affected by the variation of parameters during the investigation are to be considered.

The involved cost factors are :
- material
- direct labour
- overheads.

It has already been demonstrated that changes in the structural pattern affect material weight and costs and that these changes also affect work content, hereby altering the amount of labour effort and costs. Information on these two factors is directly available from the design solution.

The influence of the third cost factor, overhead costs, is not yet known since its relation with the structural pattern has not yet been established.

Another point of interest is the absorption of overheads in the building costs for which three basic methods were presented (Chapt 2, par. 2). Of these, the method of absorption on the basis of hourly rates (the tariff method) and the direct absorption method include the relation between structure and overhead costs and are suitable for the purpose of this study.

Preference is given to the tariff method which is commonly used in Dutch Marine Industry and for which the necessary data is availabl

Starting with the determination of overhead costs, the calculation of tariffs will be discussed, whereafter the procedure for the calculation of costs will be established. The necessary data on overhead costs is derived from a reference production facility (see chapter 1) which comprises all factors used in the calculation of costs (see Fig. 5.15).

5.4.2 Overhead costs

An overview of expenditures on a marine construction yard was given in appendix 2.1 where a distinction was made between general and production cost centres. The latter are identified with the work-station analogy used to represent the production facility. The former concerns general yard overheads as well as overheads necessary to maintain and operate the work-station. The distinction made between overhead costs is used as a basis for its absorption into work-station tariffs, where the general overheads are allocated to work-stations by means of a distribution key related to local work-station production (chapter 2, par. 2).

Distribution keys and tariff calculation procedure are determined by the yard, usually based on prognoses concerning the expected level of activity and price development /5.22/. The above aim to provide an overview of expenditures in a complex organization for the purpose of cost and annual results calculations.

However, for the purpose of this investigation, general yard overheads which are not traceable directly to some causative factor affecting the building costs of the structure will not be considered in the calculation of tariffs. Causative factors directly related to the work-stations are /5.5/:

1. Capital investment
2. Production output
3. Direct labour force
4. Area.

The basis for the aportionment of general yard overheads and absorption of work-station overheads is the level of activity (production) at the work-station. A distinction in made between :

- A fixed level of production which was determined at the initiation of the facility. The relevant overheads are termed fixed, the corresponding level of production is termed normal.
- A variable level of production which is determined by the work content of the specific structure contracted by the yard. The relevant overheads are termed variable, the corresponding level of production is termed planned.

The contribution of both fixed and variable overheads is necessary; the latter due to its link with structure's work content, the former because it involves the time factor, hereby establishing a link between costs which are independent of the level of activity and the structure.

An overview of overhead costs and the relation with the relevant causative factors is given in table 5.12.

5.4.3 Tariff calculation

The elements involved in tariff calculation are :

1. Direct labour costs of human labour
2. Overhead costs from yard and work-stations.

5.4.3.1 Direct labour costs

Direct labour costs consist of the following :

a. Basic salary
b. Obligatory social schemes
c. Additional overheads related to the direct labour force and including :

1. social services, medical care, canteen and washroom, protective clothing, training, etc.
2. supervision of direct labour force at the work-station.
3. temporary and local facilities such as heating, lighting, ventilation, etc.

Items (b) and (c) are given as a percent addition on top of the basic salary; figures relevant for the Dutch labour market are given in table 5.13.

5.4.3.2 Overhead costs

The quantification of normal and planned levels of production follows from the definition of work content and production performance (see par. 2). The former is given by the amount of connections, the latter by the amount of manhours required to perform a unit of connection. Following these definitions :

- Planned production is given by the amount of manhours necessary to perform a given work content.
- Normal production is seen as a potential level of activity (labour effort), which, depending on the production performance, can be used to effectuate any work content within the capability of the facility. Considering the factor direct labour as the principal production element, the normal level is given by :

$$NP_j = M_j \times T_a \quad , \text{where :} \qquad (5.1)$$

NP_j = normal level of production in manhours/annum at work-station j.

M_j = direct labour force associated with work-station j.

T_a = the number of manhours per year, per worker.

The total overhead contribution to tariffs, per one manhour :

$$\text{overhead/manhour} = \frac{\text{variable overheads}}{\text{planned production}} + \frac{\text{fixed overheads}}{\text{normal production}}$$

or :

$$Coh_j = \frac{Cov_j}{PP_j} + \frac{Cof_j}{NP_j} \quad \text{, where :} \qquad (5.2)$$

Coh_j : overhead costs/manhour, at work-station j

Cov_j : variable overheads at work-station j

Cof_j : fixed overheads at work-station j

PP_j : planned production at work-station j

NP_j : normal production at work-station j

Fixed and variable overheads are calculated on the basis of data from tables 5.13 and 5.14.

5.4.4 The reference building facility

In real marine construction practice, the levels of planned and normal production as well as those of overhead costs differ over the various work-stations; this is expressed by different tariffs for the work-stations.

To obtain a realistic effect in the calculation of cost price, a reference construction yard was assumed, where the four causative factors mentioned in par. 5.4.2 were quantified on the basis of :

- a simplified work-station set-up corresponding to the analogy presented in chapter 2, par. 2.
- production system i.e. facilities and labour force suitable for the building of semi-submersible platforms of the type used in this study.
- a level of investments and overhead costs corresponding with the practice in current Dutch marine construction yards (see also tables 5.13-14).

A layout of the yard is shown in Fig. 5.15.
The relevant data is given in appendix 5.1.

5.4.5 Summary

The cost calculation procedure follows the tariff method where the building costs are determined on the basis of three cost factors :

1. Material costs
2. Direct labour costs
3. Overhead costs.

Material costs are directly derived from the structural design and are proportional with the variation in the structural pattern. At known unit prices for plate and section materials, an exact calculation of costs is possible.

The other cost factors are involved through work-station tariffs. The contribution of direct labour costs is derived from the building procedure which determines the distribution of structure's work content over the work-stations. At known production performance, the labour effort, in manhours, can be calculated. The relevant costs are represented by the contribution of salaries, social schemes, etc. in work-station tariffs. The other contribution is derived from the various yard and work-station overheads.

The overhead costs involved here are directly related to the building process concerning the semi-submersible structure through the causative factors. Other overhead costs, though important for the total yard financial results, bear no relation to the structure itself and will not be included in the comparison between alternative design solutions.

In the schematic representation of the cost calculation procedure from Fig. 5.3, the missing element of production performance will now be discussed.

5.5 Production performance data

5.5.1 Introduction

Following the evaluation of welding and rest activities (par.5.2) production performance data is given by :

$$T_p = F(C_i\ ,\ f_1\ (l_i),\ f_2\ (t_i))\quad ,\ \text{where :} \qquad (5.3)$$

T_p : production performance, in manhours per unit of connection

C_i : general expression for job-related constants

$f_1(l_i)$: a function of the main parameters l_i

$f_2(t_i)$: a function of the characteristic parameters t_i

The total number of manhours is found by multiplying T_p by the number of connection units which is given :

- for line connections, by the number of seams x seam length
- for point connections, by the number of connections.

The expression for T_p above is valid for welding and rest activities.

$f_1(l_i)$ and $f_2(t_i)$ are usually linear functions of the main, respectively characteristic parameters with the general form :

$$f_1 = B_{1i} l_i \times B_{2i}$$

$$f_2 = D_{1i} t_i + D_{2i}$$

The numerical values of B_{1i}, B_{2i}, C_i, D_{1i} and D_{2i} are established by time measurements and depend on the following factors :

a. The type of connection given by its primary and secondary classification (see par. 5.2.2)

b. The employed technology, processes and facilities; these are, to a large degree, determined by the connection itself and by circumstances occuring at the work-station.

The factors under (a) are directly related to the structure and possess an universal character.
The factors under (b) are related to local yard conditions.

5.5.2 Basic assumptions

Data on production performance is mainly derived from current practice on Dutch marine construction yards and based on time measurements of a variety of marine products such as tankers, bulk-carriers, cargo vessels, barges, etc. /5.26-28/.

Basic assumptions for the use of data are :
- normal strength steel in thickness up to about 30 mm;
- special welding bank for sub-assemblies;
- special panel-line with turn-over facilities for two-sided welding;
- no turn-over facilities for unit blocks;
- standard times are given, based on optimum functioning of facilities.

In principle, standard times concern netto-hours, with no account for delays, personal care, etc., but including time losses due to co-ordination when more than one man is involved. This coincides entirely with the definition of rest activities (par. 5.2.3.2.2) and partly with the definition of welding activities (par. 5.2.3.2.1). The differences for the latter group are found in the inclusion of some supporting activities in welding operations (group 2.2 from table 5.2).

The possibility to include complete supporting for rest and welding activities is given in the form of a percentual addition, above the netto standard times, depending on :
- the structural level;
- the work-station;
- the type of activity, i.e. welding or rest.

The relevant figures are shown in table 5.15; in general, there is an increase in the addition with increasing structural complexity whereas the figures for rest activities are higher than those for welding activities.

A disadvantage of the above is that while netto standard times are specifically related to the type of connection and, thus, proportional with main and characteristic parameters of the involved structural components, no such relation was established for the addition figures from table 5.15. Supporting activities from group 2.2, table 5.2, depend mainly on the job to be performed rather than the particular connection which has to be effectuated.

On the other hand, the difference between the various figures with respect to factors such as type of connection, the structural level and the work-station provide useful information on the relative importance of these factors which otherwise cannot be included.

Following the above, it was decided to augment netto figures on production performance by the relevant figures from table 5.15.

5.5.3 Data

Data on production performance is provided for all four workstations. In general, a distinction is made between rest and welding activities; the relevant parameters are given for all types of connections, the standard times are given in man-minutes.

Examples on production performance data are shown in :
- Fig. 5.16.a-d, concerning line connection activities
- Fig. 5.17.a-b, concerning point connection activities

The use of production performance data raises some questions on the following aspects :
- detailing of information
- accuracy of information
- applicability

These aspects will now be briefly discussed.

5.5.3.1 Detailing

The detailing of information concerns the following :

- the activities
- the facilities
- the parameters

In general, there is a higher level of detailing at the lower structural levels, at work-stations 2 and 3. This is explained by the greater simplicity of the structure and lesser variation of components which have resulted in the development of special purpose facilities.

The above is also valid when observing the relation between main and characteristic parameters and production performance data. At lower structural levels, this relation is more specific due to the absence of supporting and preparatory activities required at higher structural levels. Here again, the greater uniformity between structures (panels) eases the determination of the relation standard time-parameters.

5.5.3.2 Accuracy of information

A two-fold meaning can be attributed to the accurary :

1. The extent to which standard times represent a certain activity, i.e. the ambigousness of the relation activity - standard time.

2. The extent to which standard time is affected by main and characteristic parameters.

With respect to the former, a high level of accuracy can be achieved through break-down of activities into simple and well defined handlings or tasks for which basic, elemental times are determined on the basis of time measurements or already existin norms. The obtained data is stored in a data bank and used, after suitable factoring to allow for delays, to estimate the labour effort necessary to effectuate a given work-content /5.6/ The above is related to the degree of detailing mentioned in par. 5.5.3.1.

Data on production performance which was made available for thi investigation was derived from a data bank similar to the above, though no direct access to the bank itself was available. However, the normative character of the available figures and the allowances for netto/brutto standard times enable to investigat the relation structural patterns - labour effort on a comparati basis which is in conformance with the purpose of this study.

With respect to the latter meaning, the distinction between mai and characteristic parameters which was discussed in par. 5.2.2.1-2 will be involved.
For welding operations, characteristic parameters such as plate thickness for butt welds and the corresponding throat thickness for fillet welds are of primary importance.
For rest activities, the main parameters length and width of components are of primary importance, though for certain types of line connections such as plate/plate butts, characteristic parameters are also involved.

5.5.3.3 Applicability

The matter of applicability concerns the validity of results obtained by using the available figures on production performance. Such figures are related to specific facilities and cannot be applied indiscriminately. Here too a distinction is made between the more universal welding processes and the more yard-related rest activities.

However, the evaluation of building costs will be performed on the basis of comparison between results rather than absolute values. As long as the proper relations between work-stations, with respect to standard times, are being observed and main and characteristic parameters are consequently used, the available data will provide insight in the effect achieved by variation of the structural pattern on the building costs.

5.6 Application to second level structures

5.6.1 Introduction

To obtain a first insight in the various aspects of the modular concept with respect to work content, labour effort and costs, an evaluation of second level structures was performed. Subject of investigation was a stiffened, flat panel under uniformly distributed lateral loading (Fig. 5.18.a).

Another point of interest was the evaluation of the structural pattern with the purpose of establishing the ratio k = S/s, i.e the ratio of (transverse) webframe spacing S to (longitudinal) stiffener spacing s (see chapter 3, par. 3.2).

Since flat panels in floater, column and deck structures are subject to different levels of lateral loading, the loading was also varied over a range of values corresponding with the actua range found for platforms of the type investigated here. Streng criteria are maximum permissible stress levels following classification rules.

Finally, the impact of a varying labour costs/material costs ratio was involved. This was done by varying hourly tariffs over a range of values covering the current practice in marine constructions and dividing those values by a basic steel-plate price /5.5, 5.23/. The obtained cost results are given, thus, in non-dimensional form.

The values used for this investigation are given below :

- The spacing s : 0.4 - 1.0 metres, with steps of 0.2 m
- The ratio S/s = k : 1 - 4
- The lateral pressure : 90 - 360 N/mm^2, with steps of 90 N/mm^2
- The hourly tariff : 25 - 100 Fl., with steps of 25 Fl.
- Basic steel price : 1000 Fl./t for plating and web material
  1100 Fl./t for sections (stiffeners)

The results of cost calculations are given by means of the cost index CI defined as :

$$CI = \frac{\text{labour costs + material costs + overhead costs}}{\text{basic material price (mild steel plates)}}$$

A flow diagram representing the followed procedure is shown in Fig. 5.18.b.

5.6.2 Results

5.6.2.1 General

Results are presented in fig. 5.19-21.
Fig. 5.19 shows typical cost output, per panel, for a given lateral pressure and labour costs/material costs ratio. Four curves are plotted, each representing a certain S/s ratio; the various curves intersect each other as costs vary with the variation of s. The lowest portions of these curves represent the panel minimum total costs over the investigated range of spacing values. By combining results for all variations of parameters (par. 5.6.1), figures 5.21.a-d are obtained; each figure represents a certain ratio of labour costs/material costs. The intersection points between curves with different k-values were connected so that the area of minimum panel costs corresponding to a particular k-value is distinguished from other k-values. Given the hourly tariff, the lateral pressure and the spacing s, panel total costs can be determined for each k-value.

The values of work-content, labour and material costs adopted at varying s-values are shown in Fig. 20.a. The work content is given for all connections at work-stations 1 and 2 :

- Column 1 : line connections, web-flange, at work-station 1
- Column 2 : line connections, web-plate, at work-station 2
- Column 3 : line connections, stiffener-plate, at work-station 2
- Column 4 : line connections, plate-plate, at work-station 2

- Column 5 : point connections, stiffener-web, at work-station
- Column 6 : total line connections, work-stations 1 and 2.

The break-down in material and labour costs are given by separate curves, Fig. 5.20.a.
A further break-down of labour effort over the type of connections and activities is shown in Fig. 5.20.b.

5.6.2.2 Discussion

The impact of the structural pattern on labour effort and costs is clearly demonstrated by the obtained results. First, the reduction of work content, given by the amount or connections in Fig. 5.20.a, shows a decrease in line and point connections with increasing value of s. This increase applies to all types of connections, with the exception of the plate-plate connection. The associated labour costs diminish; the increase of material costs indicates an ever heavier becoming structure. The total costs reflect the balance of labour and material costs which, after an initial decrease to its minimum value at a s-value of about 0.55 m, increases again.

Fig. 5.20.b shows the decrease of labour effort in conformity with the decrease of work content. This is reflected by the total labour effort curve as well as by its component curves in terms of types of connections (i.e. line and point) and activities (i.e. welding and rest). The results are given with respect to the maximum labour effort calculated at a s-value of 0.4 m.

Another aspect here is the share of labour effort with respect to the type of connection and activity. Point connections require a labour effort which is small but not negligible with respect to line connections labour effort. The share of point connections amounts to about 18% of total panel labour effort at the lowest s-value, decreasing gradually to about 12% at the highest s-value.

The share of welding labour and rest labour are almost equal over the investigated range of s-values, the former amounting to about 56% of the total labour effort at the lowest s-value, gradually decreasing to about 53% at the highest s-value.

The impact of all variables on costs shown in Fig.5.21.a-d are :

1. Loading

   Increase of the lateral loading results in a heavier structure. The increase in costs concerns the contribution of material as well as labour costs, in particular welding labour. The former due to increase of material weight, the latter due to the increase of scantlings, i.e. plate and web thickness, etc. (Fig. 5.22).

2. Spacing s

   In general, this is reflected by Fig. 5.20; the heavier structure accounts for the increase of material weight and costs, but the increase of scantlings is cancelled by the decrease of work content (Fig. 5.20.a) which results in a decrease of labour input and costs.

3. The ratio S/s = k

   The value of k represents the structural pattern; an increase in the value of k results in a decrease of work content by reducing the amount of line and point connections.

The combination of the above is generally given in terms of light structure of high work content and heavy structure of low work content. The balance between material and labour costs will further depend on the tariffs or the ratio labour costs/material costs. This is demonstrated in Fig. 5.21.a-d; for low values of the ratio labour costs/material costs light structures, i.e. low k-values, are cheaper whereas for high ratios of same, heavier structures are cheaper. A point of interest here is that the sensitivity of the cost curves to variation of the spacing s decreases with increasing ratio of labour costs/material costs to a point where the curves are almost horizontal (Fig.5.21.d);

material and labour costs balance each other, for various values of s and k.

Another point of interest is the choice of a fixed value for k which will be maintained in the course of this study. The above results show that the value of k is not independant of other variables. In general, the figures k = 2 and k = 3 dominate over values of labour costs/material costs corresponding with the current practice in Dutch marine constructions (Fig. 5.21.b-c). Considering that most stiffened panels in columns and deck are subjected to lateral loadings less than 270 N/mm squared, the value of k = 3 is selected as a fixed value for the continuation of this study.

5.6.3 Conclusions

Calculation of building costs for the important second-level structures was performed by combining material and labour effort costs. The former were based on the structural weight derived from scantlings, the latter from the required work content given by the various connections and production performance data.

The obtained results confirm the generally acknowledged trends on the impact of structural pattern, laoding and manhour tariffs on material and labour costs /5.5/; hereby, the validity of production performance data is also confirmed.

Following the modular approach, calculation of labour effort on the basis of work content and production performance data related to characteristic and main parameters of structural components, has proved to be an accurate method which provides insight in the following :

- the relation structural pattern - labour effort and costs
- the relation loading - material and labour costs
- the relation tariffs - labour costs.

With respect to the influence exerted by the various types of connections on labour effort, the conclusions are :

- The labour effort associated with line connections takes the larger share of the total labour effort. This share increases with increasing spacing s.
- The share of point connections is small with respect to that of line connections, but not negligible. For loadings and k-values assumed in Fig. 5.20.b, this share varies between 18 and 12% of the total labour effort corresponding with the variation of the spacing s.

With respect to the influence exerted by the various types of activities, the following is concluded :

- Labour effort is almost evenly distributed over welding and rest activities.
- Welding labour increases slightly with increasing spacing s; a further break-down of labour effort over types of connections and activities indicates that this increase is mainly due to point connections which is explained by the introduction of connecting lugs at higher lateral loadings (Fig. 5.22).

The choice of the structural pattern for the continuation of this study was based on the results shown in Fig. 5.21.a-d and consists of a pattern established by the ratio S/s = 3.

5.7 Application to first-level structure

5.7.1 Introduction

Insight in aspects of the modular concept at higher structural levels is obtained by evaluating a first-level structure. Subject of interest is the distribution of labour effort and costs over work-stations, types of activities and types of connections. Subject of study is a complete floater element.

Floater particulars were derived from a design solution obtained in chapter 4; structural design was performed according to the practice outlined in chapter 4, par. 3.3.

Following the structural design, the floater is broken-down in series of first and second-level structures in conformity with the building procedure from par. 5.3.3. In addition, sub-assembly series are formed on the basis of their length dimension. The length of second and first-level structures is limited by a aforedetermined length measure which corresponds with a maximum assumed plate length; crane capacity, at all work-stations, is considered available.
Structural weights of plate, stiffener, web-frame, cross-tie and bracket element are calculated.

The obtained main and characteristic dimensions are used to calculate labour effort, at all work-stations. Data from the reference building facility is used to calculate tariffs, whereafter material and labour costs are calculated.

The free variable used in this evaluation is the spacing s.
Cost calculation results are presented in non-dimensional form, similar to that of par. 5.6.

A flow diagram representing the followed approach to calculations is given in Fig. 5.23.a. Flow diagrams showing, in more details, the followed approach to the calculation of labour effort and cost-price is given in Fig. 5.23.b-c.

5.7.2 Results

5.7.2.1 General

Results are given by means of 6 basic tables :

- Table 1 : panel data (Fig. 5.24.a)
- Table 2 : series data (Fig. 5.24.b)
- Table 3 : steel weight data (Fig. 5.24.c)
- Table 4 : labour effort results (Fig. 5.24.d)
- Table 5 : tariff calculation (Fig. 5.24.e)
- Table 6 : cost calculation (Fig. 5.24.f)

Next, the following relations are established :

- Relation structural pattern - material and labour costs; a distinction is made between labour costs at various work-stations. (Fig. 5.25)
- Relation structural pattern - labour effort; a distinction is made between work-stations, types of connections and activities. (Fig. 5.26-8)

5.7.2.2 Discussion

Relation structural pattern - material and labour costs

The balance between material and labour costs is shown in Fig. 5.25.a. The total costs show a decrease from the initial calculated value at s = 0.4 m to a minimum level at about s = 0.55 m, whereafter a gradual rise of the total cost curve is observed. The constant rise in material costs is typical for pressure designed panels comprised in the floater structure.

The distribution of labour costs over all work-stations is shown in Fig. 5.25.b. A reduction of labour effort is observed at work-stations 1 and 2 which corresponds with the findings from par.5.6. For work-stations 3 and 4, a slight increase in labour costs is observed.

The largest share of costs goes to work-station 2 over almost the entire range of s-values up to about 0.95 m, whereas work-station 1 captures the smallest share (see Fig. 5.25.b).

Distribution of costs over types of connections and activities shows :

- Line connections take the larger share out of the total costs, but the share of point connections is of the same order of magnitude (see Fig. 5.25.c).
- Welding and rest activities are more balances with respect to their share of the total costs, with welding capturing the larger share (Fig. 5.25.c).

Labour costs' distribution is to be seen in relation with work-station related tariffs (Fig. 5.24.e); the obtained values for work-stations 1 and 2 justify the chosen k-value ($k = S/s = 3$).

Relation structural pattern - labour effort

The distribution of labour effort is shown at several levels :

1. Work station level (Fig. 5.26.a).
   The trend observed at the distribution of labour costs is maintained, but the share of work-station 2 is largest over a smaller range of s-values, 0.4 - 0.75 m. Beyond the latter point, the share of work-station 3 is largest.

2. The type of connections (Fig. 5.26.b).
   The larger share is taken by line connections, but the share of point connections is of the same order of magnitude. At work-station level (Fig. 5.27), there is an increase of labou effort associated with line connections at work-stations 3 and 4, whereas at work-stations 1 and 2 it decreases. Labour effort associated with point connections decreases, at all work-stations, with increasing value of s.

3. The type of activity (Fig. 5.26.c)
   The larger share is taken by welding activities, but the share of rest activities is of the same order of magnitude. At work-station level (Fig. 5.27), there is an increase of labour effort associated with welding activities at work-stations 3 and 4, whereas at work-stations 1 and 2 it decreases. Labour effort associated with point connections decreases, at all work-stations, with increasing value of s.

Explanations for the above are found by a further breakdown of labour effort, at work-station level, for combinations of types of connections and activities (Fig. 5.28). Welding and rest labour associated with line connections increases at work-stations 3 and 4 with increasing value of s; this is explained by increase of scantlings, at maintained work content (assembly of unit blocks, in terms of numbers and geometrical dimensions, is maintained).

5.7.3 Conclusions

In general, conclusions drawn at the evaluation of second-level structure are also applicable here with respect to :

- The significance of point connections with respect to the total labour effort.
- The significance of rest activities with respect to the total labour effort.
- The impact of characteristic dimensions of structural components on labour effort associated to welding activities prevails above the general trend of work-content-decrease with increasing value of s. Such is not the case for rest activities which are less dependent on components' characteristic dimensions.

The balance between the above is given by the total cost curve and indicates that work content is a dominant factor at low values of the spacing s. The decrease of work content at highe values of s is compensated by an increase of characteristic dimensions of structural components, finally resulting in a slo rise of the total cost curve (Fig. 5.26.a). This curve shows relatively less sensitivity to variations of s over the range 0.5 - 0.7 m than elsewhere.

The above trends are valid for the investigated floater element the considered reference facility and cost factors. The evaluation was performed on a static basis, without considering the impact of leadtime on the final costs of the structure.

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Table 5.1: Review of connections

connections	primary classification				secondary classification					parameters				
	line		point		weld - type		positional mode			characteristic			main	
	in plane	orthog	in plane	orthog	butt	cross	down hand	over head	vert.	thickn.	height	area	length	width
plate/plate	X	X	-	-	X	X	X	X	X	X	-	-	X	X
stiffener/plate	-	X	-	-	-	X	X	X	X	X	-	-	X	-
web-frame/plate	-	X	-	-	-	X	X	X	X	X	-	-	X	-
stiffener/web-frame	-	-	-	X	-	X	X	X	X	X	X	-	-	-
stiffener/stiffener	-	-	X	X	X	X	X	X	X	X	X	-	X	-
web-frame/web-frame	-	-	-	X	X	X	X	X	X	X	X	-	X	-
stiff/brack/stiff	-	-	X	-	X	-	X	X	X	X	X	-	-	-
webfr/brack/webfr	-	-	X	-	X	-	X	X	X	X	X	-	-	-
webfr/brack/stiff	-	-	X	-	X	-	X	X	X	X	X	-	-	-
stiff/brack/plate	-	-	X	-	X	-	X	X	X	X	X	-	-	-
webfr/brack/plate	-	-	X	-	X	-	X	X	X	X	-	-	-	-
strut/web frame	-	-	-	X	-	X	X	X	X	X	-	-	-	-
strut/plate	-	-	-	X	-	X	X	X	X	X	-	-	-	-
strut/brack/plate	-	-	-	X	-	X	X	X	X	X	-	-	-	-

X : influence

\- : no influence

Table 5.2: Review of activities

GROUP	DESCRIPTION OF ACTIVITIES
. PREPARATION	
1.1	. preparatory processes directly related to structural components : straightening, shot blasting/priming, marking off/flame cutting/edge preparation
1.2	. general activities : transport of components, tools, materials ; preparation of lighting, ventilation, staging ; welding of lifting eyes
. CONNECTION	
2.1	. preparatory activities directly related to the connection : positioning, aligning, fairing, tack-welding, intermediate cleaning of welds
2.2	. support activities of general nature : shifting and positioning of welding gear, changing rods, adjust current
2.3	. the actual welding
. FINISHING	
3.1	. activities related to the connection itself : final weld inspection, (eventual) grinding of weld
3.2	. activities of general nature : removing tools, gear and aids, cleaning of the structure and work area

Table 5.3: Combinations crane capacity and structure dimensions

case	length factor		crane cap. factor	
	limited	unlimited	limited	unlimited
1	X	-	X	-
2	-	X	X	-
3	X	-	-	X
4	-	X	-	X

Table 5.4: Activities at work station 1

activity	connection type	welding process	parameters of importance
placing and ranging of webs ; tack welding	line, orthogonal	--	--
welding web/flange	line, fillet, down-hand	automatic or gravity welding	throat thickness

Table 5.5: Activities at work station 2

activity	connection type	welding process	parameters of importance
. placing/ranging plates; tack welding . welding of seams	line, in-plane line, butt, down hand	-- automatic, sumberged arc	plate thickness plate thickness
. marking/cutting circumference	--	--	panel dimensions plate thickness
. placing/ranging, tack weld of stiffeners . welding of stiffeners	line, orthogonal line, fillet, down hand	-- automatic or gravity	-- throat thickness
. placing/ranging, tack weld of webs . placing/ranging, tack weld of stiffener/web connection	line, orthogonal point, orthogonal	-- --	-- weld area stiffener-web
. welding web frames/plate . welding web/stiffener	line, fillet, down hand point, fillet, down hand	manual or gravity manual arc	throat thickness stiffener height

Table 5.6: Activities at work station 3, phase 1

activies	connection type	welding process	parameters of importance
. placing/ranging of 2x vertical and 2x horizontal panels . welding of panels	line, orhtogonal line, fillet, down hand and over head	-- manual arc inside semi/automatic arc outside	-- plate thickness
. placing/ranging of transverse/end bulkhead . welding	line, orthogonal line, fillet, downhand, overhead and vertical	-- manual arc	plate thickness bulkhead width/height throat thickness
. placing/ranging of point connect. type 1 . welding point connections type 1	point, in-plane and orthogonal point, fillet and butt, downhand and overhead	-- manual arc	-- throat thickness plate thickness
. placing/ranging point connection type 2 . welding point connection type 2	point, orthogonal point, fillet, down hand	-- manual arc	-- throat thickness
. placing/ranging point connection type 3 . welding point connection type 3	point, in-plane and orthogonal point, fillet, down hand and over head	-- manual arc	-- throat thickness
. placing/ranging point connection type 4 . welding point connection tupe 4	point, in-plane and orthogonal point, fillet, down hand and over head	-- manual arc	-- throat thickness

Table 5.7: Activities at work station 3, phase 2

activity	connection type	welding process	parameters of importance
. placing/ranging wing sections and hor. panels ; tack welding . welding	line, in-plane line, butt, down hand and overhead	-- semi/automatic arc	-- plate thickness
. placing/ranging transverse bulkheads; tack welding . welding	line, orthogonal line, fillet, downhand, overhead and vertical	-- manual arc	plate thickness, height and width of bulkhead plate thickness
. placing/ranging point connection type 5; tacking . welding point connection type 5	point, orthogonal and in-plane point, fillet, downhand and orhtogonal	-- manual arc	-- throat thickness
. placing/ranging point connection type 2; tacking . welding point connection type 2	point, orthogonal point, fillet, downhand	-- manual arc	-- throat thickness
. placing/ranging poitn connection type 4 ; tacking . welding point connection type 4	point, orthogonal point, fillet, downhand and overhead	-- manual arc	-- throat thickness

activity	connection type	welding process	parameters of importance
. placing/ranging of seams; tack weld	line in-plane	--	--
. welding of seams	line, butt, downhand and vertical	manual arc and aut. submerged arc	plate thickness
. ranging point connections type 6	point, in-plane	--	stiffener height
. welding point connections type 6	point, butt, downhand and overhead	manual arc	stiffener height

Table 5.9: Column erection, work station 4

activity	connection type	welding process	parameters of importance
. placing/ranging of seams; tack weld	line, lowest block orthog. other blocks in-plane	--	--
. welding of seams	line, lowest block fillet downhand, other blocks butt horizontal	manual arc and autom. welding(flux) for fillet welds; manual gas shielded arc, butt	throat thickness, fillet plate thickness, butt
. ranging point connections types 4/6 ; tack weld	point, in-plane and orthogonal	--	--
. welding point connections	point, fillet(4), butt(6)	manual arc	throat thickness, stiffener height

Table 5.10: Deck erection, work station 4

activity	connection type	welding process	parameters of importance
. placing/ranging seams of longit. complete circumference elements; tack weld	line, blocks above columns orthogonal, otherwise in-plane	--	--
. welding of seams	line, blocks above columns fillet overhead, otherwise butt downhand, overhead and vertical	manual/arc automatic welding for fillet, manual gas shielded arc for butts	throat thickness fillet plate thickness butts
. placing/ranging seams of transv. complete circumference elements; tack weld	line, external blocks orthogonal, otherwise in-plane	--	--
. welding of seams	line, external blocks fillet downhand, overhead and vertical; otherwise, butt, downhand, overhead and vertical	manual arc and automatic welding for fillet welds; manual gas shielded arc for butts	throat thickness fillet plate thickness butts
. placing/ranging seams of intermediate deck elements; tack weld	line, in-plane	--	--
. welding of seams	line, butt downhand and overhead	manual and automatic submerged arc	plate thickness
. ranging point connection types 4 & 6; tack weld	point, in-plane and orhtogonal	--	--
. welding point connections	point, fillet (4), butt (6)	manual arc	throat thickness stiffener height

Table 5.11 : Overview component series

structur. level	description	type	application	external geometry			internal arrangem.	remarks
				lenght	width	height		
1	wing block	compl. circum	floaters	(1)	(2)	module		
1	wing block	uncompl. circ	column/deck	(1)	(2) or ½ x module	module		
1	stand. module	compl. circ.	a. floater b. column/ deck	(1) (1)	module module	module module	10 panels 8/6 panels	
1	stand. module	uncopl. circ.	deck	(1)	(3)	module	(3)	
2	panel	1/vertical	flo/col/deck	(1)	-	module		shorter web frames
		1/horizontal	flo, possib. col/deck	(1)	-	module		
2	panel	2/horizontal	flo, possib. col/deck	(1)	(4)	-		
2	panel	3/horizontal	poss. col/deck	(1)	½ x module	-		
2	panel	4/horizontal	interm. deck	(1)	(5)	-		
2	panel	w.block bulkh	flo. evt. co/de	-	(1)	module		
2	panel	c.tank bulkh	flo. evt. co/de	-	mod.height.	module		
2	panel	w.block bulkh	evt. co/deck	-	½ x module	module		
2	panel	interm.deck	interm. deck	-	(5)	module		

Table 5.12 : Overview overhead costs

item	causative factor	
1. depreciation	capital investmant	fixed
2. maintenance&repairs	capital investment	fixed
3. insurance	capital investment	fixed
4. energy	production output	variable
5. tooling, materials	production output	variable
6. accommodation costs	area	fixed
7. administration	direct labour force	fixed

Table 5.13 : Additions above basis salary

item	calculation %
a	100
b	70
c.1	18
c.2	25
c.3	27

total, based on the parameter basis salary 240

Table 5.15 : Additions above netto times for performance data

activity	structural level	work station	addition %
rest activities	3	1	40
	2	2	45
	1	3,4	50
welding activities	3	1	35
	2	2	40
	1	3,4	40

Table 5.14 : Data on fixed yard overhead costs

item	per-centage of (1) investment/annum
1. <u>Depreciation</u>	
. buildings	2.5
. civil works	3.0
. systems	4.0
. machines	
- group 1 (investment below 10^5fl.)	10.0
- group 2 (investment above 10^5fl.)	7.0
- group 3 (numerical controlled)	15.0
- group 4 (panel line)	5.0
- group 5 (various)	5.5
. transport means	5.0
. tools	20.0
2. <u>Repairs & Maintenance</u>	6.0
3. <u>Insurance</u>	2.0

(1) : figures given are characteristic to the current practice in Dutch Marine Construction Industry

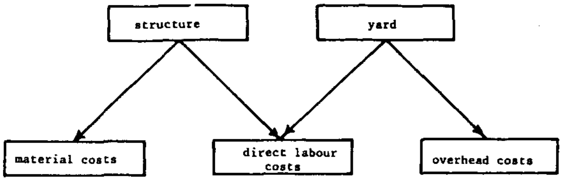


Fig.5.1 : Main factors in cost price calculation

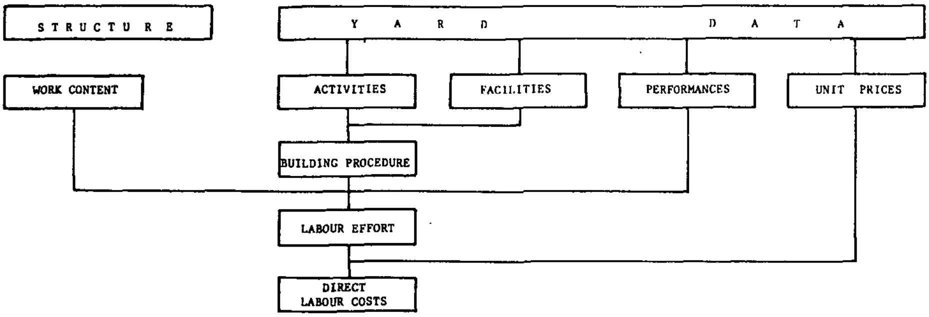


Fig.5.2 : Relation structure & yard - direct labour costs, at given production facilities

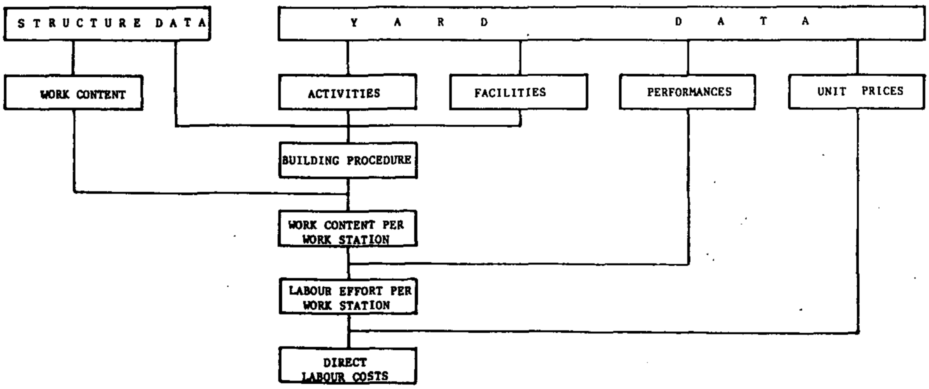


Fig.5.3 : Relation and information exchange between structure, yard and direct labour costs

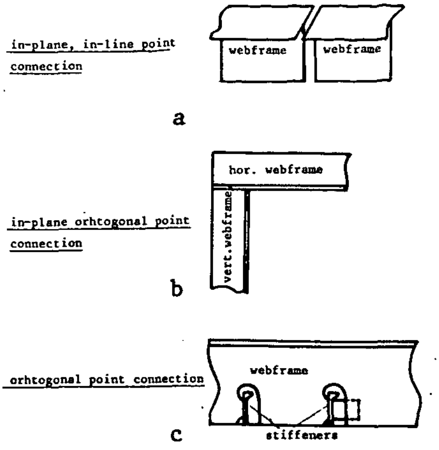


Fig.5.5 : Point connections

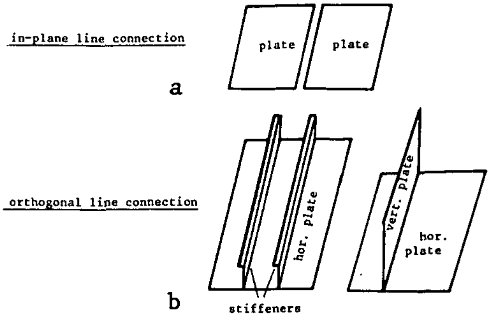


Fig.5.4 : Line connections

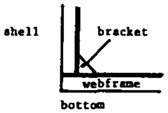


Fig.5.6.a : Point connection 1
(webframe/bracket/webframe)

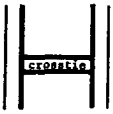


Fig.5.6.b : Point connection 2
(webframe/crosstie/webframe)

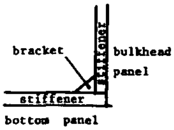


Fig.5.6.c : Point connection 3
(stiff/bracket/stiff)
or
(stiff/bracket/webframe)

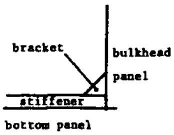


Fig.5.6.d : Point connection 4
(stiff/panel/bracket)
or
(webframe/panel/bracket)

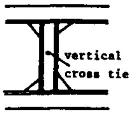


Fig.5.6.e : Point connection 5
(double bracketed webframe/
crosstie/webframe)

Fig.5.6.f : Point connection 6

Fig.5.7.a : Typical butt weld

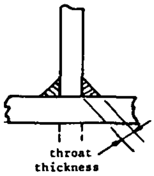
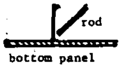
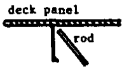


Fig.5.7.b : Typical Tee or fillet weld

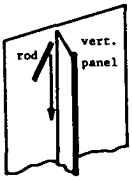
ig.5.8.a : Down - hand weld

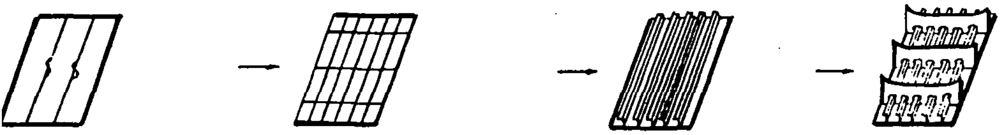


ig.5.8.b : Over - head weld



ig.5.8.c : Vertical weld





ing/joining plates

Marking/ cutting

Placing longit. members; tack welding; weld up

Placing transv. members; tack welding; weld up

Fig.5.9 : Assembly scheme for panels, work station 2

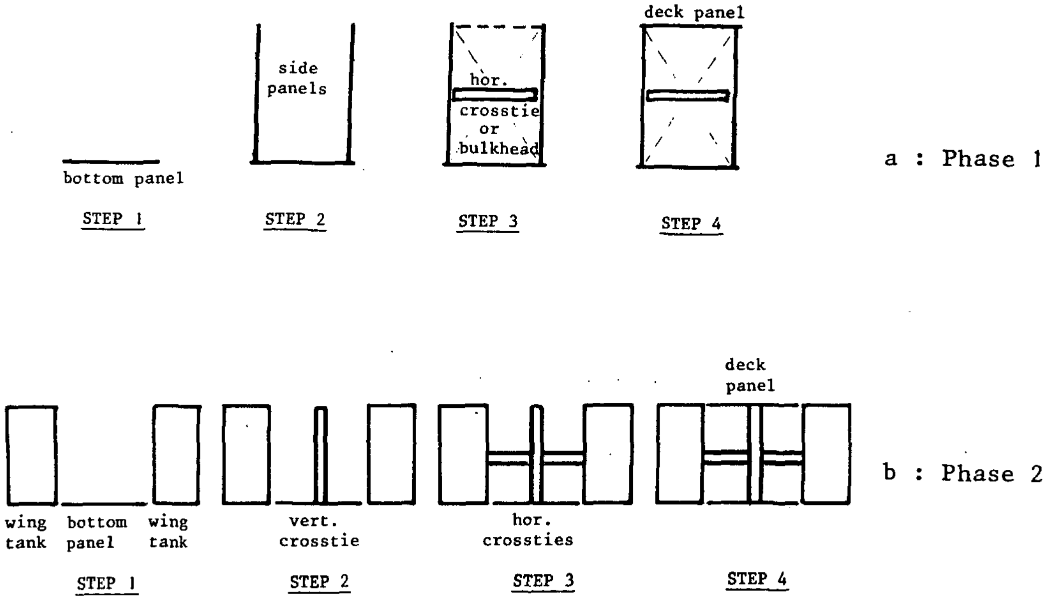


Fig.5.10 : Assembly scheme for floater elements in two phases

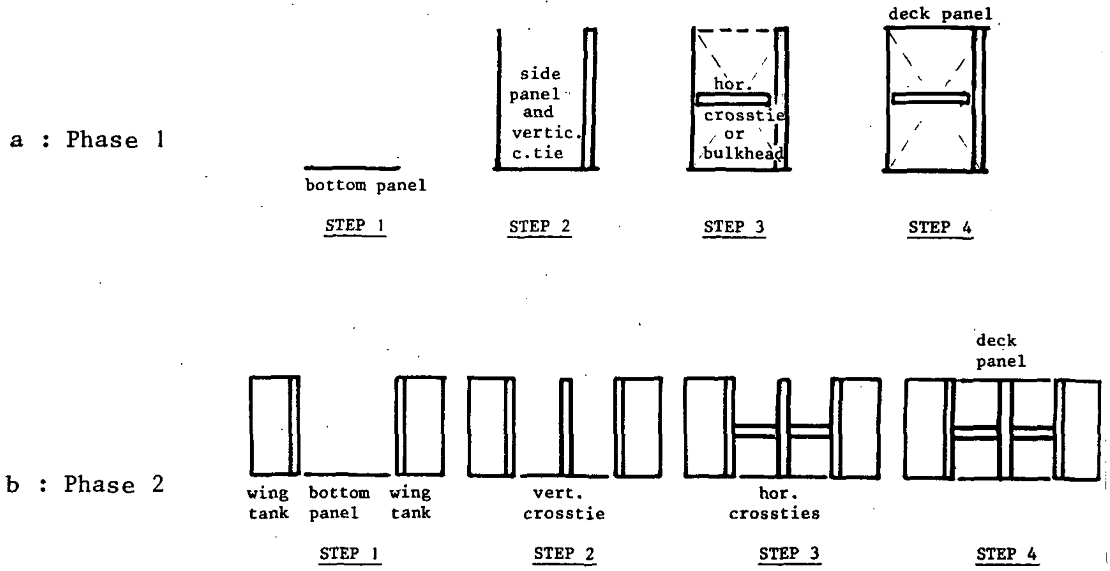
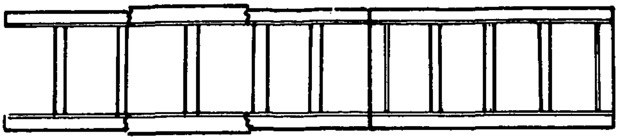


Fig.5.11 : Assembly scheme for column elements in two phases



incomplete circumference module

Fig.5.12.b

complete circumference module

Fig.5.12.b

Fig.5.12 : Arrangement of deck modules

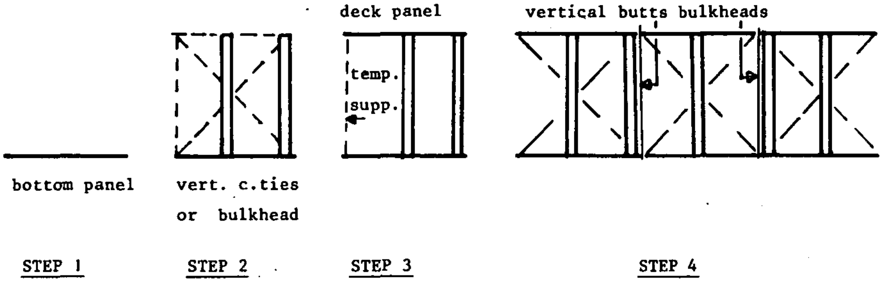


Fig.5.13 : Assembly scheme for incomplete circumference deck modules

Fig.5.14.a : Erection of floater elements

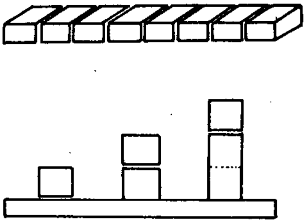


Fig.5.14.b : Erection of column elements

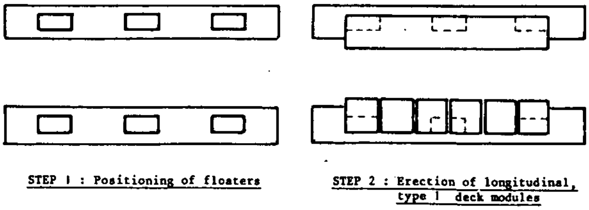
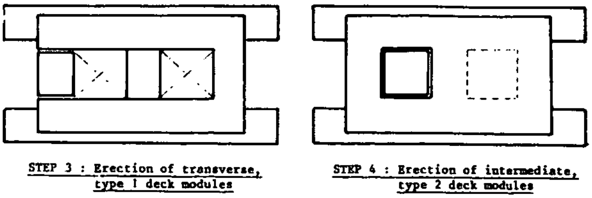


Fig.5.14.c : Erection of deck structure in four steps



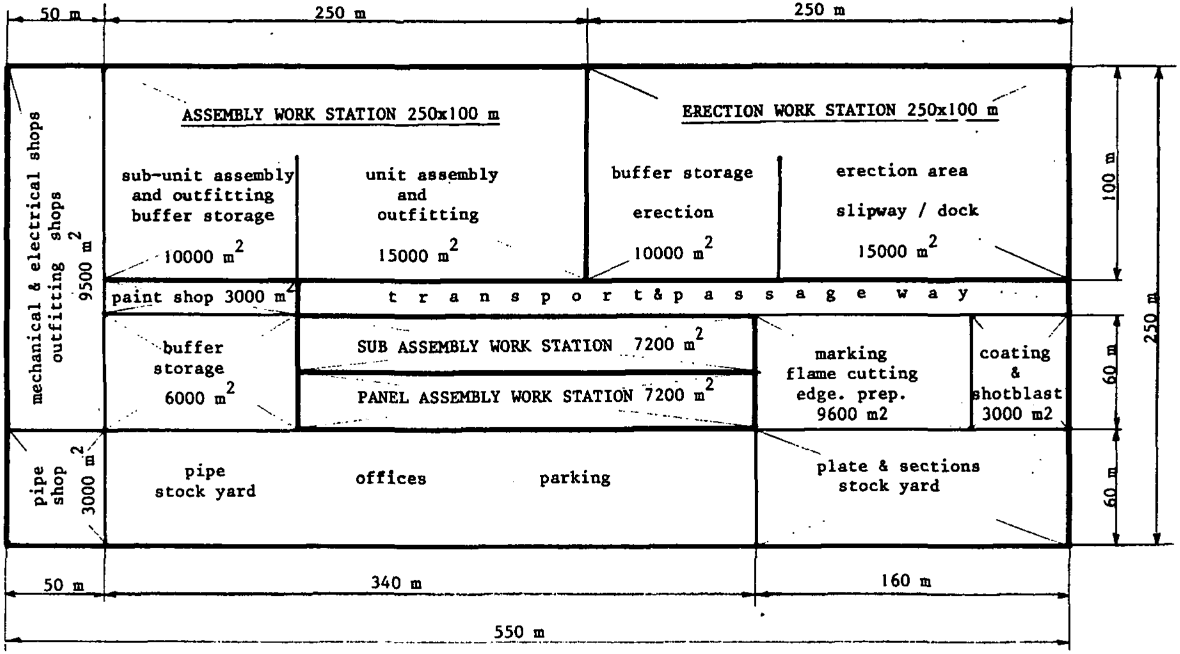


Fig.5.15 : Reference yard lay - out

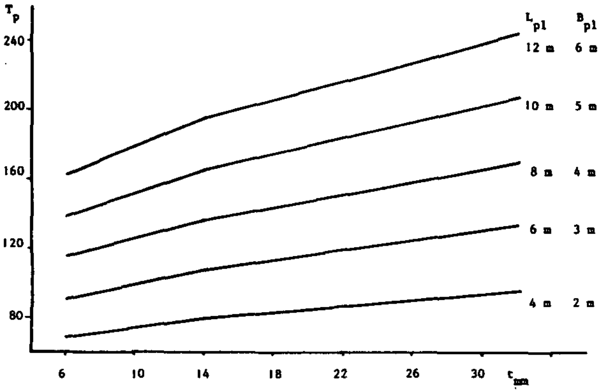


Fig.5.16.a : Panel-related rest activities

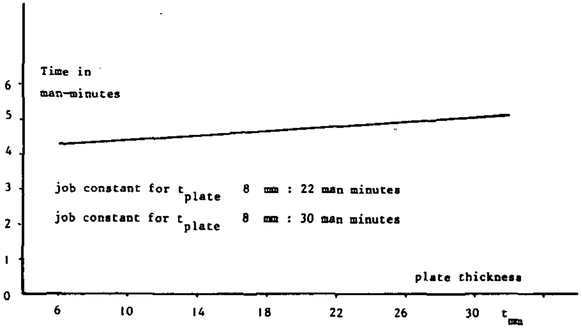


Fig.5.16.b : Plate-related rest activities, rate per/m plate length

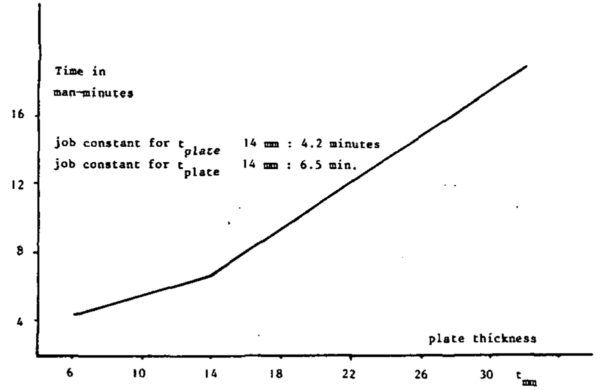


Fig.5.16.c : Seam-related rest activities

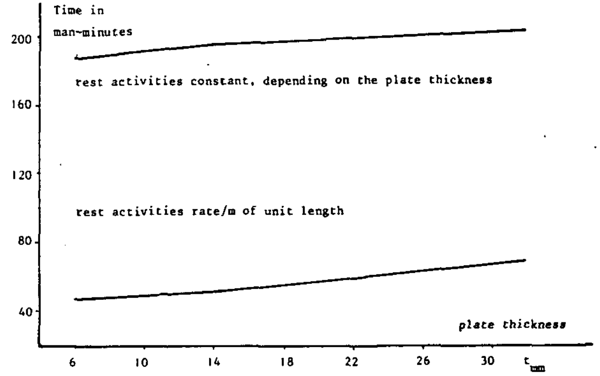


Fig.5.16.d : Rest activities, per average butt weld line connection

connection type		downhand mode	overhead mode
web/web/panel connection		 21.2 min.	 26.4 min.
loose bracket connection	0.5x0.5 m	 8.2 min	 14.6 min.
	1.0x1.0 m	14.8 min.	18.6 min.
	1.5x1.5 m	18.8 min.	28.8 min.
crosstie/web(pan) without bracket		61.0 minutes	

Fig.5.17.a : Point connections, rest activities for wing modules

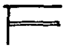
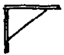
<table>
<tr><td colspan="2">connection type</td><td colspan="2">downhand mode</td><td>overhead mode</td></tr>
<tr><td colspan="2">panel/web/panel connection</td><td colspan="2"> 15.0 min.</td><td> 30.0 min.</td></tr>
<tr><td rowspan="3">loose bracket connection</td><td>0.5x0.5 m</td><td colspan="2"> 18.0 min.</td><td> 27.0 min.</td></tr>
<tr><td>1.0x1.0 m</td><td colspan="2">45.0 min.</td><td>70.0 min.</td></tr>
<tr><td>1.5x1.5 m</td><td colspan="2">70.0 min.</td><td>105.0 min.</td></tr>
<tr><td rowspan="3">cross-tie/ web(pan)</td><td colspan="4">length crosstie in m.</td></tr>
<tr><td colspan="2">5.0</td><td>7.5</td><td>10.</td></tr>
<tr><td colspan="2">158.0 min.</td><td>180.0 min.</td><td>203.0 min.</td></tr>
</table>

Fig.5.17.b : Point connections, rest activities for complete modules

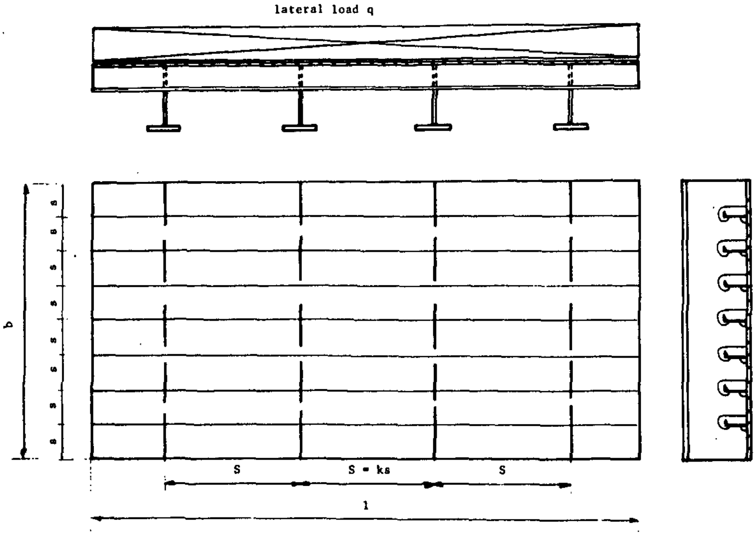


Fig.5.18.a: Flat stiffened panel under uniform lateral loading

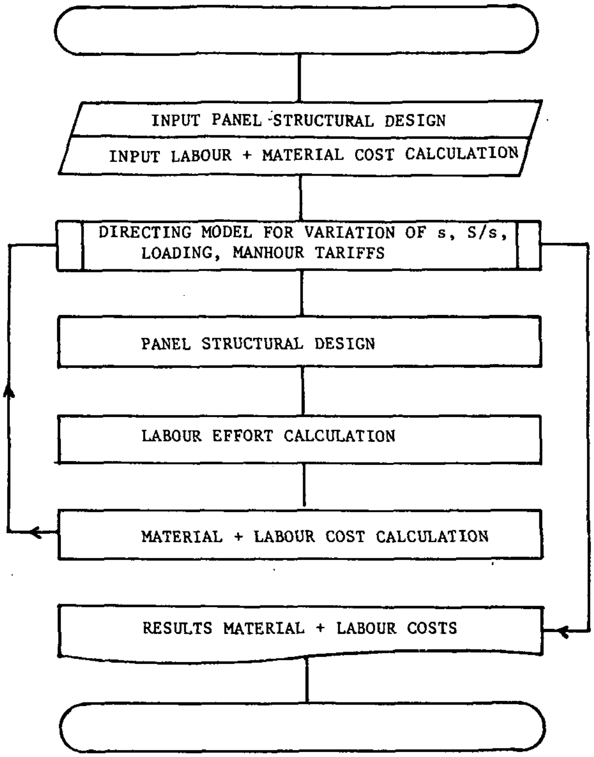


Fig.5.18.b : Flow diagram determination of structural pattern

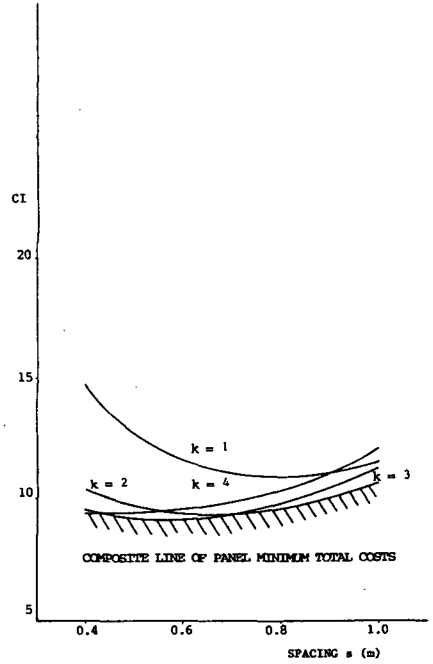
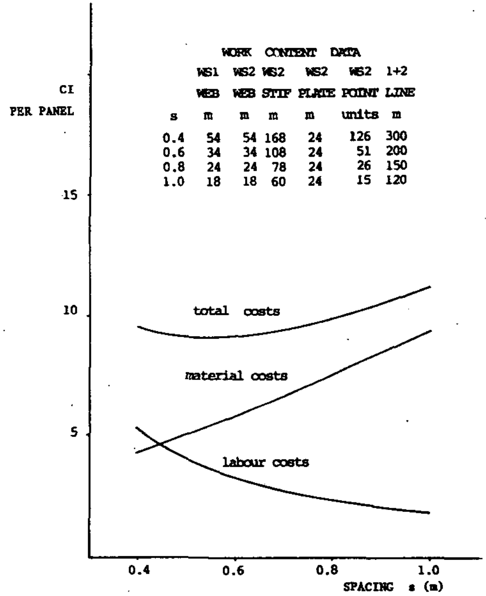


Fig.5.19: Typical panel costs, lateral pressure of 90 N/mm^2



WORK CONTENT DATA

	WS1 WEB	WS2 WEB	WS2 STIF	WS2 PLATE	WS2 POINT	1+2 LINE
s	m	m	m	m	units	m
0.4	54	54	168	24	126	300
0.6	34	34	108	24	51	200
0.8	24	24	78	24	26	150
1.0	18	18	60	24	15	120

Fig.5.20.a: Total,material and labour costs, typical results (data from Fig.5.19)

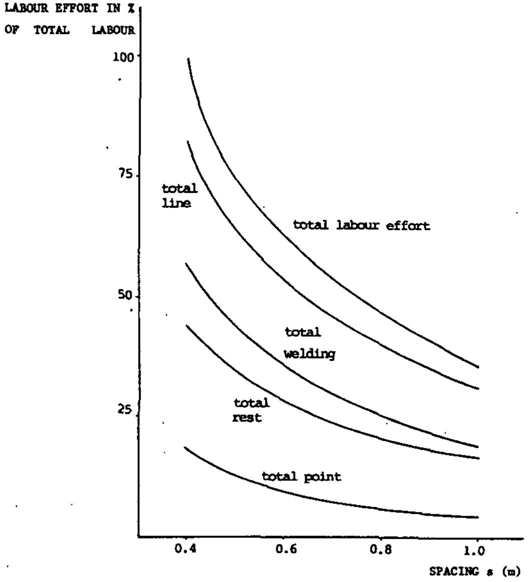


Fig.5.20.b: Breakdown of labour effort over types of connections and activities (data from Fig.5.19)

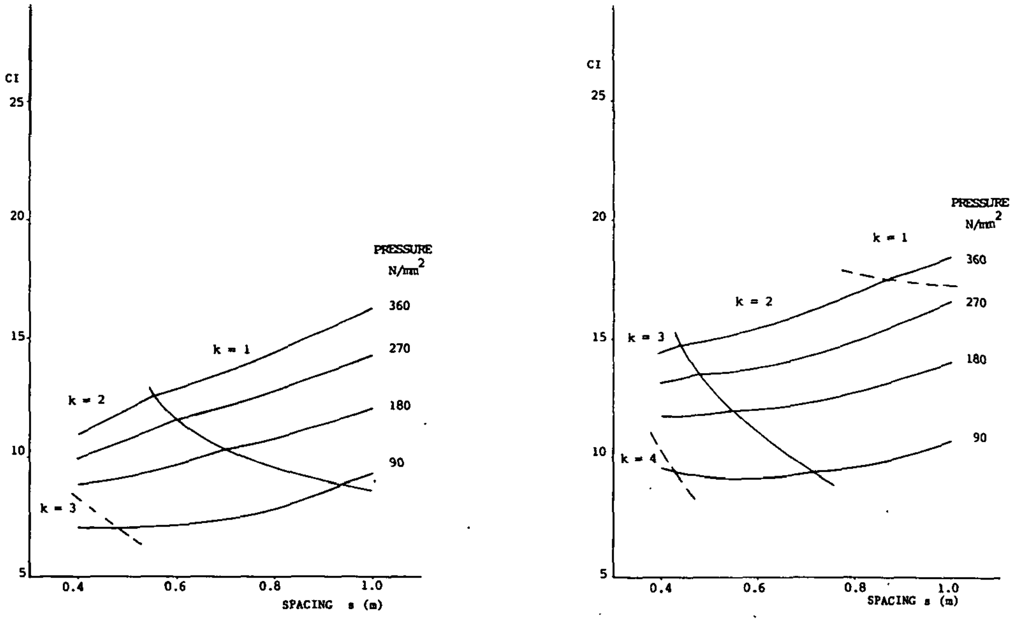


Fig.5.21.a: ratio = 0.025

Fig.5.21.b: ratio = 0.050

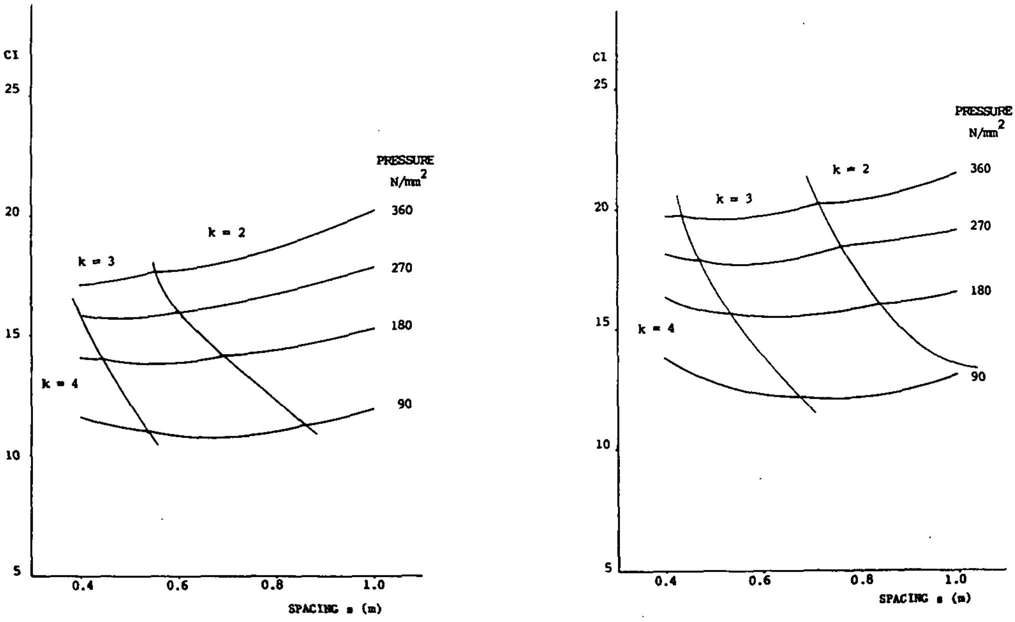


Fig.5.21.c: ratio = 0.075

Fig.5.21.d: ratio = 0.10

Fig.5.21: Cost calculation data for various ratios of labour costs/material costs, at different k-values, lateral loadings and spacings s

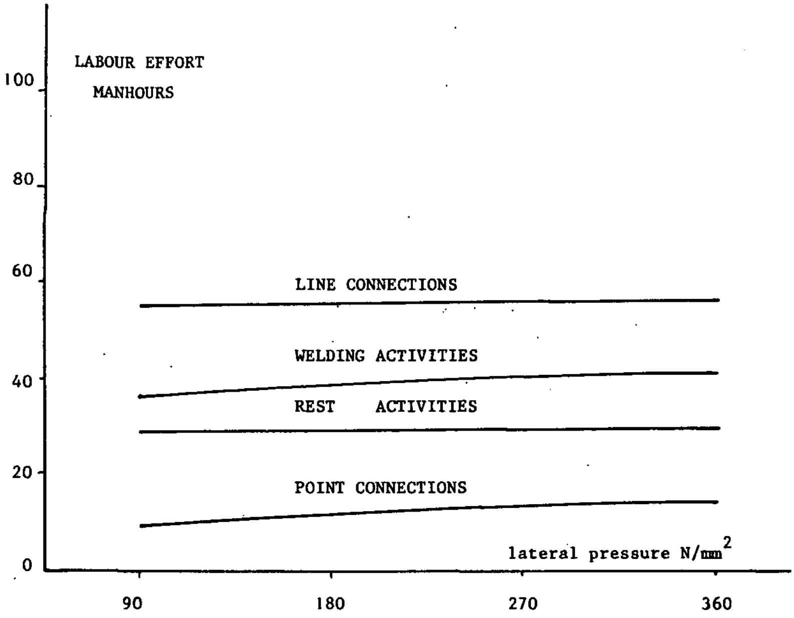


Fig.5.22 : Impact of loading on labour effort, s = 0.6 m.

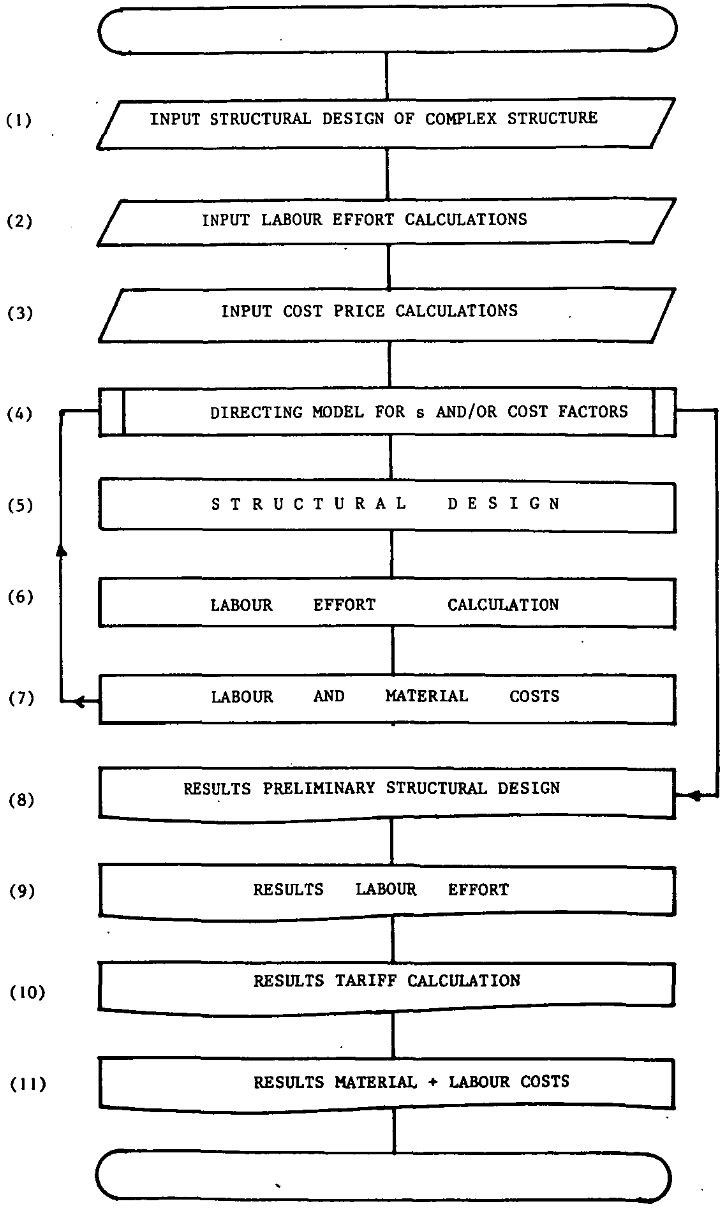


Fig.5.23.a : Flow diagram complete calculation cycle

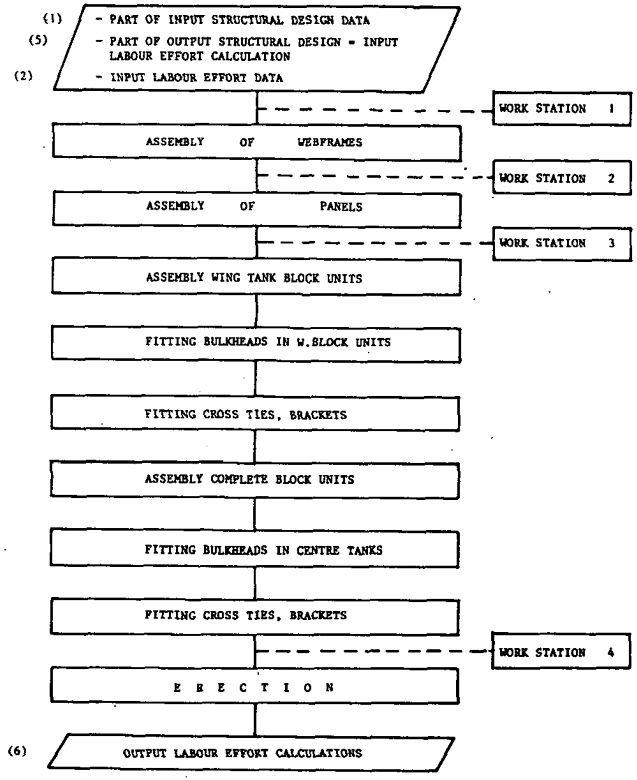


Fig.5.23.b : Flow diagram labour effort calculation; numbers in brackets refer to fig.5.23.a

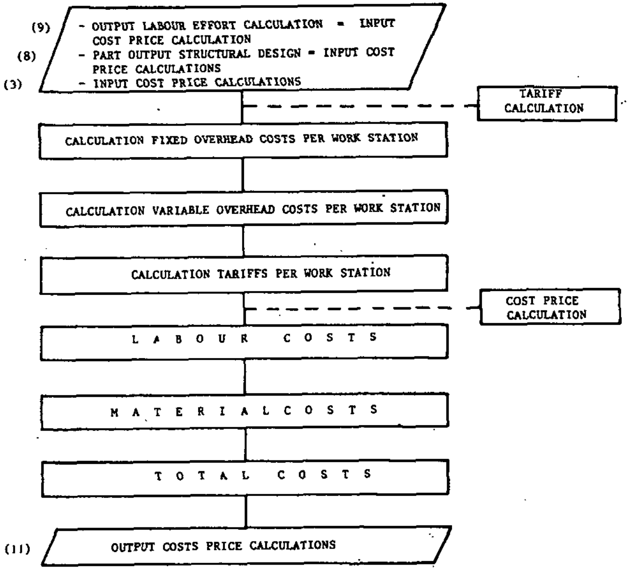


Fig.5.23.c : Flow diagram cost price calculation; numbers in brackets refer to fig.5.23.a

```
                  M       M       M    MM                            CM2   CM    CM              CM    CM   CM2

C.T.BOTTOM   12.00   6.20  0.00 16.00  4.00   3.00   9.33 52.45 30.00 25.50  1.00  5.84 65.25  0.90 24.36  9.34  2.36  4.61  8.44
C.T.DECK     12.00   6.20  0.00 15.00  4.00   3.00   9.33 47.10 30.00 25.50  1.00  5.84 59.04  0.90 22.13  8.75  2.14  4.14  8.44
W.T.BOTTOM   12.00   3.10  0.00 16.00  2.00   1.00   4.16 52.45 30.00 25.50  1.00  5.84 65.25  0.90 24.36  4.67  1.18  2.06 16.88
W.T.DECK     12.00   3.10  0.00 15.00  2.00   1.00   4.16 47.10 30.00 25.50  1.00  5.84 59.04  0.90 22.13  4.38  1.07  1.85 16.88
W.T.L.BLHD   12.00   0.00  6.20 14.26  4.00   3.00   9.33 49.07 30.00 25.50  0.00  5.84 54.80  0.90 20.62  8.32  1.63  4.31 16.88
W.T.SH.PAN   12.00   0.00  6.20 14.97  4.00   3.00   9.33 51.95 30.00 25.50  0.00  5.84 57.85  0.90 21.64  8.74  1.70  4.56 16.88
TR.BHD CT     0.00   6.20  6.20 11.00  4.00   3.00   9.33 36.37 24.00 19.50  1.00  2.44114.03  1.00 60.80  3.32  2.08  1.65  6.00
TR.BHD WT     0.00   3.10  6.20 11.00  4.00   3.00   4.16 36.37 24.00 19.50  1.00  2.44 60.09  0.90 24.98  1.66  0.47  0.74 12.00
END BHD CT    0.00   6.20  6.20 11.97  4.00   3.00   9.33 38.53 24.00 19.50  1.00  2.44120.49  1.00 62.83  3.61  2.18  1.75  2.00
END BHD WT    0.00   3.10  6.20 11.97  4.00   3.00   4.16 38.53 24.00 19.50  1.00  2.44 63.49  0.90 25.86  1.80  0.49  0.78  4.00
```

Fig.5.24.a: Results structural design for a complete floater element (panel data)

```
                                DATA MODULE SERIES
                  SERIES1    SERIES2   SE RIES3    SERIES4    SERIES5    SERIES6

SUB ASSEMB.       98.54      197.07     197.07      19.54      39.08       0.00
PANELS            50.64       33.76       8.00      16.00       0.00       0.00
WING BLOCKS       16.88        0.00       0.00       0.00       0.00       0.00
UNIT BLOCKS        8.44        0.00       0.00       0.00       0.00       0.00
WHOLE ELEMENTS     1.00        0.00       0.00       0.00       0.00       0.00
```

Fig.5.24.b: Results breakdown of floater element into structure series

```
                              STEEL WEIGHT DATA

PLATE MAT     WEB MAT     STIFF MAT     BRACK MAT     C.TIE MAT    TOT FLOATER

647.569       156.628     314.890        11.762        65.485      1196.333
```

Fig.5.24.c: Results steel weight data for a complete floater element

```
                              LABOUR EFFORT RESULTS IN MAN HOURS

              L.WELD   L.REST   P.WELD    P.REST   T.LINE   T.POINT  T.WELD   T.REST   TOTAL

W.STATION 1    374.2    520.5      0.0       0.0    894.7      0.0    374.2    520.5    894.7
W.STATION 2   1835.2   1753.5   1645.7     370.3   3588.7   2016.0   3480.8   2123.8   5604.6
W.STATION 3   1063.0    551.5   1434.0     891.2   1614.6   2325.2   2497.0   1442.7   3939.8
W.STATION 4    945.1    729.8    105.9      78.4   1674.9    184.3   1051.0    808.2   1859.2

TOT. LABOUR   4217.5   3555.3   3185.6    1339.9   7772.8   4525.5   7403.1   4895.2  12298.3
```

Fig.5.24.d: Results labour effort calculation for a complete floater element

```
                                  TARIFF CALCULATION

W.STATION  N.PRODUCT  P.PRODUCT  F.OVERHDS  V.OVERHDS   F.O.COSTS  V.O.COSTS  T.SALARY   TARIFF

           MANHOURS   MANHOURS   FLX1000    FLX1000       FL          FL         FL         FL

    1       80000.0     894.7     1930.2       2.7        24.1        3.0       42.0       69.1
    2       96000.0    5604.6     2681.5      33.6        27.9        6.0       42.0       75.9
    3      856000.0    3939.8    11368.4       5.4        13.3        1.4       42.0       56.7
    4      320000.0    1859.2    13674.3       2.8        42.7        1.5       42.0       86.2
```

Fig.5.24.e: Results tariff calculation for the reference building yard

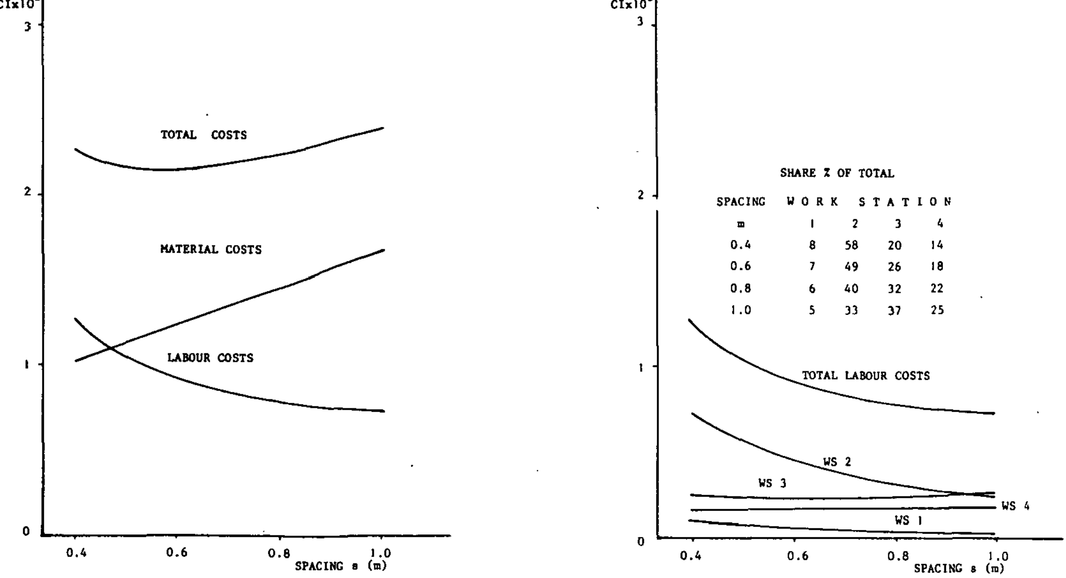
```
                               COST CALCULATION RESULTS

W.STATION   L.WELD  L.REST  P.WELD  P.REST  T.LINE T.POINT  T.WELD T.REST  LABOUR  MATER.  T.COST

    1        27.2    37.9     0.0     0.0    65.1     0.0    27.2   37.9    65.1     0.0     0.0
    2       146.7   140.2   131.5    29.6   286.8   161.1   278.2  169.8   448.0     0.0     0.0
    3        63.4    32.9    85.5    53.1    96.3   138.7   148.9   86.0   235.0     0.0     0.0
    4        85.8    66.2     9.6     7.1   152.0    16.7    95.4   73.4   168.8     0.0     0.0

  TOTAL     323.1   277.2   226.7    89.9   600.3   316.5   549.8  367.0   916.8  1229.0  2145.8
```

Fig.5.24.f: Results cost calculation for a complete floater element

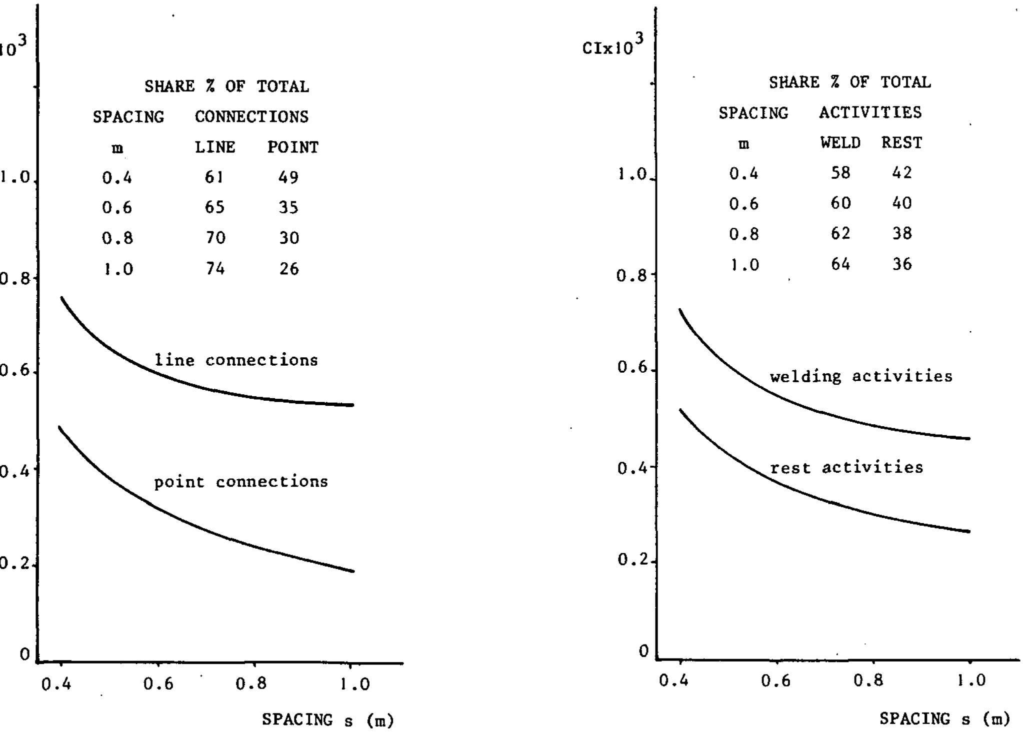


SHARE % OF TOTAL

SPACING	WORK STATION			
m	1	2	3	4
0.4	8	58	20	14
0.6	7	49	26	18
0.8	6	40	32	22
1.0	5	33	37	25

a : Total, labour and material costs

b : Breakdown of labour costs over work stations



SHARE % OF TOTAL

SPACING	CONNECTIONS	
m	LINE	POINT
0.4	61	49
0.6	65	35
0.8	70	30
1.0	74	26

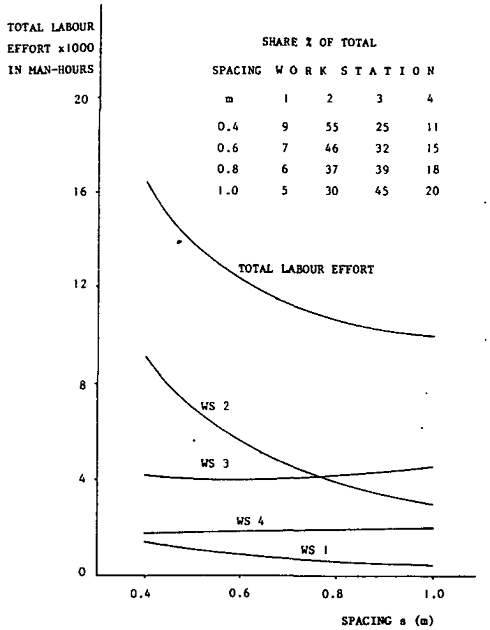
SHARE % OF TOTAL

SPACING	ACTIVITIES	
m	WELD	REST
0.4	58	42
0.6	60	40
0.8	62	38
1.0	64	36

c : Breakdown labour costs over types of connections

d : Breakdown labour costs over types of activities

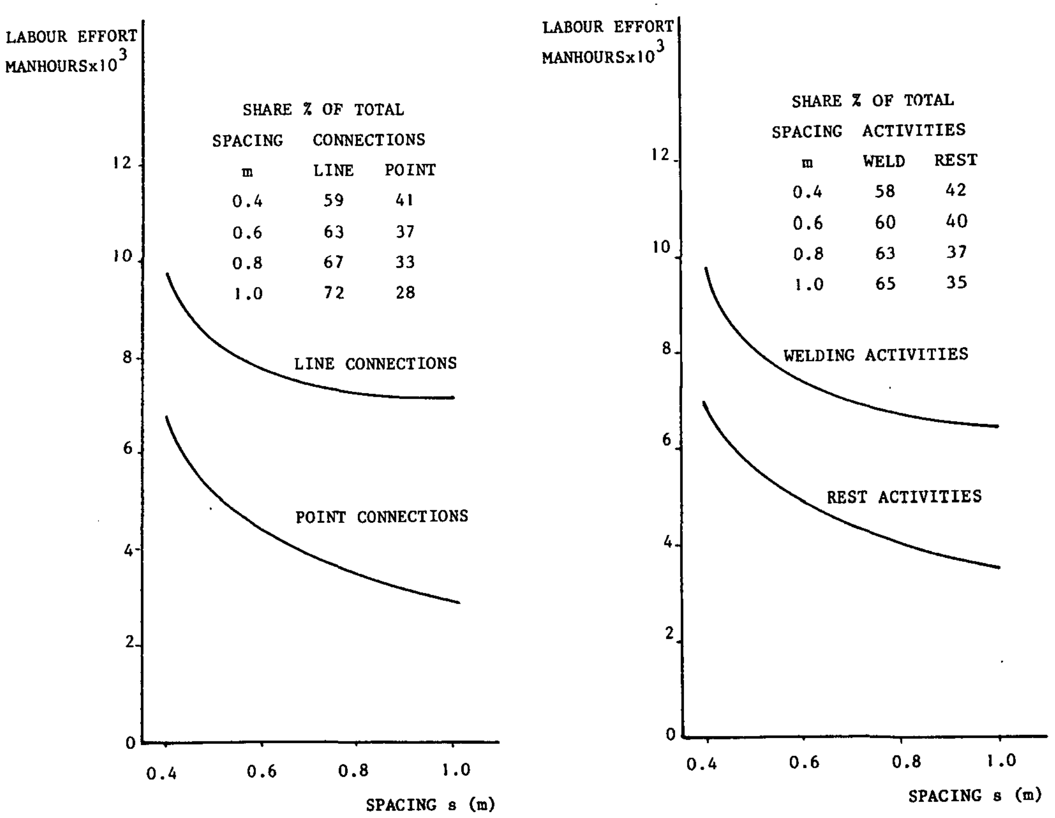
Fig.5.25: Material and labour cost results for a floater element



SHARE % OF TOTAL

SPACING	WORK STATION			
m	1	2	3	4
0.4	9	55	25	11
0.6	7	46	32	15
0.8	6	37	39	18
1.0	5	30	45	20

a : Breakdown of labour effort over work stations and data on the work content (%)



SHARE % OF TOTAL

SPACING	CONNECTIONS	
m	LINE	POINT
0.4	59	41
0.6	63	37
0.8	67	33
1.0	72	28

SHARE % OF TOTAL

SPACING	ACTIVITIES	
m	WELD	REST
0.4	58	42
0.6	60	40
0.8	63	37
1.0	65	35

b : Breakdown of labour effort over types of connections

c : Breakdown of labour effort over types of activities

Fig.5.26 : Breakdown of labour effort for a complete floater element

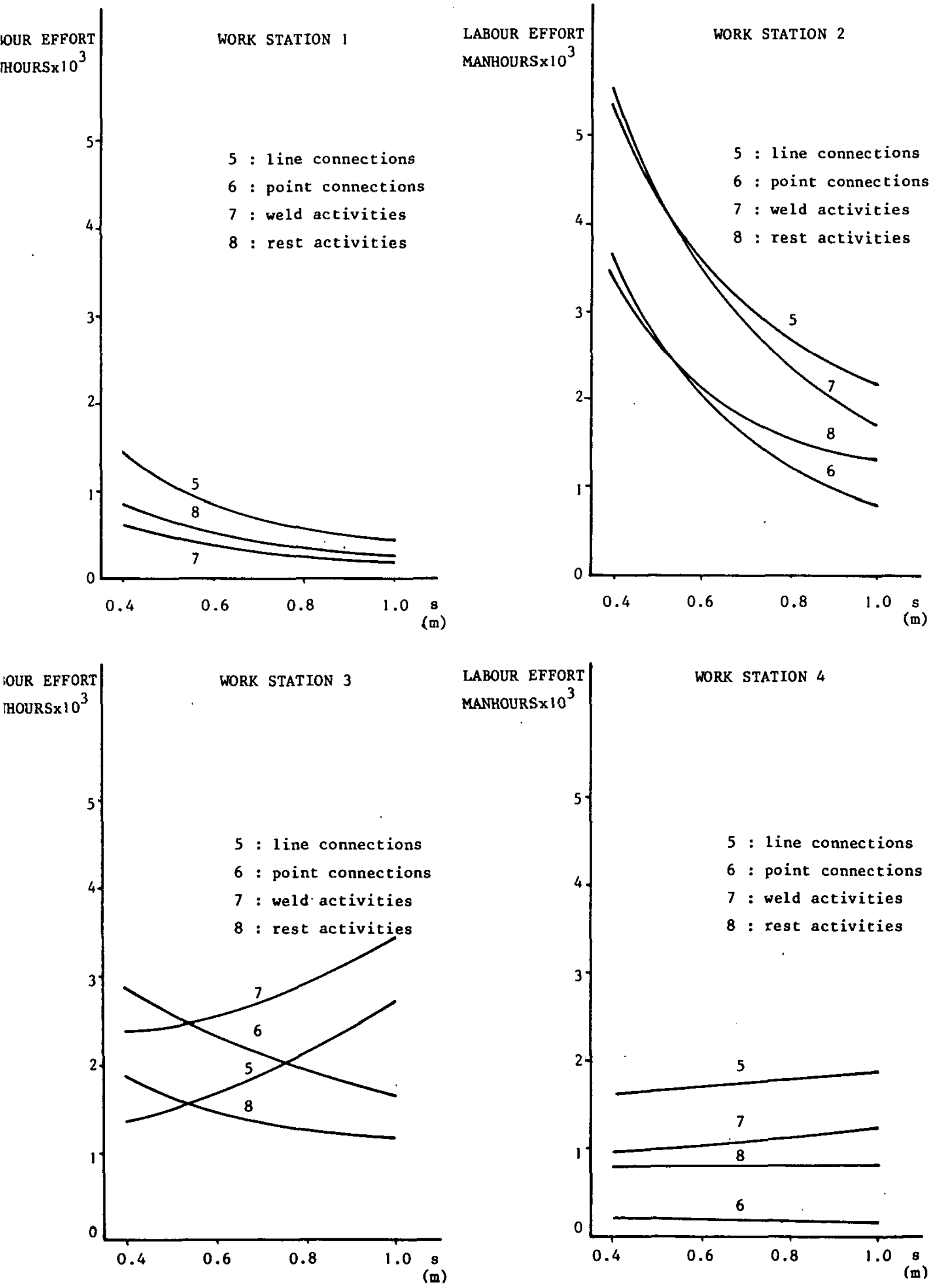


Fig.5.27 : Breakdown of labour effort, per work station, per type of connection and activity (totals)

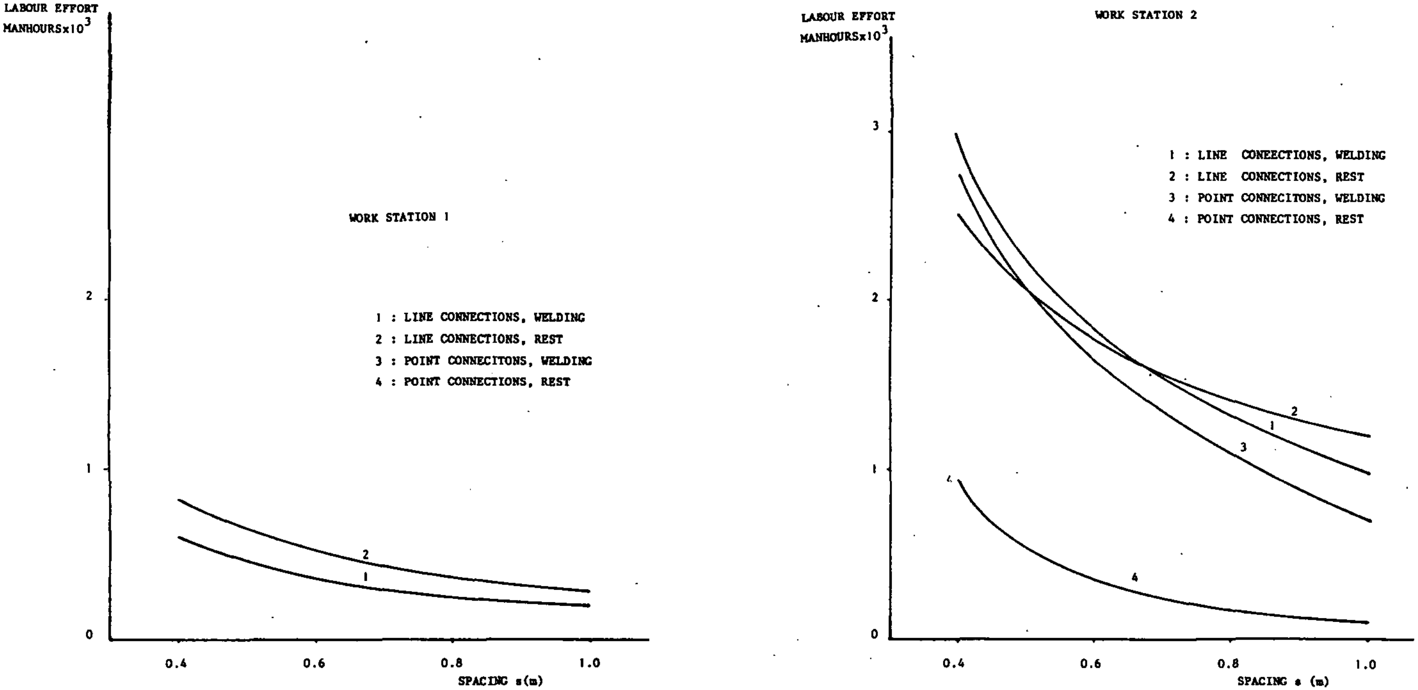


Fig.5.28 : Breakdown of labour effort, per work station, for combinations of types of activities and connections (work stations 1 and 2)

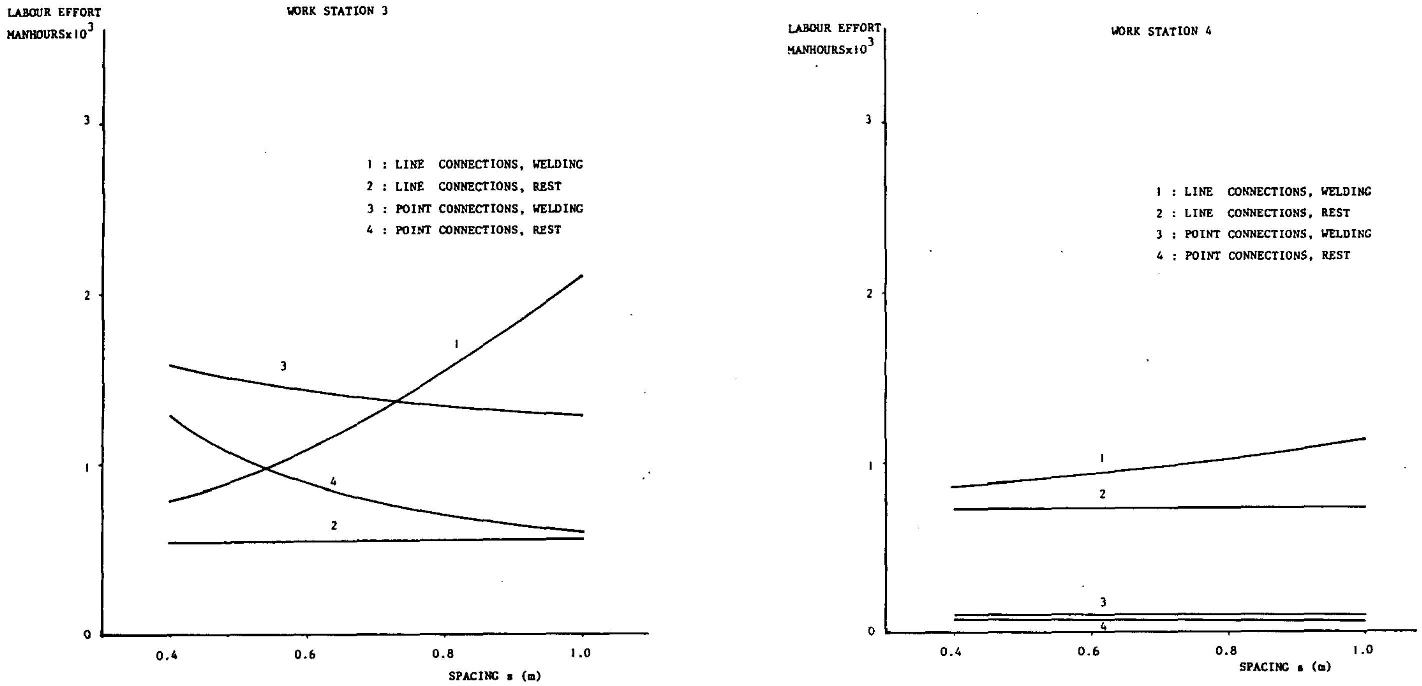


Fig.5.28 : Breakdown of labour effort, per work station, for combinations of types of activities and connections (work stations 3 and 4)

Appendix 5.1

Reference Yard Data

Item	Investments, per work-station, x 1000 Fl.			
	WS 1	WS 2	WS 3	WS 4
Buildings	4000.	4000.	40000.	0.
Civil works	2000.	2000.	20000.	30000.
Systems	1000.	1000.	6000.	18280.
Mach.group 1	1000.	1000.	2000.	4000.
Mach.group 2	1500.	500.	1000.	2000.
Mach.group 3	0.	0.	500.	0.
Mach.group 4	0.	7000.	0.	0.
Mach.group 5	2000.	2000.	15000.	15000.
Transport	1000.	1000.	15000.	30000.
Tools	100.	40.	1000.	400.
Total investments	12600.	18540.	84500.	73120.

Allocated investment for administration of labour force Fl. 5000 for every 12 men.

Labour Force Data

Work-station	Force	No. shifts	Manhours/year x man
1	50	1	1600
2	30	2	1600
3	535	1	1600
4	200	1	1600

Area and Rates Data

Work-station	Area m^2	Rates Fl/m^2
1	7200.	50.
2	7200.	50.
3	25000.	50.
4	25000.	50.

Installed Power Data

Work-station	Power KW	Load factor	Rate fl/KWhr
1	500.	0.80	0.25
2	1000.	0.60	0.25
3	2000.	0.40	0.25
4	1000.	0.40	0.25

Cost of tooling, per manhour, all work-stations = 1. Fl.

Chapter 6

The learning effect

6.1 Introduction

Learning effects associated with large numbers of products have been used as a major factor in industrial production already at the beginning of the century. The Ford Motor Company introduced line production techniques in the fabrication of their famous "T" model. These techniques and uniformity of components enabled the reduction of the amount of labour input and costs per unit of production (See Fig. 6.1 and /6.1/).

A similar effect was experienced in the aircraft industry /6.2-3/. Here too, line production techniques and uniformity of components, at all phases of production, enabled to reduce the amount of labou input and costs (Fig. 6.2).

Contemporary experiences in the shipbuilding industry at Hog Islan resulted in a certain amount of centralized pre-fabrication for a large series of standard ships, though line assembly techniques, in analogy with the former examples, were not adopted /6.4-5/.

It took almost 25 years and the cataclysm of a world war to initiate a second and more successful attempt in series production of standard ships in Great Britain and the United States /6.5-6/. Especially in the latter country, reduction of labour input, per unit of production, was achieved (Fig. 6.3-5). Such scale of standard shipbuilding (in numbers) has, since, not been matched again; however, even on a more modest scale, the learning effect was noticeable (Fig. 6.6-7) and became an important factor in shipbuilding economy /6.10-11/.

The theory of the learning effect is based on improving the efficiency, i.e. the ratio between normative and real labour input, of production operations so that direct labour input per unit declines. This effect characterizes cost reduction in a product in relation to the total quantity of units produced as well as the unit sequence number /6.1/. The curve of direct labour or costs, per unit of production, against the unit sequence number is called the "learning curve" (otherwise also the "experience curve" or the "manufacturing progress curve").

Factors of importance in the establishment of learning curves are:
- the (industrial) organization
- technology and technique
- the product
- the labour force.

The (industrial) organization controls the total of activities within the plant and concerns :
- procedures, methods and distribution of work
- materials' and supplies' flow
- appropriate lay-out of production and auxiliary facilities.

Technology and technique comprise the following :
- procedures at the various product assembly phases
- processes and handlings
- the use of mechanized/automatic facilities and the development of special-purpose tools and other aids.

The above are related to two factors of importance :
- the complexity and variation of activities in the production process
- the accuracy and tolerances at all phases of production.

The product itself is used to reduce the required labour input and costs by appropriate design and engineering, standardization (uniformity) of components and reduced complexity /6.3, 6.7-8/.

By proper management and support of the labour force in matters such as :
- equipment
- the implementation of produceability improvement
- changes in design and/or tooling

reduction of the required labour input and costs are obtained.

Increase of routine due to repetitive activities and improvement of attunement within a group of workers performing a joint task are also important factors in learning.

The quantification of the above factors and the determination of learning curves for new products are done by means of comparative studies of similar, already built products. Once the new production line is started, continuous reporting and account of labour input are used to establish the behaviour of this input with increasing volume of production and determine the learning curve (Fig. 6.2).

Learning effects in ship constructions were applied to the complete (ship) structure. In principle, this can also be applied to phases of construction prior to the assembly of the final product. The points of interest here will be the application to second and first level structures. i.e. panel and unit block series in the building of the modular semi-submersible platform.

6.2 The learning curve theorem

In principle, the learning curve theorem states that every time that the unit number of a product doubles, the required input (in manhours or other units of input measurement) declines with a fixed percentage.

This decline is attributed to either the cumulative average input of a unit out of a series of products or to the input of the N-th unit of production in a series.

6.2.1 The cumulative average learning curve

The cumulative average input is defined at the ratio of the total series' input to the number of units in the series; at doubling of production, the new cumulative average input declines by a fixed percentage of the previous cumulative average. The fixed percentage indicates the achieved learning /6.2, 6.9/.

An example is shown in Fig. 6.8 and concerns a 90% curve, i.e. by doubling production, the ratio new cumulative average/old cumulative average equals 0.9 (90%). If the numerical values of production units and cumulative average input from Fig. 6.8 are plotted on a log-log scale, a straight line is obtained (Fig.6.9).

The cumulative average learning curve is represented by the following expression /6.9/ :

$$C_N = C_1 \times N^L \quad \text{, where :} \qquad (6.1)$$

C_N : the cumulative average value (costs, etc.) of N units

C_1 : the value (theoretical or otherwise established) of the first unit.

N : the number of units produced (series size).

$$L = tg \frac{\log C_N}{\log N} \text{, the slope of the learning curve.} \qquad (6.2)$$

The determination of the slope L is done as follows :

- The ratio between the respective cumulative average values of the series 2N and N is :

$$\text{ratio} = \frac{C_{2N}}{C_N} \qquad (6.3)$$

Expression (6.3) is by definition the learning curve (learning %

- Substitution of (6.1) for both series :

$$\text{learning (\%)} = \frac{C_1(2N)^L}{C_1(N)^L} \qquad (6.4)$$

- Solving for L :

$$L = \frac{\log \text{learning}}{\log 2} \qquad (6.5)$$

For the learning curve to decline it is necessary that $L < 0$, thus learning < 100%; a learning of 100% means no learning effect.

6.2.2 The individual unit learning curve

The individual (unit) learning curve indicates the unit price or input of the N^{th} unit of production in a series and is written as:

$$C_{UN} = N \times C_N - (N-1) \times C_{N-1} \qquad (6.6)$$

Substitution of (6.1) in (6.6) :

$$C_{UN} = N \times C_1 N^L - (N-1) \times C_1(N-1)^L = C_1 N^{L+1} \left(1 - \left(1 - \frac{1}{N}\right)^{L+1}\right)$$

(6.7)

The term $(1 - \frac{1}{N})^{L+1}$, if developed in an infinite series of the type $(1 + x)^m$, yields :

$$(1 - \frac{1}{N})^{L+1} = 1 - \frac{L+1}{N} + \frac{(L+1)L}{2!N^2} - \frac{(L+1)L(L-1)}{3!N^3} \quad ..... \qquad (6.8)$$

Substitution in (6.7) :

$$C_{UN} = C_1 N^{L+1} (\frac{L+1}{N}) \times (1 - \frac{1}{2!N^2} + \frac{L(L-1)}{3!N^3} \quad .....)$$

$$= C_1 (L+1) \times N^L (1 - \frac{L}{2!N} + \frac{L(L-1)}{3!N^2} \quad ....) \qquad (6.9)$$

For large values of N, the second and following terms in the expression in brackets are negligible, so that :

$$C_{UN} = (L+1) \times C_1 N^L \qquad (6.10)$$

If plotted on log-log scale, the unit learning curve turns also to be a straight line for N-values above 10, parallel to the cumulative average curve, thus having the same slope (learning) (Fig. 6.10 and /6.9/).

The relation between C_N and C_{UN} is :

$$C_{UN} = C_N (L+1) \qquad (6.11)$$

6.2.3 Composite curve

Learning effects are not limited to direct labour input only; decline in materials' input costs due to decrease of rejects, decline in overhead costs, etc. are also possible in series production /6.2/. The corresponding (learning) curves may have differing learning figures. The behaviour of the total curve which represents the sum of all individual cost contributions does not follow the same principles outlined in par. 6.2.1 and the slope of this curve, on log-log scale, will decrease with increasing volume of production (thus, no straight line, Fig. 6.11).

Another type of composite curve concerns the case of a 100% learning component and a component less than 100% (Fig. 6.12.a). The former component is termed non-compressible element in production which involves intensive use of technology-related processes; this composite curve is known as the de-Jong curve. The latter component concerns the compressible element in production where decline in production inputs can be achieved; the corresponding composite curve on log-log scale is approached as shown in Fig. 6.12.b.

6.2.4 Summary

The use of learning curves in series fabrication is based on the experience and practice at each particular production facility. The developing of "laws" such as the cumulative average law are theories which are to be realized by management of the production facility.

The adoption of cumulative average or unit price is a matter of preference of the particular enterprise and the type of product involved. For the ship construction industry, ship unit price has been used /6.5/.

This study deals with the manufacturing of whole series which are comprised within one single steel structure. The cost-price of the steel structure equals, thus, the sum of the cost-prices of all comprised series :

$$C_T = \sum_i C_i \text{ , where :} \qquad (6.12)$$

C_T = total cost-price of the complete structure

C_i = cost-price of series i

The cost-price of any series i is :

$$C_i = C_N \times N \quad (6.13)$$

Following the above it becomes clear that the subject of interest is C_N, the cumulative average cost, and it is therefore that the cumulative average approach to learning will be used.

6.3 Determination of the learning curve

6.3.1 Learning curve in shipbuilding

Post World War II studies on learning effects in shipbuilding we directed towards the total building costs as well as individual costs components such as :

1. Engineering and development cost improvement
2. Construction labour effort improvement
3. Material cost improvement.

Suggestions on the type of learning curve and values for learnin are shown in table 6.1.

Improvement of engineering and development costs concerning ship series-building are, in general, not applicable to single produc Such improvement with respect to engineering and development cos of the semi-submersible steel structure is, in principle, possib but is considered to be of secondary importance and will not be included in present work.

Improvement of material costs on the basis of structure series within a single product is considered as a liable possibility. According to /6.12/, the improvement results from purchasing materials in larger quantities as well as reduced scrappage. The matter of material purchasing is, however, not applicable to a single product. The matter of scrappage is related to the preparation of structural components which has not been included in this study.

With respect to improvement of labour effort, no distinction was made, in general, between the various work-stations /6.12/. Some data was found in /6.5/ (Fig. 6.13), but the restricted amount of information does not provide any insight in the underlying principles for introduction of learning effects in present work. Since the existance of relevant and more reliable such information in current marine constructions is not known at the present, information available from other industries will be used as a basis for developing an approach to learning for structure series in the building of modular semi-submersible platforms. The followed procedure will be :

- In the first place, principles for learning will be established on the basis of factors related to aspects of series production.
- On the basis of these principles, quantification of learning will be anticipated for the various building phases of the modular semi-submersible platform.

6.3.2 Principles for learning

Factors of importance in learning mentioned in par. 6.1 are :

1. The (industrial) organization
2. Technology and technique
3. The product
4. The labour force.

The industrial organization concerns the reference building yard, outlined in Chapter 5, which corresponds with the current practice in matters of organization and distribution of work, materials' supplies and flow and the lay-out of facilities. The impact of the modular concept here was not included in this study.

The contribution of the product to learning has been implemented, through the modular concept, by means of uniformity in structural patterns and main dimensions of structures, at various levels of structural complexity.

The factors technology and technique have been altered to suit the modular concept in matters of building procedures by approaching platform construction in terms of assembly of structure series at various levels of complexity. Hereby, the current assembly processes and handlings as well as the use of the labour force have been maintained. The uniformity adopted in structural patterns and components' dimensions is expected to yield the effect of learning due to repeated activities involved in the assembly process. The principles on which this expectation is based are derived from an analysis of learning data related to the current practice in series and mass production (tables 6.2-4) with respect to the following :

- Phases in the building process
- The type and nature of activities
- The employed technology
- The skills of the labour force.

Following the above, the following principles are established :

- Machine-related, thus process-related labour, is less liable t learning; this concerns activities of a high degree of mechanization/automation such as item (1) from tables 6.2-3 (90 - 100% learning) and, to a lesser extent, item (1) from table 6.
- Manual labour, thus handlings-related labour, is more liable t learning, the degree of learning will increase with increasing
  - . complexity of the structure
  - . complexity of operations
  - . size of the labour force involved with a particular structur
  - . experience of the labour force.

These principles are recognized in the following elements of the modular approach to the building process from Chapter 5 :

- The structural levels
- Work-stations set-up
- Distribution of labour effort over welding and rest actitivies
- Distribution of work content over line and point connections.

The relations between the above principles and elements of the modular concept are presented in table 6.5 :

- Structural components and complexity of operations are related to structural levels and corresponding work-stations. The simplest, thus lowest-level structures are found at work-stations 1 and 2, the more complex structures at work-stations 3 and 4. Increasing complexity will also require a larger labour force at the latter work-stations, so that learning is expected to be highest at these work-stations.
- Welding is a process-related activity, thus less liable to learning. This operation is usually performed by one worker only, either manually of by controlling some semi-automatic/automatic welding device; the learning here is expected to be limited.
- Rest activities are usually performed manually and require more than one worker at the higher levels of structural complexity; the learning here is expected to be higher.
- Line connections involve two structural components; at low structural levels, use of semi/fully-automated welding devices is common practice, whereas introduction of mechanized/automatic devices for rest activities are becoming available.
- Point connections involve usually more than two structural components and the degree of mechanization/automation in the performance of rest and welding activities is reduced with respect to line connections.

  Following the above, it is expected that learning associated with point connections will be in excess of the one associated with line connections.

Summarizing, the application of learning in the building of semi-submersible platforms is based on the following principles :

1. A primary distinction between welding and rest activities; the learning related to the latter is expected to increase with increasing structural level.
2. A secondary classification between line and point connections; in general, learning associated to point connections is expected to be higher, with due consideration for the type of activity.

3. Increasing learning is expected at increasing structural complexity, at the corresponding work-station.
4. Since the subject of investigation is the learning effect fo whole structure series, the cumulative average and total inpu of labour effort and costs rather than the individual unit cost of a particular component in a series is of importance (see also par. 6.2.4).

6.3.3 Summary

The investigation of learning in shipbuilding was initiated afte World War II on the basis of standard series of ships built during that war. Main subjects of interest were total costs and the distribution of same over :
- development and engineering
- construction labour effort
- material costs.

No distinction between the various phases in the building proces was made. In view of the advances in shipbuilding technology an techniques, data on the above is obsolete and of little use in the modular concept presented here.

Principles for learning in modular building of semi-submersible platforms were derived from the current practice in series/mass production established in other industries; these principles concern :
- the use of machine and manual labour
- the complexity of the product and production operations
- the size and experience of the labour force.

The above were related to elements of the modular concept in building concerning :
- the structural level and corresponding work-station
- the type of activity, i.e. welding or rest
- the type of connection, i.e. line or point.

On basis of the above, numerical values for learning were attributed to activities concerning the various phases in the building of modular semi-submersible platforms (table 6.6); these values are judicious and may vary with respect to :

- building facilities and procedures
- technology and technique
- experience of the labour force.

6.4 Application to a floater element

6.4.1 Introduction

The principles of learning and the impact on labour effort and costs are investigated here with respect to a complex, first-level structure. The investigation addresses the following aspects :

- the reduction of labour effort and costs;
- the obtained distribution of labour effort over work-stations;
- the distinction between types of activities and connections.

For purpose of comparison, the floater element from Chapter 5, par. 7 was used, along with its structural data and the established breakdown of structure series (Chapter 5, Fig. 5.24.b); a review of these series is given in appendix 6.1.
Since one floater only is evaluated, no learning effects were applied for work-station 4.

The free variable used for the investigation is the structural pattern given by the spacing s. In principle, the value adopted by the spacing s does not affect the breakdown of the floater into first and second-level structure series since those are derived from the maximum plate length and the building procedure without limitations of transport/lifting facilities. The only exception here is the breakdown at the third level, thus webfram series, which are determined through the relation S/s = k = 3. (see Chapter 5, par. 6).

6.4.2 Results

6.4.2.1 General

Results are presented in analogy with Chapter 5, par. 5.7.2 :

- Relation structural pattern - material and labour costs and the distinction at work-station level : (Fig. 6.14)

- Relation structural pattern - labour effort, with the distinction between work-stations, types of connections and activities :(Fig.6.15-17)

For purpose of comparison, results obtained for the floater element calculated without learning (hereafter case 1), are also plotted in the above figures (dotted lines); the case with learning is referred to as case 2.

6.4.2.2 Discussion

Relation structural pattern - material and labour costs

The balance between material and labour costs is shown in Fig. 6.14.a; the total cost curve is flatter in comparison with case 1, with little sensitivity to the variation of the spacing s over the range of values 0.4 - 0.7 m. Total and labour costs are, for case 2, lower than for case 1; the reduction of costs, at various values of s, is shown in table 6.7. The reduction is largest at low s-values, decreasing gradually with the increase of s; the average reduction of labour costs is about 25%, for total costs about 10%.

The distribution of labour costs over work-stations is shown in Fig. 6.14.b; the curves for work-station 1-3 are plotted (for work station 4, no learning).

In general, the trends observed for case 1 are also here observed, showing a decrease of costs for work-stations 1 and 2 and an increase for work-station 3. Of interest is the re-distribution of costs over the work-stations (Fig. 6.14.b). In general, the share of work-station 4 increases, whereas the share of all other work-stations decreases; the latter vary slightly with the variation of s.

Relation structural pattern - labour effort

1. Work-station level (Fig. 6.15.a)

   The results follow the trend observed for case 1; the range of values for which the share of work-station 2 is largest slightly increases. The re-distribution of labour effort over work-stations shows an increase for work-station 4. The reduction of labour effort (table 6.8) shows :

   - the largest average reduction is obtained at work-station (about 35%); this is explained by the size of third-level series which exceeds, by far, all other series (Chapter 5, Fig. 5.24.b).
   - the average reduction for work-stations 2 and 3 is 28% an 34%, respectively.
   - the total reduction in labour effort amounts to about 26%.

2. The type of connection

   This is shown first in Fig. 6.16.a, at yard-level, in comparison with case 1. The reduction of labour effort is larges for point connections due to the higher learning (34%, resp. 22% for line connections; see also table 6.9); at work-station level (Fig. 6.17.a-d), the curves follow in general the trend set in case 1 (dotted curves).

3. The type of activity

   This is shown first in Fig. 6.16.b, at yard-level, in comparison with case 1. Due to higher learning, rest activities are reduced by a larger percentage (43% against 15%); the results at work-station level are also shown in Fig. 6.17, in comparison with case 1.

6.4.3 Conclusions

The calculation of labour and total costs for a first-level structure consisting of several structure series has been demonstrated.

Learning effects were applied on the basis of established principles (par. 6.3), where a distinction is made between :
- the type of connection;
- the type of activity;
- the structural complexity at the relevant work-station.

The obtained results reflect the above principles in terms of average reduction of labour effort. The re-distribution of same in terms of the share of each work-station out of the total labour effort is hereby not essentially altered.

On the basis of activity types, the reduction of labour effort associated with welding activities is larger than for rest activities; the importance of the former with respect to the total labour effort is hereby not essentially altered.

The balance between material and labour costs has changed to a degree where the sensitivity of the total cost curve to variations of the structural pattern is low over a large range of s-values.

6.5 Impact on yard set-up

6.5.1 Introduction

The effect of learning on production performance has lead to a reduction in labour effort required to accomplish a given work content; the consequences, economical and otherwise, are reflected on two levels :

1. The level of the product (structure)
2. The level of the yard set-up.

The effect on the product was discussed in par. 6.4, showing a reduction of labour input for the considered structure series and learning.

The effect on yard set-up is derived from the same reduction of labour effort; an amount of manhours becomes available of superfluous, that is :

1. Increase (steel) production output by using the available manhours for additional contracts; two alternatives are possible :
   - 1.1 Additional contracts concern structures which differ from the initial modular structure so that the initially obtained structure series cannot be implemented in the new contracts.
   - 1.2 Additional contracts concern modular structures enabling to extend the initially obtained structure series, at all work-stations.
2. The available manhours obtained through learning are rejected; this implicates a reduction of the labour force at the four work-stations.

The above are reflected in the expression :

$C_T = Y \times R = Y \times (Cov/PP + Cof/NP + W)$, where : (6.14)

C_T : cost (labour) per unit of production (module)

Y : related labour effort per module

R : hourly tariff

Cov : level of variable overhead costs

Cof : level of fixed overhead costs

PP : planned production

NP : normal production

W : hourly wages and other wages-related costs.

Using the notation 0 (zero) for the initial situation, thus without learning, and 1 (one) for the situation following a change in any of the above parameters, the following expressions are obtained :

$$Y_1 = Y_0 \times N_0^L \qquad (6.15)$$

$$C_{T1} = Y_1 \times R_0 = Y_1 \times (Cov_0/PP_0 + Cof_0/NP_0 + W_0) \qquad (6.16)$$

N_0 : the initial series size

The available becoming manhours/module are :

$$Y_0 - Y_1 = Y_0 - Y_0 \times N_0^L = Y_0 \times (1-N_0^L) \qquad (6.17)$$

Expression (6.16) reflects alternative 1.1 above; terms between brackets are unchanged, so that the initial tariff R_0 is unchanged.

Alternative 1.2 above implicates an increase of series size from N_0 to N_1, hereby altering the value of Y_1; still, terms between brackets are unchanged.

Alternative 2 above implicates a reduction of the normal production capacity from NP_0 to NP_1, hereby altering the tariff from R_0 to R_1.

In addition to the above, the introduction of the modular concep may require a change in production facilities, hereby altering the level of fixed and variable overheads; here too, a change i tariffs will occur.

The various alternatives above will be reflected in the calculation of labour costs and will indicate to what extent the gain in labour costs is maintained with respect to the gain in labour effort. The corresponding evaluation of learning effects is shifted from the level of the product (structure) to the level of the production facility.

To obtain insight in the various alternatives, a more detailed evaluation of the above matters is performed below, at work-station level; the following are assumed :

- only one series of modules is produced;
- learning is represented by one curve only;
- variable overhead costs are considered proportional with the volume of planned production, assuming a fixed value per unit of production (Cov = constant);
- wages are constant (W = constant);
- the used measure of merit is the gain, cost-wise, per unit of production, with respect to the situation without learning.

6.5.2 Yard set-up at maitained normal production capacity

6.5.2.1 Maintained size of initial series

This concerns alternative 1.1 from par. 6.5.1; the gain dC, cost-wise, per module is given by :

$$dC_T = C_{T0} - C_{T1} = Y_0 \times R_0 - Y_0 \times N_0^L \times R_0 = Y_0 \times R_0 \times (1-N_0^L) \tag{6.18}$$

The magnitude of the term between brackets depends on the values adopted by N_0 and L and will increase with increasing series size and/or learning; for any such combination, the corresponding dC-value is found on a straight line (Fig. 6.18) :

- for $N^L = 1$, thus zero learning, dC equals zero, no gain
- for $N^L = 0$, $dC_T = Y_0 \times R_0$, no labour costs (max. gain)

6.5.2.2 Increased size of initial series

This concerns alternative 1.2 from par. 6.5.1. Considering the initial level of normal production NP_0, the maximum number of modules N_1 which can be produced (i.e. normal production capacity equals planned production capacity), is obtained as follows :

$$NP_0 = Y_0 \times N_1^L \times N_1 = Y_0 \times N_1^{(1+L)} \tag{6.19}$$

Since $\frac{NP_0}{Y_0} = N_0$, then :

$$N_1 = N_0^{\frac{1}{1+L}} \tag{6.20}$$

The labour effort, per unit of the increased series, is :

$$Y_1 = Y_0 \times N_1^L \tag{6.21}$$

The gain, dC_T, per unit of the increased series, is :

$$dC_T = Y_0 \times R_0 - Y_1 \times R_0 = R_0 \times (Y_0 - Y_0 \times N_1^L) \tag{6.22}$$

Substitution of (6.20) in (6.22) yields :

$$dC_T = R_0 \times Y_0 \times (1 - N_0^{L/(1+L)}) \tag{6.23}$$

For a given combination of N_0 and L, the dC_T-value here is higher than the corresponding gain in case 1.1; the envelope curve for all dC_T-values is shown in Fig. 6.19 :

- for $N_0^L = 1$, thus zero learning, $dC_T = 0$, no gain

- for $N_0^L = 0$, $dC_T = Y_0 \times R_0$, no labour costs (max. gain)

The comparison between cases 1.1 and 1.2 from par. 6.1 is also shown in Fig. 6.19.

6.5.3 Yard set-up at reduced normal production capacity

This corresponds with alternative 2 from par. 6.5.1. If the initial level of normal production capacity is reduced from NP_0 to NP_1, while maintaining the same level of fixed overheads, tariffs will increase. The extent of this increase depends on the extent of reduction of the normal production capacity. In general, the normal production capacity varies between :

$$NP_{1(min)} \leqslant NP_1 \leqslant NP_0 \tag{6.24}$$

If for the lower boundary it is assumed that the reduction in normal production capacity is proportional with the reduction in planned production capacity, then this boundary is given by :

$$NP_1 = NP_0 \times \frac{PP_1}{PP_0} = NP_0 \times \frac{Y_0 \times N_0^{1+L}}{Y_0 \times N_0} = NP_0 \times N_0^L \tag{6.25}$$

The gain dC_T, per unit of production, at the reduced level of normal production capacity is :

$$dC_T = Y_0 \times (Cov + Cof_0/NP_0 + W) - Y_0 \times N_0^L \times (Cov + Cof_0/NP_1 + W) \tag{6.26}$$

By re-arranging, the following is obtained :

$$dC_T = Y_0 \times ((Cov + W)(1 - N_0^L) + Cof_0/NP_0 \times (1 - N_0^L \times NP_0/NP_1)) \tag{6.27}$$

For the upper boundary, thus $NP_1 = NP_0$, expression (6.27) reduces to :

$dC_T = Y_0 \times (1 - N_0^L)(Cov + Cof_0/NP_0 + W)$, which corresponds with alternative 1.1 from par. 6.5.1.

For all other values of NP_1, expression (6.27) reduces to :

$$dC_T = Y_0 \times (1 - N_0^L)(Cov + W) \qquad (6.28)$$

For any combination of N_0 and L values, the corresponding dC_T-value is found along a straight line (Fig. 6.20) :

- for $N_0^L \doteq 1$, thus zero learning, $dC_T = 0$, no gain

- for $N_0^L = 0$, $dC_T = Y_0 \times (Cov + W)$, maximum gain.

However, this latter figure is lower than the figure obtained for alternatives 1.1 and 1.2 from par. 6.5.1 (see Fig. 6.21). The gain will vanish if the other factors determining tariffs' value, Cov and W, assume low values in relation to Cof (Cov + W approx. zero).

6.5.4 Altering level of capital investment

An altering level of capital investment will change the contribution of fixed overhead costs from Cof_0 to Cof_1, hereby changing work-station tariffs. The extent of this change depends on the share of capital-related fixed overheads with respect to other contributing factors. The dominating role of capital-related contribution to tariffs is shown in table 6.10; in the further evaluation it will be assumed that fixed overheads are proportional with capital-related costs only.

6.5.4.1 Maintained normal production and series size

Assuming conditions corresponding with alternative 1.1 from par. 6.5.1, the gain per unit of production dC becomes :

$$dC_T + Y_0 \times (Cov + Cof_0/NP_0 + W) - Y_0 N_0^L \times (Cov + Cof_1/NP_0 + W)) \tag{6.29}$$

By re-arranging :

$$dC_T = Y_0 \times ((Cov + W)(1 - N_0^L) + Cof_0/NP_0 \times (1 - Cof_1/Cof_0 \times N_0^L)) \tag{6.30}$$

dC_T is plotted in Fig. 6.21 (line 1) for various values of the ratio Cof_1/Cof_0; hereby, one combination of N_0 and L-values is considered :

- for $Cof_1/Cof_0 < 1$, the gain/unit is higher then for alternativ 1.1 (par. 6.5.1), at equal N_0^L-values.

- for $Cof_1/Cof_0 = 1$, expression (6.30) reduces to expression (6.18) and the gain/unit corresponds with alternative 1.1.

- for $Cof_1/Cof_0 > 1$, the gain/unit is lower than for alternative 1.1 from par. 6.5.1.

The gain will vanish if :

$$(Cov + W)(1 - N_0^L) = Cof_0/NP_0 \times (1 - Cof_1/Cof_0 \times N_0^L) \tag{6.31}$$

or :

$$Cof_1/Cof_0 = \frac{Cov + W + Cof_0/NP_0}{Cof_0/NP_0 \times N_0^L} - \frac{Cov + W}{Cof_0/NP_0} \tag{6.32}$$

Expression (6.32) represents the allowable increases in capital investments (fixed overheads) at which the gain per unit of production in cancelled by the corresponding increase in work-statio tariffs. The allowable increase in capital investment will depend on the share of capital-related costs with respect to other components, namely Cov and W :

- for Cov + W = 0,

$$Cof_1/Cof_0 = \frac{1}{N_0^L} > 1 \text{ for } N_0^L < 1$$

This represents a building yard with low variable overheads (energy costs, etc.) and low wages; the ratio Cof_1/Cof_0 will increase, along the ordinate, with increasing value of production and/or learning.

For $N_0^L = 1$ (no learning), $Cof_1/Cof_0 = 1$

- for Cov + W > 0, expression (6.32) is re-written as follows :

$$Cof_1/Cof_0 = \frac{1}{N_0^L} + \frac{Cov + W}{Cof_0/NP_0} \times (\frac{1}{N_0^L} - 1) \qquad (6.33)$$

The first term at the right side of the expression represents the start value of the Cof_1/Cof_0 curve.

The expression between brackets of the second term is always positive for $N_0^L < 1$, so that the ratio Cof_1/Cof_0 increases in direct proportion with increasing value of (Cov + W).

For $N_0^L = 1$, $Cof_1 = Cof_0$ for all values of (Cov + W).

The above are plotted in Fig. 6.22 (full lines); the lowest, horizontal, line coincides with the situation without learning. All other lines represent allowable increases in fixed overheads, at given values of N_0^L and (Cov + W).

6.5.4.2 Maintained normal production, increased series size

The expressions from par. 6.5.4.1 are, in principle, also applicable here if the term N_0 is replaced by the term $N_0^{L/1+L}$ which accounts for the increased series. The gain, dC, is given by :

$$dC_T = Y_0 \text{ x } ((Cov + W)(1 - N_0^{L/1+L}) + \frac{Cof_0}{NP_0} \text{ x } (1 - \frac{Cof_1}{Cof_0} \text{ x } N_0^{L/1+L}) \tag{6.34}$$

dC_T is also plotted in Fig. 6.21 (line 2).

The allowable increase in fixed overheads Cof_1/Cof_0 is given by

$$\frac{Cof_1}{Cof_0} = \frac{Cov + W + Cof_0/NP_0}{N_0^{L/1+L} \text{ x } Cof_0/NP_0} - \frac{Cov + W}{Cof_0/NP_0} \tag{6.35}$$

(see Fig. 6.22, dotted lines)

The differences between full and dotted lines are derived from the N_0^L , respectively $N_0^{L/1+L}$; the latter results in higher start values for Cof_1/Cof_0 and steeper increase of that ratio, at increasing values of (Cov + W).

6.5.4.3 Reduced level of normal production

Assuming conditions corresponding with alternative 2 from par. 6.5.1, the gain dC per unit of production is :

$$dC_T = Y_0 \text{ x } (Cov + Cof_0/NP_0 + W) - Y_0 \text{ x } N_0^L \text{ x } (Cov + Cof_1/NP_1 + W) \tag{6.36}$$

Substitution of (6.25) and re-arranging :

$$dC_T = Y_0 \text{ x } ((Cov + W)(1 - N_0^L) + Cof_0/NP_0 \text{ x } (1 - Cof_1/Cof_0)) \tag{6.37}$$

- for $Cof_1/Cof_0 = 1$, expression (6.37) reduces to expression (6.28)
- for $Cof_1/Cof_0 < 1$, the gain is higher than in alternative 2 from par. 6.5.1
- for $Cof_1/Cof_0 > 1$, the gain is lower than in alternative 2 from par. 6.5.1

(see Fig. 6.21).

The gain will vanish if :

$$(Cov + W)(1 - N_0^L) + Cof_0/NP_0 \times (1 - Cof_1/Cof_0) = 0 \qquad (6.38)$$

or :

$$\frac{Cof_1}{Cof_0} = \frac{(Cov + W)(1 - N_0^L)}{Cof_0/NP_0} + 1 \qquad (6.39)$$

- For Cov + W = 0, $Cof_1/Cof_0 = 1$

- For Cov + W > 0 :

  . for $N_0^L = 1$, zero learning, $Cof_1/Cof_0 = 1$ at all values of (Cov + W)

  . for $N_0^L < 1$, Cof_1/Cof_0 increases with increasing values of (Cov + W); all lines will start at $Cof_1/Cof_0 = 1$ (Fig. 6.23).

6.5.5 Conclusions

The effect of learning is not limited to the product only and its impact has to be considered within the broader frame of yard set-up. Hereby, two aspects are involved :

1. The maintaining of normal production capacity.
2. The financial room provided by the reduced labour costs with respect to capital investments, resulting in fixed overheads above the initial level.

With respect to the first aspect, the highest gain is obtained when the existing structure series are extended by additional contracts. Reduction of normal production capacity raises tariffs, hereby reducing the gain obtained through learning with respect to the alternative of maintained normal production capacity.

The financial room obtained depends on the share of capital-related costs with respect to the contributions from variable overheads and wages. In general, the possibility to raise the contribution of the former factor increases with increasing contribution of the latter factors. The combined effect of learning and series size is of importance as well as yard possibilities to maintain the initial normal production capacity.

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Table 6.1 : Learning curves in shipbuilding

Item	curve type		Learning %
	cumul. average	individual unit	
engineering and development	ref. 6.11	--	51 - 52.5
	ref. 6.12	--	52.5
construct. labour effort	---	ref. 6.11	90
	ref. 6.12	--	94.5
material	ref. 6.11	--	97.0
	---	ref. 6.12	95.0

Table 6.2 : Learning associated with the building process (ref.6.7)

Item	Learning %
1. fabrication of parts	90 - 95
2. sub-assembly/assembly	80 - 85
3. final assembly(erection)	75

Table 6.3 : Learning associated with the type and nature of activites (ref.6.8)

Item	Learning %
1. machine-related labour	86
2. manual labour	74
3. experianced labour force	75
4. un-experienced labour force	80

Table 6.4 : Learning associated with technology and labour force (ref.6.7)

Item	Learning %
1. machine-intensive labour	95 - 100
2. simple manual labour for one worker	85 - 95
3. complex manual labour for one worker	80 - 85
4. very complex labour by a group of workers	75 - 80

Table 6.5 : Relations between learning principles and elements in the building process of modular structures

Principles / Elements	machine, thus process-bounded labour	manual, thus handlings-bounded labour	complexity of structure	complexity of operations	size of the labour force
strucural levels			X	X	
work stations			X	X	X
welding activities	X				X
rest activities		X			X
line connections	X				
point connections		X			

Table 6.6 : Learning figures for the assembly of complex structures

work station	line connections		point connections	
	welding	rest	welding	rest
1	0.95	0.85	---	---
2	0.95	0.85	0.90	0.80
3-w.blocks 3-fl.blocks	0.90 0.90	0.80 0.80	0.90 0.90	0.75 0.75
4	0.90	0.80	0.90	0.75

Table 6.7 : Reduction of labour and total costs (%)

ITEM	SPACING s(m)			
	0.4	0.6	0.8	1.0
TOTAL COSTS	15	11	8	7
LABOUR COSTS	28	25	24	23

Table 6.8 : Reduction of labour effort, at work station level

WORK STATION	SPACING s(m)			
	0.4	0.6	0.8	1.0
1	38	36	34	33
2	29	28	28	28
3	38	35	33	31
4	--	--	--	--
TOTAL	29	27	25	24

Table 6.9 : Reduction of labour effort, per type of connection and activity (%)

ITEM	SPACING s(m)			
	0.4	0.6	0.8	1.0
LINE	23	22	21	21
POINT	36	34	33	32
WELDING	15	15	16	16
REST	47	44	41	40

Table 6.10 : Breakdown of fixed overhead components

work station	contribution of causative factors (%)		
	cap.investmnt	acc. costs	adm.lab.force
1	81.2	18.6	0.2
2	86.5	13.4	0.1
3	88.8	11.0	0.2
4	90.8	9.1	0.1

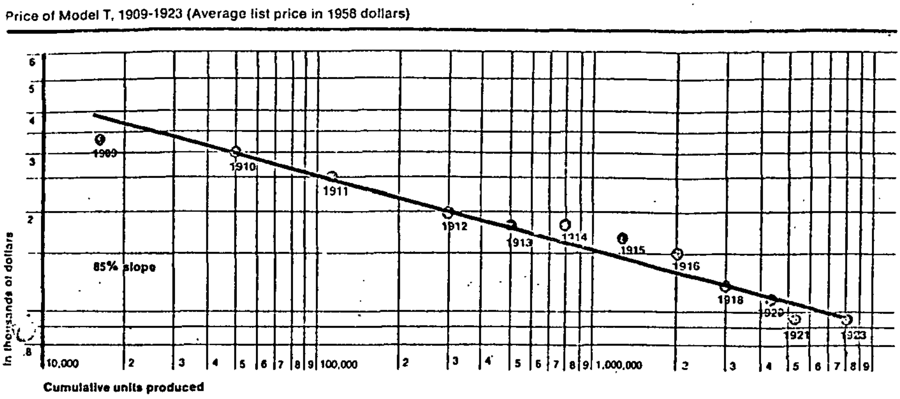


Fig.6.1 : Learning curve for "T" Ford car model 1909 - 1923 (ref.6.1)

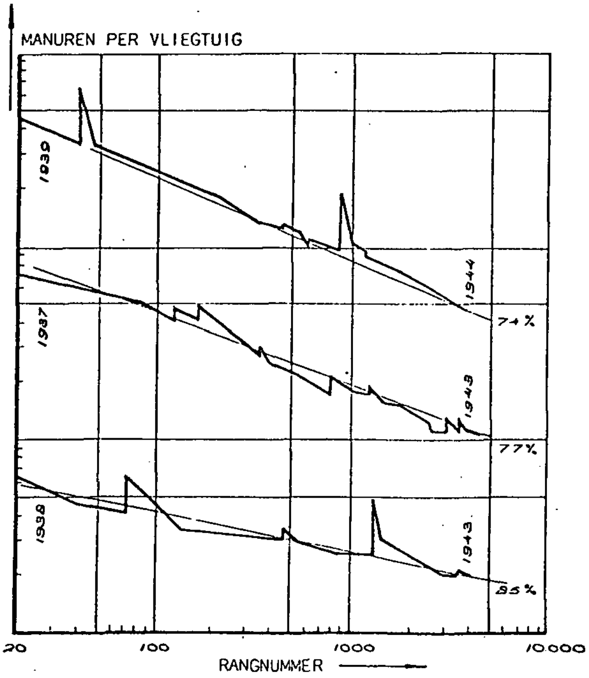
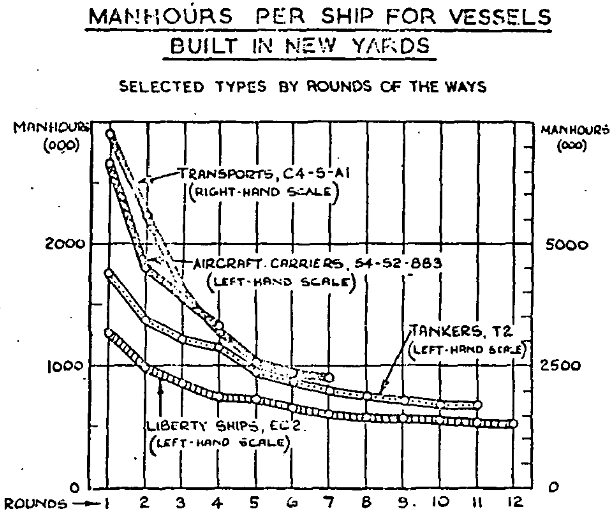


Fig.6.2 : Learning curve in aeroplane industry (ref.6.3)



FROM: "SHIPS FOR VICTORY" BY F.C.LANE,
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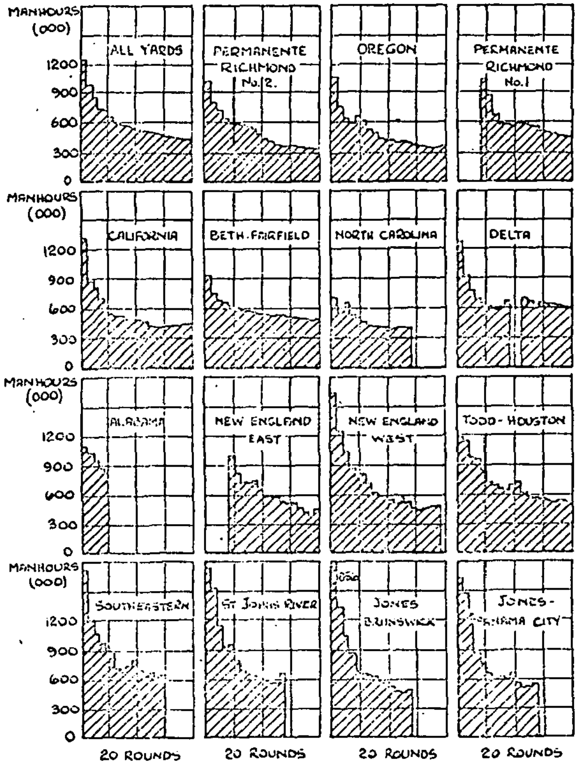
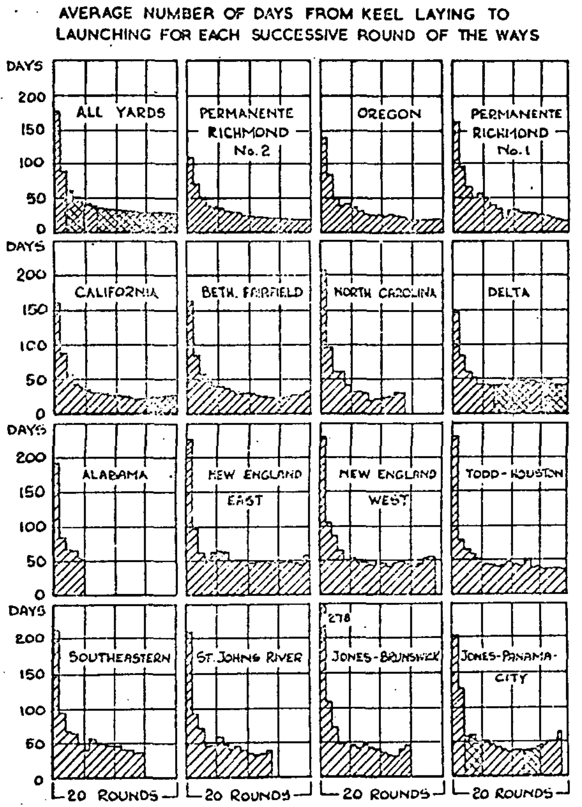
Fig.6.3 : Learning curves for standard shipbuilding, World War II (ref.6.6)



FROM: "SHIPS FOR VICTORY" BY F.C.LANE,
JOHNS HOPKINS PRESS, 1951.

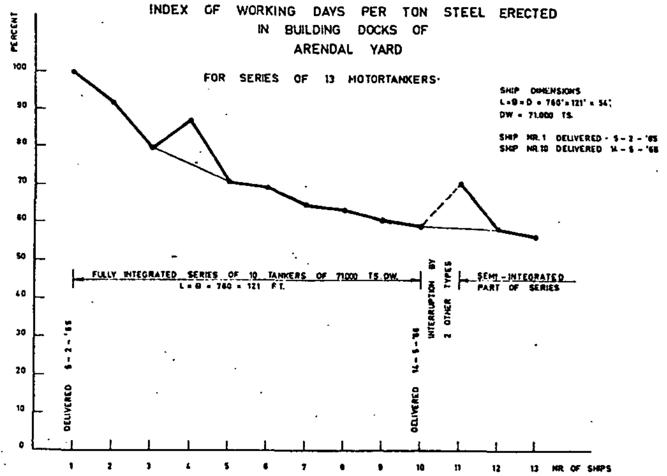
Fig.6.4 : Learning effects in "Liberty" shipbuilding, manhours (ref..6.)



AVERAGE NUMBER OF DAYS FROM KEEL LAYING TO LAUNCHING FOR EACH SUCCESSIVE ROUND OF THE WAYS

DARKER BARS INDICATE INCLUSION OF LIBERTY TANKERS OR OTHER MODIFIED LIBERTY DESIGNS. AVERAGES PER ROUND FOR FIRST TWENTY ROUNDS. FROM: "SHIPS FOR VICTORY" BY F.C.LANE, JOHNS HOPKINS PRESS, 1951.

Fig.6.5: Learning effects in "Liberty" shipbuilding, numbers of days



INDEX OF WORKING DAYS PER TON STEEL ERECTED IN BUILDING DOCKS OF ARENDAL YARD

FOR SERIES OF 13 MOTORTANKERS·

Fig.6.7: Learning curves, post-war standard shipbuilding

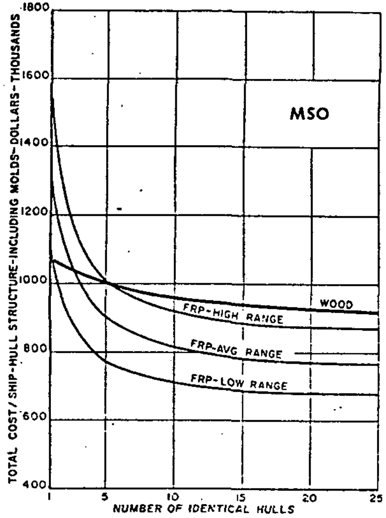


Fig.6.6: Learning curve in post-war standard shipbuilding (Ref.6.10)

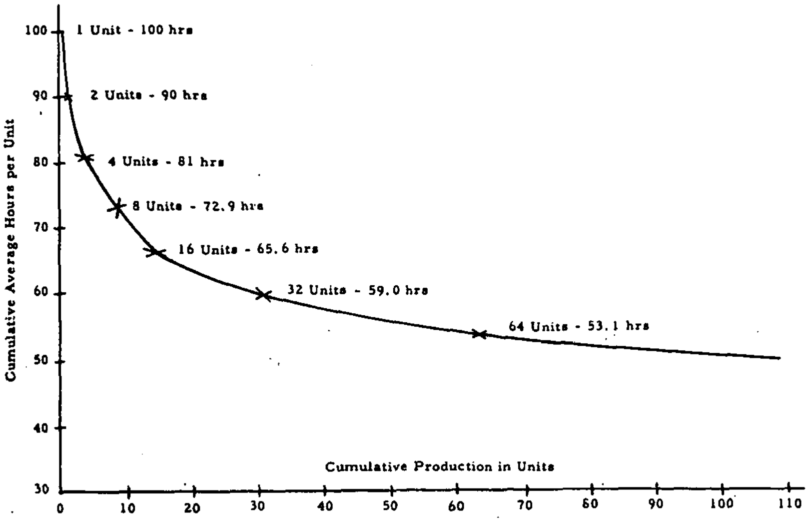


Fig.6.8 : 90 % learning curve on linear scale

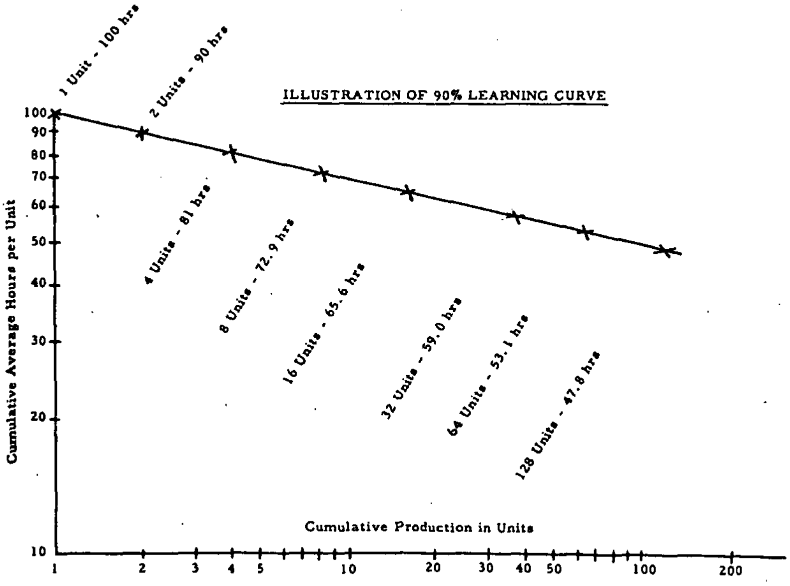


Fig.6.9 : 90 % learning curve on log-log scale

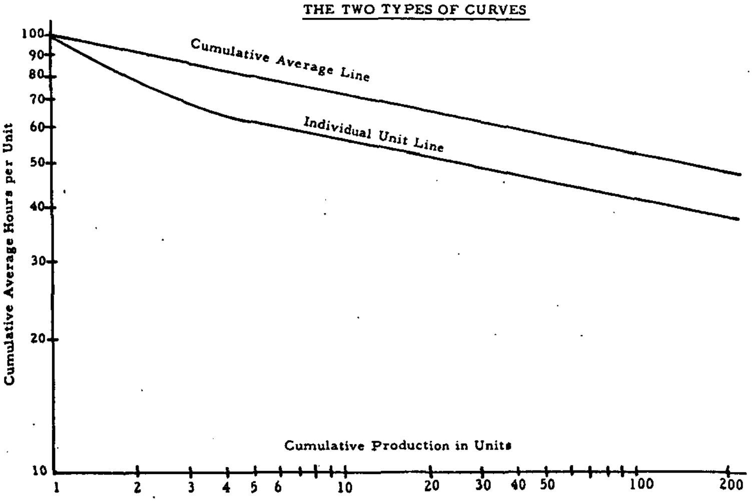
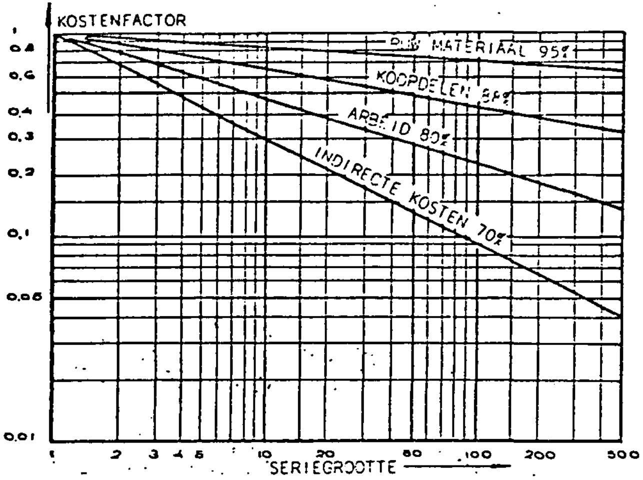
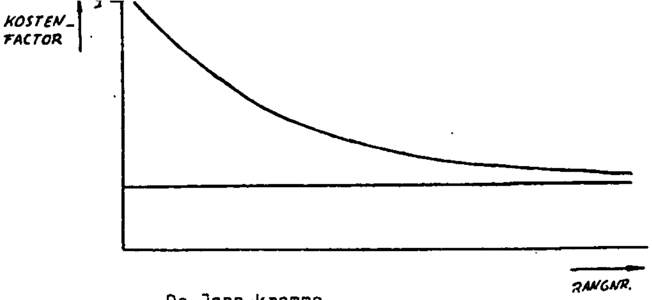


Fig.6.10 : Individual unit and cumulative average types of learning curves



Wright-afloopercentages van de kostenelementen

Fig.6.11 : Composite curve with learning components



De Jong-kromme

Fig.6.12.a : Composite curve with a 100 % learning component, linear scale

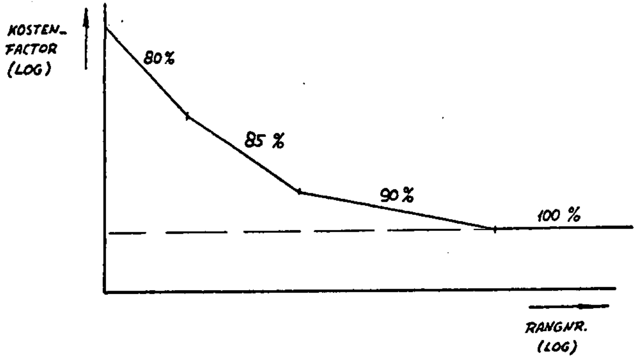


Fig.6.12.b : Composite curve with 100 % learning component, log-log scale

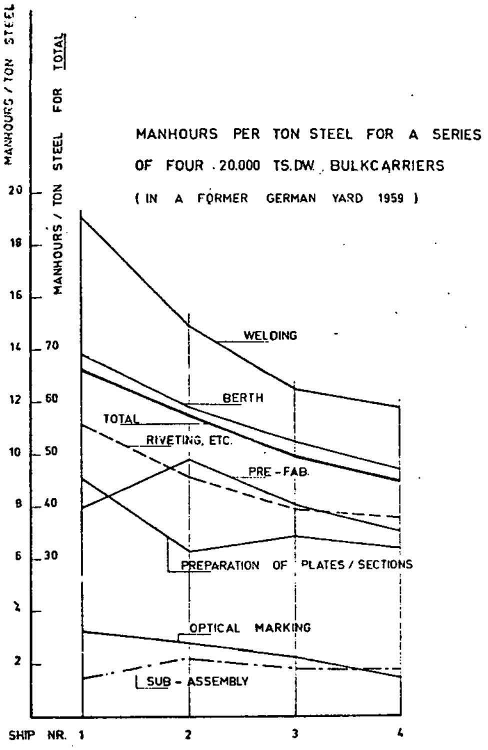


Fig.6.13 : Breakdown of labour effort over work stations and activites (Ref.6.5)

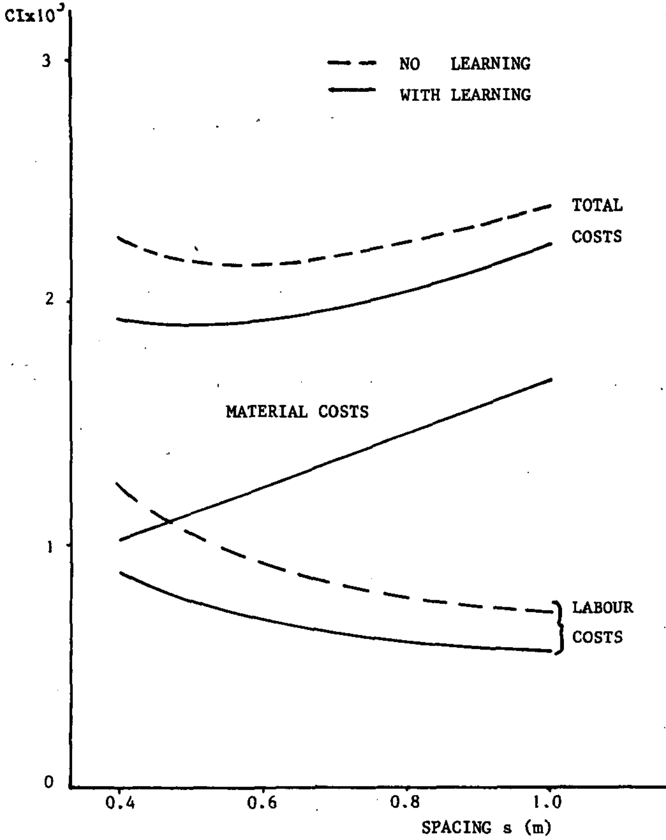
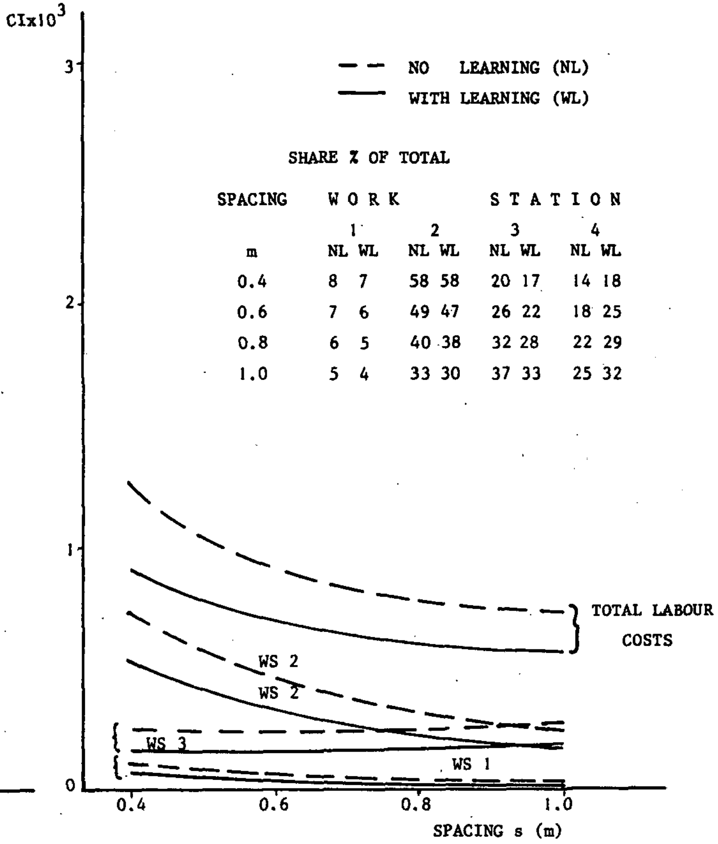


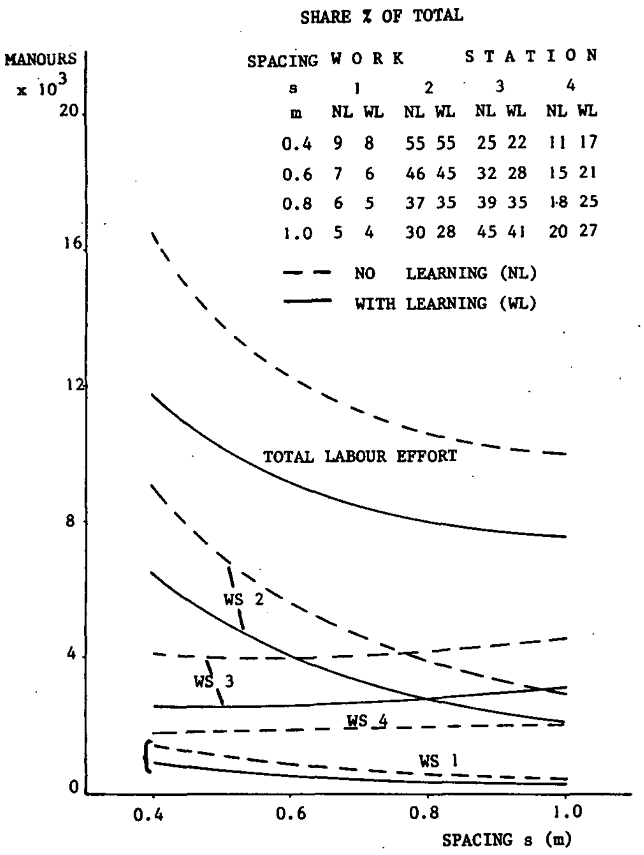
Fig.6.14.a: Material, labour and total costs for a floater element, with and without learning



SHARE % OF TOTAL

SPACING	WORK				STATION			
	1		2		3		4	
m	NL	WL	NL	WL	NL	WL	NL	WL
0.4	8	7	58	58	20	17	14	18
0.6	7	6	49	47	26	22	18	25
0.8	6	5	40	38	32	28	22	29
1.0	5	4	33	30	37	33	25	32

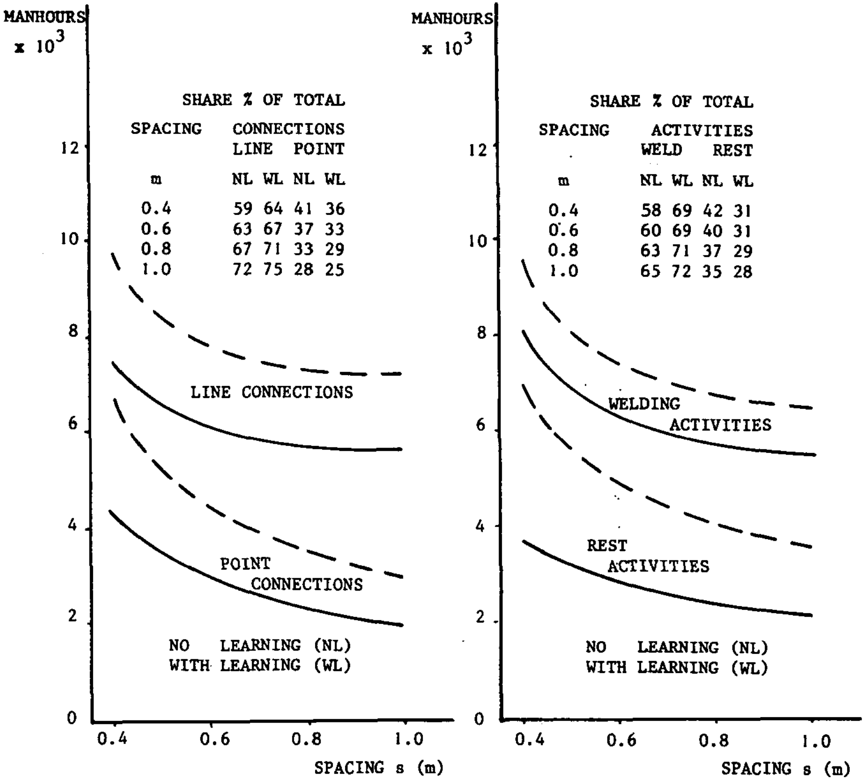
Fig.6.14.b: Distribution of labour costs over work stations, with and without learning



SHARE % OF TOTAL

SPACING	WORK				STATION			
s	1		2		3		4	
m	NL	WL	NL	WL	NL	WL	NL	WL
0.4	9	8	55	55	25	22	11	17
0.6	7	6	46	45	32	28	15	21
0.8	6	5	37	35	39	35	18	25
1.0	5	4	30	28	45	41	20	27

Fig.6.15.a: Distribution of labour effort over work stations



SHARE % OF TOTAL

SPACING	CONNECTIONS			
	LINE		POINT	
m	NL	WL	NL	WL
0.4	59	64	41	36
0.6	63	67	37	33
0.8	67	71	33	29
1.0	72	75	28	25

SHARE % OF TOTAL

SPACING	ACTIVITIES			
	WELD		REST	
m	NL	WL	NL	WL
0.4	58	69	42	31
0.6	60	69	40	31
0.8	63	71	37	29
1.0	65	72	35	28

a : connections

b : activities

Fig.6.16: Distribution of labour effort over types of connections and activities

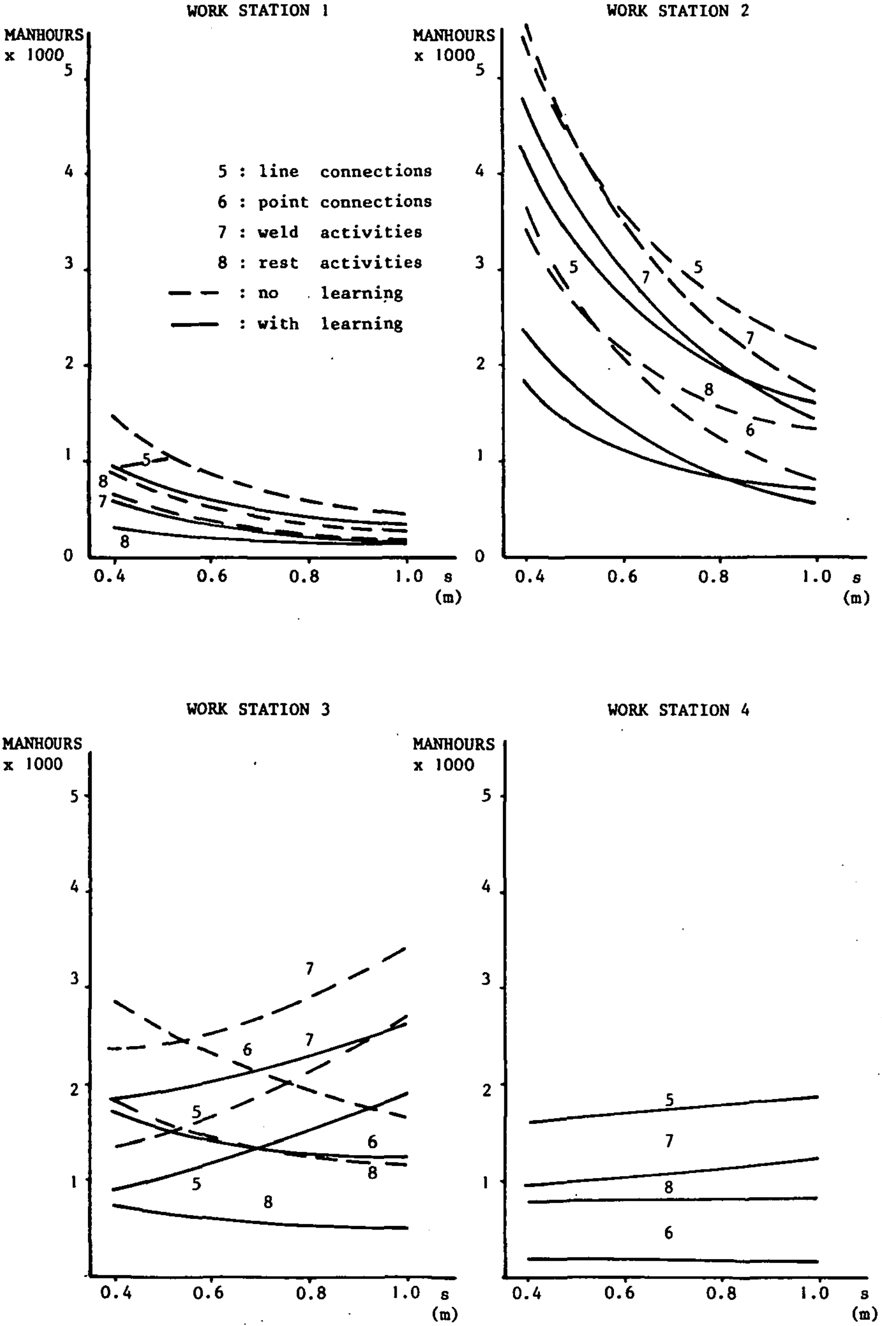


Fig.6.17: Distribution of labour effort, at work station level, over types of connections and activities

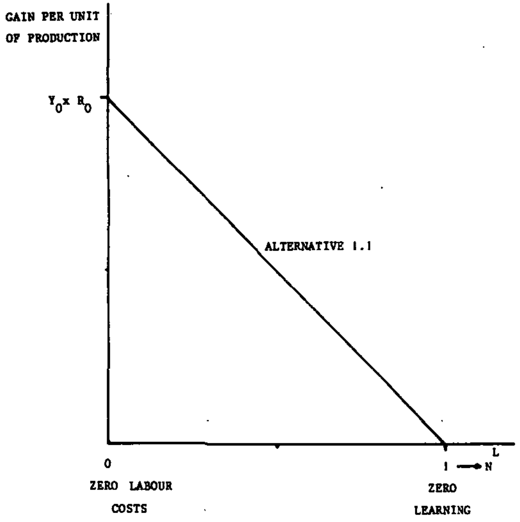


Fig.6.18: Gain per unit of production depending on learning and series size, alternat. 1.1 (maintained normal production capacity)

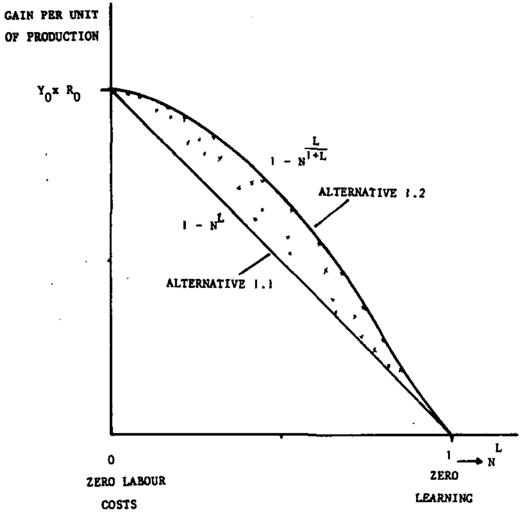


Fig.6.19: Gain per unit of production depending on learning and series size, alternat. 1.2 (maintained normal production capacity)

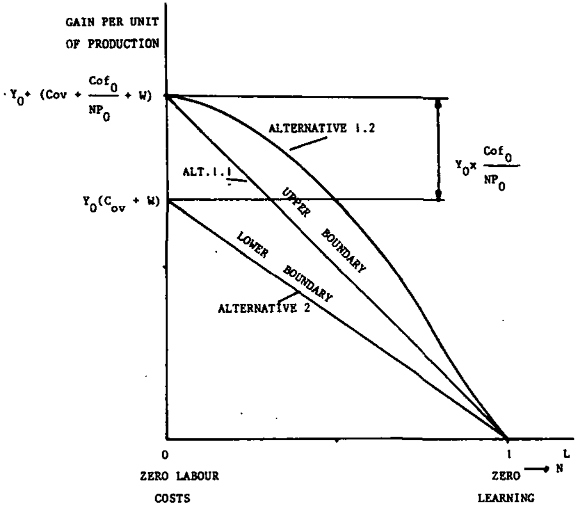


Fig.6.20: Gain per unit of production depending on learning and series size, alternat. 2 (reduced normal production capacity)

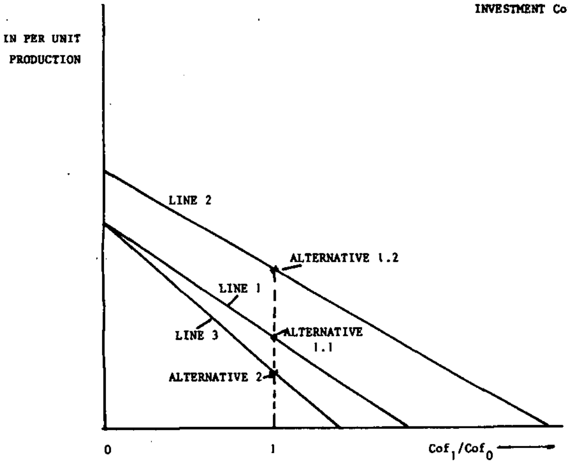


Fig.6.21: Gain per unit of production depending on the level of capital investment for all alternatives

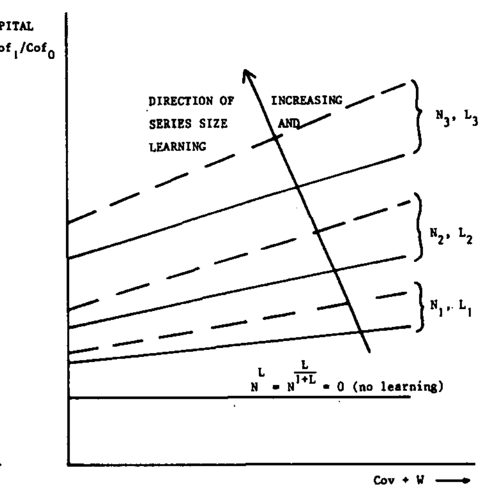


Fig.6.22: Allowable level of capital investment depending on the level of variable overheads and wages (alternatives 1.1 and 1.2)

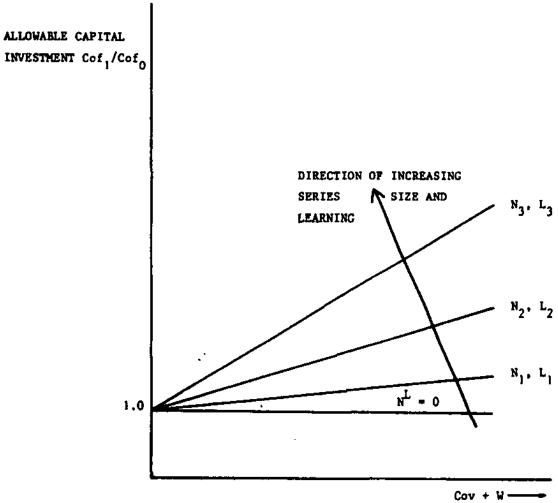


Fig.6.23: Allowable level of capital investment depending on the level of variable overheads and wages (alternative 2)

Appendix 6.1

Series Data for a Floater Element

For second-level structures, four different panel series were observed :

1. centre tank bottom panels
   centre tank deck panels
   wing tank longitudinal bulkhead panels
   wing tank longitudinal shell panels

2. wing tank bottom panels
   wing tank deck panels

3. centre tank transverse bulkheads
   centre tank end bulkheads

4. wing tank transverse bulkheads
   wing tank end bulkheads

To these second-level series, the following third-level series (webframes) were attributed :

1. centre tank bottom panel webframes
   centre tank deck panel webframes

2. wing tank longitudinal bulkhead webframes
   wing tank longitudinal shell webframes

3. wing tank bottom panel webframes
   wing tank deck panel webframes

4. centre tank transverse bulkhead webframes
   centre tank end bulkhead webframes

5. wing tank transverse bulkhead webframes
   wing tank end bulkhead webframes

The following first-level structure series :

1. wing-block units corresponding with phase 1 in the building process
2. centre-block units corresponding with phase 2 in the building process.

Chapter 7

Test case

7.1 Introduction

The previous two chapters dealt with the various aspects of building and building cost calculation for a complex modular structure where the effect of learning was introduced and evaluated for a floater element. The basis for this was the assumption that the floater was built of a limited number of types of second and first level structure series. By extending these series throughout the entire platform structure in conformity with Chapter 6 par. 2.5, a complete modular (semi-submersible) structure is obtained.

The merit of the modular set-up in design and construction of this platform will now be evaluated. In general, two points of interest will be investigated :

1. In the first place, the inter-action between design and construction within the modular concept; this is obtained by means of the involved design and yard variables, the results are expressed by the total building costs.
2. In the second place, the impact of learning on the construction yard; the becoming available of production capacity and the possibility of altering the level of capital-related fixed overhead costs through variation of capital investments.

When performing this phase of investigation, one must be aware of the large number of variables involved (see table 7.1) and, thus, the large number of alternatives which must be calculated. In particular, alternatives obtained by different ranges of variation for yard & cost parameters characterizing different building locations. The role of these parameters in the calculation of building costs has been demonstrated (Chapter 5 and 6). The outcome of the calculations obtained on the basis of a specific building yard is not applicable elsewhere.

It is therefore that the main interest here goes to the sensitivity of the developed modular design and construction system to variations of parameters of general applicability rather than the outcome of a particular combination of parameter values.

The followed procedure will be to fixate all parameters and activate (vary) only those parameters which are necessary to lighten a particular point of interest. All along, the interaction design/construction will be involved whereas building costs will be used as the ultimate measure of merit for comparison.

The results will be presented in non-dimensional form, by means of the cost index CI which is defined :

$$CI = \frac{\text{labour costs + material costs}}{\text{basic material costs}}$$

7.2 Considerations

7.2.1 General

The variables involved in the calculation of labour and building costs for the modular semi-submersible platform concern :

1. The designer : design variables
2. The builder : yard variables
   cost variables
   learning.

The mutual relations and the role in determining the building costs are shown in Fig. 7.1; the distinction made within group 2 above is done in accordance with the cost calculation model developed in Chapters 5 and 6.

In principle, all variables from table 7.1 are free variables and any combination of values, within a practical range, between groups (1) and (2) above is feasible. This results in a large number of alternatives which have to be evaluated; however, if the investigation into the points of interest above is limited to one building location, a number of free (yard) variables will assume fixed values and become input data. A description of all variables and the choice of those which will be involved in calculations is given below.

7.2.2 Choice of free variables

7.2.2.1 Relation design-building costs

In this relation, the determination of labour effort is a key factor involving :

1. Design variables
1.1 structural
1.2 geometrical

2. Yard variables
2.1 facilities
2.2 performances

(see Fig. 7.1)

Variable 2.2 is a direct input for the labour effort factor through which the effect of learning on labour costs is channeled Once learning is established, performance data becomes a dependen variable determined by structural variables only (see Chapter 5, par. 4).

The relation between the other variables and the labour effort is channeled through the work content and the building procedure (se Fig. 7.1). For the location-related yard facilities, the following is assumed :

- A maximum value for the length of structures, equal for work-stations 2-4;
- A fixed value for the width of plate elements;
- A crane lifting capacity corresponding with the assumed structur length, without limitations; this is done in order to eliminat the impact of crane capacity on the forming of structure series which influences labour effort and the distribution of same ove the work-stations, hereby obscuring the relation design variables - labour effort and costs.

Furthermore, if the building procedure will follow the practice outlined in Chapter 6 par. 3, while keeping the internal structura arrangement of bulkheads and cross ties, work content and labour effort will be determined by design variables only (see Fig. 7.1).

In the selection of free design variables a distinction is made between parameters related to the external geometry of the platform and parameters related to the internal structural arrangement (see tabla 7.1). Following the modular concept outlined in Chapter 4 par.3, geometrical design solutions are generated for the following free variables :

- The number of columns m;
- The ratio submerged floater volume/submerged column volume which is given by the submerged column height h_1;
- Module aspect ratio b/h.

In searching for the (cost-wise) optimal solution, all generated alternatives are to be calculated. Since this is not the purpose of this study and in order to reduce the number of calculations, fixed values based on the governing practice in current semi-submersible platform building will be assumed for m and h_1.

Module aspect ratio b/h which bears a direct relation to the modular concept will also be varied within a range of values coinciding with the governing practice.

The variable representing the internal structural geometry is the stiffener spacing s; work content and labour effort vary in accordance with the variation of s. The spacing s also determines the characteristic dimensions of structural elements, hereby establishing material weight and costs; any variation of s will implicate changes in material costs. The ratio k between transverse webframe spacing and stiffener spacing is kept constant.

7.2.2.2 The impact on the construction yard

The becoming available of normal production capacity as a result of learning effects was discussed in Chapter 6 par. 5; the following alternatives were presented :

1. The original normal production capacity is maintained.
   1.1 Existing structure series are maintained; available normal production capacity is used for other contracts.
   1.2 Existing structure series are expanded following an extension of the original modular semi-submersible contract.
2. The original normal production capacity is reduced.

For these alternatives it was assumed that the level of capital investments and the wages are constant. At maintained normal production capacity (cases 1.1 and 1.2), this implicates unchanged tariffs. For both cases, the effect of learning is channeled through the production performance.

At reduced normal production capacity (case 2) and constant level of capital investments and wages, a change in tariffs occurs due to the change in the contribution of fixed overheads (Chapter 6, par. 5.3). The effect of learning is channeled through the production performance; normal production becomes an active, though dependant variable in the calculation of building costs.

The reduction of normal production capacity is, however, an ambigous matter; the impact on tariffs will depend on the share of the calculated labour effort with respect to the initial normal production capacity (see Chapter 6, par. 3). Maximum impact is achieved when the initial production capacity is identical with the calculated labour effort (or planned production capacity).

The obtained financial gains through the introduction of a modular building concept must be weighted against increased contribution of fixed overheads in tariffs due to eventual capital investments in production facilities beyond the original set-up. The free variable here is capital investment, at all work-stations.

The two other cost factors are wages and material prices; both variables are estimated by the governing circumstances in Dutch labour and steel material markets which are not fully controlled by the Dutch builder. However, the possibility to apply the proposed modular concept elsewhere raises the question of the relation between the merits of this concept and altering market circumstances; this will be investigated by varying the contribution of wages in tariffs.

Finally, the sensitivity of the modular concept will be investigated by varying the learning, at all work-stations, for different activities and types of connections.

The involvement of all active variables in the calculation of building costs is schematically shown in Fig.7.2.a. The scheme also indicates which variables are kept constant and which are free.

7.3 Choice of values

7.3.1 Design variables

Choise of values for design variables concern :

1. External geometrical form
2. Internal structural arrangement.

7.3.1.1 External geometry

With respect to this group of variables, data corresponding with a 3000 t variable deck load drilling platform will be used. Other geometrical (input) data is given in appendix 7.1.
The active variable is module aspect ratio b/h which will be varied over the range 1.75 - 2.5; over this range of values, the initial arrangement of longitudinal bulkheads and cross ties coincides with the one described in Chapter 4 par. 3.

7.3.1.2 Internal structural arrangement

The stiffener spacing s will be varied between 0.4 and 1.0 metres. Correspondingly, the spacing S between webframe elements will vary according to the ratio S/s = 3 (see Chapter 5 par. 6).

7.3.2 Yard variables

The involved yard variables are :

1. Structure and plate length
2. Plate width
3. Crane capacity

Available main dimensions for plate elements from /7.1/ are based on a maximum plate weight of about 9.5 t.

However, most plate material delivered on the Dutch market is based on a maximum plate weight of about 6.0 t /7.1/. Considering the plate thickness range involved in the construction of the platform (6-30 mm), plate main dimensions to be used are :

- length : 12.0 metres
- width : 2.0 metres

The above plate length will also be used as the maximum length of first-level structures at work-stations 3 and 4.
For reasons given in par. 7.2, crane capacity will not be limited.

7.3.3 Cost variables

The involved cost variables are :

1. Normal production capacity
2. Investments
3. Material prices
4. Wages

The initial normal capacity is derived from the reference yard in terms of labour force, number of shifts and the amount of manhours per year, per man (see Chapter 5 par. 4). This initial normal production capacity forms the basis for the calculation of fixed overheads contribution to tariffs; however, the normal production capacity is not necessarily fully committed to modular constructions (see also Chapter 6 par 5.3). The impact of the reduction of normal production capacity on the contribution of overhead costs to tariffs will depend on the ratio PP/NP. The following alternatives are possible :

1. PP/NP = 1
   In this case, the initial normal production capacity is reduced in proportion with the reduction in planned production capacity, thus :

$NP_1 = NP_0 \times PP_0 / PP_1$ where :

NP_0 , PP_0 : initial normal, resp. planned production capacity

NP_1 , PP_1 : reduced normal, resp. planned production capacity.

2. $PP/NP < 1$

   In this case, the initial normal capacity is reduced by the gain in labour effort due to learning :

   $NP_1 = NP_0 - (PP_0 - PP_1)$

Both alternatives will be evaluated; the exact figures for NP_0, PP_0 and PP_1 will be established following the calculation of labour effort with and without learning.

For capital investments and other data, figures related to the reference construction yard (Appendix 5.1) will be used.

The variation in the level of investments will be done to the extent which annules the economic gain obtained by learning.

Material prices are based on figures relevant to the Dutch (steel) material market /7.2/.

Data for basic wages, social schemes, etc. is based on Chapter 5 par. 3; the influence of altering wages will be investigated over a range of values in excess of those from Chapter 5.

7.3.4 Learning

The relation learning-building costs involves the following :

a. The distribution of building activities over work-stations
b. The nature of building activities
c. The types of connections
d. The number and size of structure series
e. The number and value of learning curves.

Combination of the above factors results in a large number of alternatives concerning the relation learning-building costs. An investigation of all alternatives goes beyond the scope of this work; the purpose here is to evaluate the relation learning-building costs on the basis of a combination of factors a-d above which corresponds with :

- The building procedure outlined in Chapter 5 par. 3.
- The number and size of series resulting from this building procedure.

The investion is done by varying the entire set of learning figures (14 curves) over a certain interval within the practical range of learning (Appendix 7.2). The numerical differences between the curves are maintained; these differences are based on several principles with respect to :

- The chronological location in the building process.
- The complexity of the structure, the operations and the size of the involved labour force.
- The involved technology

(see Chapter 6 par. 3).

7.4 Calculation scheme

A scheme for the calculations performed in this chapter is shown in Fig. 7.2.a. The encircled numbers stand for a particular case; the cases are numbered 1 - 9. For each case, a number of variables are free and a number is kept constant. The combination of variables for any case is given by the row of encircled, equal numbers; for example, case number 5 is given by the row of encircled numbers 5.

In the first place, the relation between external geometrical design parameters and building costs is evaluated for the chosen range of platforms; this is done by varying modules's aspect ratio b/h. A total of four platforms are calculated with and without learning (case 1 and 2 respectively), so that the influence of learning is also included in this relation. All along, the spacing s is free to vary according to par. 3.1.2 of this chapter.

On the basis of the obtained results, one platform is selected for further evaluation regarding the impact of the modular concept on yard set-up. During this evaluation, the spacing s is free to vary (see above). The investigated aspects are :

- The impact of the normal production capacity (all alternatives), cases 2-4.
- The impact of capital investments, cases 5-7; this is done in combination with cases 2-4.
- The impact of wages on building costs, case 8; this is done on the basis of maintained normal production capacity and structure series.
- The impact of differing learning figures on building costs, case 9; this is done on the basis of maintained normal production capacity and structure series.

A flow diagram showing one complete cycle of calculations, for each case, is shown in Fig. 7.2.b. This corresponds with the more detailed flow diagram from Fig. 5.23.a (see also Fig. 5.23.b-c and Fig. 4.8).

7.5 Discussion of results

7.5.1 Relation design variables - building costs

The impact of the external geometry on labour, material and total building costs is shown in Fig. 7.3.a-d (case 1, full lines). With exception of one platform (b/h = 1.75), the differences between the various geometries, at all spacing values, are small (4% and less than 1%, respectively); the lowest costs are obtained at a module aspect ratio b/h = 2.25.

In principle, the above situation is maintained when learning effects are applied (Fig. 7.3.a-d, case 2, dotted lines). Total and labour costs are lower than in case 1; the lowest costs are too obtained at a module aspect ratio b/h = 2.25.

On the other hand, the impact of the internal structural arrangement on the total building costs is significant. The results for cases 1 and 2 are shown in Fig. 7.4.a for a b/h ratio of 2.25; the difference between the highest and lowest costs for the investigated range of spacing values reaches 15% for case 1 and 8.4% for case 2 (full, respectively dotted line). Minimum costs are found at the spacing values :

- s = 0.8 m for case 1
- s = 0.6 m for case 2.

The cost-calculation results presented above reflect a situation determined by the assumed values for the involved cost variables. Moreover, due to variation of work-station tariffs, labour cost results are not proportional with labour effort results. In this respect it is useful to consider the development of labour effort with respect to the spacing s and the distribution over work-stations, types of connections and activities (Fig. 7.5.a-d and table 7.2). The obtained results indicate in general :

- Reduction of labour effort is obtained at work-stations 1-3 with a slight increase at work-station 4.

- The largest contribution is obtained at work-station 2 (64.1% and 70% for cases 1 and 2 respectively).
- Labour effort reduction obtained through point connections is larger than the reduction obtained through line connections for both cases 1 and 2 (63.6% and 66.9% respectively).
- Labour effort reduction obtained through rest activities is larger than the reduction obtained through welding activities for both cases 1 and 2 (61.4% and 51.4% respectively).

To obtain a more exact view, a further breakdown of labour effort which combines types of connections and activities, was performed (Fig. 7.6 and 7.7 for cases 1 and 2 respectively); the results, per work-station, indicate :

- Reduction of labour effort at work-station 2 concerns all types of connections and activities in general; in particular, the reduction is dominated by labour associated with line connections and welding activities (Fig. 7.6.b, curves 5 and 7 respectively). This situation applies to both cases 1 and 2.
- Reduction of labour effort at work-station 3 concerns in genera point connections only which dominate over the spacing range of 0.4-0.7 m; labour effort associated with line connections increases with increasing spacing values, in particular welding activities which dominate beyond s = 0.7 m.
  The latter is even more emphasized in case 2, where the increas of labour effort associated with line connections, in particula welding activities, dominates beyond s = 0.5 m.

On the basis of the above, the relation design variables/building costs for the range of investigated platforms is summarized as follows :

- The external geometry represented by module aspect ratio b/h ha a negligible impact on building costs for values between 2 and 2.5 and does not constitute a measure of merit for the builder. This enables to found the choice of a particular b/h value on other grounds such as motion response, etc.

- For b/h ratios lower than 2, building costs increase by an important, if small, amount. This applies to both cases 1 and 2.
- The internal structural arrangement constitutes an important measure of merit for the builder.

In general, structure's work content and associated labour effort decrease with increasing spacing value s. The measure of decrease differs over the range of s-values and is determined by the balance between the amount of labour concerning point and line connections at work-stations 2 and 3.

In other words, by varying the stiffener spacing s, a measure of financial room is provided in which the optimal, cost-wise, structural design solution is determined by the sum of labour and material costs. Both financial room and costs are established by:

- The values assumed by cost variables; these were kept constant for cases 1 and 2.
- The volume of labour effort.

The modular concept makes it possible to decrease the amount of labour effort hereby :

- limiting the financial room obtained through variation of the spacing s;
- altering the balance between labour and material costs within this room.

In other words, the modular concept diminishes the importance of the internal structural arrangement as a tool for building-cost reduction.

The above lead to the following conclusion :

" The application of a modular concept in design and building reduces the impact of internal structural variables on building costs hereby increasing the possibilities of the designer towards design for product performances."

The difference between cases 1 and 2 represents the reduction of costs due to learning. This difference is not constant over the investigated range of s-values and varies between 18 - 30% for the total costs and between 39 - 46% for the labour costs (see table 7.3 and Fig. 7.8).

7.5.2 The impact on the construction yard

7.5.2.1 General

The reduction of labour effort obtained through learning effects associated with the modular concept in design and building has created a measure of financial room. This is not constant but varies over the different values of the spacing s in conformity with the sum of labour and material costs. Considering the total building costs calculated for cases 1 and 2 as the upper, respectively lower boundary of the obtained financial room, the merits of any change in yard set-up will be judged with respect to these boundaries.

Following Fig. 7.1, any change of cost-variables, with exception of material prices which are not considered here, is channeled through work-station tariffs. The location of the total cost curve with respect to the above boundaries depends on the values assumed by the cost variables in relation with the initial values. The point of interest here is the extent to which these variables can be altered before the financial gain obtained by means of the modular concept is annulled. The extent of variation is evaluated with respect to the financial gain which is hereby defined at s = 0.6 m:

$$\text{CI case } (1\text{-}2)_{(s\,=\,0.6\text{ m})} = 100\%\text{ gain}$$

For further evaluations, the platform based on a module aspect ratio b/h = 2.25 will be used.

7.5.2.2 Cost variables

The normal production capacity

The reduction in costs for cases 3 and 4 with respect to case 1 is shown in Fig. 7.8 (see also table 7.3). The impact of the normal production capacity on total building costs is shown in Fig. 7.9.a (curves 2, 3 and 4 corresponding to cases 2, 3 and 4 respectively). By assigning available becoming production capacity to modular structures, hereby extending the original structure series, an increase in the reduction of labour effort due to learning is obtained (see Fig. 7.9.a, curve 3). The gain, cost-wise, is increased by an average of 14% with respect to case 2 and the lower boundary of the obtained financial room is lowered even more.

If the available becoming capacity is rejected, the initial normal production capacity at each work-station is reduced, causing an increase of fixed overheads contribution to tariffs (see Fig. 7.9.a, curve 4). The gain, cost-wise, is reduced by an average of 3.5% with respect to case 2. This small difference is explained by the fact that the planned production capacity for the semi-submersible structure concerns only a fraction of the total available normal production capacity (8.8% and 4.7% for cases 1 and 2 respectively). This corresponds with alternative 2 from par. 3.3 of this chapter.

Should the entire capacity of the yard be employed in modular constructions so that the initial normal production capacity is decreased beyond the figures for case 2, the corresponding total cost curves will approach the upper boundary of the obtained financial room given in Fig. 7.9.a by curve 1. This corresponds with alternative 1 from par. 3.3 of this chapter. The extent of reduction of the normal production capacity is shown in Fig.7.9.b; it should be mentioned that this extent is determined by the sum of labour and material costs at the chosen value of s.
On basis of the obtained results, the initial normal production capacity can be reduced by about 69% before the financial gain obtained through learning effects is annulled.

The investment of capital

The allowable level of capital investment with respect to the obtained financial room is shown in Fig. 7.10. First, the total costs were calculated at maintained level of normal production and structure series (case 5); the results are shown in Fig. 7.10.a in comparison with case 1 (full, respectively dotted lines). The curves from Fig. 7.10.a emphasize again the relation between design and cost variables at various s-values.

The implications of different yard policies with respect to the available becoming production capacity are shown in Fig. 7.10.b in terms of the financial gain at increasing level of capital investment. The financial gain was calculated on the basis of the difference between case 1 and case 5, at zero increase in the level of investment, for the following cases :

- case 5 : see above
- case 6 : maintained level of normal production capacity with increased size of structural series
- case 7 : reduced level of normal production capacity at maintained size of structural series.

The results indicate :

- In general, the obtained financial room allows an increase of fixed overhead costs representing a capital investment three to four times the initial investment.
- The extent of increase is largest for case 6, followed by case 5 and 7, respectively 315%, 250% and 230%.

The variation of wages

The cost variable wages was investigated by establishing the extent to which wages can be raised before the obtained financial gain is annulled by the increased cost of labour. For this purpose wages were gradually raised above the initial level. The results are shown in Fig. 7.11 and indicate that the financial gain is annulled at a level of wages more than twice the initial assumed value (120%)

The impact of learning

The relation learning-building costs is shown in Fig. 7.12. First the total building costs in comparison with case 1 (Fig. 7.12.a); then the financial gain at different values of learning (app. 7.2) is shown in Fig. 7.12.b; The results show that even for the lowest set of values the gain is significant with respect to case 1 (about 75% of the initial gain).

Further insight is obtained by considering the combined effect of learning and series size on labour effort. In principle, the effect of learning increases with increasing series size and learning (Chapter 6, par. 2). Following the established building procedure, the largest series occur at the lowest structural levels (work-stations 1 and 2; see also Fig. 5.23.b). On the other hand, the lowest learning occurs at the highest structural levels (app. 7.2).

The combined effect of learning and series size is shown in Fig. 7.13, for each work-station. The results concern the increase of labour effort with decreasing learning; the basis for comparison is given by :

- labour effort case $1_{(s = 0.6 \text{ m})} = 100\%$

The results indicate :

- The largest increase of labour effort occurs at the lowest structural levels, i.e. work-stations 1 and 2.
- The largest reduction of labour effort with respect to case 1 is obtained at the lowest structural levels over the entire range of learning values.

The above implicates that for the considered structure, the much larger structure series at work-stations 1 and 2 compensate for the lesser learning at these work-stations with respect to work stations 3 and 4 (see table 7.4 and appendix 7.2).

To evaluate the impact of learning on the allowable extent of variation for cost parameters, an additional case was calculated where :

- Minimum learning according to appendix 7.2.
- Variation of capital investment corresponding to case 5, thus maintained level of normal production capacity and size of structure series.

The results are shown in Fig. 7.14 in comparison with case 5 :

- The financial gain is reduced, at zero increase of capital investment, to 73% of the initial gain.
- The maximum allowable increase in capital investment is about 150%.

7.6 Conclusions

The variation of geometrical and structural variables indicates that the former has a negligible influence on building costs over the largest part of the investigated range of values. On the other hand, the structural pattern exerts an important influence on labour and material costs (case 1 from Fig. 7.2.a).

The introduction of learning effects reduces building costs with respect to the conventional concept; this reduction is achieved in particular at the assembly of second and first-level structure series. In principle, learning does not affect the conclusions regarding the relation between geometrical and structural variables and building costs (case 2 from Fig. 7.2.a).

The financial room obtained through learning allows to increase the value of cost variables by an order of magnitude with respect to the initially assumed values, before the financial gain is annulled.

The alternatives regarding the assignment of available becoming production capacity to new orders or rejection of this capacity are all feasible and affect the obtained financial gain by a small, if important, percentage (cases 2, 3 and 4 from Fig. 7.2.a). This is also reflected in the allowable increase of the level of capital investments (cases 5, 6 and 7 from Fig. 7.2.a).

The conclusions regarding the variation of learning are more general. Variation of learning over the investigated interval of values affects building costs and, thus, financial gain.
The combined effect of learning and series size indicates that, for the considered structure, the latter factor dominates; the reduction of labour effort at the lower structural levels is highest over the entire interval of learning-values (case 9 from Fig. 7.2.a). The financial gain calculated for the lowest set of learning curves still allows an increase in the level of capital investments up to twice-three times the initial value.

List of references Chapter 7

7.1 Medium and Thick Steel Plates (in Dutch)
Hoogovens ESTEL Verkoopkantoor b.v.
IJmuiden, Holland

7.2 Basic Prices Ship Steel Plates (in Dutch)
Hoogovens ESTEL Verkoopkantoor b.v.
IJmuiden, Holland

Table 7.1 : List of Variables Involved in Building Cost Calculations

type	description
design	geometrical : module aspect ratio b/h number of columns m column height H_c submerged col. height h_l volume ratio floater/colum structural : spacing s
yard	facilities : crane capacity section/plate length plate width performance : manhours/unit of connection
cost	normal production capacity investments wages material prices
learning	learning curves for types of connections and activities

Table 7.2 : Distribution of Labour Effort Results

case	total reduction over s=0.4-1.m in %	distribution of reduction over (in %)							
		work stations				type of connections		type of activity	
		1	2	3	4	line	point	weld	rest
1	- 36.5	- 12.6	-64.1	-24.4	+1.1	-36.4	-63.6	-38.6	-61.4
2	- 29.0	- 9.7	-70.0	-22.1	+1.8	-33.1	-66.9	-48.6	-51.4

Table 7.3 : Reduction of labour and total costs due to learning effects, in %

CASE	s = 0.4 m		s = 0.6 m		s = 0.8 m		s = 1.0 m	
	TOTAL COSTS	LABOUR COSTS	TOTAL COSTS	LABOUR COSTS	TOTAL COSTS	LABOUR COSTS	TOTAL COSTS	LABOUR COSTS
2	30.0	45.7	24.3	42.8	20.5	60.2	18.0	39.0
3	34.0	51.9	28.0	48.8	23.5	46.4	20.6	44.7
4	29.0	44.2	23.5	41.4	20.0	39.3	17.5	37.9

Table 7.4 : Structure series for the complete platform

```
                  SERIES1     SERIES2     SERIES3     SERIES4     SERIES5     SERIES6     SERIES7

SUB ASSEMB.        993.62      964.86     1565.85      153.45      269.70       52.67        9.30
PANELS             248.82      197.93       54.00       92.00        9.70        4.00
WING BLOCKS         31.49       67.47        9.70        0.00        0.00        0.00
UNIT BLOCKS         15.75       33.74        4.85        0.00        0.00        0.00
WHOLE ELEMENTS       2.00        6.00        2.00        3.00        2.00        0.00
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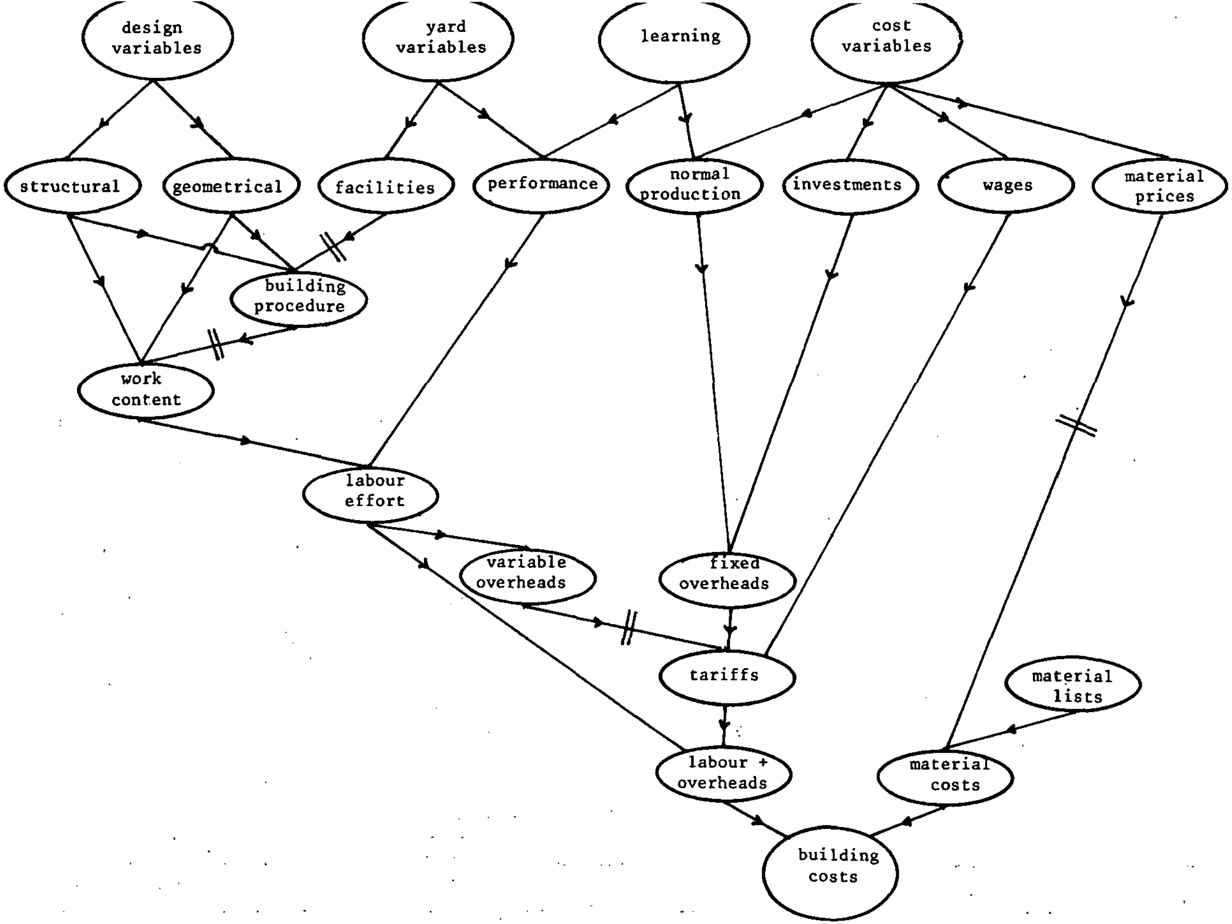


Fig.7.1 : Involvment of variables in the calculation of building costs

—╫— active variable kept constant

—→— active variable free

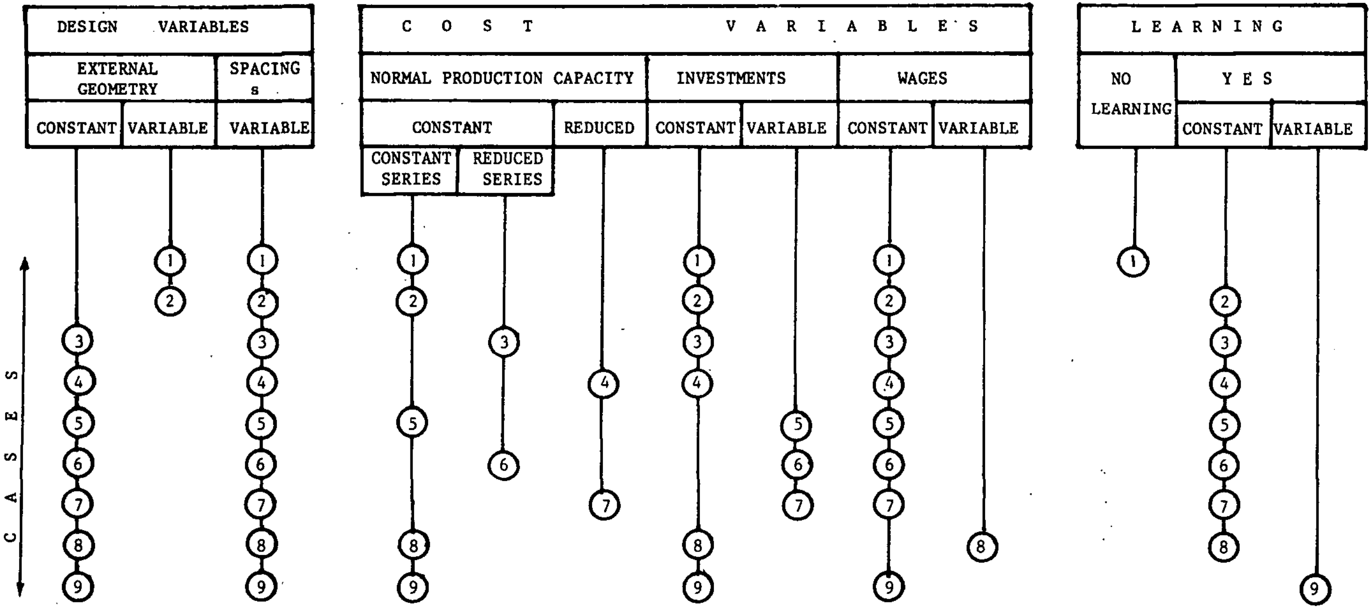


Fig.7.2.a : Calculation scheme

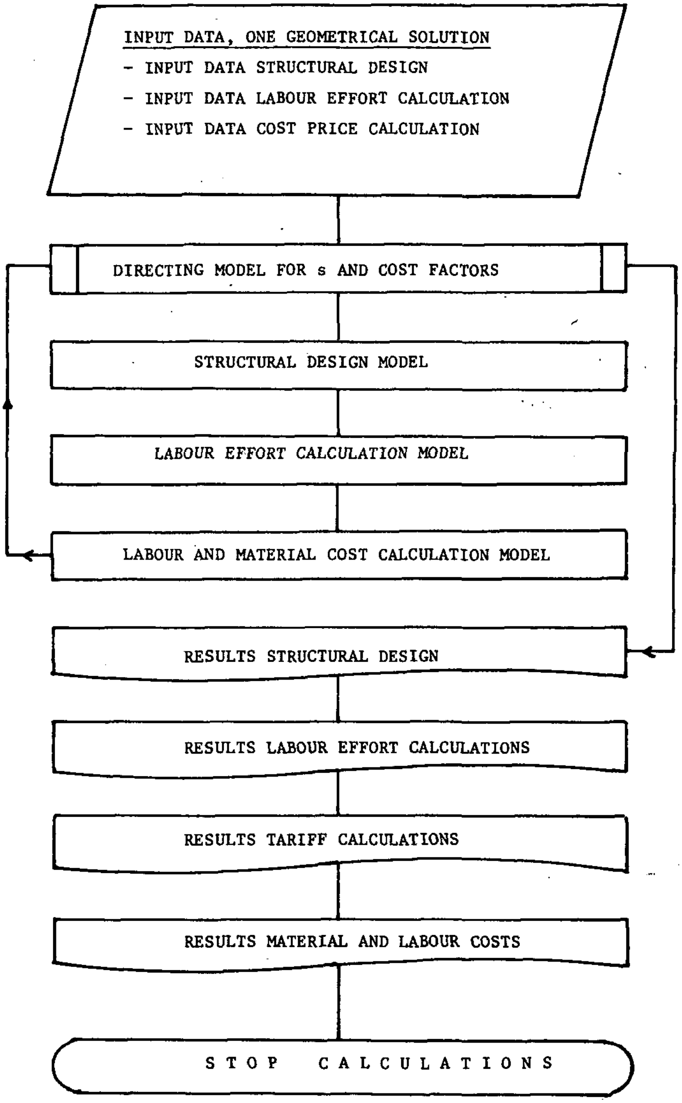


Fig.7.2.b : Flow diagram, one complete cycle of calculations per case

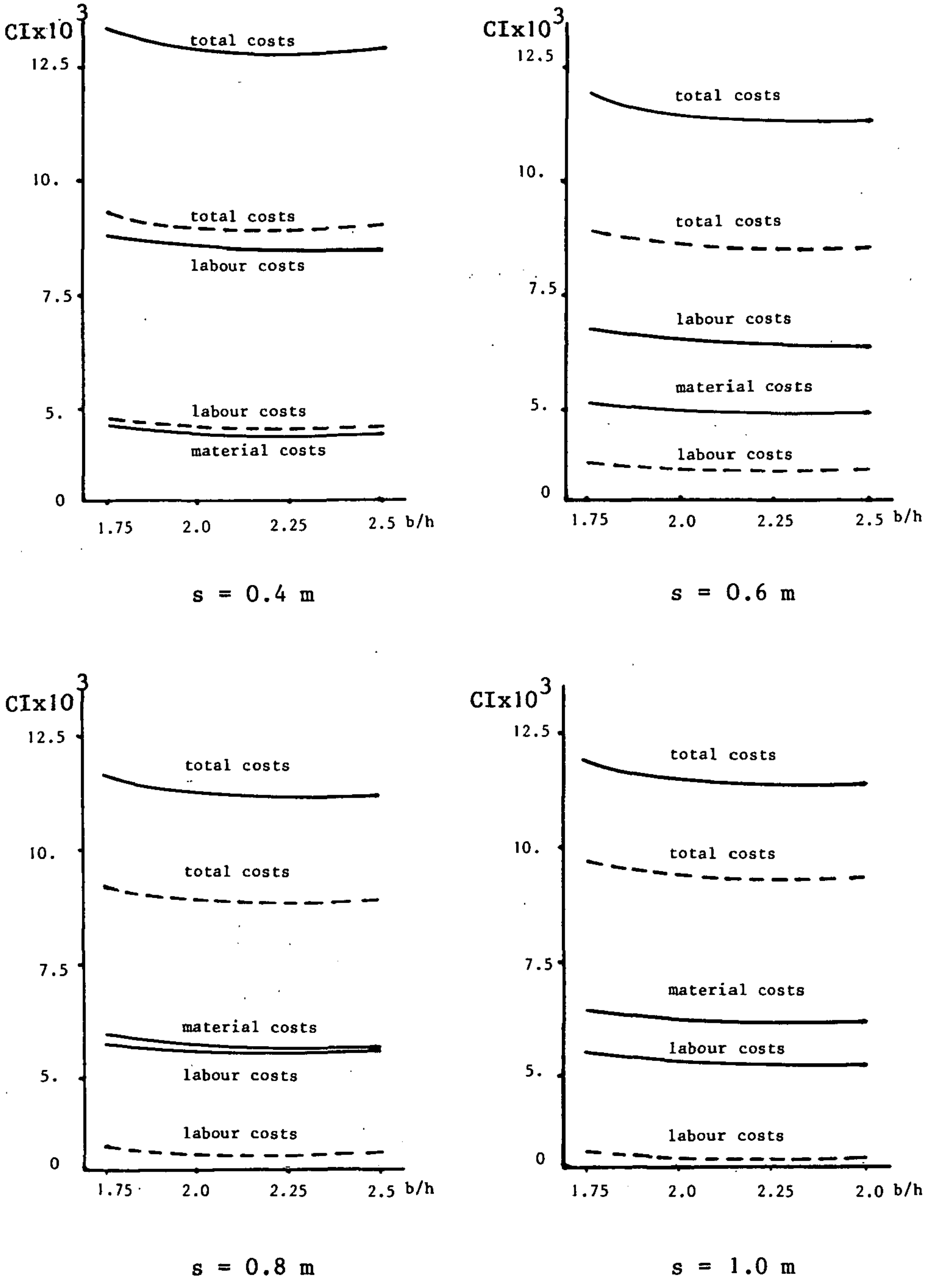


Fig.7.3 : Distribution of labour, material and total costs, at various module aspect ratios b/h and spacing values s

—— case 1, without learning

– – – case 2, with learning

$$CI = \frac{\text{labour costs + material costs}}{\text{basic material costs}}$$

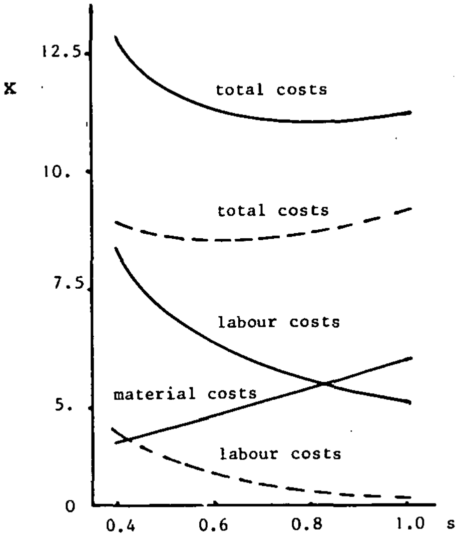


Fig.7.4.a : Labour, material and total costs

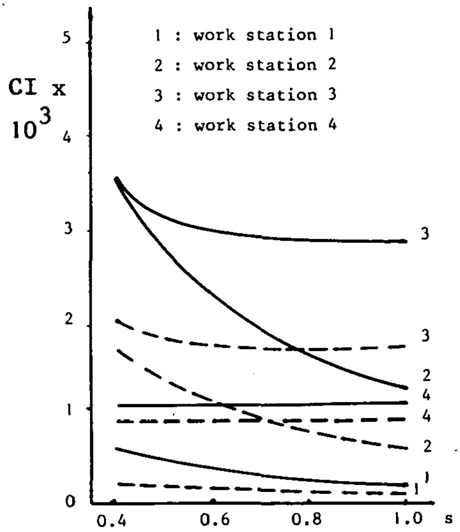


Fig.7.4.b : Distribution of labour costs over work stations

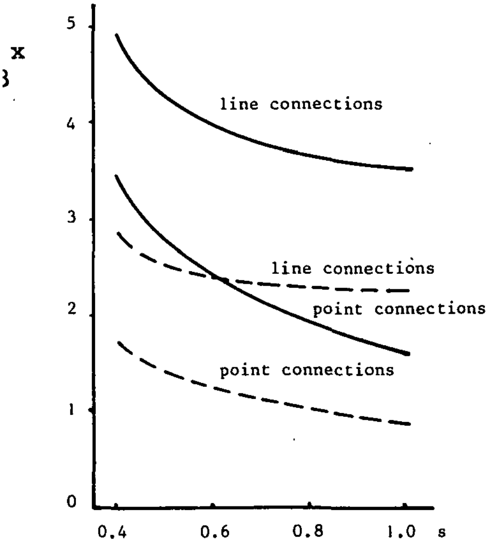


Fig.7.4.c : Distribution of labour costs over types of connections

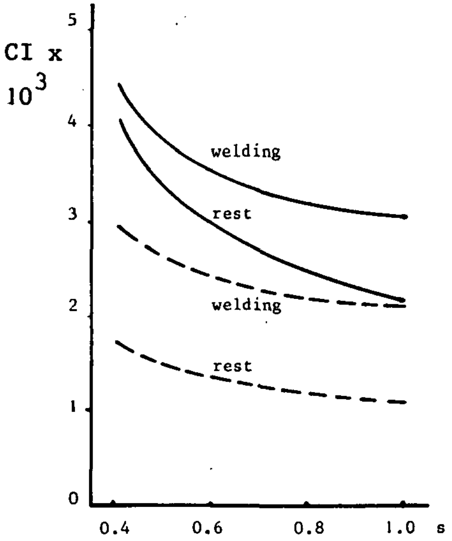


Fig.7.4.d : Distribution of labour costs over types of activities

—— case 1, without learning

– – – case 2, with learning

$$CI = \frac{\text{labour costs + material costs}}{\text{basic material costs}}$$

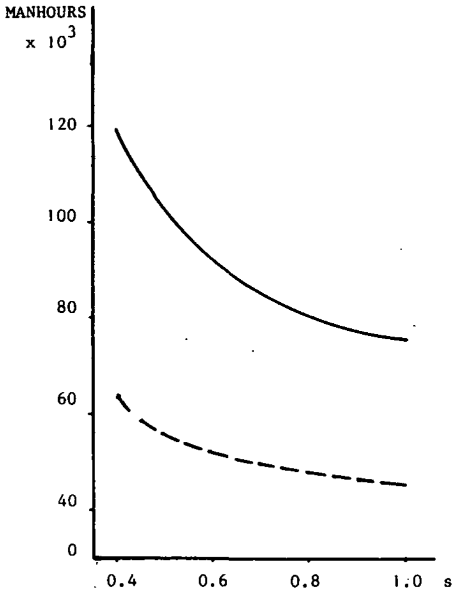


Fig.7.5.a : Total labour effort

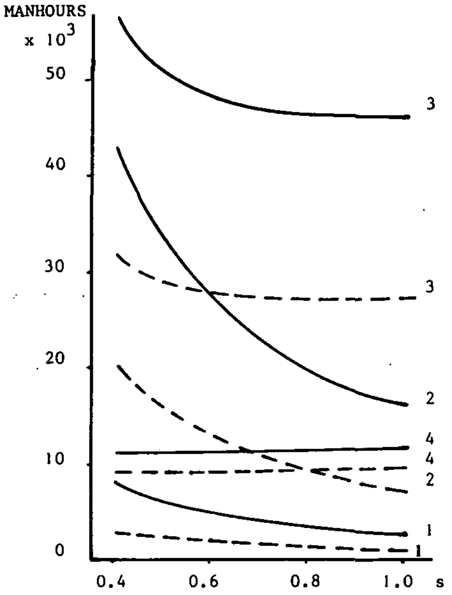


Fig.7.5.b : Distribution of labour effort over work stations

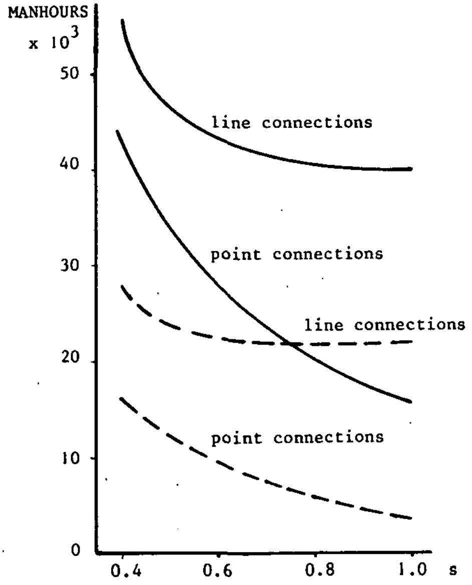


Fig.7.5.c : Distribution of labour effort over types of connections

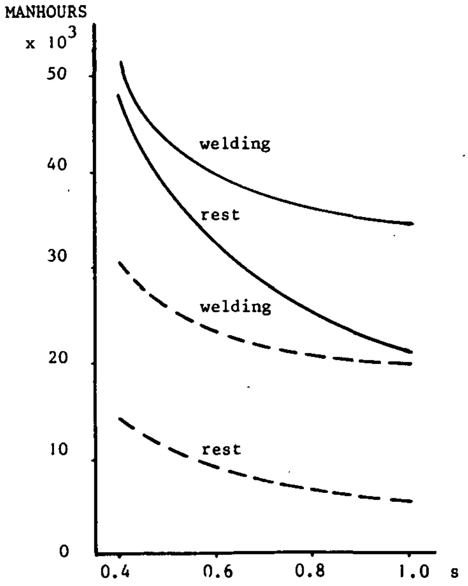


Fig.7.5.d : Distribution of labour effort over types of activities

——— case 1, without learning

— — — case 2, with learning

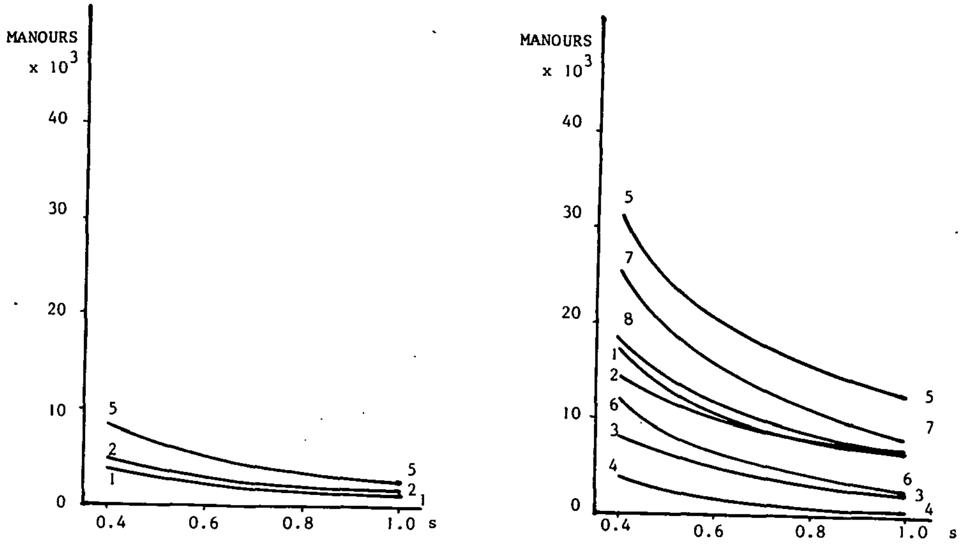


Fig.7.6.a : Work station 1

Fig.7.6.b : Work station 2

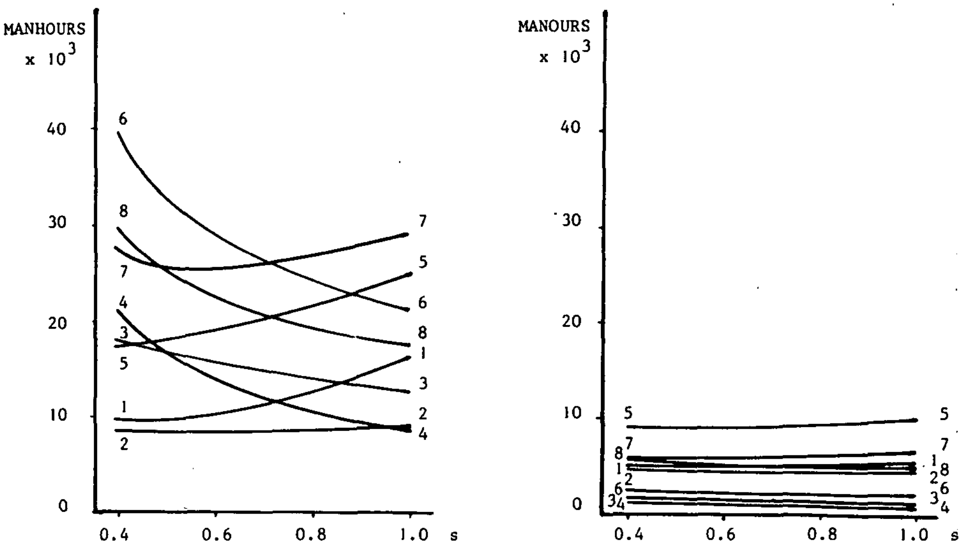


Fig.7.6.c : Work station 3

Fig.7.6.d : Work station 4

Fig.7.6 : Distribution of labour effort over types of connections and activities, per work station (case 1, without learning)

1 : line welding
2 : line rest
3 : point welding
4 : point rest

5 : line connections
6 : point connections
7 : weld activities
8 : rest activities

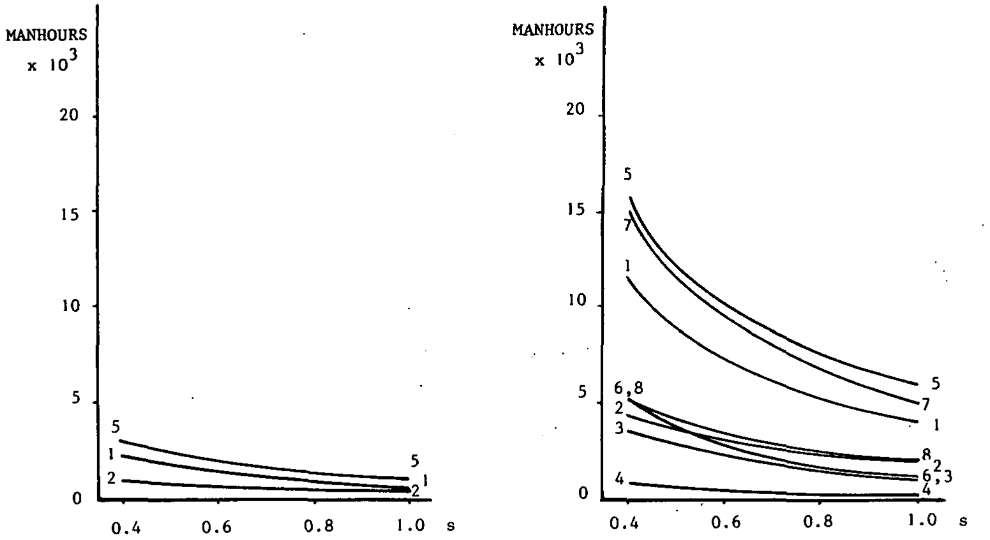


Fig.7.7.a : Work station 1

Fig.7.7.b : Work station 2

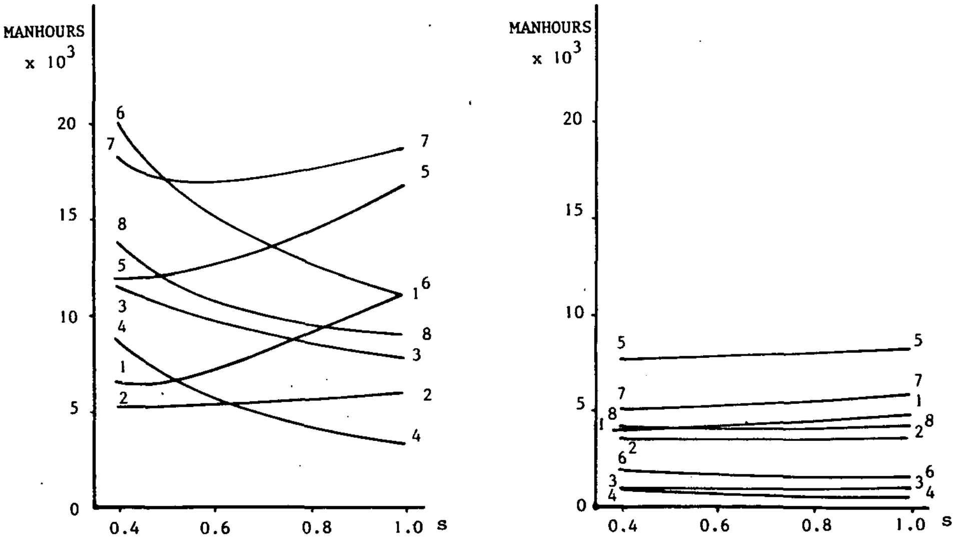


Fig.7.7.c : Work station 3

Fig.7.7.d : Work station 4

Fig.7.7 : Distribution of labour effort over types of connections and activities, per work station (case 2, with learning)

1 : line welding	5 : line connections
2 : line rest	6 : point connections
3 : point welding	7 : weld activities
4 : point rest	8 : rest activities

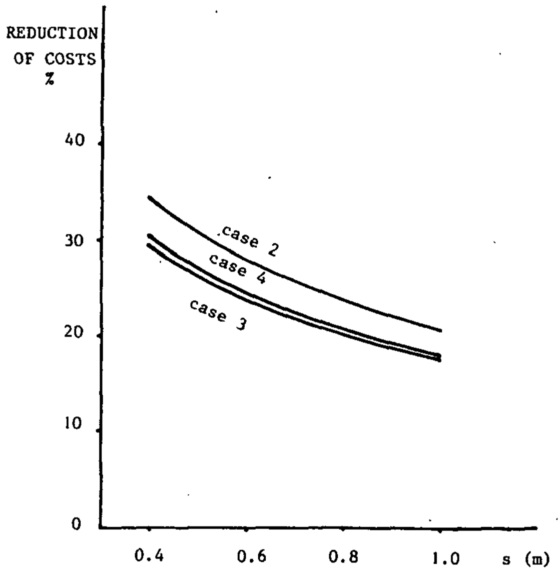


Fig.7.8 : Reduction of costs with respect to case 1

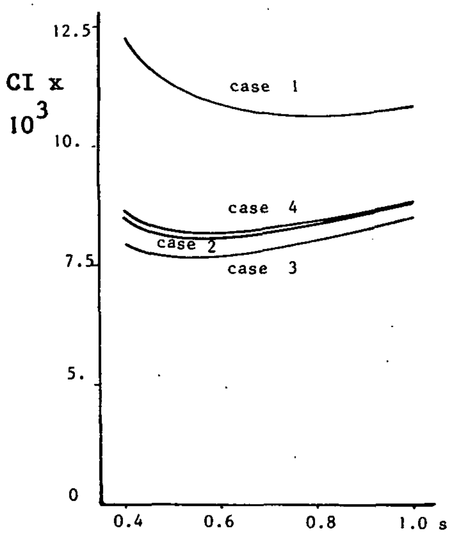


Fig.7.9.a: Total costs with respect to normal production capacity and series size

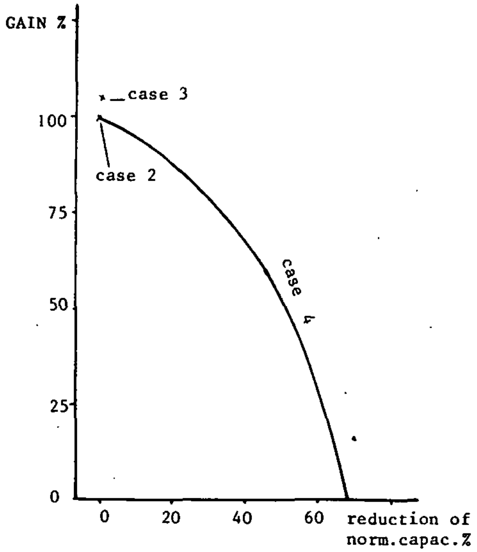


Fig.7.9.b: The extent of allowab reduction of normal production capacity

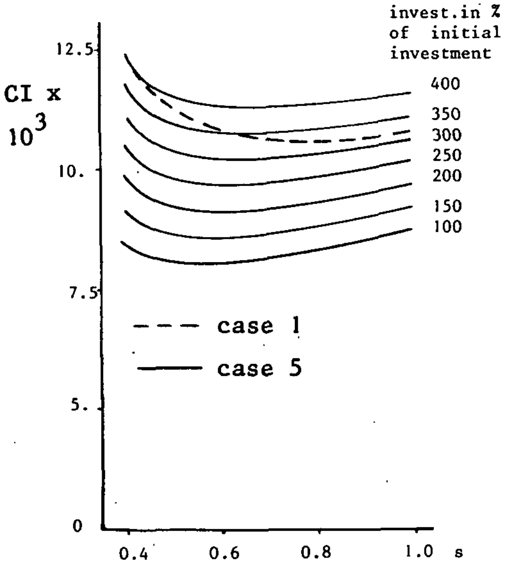


Fig.7.10.a: Total costs at various levels of capital investment

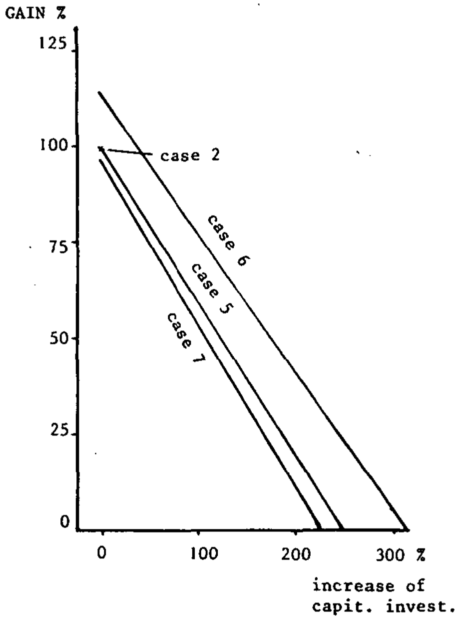


Fig.7.10.b: Allowable increase capital investment (figures for s = 0.

$$CI = \frac{\text{labour costs + material costs}}{\text{basic material costs}}$$

GAIN = CI (case 1) - CI (case 2) = 100 %

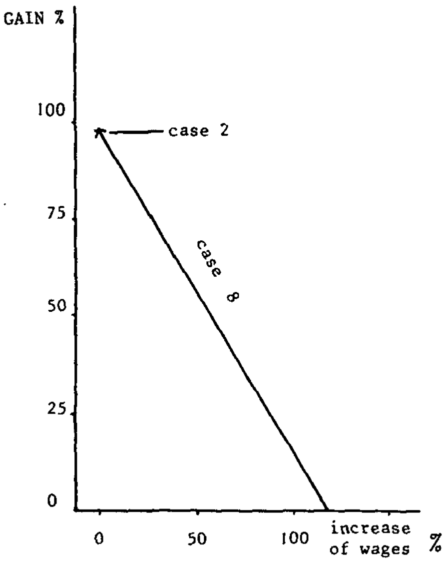


Fig.7.11: Financial gain at varying level of wages (s = 0.6 m)

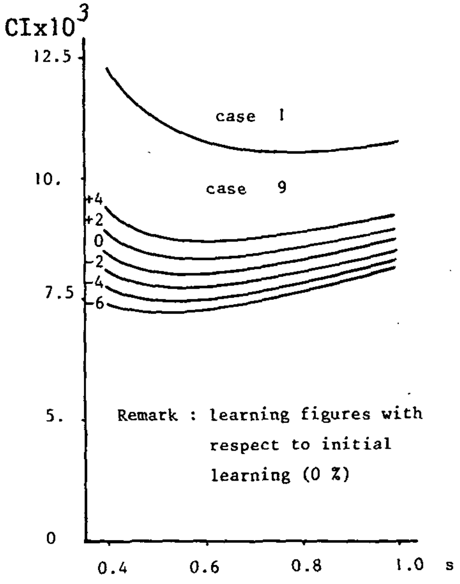


Fig.7.12.a : Total costs at varying learning figures and values of the spacing s

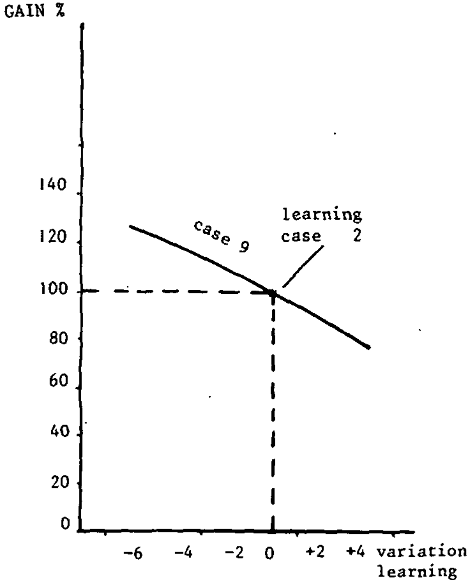


Fig.7.12.b : Financial gain at varying learning (s = 0.6 m)

$$CI = \frac{\text{labour costs + material costs}}{\text{basic material costs}}$$

GAIN = CI (case 1) - CI (case 2) = 100 %

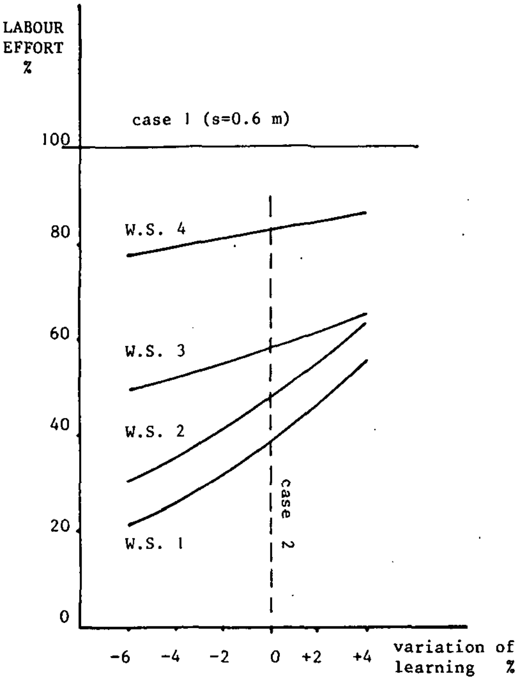


Fig.7.13 : Increase of labour effort, per work station, with respect to case 1

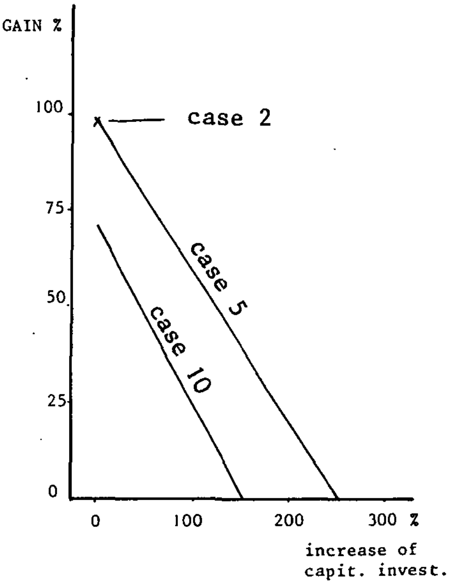


Fig.7.14 : Allowable increase of capital investment

Appendix 7.1

Platform data used for calculations

Displacement V : 22.000 m^3

Variable deckload : 3.000 T

Number of columns m : 6

Column height H_c : 28 m

Submerged column height h_1 : 14 m

Initial, final and interval b/h : 1.75, 2.5, 0.25

Natural period heave T_h : 22 sec.

Geometrical data platforms

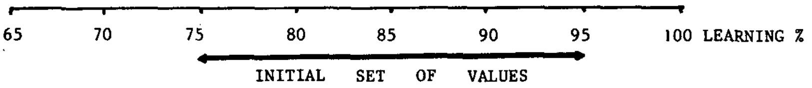
b/h	b (m)	h (m)	L_f (m)	B_d (m)	L_d (m)	KB (m)	BM (m)	KG (m)
1.75	11.272	6.551	109.508	60.070	76.954	6.054	14.237	17.291
2.00	12.391	6.196	101.282	57.890	75.703	6.058	13.988	17.046
2.25	13.467	5.985	94.473	56.037	74.767	6.068	13.767	16.835
2.50	14.491	5.797	88.952	54.479	74.115	6.073	13.574	16.647

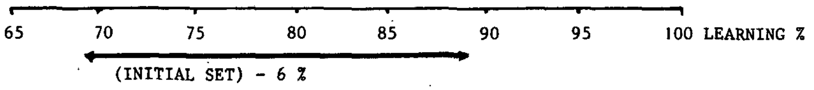
App.7.2

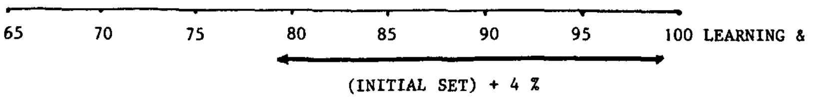
Variation of Learning Data

WORK STATION	WELDING ACTIVITIES						REST ACTIVITIES					
	LINE CONNECTIONS			POINT CONNECTIONS			LINE CONNECTIONS			POINT CONNECTIONS		
	MIN	NOM	MAX	MIN	NOM	MAX	MIN	NOM	MAX	MIN	NOM	MAX
1	0.89	0.95	0.99	-	-	-	0.79	0.85	0.89	-	-	-
2	0.89	0,95	0.99	0.84	0.90	0.94	0.79	0.85	0.89	0.74	0.80	0.84
3	0.84	0.90	0.94	0.84	0.90	0.94	0.74	0.80	0.84	0.69	0.75	0.79
4	0.84	0.90	0.94	0.84	0.90	0.94	0.74	0.80	0.84	0.69	0.75	0.79

Data given above indicates minimum, nominal and maximum values, in % ; interval size is 2 %. The principle of variation is shown below :







Chapter 8

Summary of conclusions and new aspects

The study performed concerns a new approach in "design-for-production". The building of the marine product is considered as an assembly process of module series, at different levels of structural complexity. All modules are built according to a standard structural pattern. This approach creates conditions for introduction of learning effects in cost calculations which have to be realized in practice, prior to the final assembly of the structure.

With a view to possible applications of the modular approach, it was decided to link on to the current practice in yard set-up with respect to activities, facilities and production performance. The principle by which overhead costs are absorbed in manhour tariffs is maintained.

The conclusions are divided as follows :

1. A group specifically related to the reference marine product, the semi-submersible platform.
2. A group of general nature.
3. A group concerning new aspects which emerged in the course of this study.

1. Conclusions related to the semi-submersible platform

1.1 Design solutions obtained by means of the modular approach have properties equivalent to those of conventionally obtained design solutions; this was demonstrated by means of motion response characteristics.

1.2 Platform cost price is relative insensitive to changes in the external geometrical form obtained through variation of module aspect ratio b/h.

2. Conclusions of general nature

Modular approach to design-for-production

2.1 The modular approach provides direct access to information related to the systems of design and production; this approach enables also the transfer of information between the two systems.

2.2 The relation between main/characteristic dimensions of structural components and the connections between these components enable an accurate determination of structure's work content.

2.3 The same relation (2.2) enables to establish the amount of labour effort and the relation design parameters - cost price; hereby, an easier and more reliable prediction of final results concerning the building of the steel structure is obtained.

2.4 Labour effort and cost calculation results show that the share of point connections is of the same order of magnitude with that of line connections. This implicates that both types of connections are to be considered with regard to any measures aiming to regulate the production process.

2.5 The same conclusion (2.4) applies also to the types of activities i.e. welding and rest.

Stiffener spacing "s"

2.6 Increase of the stiffener spacing "s" causes a decrease of work content and an increase of structure scantlings. Decrease of labour effort due to decrease of work content is larger than increase of labour effort due to increase of scantlings. Thus, if reduction of labour effort is a primary objective, such reduction can be obtained by increasing the stiffener spacing "s"

2.7 The sum of material and labour costs against the spacing "s" shows a sharp decline over the lower values of "s". This is explained by the sharp decline of labour effort, in particular for point connections, due to decline of work content; over this range of "s"-values, increase of labour effort due to increase of scantlings is not significant.

The effect of learning

2.8 Learning effects do not affect, in principle, the conclusions from 1.1-2 and 2.1-6 above.

2.9 Learning effects cause a "levelling" of the decline in labour effort mentioned in 2.7. The curve representing the sum of labour and material costs has a more constant path over the investigated range of "s"-values; cost-price becomes, thus, less sensitive to changes in the structural pattern.

2.10 A measure of financial room is provided within which a considerable increase in the values of cost factors is possible, before the financial gain obtained on the basis of a single semi-submersible platform is annulled.

2.11 The highest values for cost factors are achieved when :
- The initial level of normal production capacity is maintained,
- The available becoming manhours are used to extend existing structure series in additional contracts.

2.12 The large number of learning curves and structure series involved in cost calculations does not enable the achievement of complete insight in the relation learning-building costs. Some conclusions are obtained by a systematic variation of the initial set of learning curves over a range of values between 69% and 99%; these are :
- For the considered structure, series size has a larger impact on reduction of labour costs than the numerical value of learning.
- The financial gain obtained for the lowest set of learning curves still allows an increase in the level of capital investments up to twice-three times the initial value.

3. New aspects

Design

3.1 The decrease of cost-price sensitivity to changes in the structura pattern increases the possibilities of the designer toward either improvement of product performances (more deckload) or reduction of overall dimensions (lower cost-price).

3.2 The standard structural pattern enables that stiffening elements of arbitrarily-oriented adjoining panels can be conveniently connected for purpose of load transfer; this is of particular importance for the structural design.

3.3 The choice of pattern of stiffening elements is based on the sum of material and labour costs regarding one single panel (Chapter 5, par. 6). Considering the number and types of panels involved in the building of the complete structure as well as the impact of learning effects on the costs, it is possible that a different pattern of stiffening elements will result in a lower overall cost-price. The investigation of the structural pattern should be performed with respect to the entire structure and should be done, as a part of design evaluation, for each design alternative.

Construction

3.4 The building of the steel structure was centred around the fabrication, in series, of structural components prior to the final assembly; this approach is, however, not accompanied by adjustmen of the building procedure, the facilities, etc. Such an adjustmen may lead to a more efficient yard set-up and increased economical gain with respect to the results obtained here.

3.5 Considering conclusions 3.1-4 above, a more comprehensive implementation of the modular approach should comprise the following :

- Alternative assortments of structure series in terms of structural complexity, main dimensions and number of modules.

In this respect, deviations from the current practice of ever-increasing complexity of assembly operations which associate structural complexity with dedicated work-stations, is considered to be necessary.

- Facilities based on the practice of repetitive activities with regard to series fabrication; the lay-out of the facilities and the application of mechanized, automatic and robotic devices have to be taken into account.
- The influence of the lead time should also be included in the evaluation process regarding building costs. Hereby, a more realistic relation is established between these costs and the level of capital investments.

3.6 The application of a modular approach provides a "tool of management" which can be used, in an altering market situation, to evaluate the (market) position of the yard on the basis of different alternatives provided by this approach.

Finally, if the modular approach presented here is to become normal practice in the design and construction of marine structures additional research in different areas mentioned above is required. Some suggestions are :

- The development of a more comprehensive data base on production performance based on the principles adopted here and the latest state of technology.
- The introduction of production process-simulation as a standard part of design-for-production practice where the specific conditions of the particular construction yard are involved.
- Further insight in the impact of learning on labour effort by systematic variation of learning curves and series sizes.
- The impact of learning on material usage following the modular concept in the building of marine structures.
- Research on the introduction of mechanized, automatic and robotical aids for activities which are, today, performed

manually and extension of the already existing applications of such devices.

- The type of accountacy system with regard to a higher level of mechanization, automation and robotization of the production process on marine construction yards.
- The type of management required during the construction of marine structures according to the modular approach.
- The application of the modular concept in the design and building of other types of marine structures.

Summary

The study performed concerns a new approach to design-for-production. The building of the marine product is considered as an assembly process of module series, at different levels of structural complexity. All modules are built according to a standard structural pattern. This approach creates conditions for introduction of learning effects in cost calculations which have to be realized in practice, prior to the final assembly of the structure.

To evaluate this approach with respect to current practice in marine constructions, a semi-submersible drilling platform is chosen to represent the assortment of both conventional floating and offshore structures.

An integration of design and building systems is effectuated within the frame of established constraints; these constraints address the geometry of the modules and the performances of the semi-submersible platform with respect to a conventionally designed platform.
Means for information transfer between design and building are established to a degree where a direct relation between design variables and cost price can be obtained. A necessary condition is the use of compatible parameters in both design and building. Structure work content can then directly be "translated" into labour effort.

Series fabrication implicates an industrial approach towards the building process which is not customary for current labour-intensive marine constructions; with a view to applications of the modular concept, it is decided to link on to the current yard set-up with respect to activities, facilities and production performance data.

Comparison with the existing practice requires that both design and building are carried on to a level of completion which confirms the feasibility of the design and provides sufficient information for cost calculations. The method followed involves a design procedure which respects the constraints derived from design and classificat-

ion requirements to obtain feasible solutions in a preliminary design stage. Each solution consists of an external geometrical form and an internal structural arrangement. Each structural solution can be broken-down into module series, according to a predetermined building procedure. The building procedure is limited to the most important activities related to the assembly of the steel structure.

Information transfer between the systems of design and building and the related parameter compatibility are obtained by considering the type and amount of connections between structural components.

The above method provides a range of alternatives for design solutions as well as for the breakdown of the structure into module series and the choice of a building procedure. This choice links on the current practice which provides the basis for the evaluation of the proposed modular concept. A structural pattern is established for all panel constructions, the concept is then implemented with regard to a complete floater element of the semi-submersible platform.

The effect of learning for series construction is introduced on the basis of principles and experiences from other industries. Learning effects observed in marine constructions are taken into account as well. Learning curves are applied in the cost calculation of the floater element.

Finally, the modular approach and the effect of learning are applied to a complete semi-submersible structure. The purpose is to investigate the sensitivity of this approach to variation of parameters related to design and building. With respect to the latter, the normal production capacity, the level of capital investment, manhour wages and learning figures are investigated. Hereby, a "tool of management" is created which can be applied in the decision making process concerning these yard parameters.

Besides other conclusions which may be of interest for the Dutch marine construction industry, the results indicate that the modular approach to design and building leads to a substantial reduction of the cost-price of the steel structure.

Samenvatting

Dit onderzoek betreft een nieuwe benadering tot productie-gerichtontwerpen waarbij de bouw van een maritiem object wordt beschouwd als een assemblageproces van series van modules, op verschillende niveau's van structurele complexiteit. Alle modules worden gebouwd volgens een standaard structureel patroon. Deze benadering schept de nodige voorwaarden tot toepassing van afloop in kostencalculatie die in de praktijk gerealiseerd moeten worden, voor de uiteindelijke samenstelling van de constructie.

De beoordeling van deze benadering, in vergelijking met bestaande situaties in de bouw van maritieme objecten, wordt gedaan aan de hand van een diepdrijvend boorplatform. Dat vertegenwoordigt zowel de conventionele drijvende alsmede de offshore constructies.

Een integratie van ontwerp en productie systemen wordt tot stand gebracht binnen een aantal beperkingen. Deze beperkingen worden betrokken op de geometrie van de modules en de prestaties van het diepdrijvende platform in vergelijking met een ontwerp dat op conventionele wijze tot stand wordt gebracht. De overdracht van informatie tussen ontwerp en bouw geschiedt zodanig dat er een directe relatie tussen ontwerpvariabelen en kostprijs kan worden bepaald. Een noodzakelijke voorwaarde hiervoor is het gebruik van aangepaste variabelen in ontwerp en bouw. Hiermee wordt de werkinhoud van de constructie rechtstreeks "vertaald" in arbeidsinspanning.

Seriefabricage impliceert een industrialisatie van het productieproces die niet overeenstemt met de huidige arbeidsintensieve maritieme constructies; rekening houdend met toepassingen van het modulaire concept, wordt er besloten om aan te sluiten bij de huidige werfpraktijk ten aanzien van aktiviteiten, faciliteiten en werkprestaties.

Vergelijking met de huidige praktijk vereist ook dat ontwerp en bouw worden voltooid tot een niveau waarbij de haalbaarheid van het ontwerp wordt bevestigd en voldoende informatie, ten behoeve van de kostencalculatie, beschikbaar is. De gevolgde methode berust op een ontwerpprocedure, gebaseerd op beperkingen afgeleid van ontwerp en klassifikatie-eisen, waarbij haalbare oplossingen worden bereikt in een voorlopige ontwerpfase. Elke oplossing bestaat uit een uitwendige geometrie en een inwendige structurele inrichting. Elke structurele oplossing kan worden afgebroken in series van modules volgens een bepaalde bouwprocedure. Terwille van de eenvoud worden uitsluitend de meest belangrijke, op de assemblage van het staalgedeelte betrokken, activiteiten in rekening gebracht.

Overdracht van informatie en de voorwaarde voor aangepaste variabelen worden verkregen door middel van de verbindingen, tussen onderdelen van de staalconstructie.

Deze methode voorziet in verschillende alternatieve oplossingen, het afbreken van de constructie is series van modules en het kiezen van een bouwprocedure. Deze keus wordt gedaan aan de hand van de huidige praktijk. Een structureel patroon wordt bepaald voor alle paneelconstructies, waarna het concept wordt toegepast in de bouw van een compleet drijverelement.

Afloopeffecten worden geintroduceerd op basis van beginselen en ervaring in andere industrieën. Afloopeffecten uit de maritieme industrie worden tevens betrokken. Een en ander wordt toegepast in de bouw van het drijverelement.

Het modulaire concept en het effect van afloop worden toegepast in de bouw van een volledig diepdrijvend platform met het doel de gevoeligheid van dit concept, met betrekking tot variatie van ontwerp- en bouwparameters, te onderzoeken. De onderzochte bouwparameters zijn de normale productiecapaciteit, de investeringen, de uurlonen en de afloopkrommen. Hierdoor wordt er een stuk gereedschap geschapen welke kan worden toegepast in het nemen van beleidsbeslissingen inzake deze bouwparameters.

Naast andere conclusies die van belang kunnen zijn voor de Nederlandse maritieme industrie, wijzen de resultaten op een aanzienlijke kostprijsreductie van de staalconstructie.

Nomenclature

Symbols not included in the list below are used at a specific place, where they are clarified.

A : reference area

A : force per unit relative acceleration of a floating body

A_{cwl} : column waterline area

A_h : sectional area, horizontal immersed cylinder

A_v : sectional area, vertical cylinder

A_{wl} : waterline area

B : force per unit relative velocity of a floating body

B_1, B_2 : coefficient used in production performance data in relation with main dimensions of components

B_c : column width

B_d : deck width

B_f : floater width

BM : metacentric height above centre of buoyancy

C : force per unit of displacement of a floating body from still water position

C : coefficient used in production performance data, job-related

C_L : labour costs, general

C_M : material costs, general

C_N : cumulative average cost of N units

C_O : overhead costs, general

C_T : total costs, general

C_{UN} : individual costs of N^{th} unit

C_m : hydrodynamic mass coefficient

C_d : drag coefficient

Cof : fixed overheads

Cov : variable overheads

C_s : safety factor indicating excess of righting capability

C_v : added mass factor

CI : cost index = C_T / P_{mb}

CI_L : labour costs index = R / P_{mb}

C_1 : the value (theoretical or otherwise) of the first unit in a series

D : reference diameter, general

D_1, D_2 : coefficient used in production performance data in relation with characteristic parameters of components

F_a : vertical wave-exciting force

F_d : hydrodynamic drag force on an immersed cylinder

F_{mh}, F_m: horizontal hydrodynamic mass force on an immersed cylinder

F_{vtot} : total vertical force on a floating body

F_w : wind force, general

GM : metacentric height above centre of gravity

GN : "false" metacentric height above centre of gravity

GZ : restoring arm

H_c : column height

H_d : deck height

H_f : floater height

I, I_t, I_{wl} : second waterline area moment

KB : vertical position of the centre of buoyancy

KG : vertical position of the centre of gravity

L : slope of learning curve (or learning) = log C_N / log $_N$

L_c : column length

L_d : deck length

L_f : floater length

M : direct labour force

M_{add} : added (hydrodynamic) mass for the heave motion

M_h : heeling moment

M_r : restoring moment

M_w : wind heeling moment

N : series size

NP : normal production capacity, per annum

P_m : material price, general

P_{mb} : basic material price, mild steel plates

PP : planned production capacity

R : hourly tariff

S : spacing between transverse stiffening elements (webframe)

T_a : number of manhours/year x man

T_h : natural heave period

T_l : labour effort

T_p : production performance, per unit

U_p : units of production

V : immersed volume, general

V_{hl} : volume of immersed column

V_w : wind velocity

V_1 : immersed volume of columns

V_2 : immersed volume of floaters

V.D.L. : Variable Deck Load

W : weight of steel materials

W : hourly wages

W_1 : work content, general
X : longitudinal distance between corner columns
Y : transverse distance between corner columns
Y : labour effort, per first unit of production in a series
a : horizontal acceleration of particles in an incoming wave
a_0 : wave amplitude
a_h : heeling moment arm
b : module width
d_c : dimensionless critical damping coefficient
g : acceleration due to gravity
h : module height
h : cylinder immersion
h_a : vertical position of windforce centre
h_1 : immersed column height
i : subscript, denotes relation with element or component
j : subscript, denotes relation with work-station
k : wave length = $2 \times \pi / \lambda$
k : ratio S/s
l : length horizontal immersed cylinder
m : mass, general
m : number of columns
n_1, n_2, n_3, n_4, n_5, n_6 : numbers of stiffener spacings
$n_1 = b/s$
$n_2 = h/s$
$n_3 = L_f/s$
$n_4 = H_c/s$
$n_5 = L_d/s$
$n_6 = B_d/s$

s : stiffener spacing

t : time

t : plate thickness

v : horizontal velocity of particles in an incoming wave

x : horizontal co-ordinate in the direction of wave propagation

$\overset{''}{x}$: horizontal acceleration of particles in an incoming wave

$y,\overset{'}{y},\overset{''}{y}$: vertical displacement, velocity and acceleration of the waterlevel in a wave

$z,\overset{'}{z},\overset{''}{z}$: vertical displacement, velocity and acceleration of a floating body from its still water position

z_a : amplitude of the vertical motion

α : ratio A_h/A_v

α : ratio b/h

β : ratio 1/h

η : usage factor, yielding

λ : wave length

ρ : mass density

σ : general stress notation

σ_a : von Mises equivalent stress

σ_y : material yield stress

σ_p : permissible stress

φ : heeling angle

ω : circular frequency

ω_n : natural circular frequency

ω_p : frequency of maximum wave energy

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