"DESIGN & CONSTRUCT" OF COMPLEX CIVIL ENGINEERING SYSTEMS

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A new approach to organization and contracts

PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
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Henri Arie Johan DE RIDDER

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PREFACE

This study on Design & Construct (D&C) contracts started in 1990 as a result of a vague unease about these types of contracts. Back then I was a team member of two technically very interesting projects (Lac Nord de Tunis and The Ekofisk Protective Barrier) which, unfortunately, amounted to very disappointing financial results. Despite competent teams, interesting work and challenging projects, neither myself nor anybody else in my environment could explain what exactly had gone wrong when the projects nevertheless made heavy losses.

Coinciding with the start of my study, my employer (HBW) started a new challenging D&C project as a participant of a Joint Venture: the Storm Surge Barrier in the Nieuwe Waterweg, Rotterdam. Again, I was appointed member of the design team. Within a year HBW was once again involved, as a participant of Joint Ventures, in three other D&C projects (LNG Jetty Brunei, NAM F3 Platform and Medway tunnel) for which contracts were awarded, showing the still optimistic view of Clients and Contractors with respect to these types of contracts.

The aim of my personal study was to discover an appropriate control system for D&C, which would be beneficial for all participants. It was explicitly not my intention to find out what was wrong about the present D&C situation, because an ordening to causal-variables and effect-variables is hardly possible when various related phenomenae occur simultaneously.

The reason for the study remained vague. After some time, however, the growing insight into the core of the matter also clarified what really is wrong with the present D&C situation. For the intermediate presentations in order to show the progress to my employer (HBW), I developed an anecdote conveying the present D&C situation, the reason being that most audiences are more interested in what goes wrong than in how the ideal situation should be. This anecdote, given on the next three pages, can be considered the reason for this study, showing all obstacles and misinterpretations of D&C. In the anecdote, however, does not give solutions to all mentioned problems and embarrassing situations. Otherwise the reason for writing this book would have become superfluous.

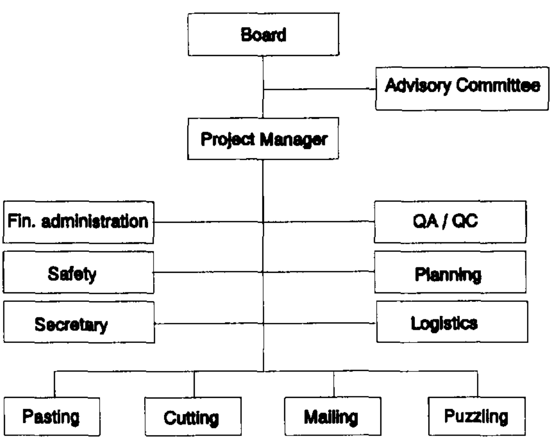
"GRANNY'S PUZZLE"

A Client's grandmother, who is fond of puzzles but who is too old for puzzling now, is celebrating her birthday. Client wants to surprise grandmother. He owns her favourite jig-saw puzzle of about 500 pieces (estimated). The Contractor is asked to solve the puzzle, paste the puzzle on a board, cut it in four pieces and send it to Client's grandmother. All to be done within 6 hours.

This can be considered a D&C project. A design process is a search process and can be compared to solving a jig-saw puzzle. The number of pieces can be seen as the number of requirements. The pasting and mailing can be seen as construction.

Two Contractors ("A" and "B"), both specialists in pasting puzzles, are invited to bid. In order to estimate the price, both Contractors set up a working plan: (1) make the puzzle on a board, (2) put a board on the finalized puzzle, (3) turn the ensemble, (4) lift the puzzle board, (5) spread glue on the back of the puzzle, (6) put the puzzle board on the puzzle, (7) wait 5 minutes, (8) cut the edges, (9) cut it into pieces, (10) put the pieces in an envelope and (11) bring it to the mailbox. The working plan has two main phases. The first phase involves solving the puzzle, an activity which does not belong to the primary process and should therefore be done as fast as possible. The second is the pasting phase in which the "real and risky" job should be done.

Contractor "A" awards the contract with a very low fixed price. His time schedule is as follows: 3 hours for solving the puzzle (those puzzlers!) and 3 hours for the "real job" (pasting, cutting and mailing). The most experienced paster of the company is appointed project manager and the organizational structure is sketched below:



Now the work can start. The Contractor is fully aware of the five golden rules for a successful production: (1) cluster elements according to location, material and process, (2) the more people, the more progress, (3) time pressure works, (4) competition is preferable (sub-optimization = optimization) and (5) no trials and certainly no errors! All team members are trained according to these rules.

However, the five golden rules for jig saw puzzling are: (1) clustering the pieces (colour, edges), (2) limit the number of puzzlers, (3) preferably no extreme time pressure, (4) no competition between the puzzlers (sneaky shifts of difficult pieces towards neighbours) and (5) stimulate trial and error! Unfortunately, none of the team members has ever heard of these puzzling rules. They merely had a pasting education and specialization.

After 3 hours, not even 20 % of the puzzle is ready. The 20 % refers to the easiest parts of the puzzle (edges and buildings). In a corner of the table a large number of pieces with identical colour (blue sky) is placed in front of a shy junior puzzler. The manager becomes a little nervous and walks around the table, calling his head office for eight extra puzzlers, which is materialized immediately. After 4 hours not even 30 % of the puzzle is ready.

At this moment the pasting people start their job, because they cannot wait anymore. They take away the edges of the puzzle and other small clusters, which are pasted on the board. Implicitly the working plan has changed! After a while, it becomes apparent that some pieces were not put in the right place by the puzzlers. Therefore, it is necessary to soak off some pieces. The organization is chaotic and the state of mind of the participants is rather bad.

At that moment, Contractor's controllers count 700 pieces instead of 500 pieces. The project manager (out of his mind) grabs about 200 pieces from the table and throws it into the dustbin shouting: "My contract covers a 500 pieces pasting job and not a 700 piece pasting job. Not one piece above the contractual 500 pieces will be pasted!". However, after three hours of trial and error, it becomes apparent that the pieces in the dust-bin are necessary to solve the puzzle.

Unfortunately, a lot of empty coffee cups have been thrown into the dust-bin. The manager himself separates the puzzle pieces from the dirt, cleans the pieces and asks the Client for extra time and extra money due to the additional 200 pieces.

The Client is fully aware of the big problem and gives the contractor one extra hour. The Client, however, does not pay extra money, since the number of pieces was defined as "ABOUT 500".

After 12 hours the puzzle is ready and after 15 hours the puzzle is mailed. At that moment, Granny's birthday celebration has been over for a few hours already.

One month after the project is finished, the Contractor claims additional money, which is fully rejected by the Client. After two years the claim is put into arbitrage. The outcome is that 50 % must be paid by the Client. With this outcome the project has two losers: (1) the Contractor who disturbed his own working method and delayed the puzzling activities by throwing away the 200 pieces, (2) the Client, who missed his goal (the birthday surprise) and who has to pay a substantial part of the Contractor's extra activities.

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EXECUTIVE SUMMARY

D&C contracts

Presently, the realization process of Complex Civil engineering systems is more and more often arranged with Design & Construct (D&C) contracts. With such a contract both design work as well as construction work are delegated to one single Contractor.
For Clients this type of contract is attractive. Dealing with one organization only, no disputed responsibilities and saving money and time due to better constructability of the design are important advantages.
The often heard and important disadvantage, namely less control possibility of the realization process, does not seem to be a constraint in the growing popularity of this type of contract for the time being. This does not mean that the present D&C practice could not be an obstacle to definite success of D&C contracts.

Purpose of this study

This study is aimed at the development of a control system for D&C of complex civil engineering systems, with organization and type of contract as main components.

D&C in theory

The goal of D&C is the search for an effective solution to a problem, which can be - and will be - implemented efficiently. The goal at the start of D&C, however, can hardly be defined as the perceived problem is different from the actual problem and the solution to the problem is, at best, known in a rough conceptual form.
In most cases, the badly defined goal makes that the required performance of the conceptual solution at the start of D&C is not sufficient for the effective solution which is needed at the end of D&C. This results in various risks for both Contractor as well as Client.
For optimal D&C, it is necessary that the risk should be carried by the party best able to either control or estimate the risk. Hence, "perception risks" are to be carried by the Client who might control the risks with goal adjustment. The "process risks" are to be carried by the Contractor, controlling the risks with the productivity of his D&C process.

The present D&C practice

The underestimation of D&C is hardly distinguished in the present D&C practice. Both Clients as well as Contractors experience D&C as a construction work preceded by some minor design work only (optimization on details). Both parties mistakenly assume that the goal is clearly defined and the efforts can be estimated. D&C is still arranged based on a Fixed-Price contract.
Due to the badly defined goal, the underestimation of efforts and the rigid type of contract, however, the D&C Contractor has a control problem. He thought to construct and install the concept, but as it turns out he must first search for an effective solution. Since, in most cases, he has already started with the execution of various components of the concept, the search for an effective solution becomes difficult, enhancing the costs. Although these additional costs originate from the previous project phases combined with the wrong perception of what D&C in fact is and not from the disappointing performance of D&C itself, these costs will not be compensated automatically.
Since the cost overruns will normally be claimed, the Client is confronted with the risk of a -possibly large - price overrun and a solution offering more possibilities than was originally called for. This last aspect is caused because there is no contractual room for goal adjustment between times.

The requirements for a control system for D&C

The main condition for optimal D&C is that the Client takes and controls the "perception risks", whereas the Contractor takes all "process risks". This is possible in case: (1) *the goal is quantified at the start of the contract period (initially required* performance of solution), (2) the actually required performance can be measured with respect to initially required performance, (3) the actual performance can be adjusted and (4) the extra efforts needed for actual performance exceeding the initially required performance, can be determined and made reimbursable.

Quantification of the required performance

The quantification of the required performance is possible by considering the conceptual solution as a system and decomposing the system into specific part-systems. *Those part-systems refer to a number of phase-systems* such as, for example, construction, utilization, etc. and to specific aspect-systems of equal scope and significance which are relevant to the distinguished phase-systems. Such aspect-systems are for instance strength and stability.

By taking into account the relations between these aspect-systems it is possible, with a simple transformation, to express the required performance into the sum of the required performances of the conceptual solution during the phase-systems. The performance itself is expressed in key-figures for aspect-systems.

Measurement of a change in the required performance

By measuring the key-figures of the aspect-systems during D&C, it is possible, using the above transformation, to establish the changes in the required performance with respect to the initially required performance.

Possibility of goal adjustment

When confronted with a change in the required performance, the Client can decide on a goal adjustment by selecting a suitable aspect-system, in most cases capacity or maintenance, on which costs can be saved. With the above transformation, the influence of such an adjustment on the overall performance can be determined.

Reimbursement of a change in the required performance

Reimbursing changes in the required performance is possible with a new type of contract, the Fixed-Price-Performance-Reimbursement D&C contract (FIPPER D&C). Without taking into account non-quantifiable uncertainties, a fixed price is agreed on for D&C with the conceptual solution as a frame of reference. With a proportionality principle between performance and efforts needed for that performance, a change in the required performance with respect to the initially required performance is made reimbursable.

Organization

The organization is aimed at controlling D&C by using aspect-systems. The Client takes over control in case the initially required performance is exceeded or a goal adjustment is desirable. Together with the type of contract as described above, it is possible to fully, dynamically and continuously control D&C.

Case studies

The present D&C situation is illustrated with a case study: The Storm Surge Barrier in the Nieuwe Waterweg, Rotterdam. The proposed control system is partially illustrated with three case studies: (1) the Ekofisk Protective Barrier, (2) the Storm Surge Barrier in the Eastern Scheldt and (3) the Storm Surge Barrier in the Nieuwe Waterweg, Rotterdam.

SAMENVATTING

D&C-contracten

Complexe civieltechnische werken worden in toenemende mate uitgevoerd op basis van een Design & Construct (D&C) contract. Met een dergelijk contract worden het ontwerp en de bouw in één opdracht aan aannemer gegund.
Voor opdrachtgevers is deze contractvorm aantrekkelijk. Slechts één realiserende organisatie, geen omstreden verantwoordelijkheden en besparingen in tijd en geld door een meer uitvoeringsvriendelijk ontwerp, zijn belangrijke voordelen.
Het veel gehoorde en belangrijke nadeel, de moeilijke beheersing van het realisatieproces, lijkt vooralsnog geen belemmering te zijn voor de groeiende populariteit van deze contractvorm. Dat neemt niet weg dat de huidige uitvoeringscultuur een blijvend succes van D&C-contracten in de weg zou kunnen staan.

Doel studie

Deze studie is er op gericht een besturingssysteem voor D&C van complexe civieltechnische systemen te ontwikkelen met als belangrijkste onderdelen de organisatie en de contractvorm.

D&C in theorie

Het doel van D&C is het zoeken naar een effectieve oplossing voor een probleem dat op efficiënte wijze kan worden - en ook wordt - geïmplementeerd.
Het doel is echter bij de aanvang van D&C nauwelijks goed te definiëren, omdat de perceptie van een probleem verschilt van het werkelijke probleem en de oplossing voor het probleem hoogstens in ruwe conceptvorm bekend is.
Dit heeft meestal tot gevolg dat de geëiste prestatie van de conceptoplossing aan het begin van D&C niet voldoende is voor de effectieve oplossing die aan het eind van D&C nodig blijkt. Dit geeft uiteenlopende potentiële risico's voor zowel de opdrachtgever als de aannemer.
Voor een optimaal D&C-proces is het noodzakelijk dat de risico's door die partij wordt gedragen die deze het best kan inschatten en ook kan beheersen. Aldus neemt de opdrachtgever de perceptierisico's voor zijn rekening, die hij kan beheersen met doelaanpassingen en neemt de aannemer de procesrisico's voor zijn rekening, die hij kan beheersen met de produktiviteit van zijn D&C-proces.

De huidige D&C praktijk

De onderschatting van D&C wordt, *in de huidige praktijk, nauwelijks onderkend*. Zowel opdrachtgevers als aannemers beschouwen D&C als een uitvoeringswerk waar nog enig ontwerpwerk (detaillering en optimalisering) aan vooraf dient te gaan. Beide partijen gaan er van uit dat het doel duidelijk is vastgelegd en dat de inspanningen aldus goed te begroten zijn. D&C wordt nog steeds aangegaan op basis van Fixed-Price contracten.
Door het slecht gedefinieerde doel, de onderschatting van de benodigde inspanningen en de rigide contractvorm heeft de D&C-aannemer echter een besturingsprobleem. Hij dacht het concept te kunnen uitvoeren, maar blijkt eerst een effectieve oplossing te moeten zoeken. Omdat hij meestal al op onderdelen begonnen is, wordt het vinden van effectieve oplossingen moeilijker, waardoor de kosten oplopen. Hoewel deze meerkosten worden veroorzaakt door het voortraject alsmede een verkeerde perceptie van wat D&C eigenlijk is en niet door de tegenvallende D&C prestatie zelf, worden ze niet automatisch vergoed.
Omdat kostenoverschrijdingen in de regel worden geclaimd, wordt de opdrachtgever geconfronteerd met het risico van - mogelijk grote - prijsverhogingen en met een oplossing die meestal meer biedt dan nodig is. Dat laatste komt omdat er door de contractvorm geen tussentijdse doelaanpassingen mogelijk zijn.

Waaraan het D&C besturingssysteem moet voldoen

Het leggen van de perceptierisico's bij de opdrachtgever en de procesrisico's bij de aannemer als belangrijkste voorwaarden voor een optimaal D&C-proces, is mogelijk als: (1) het doel bij aanvang van de werkzaamheden wordt gekwantificeerd (initieel geëiste prestatie), (2) de werkelijk geëiste prestatie t.o.v. de geëiste initieel geëiste prestatie kan worden gemeten, (3) de werkelijke prestatie eventueel kan worden aangepast en (4) de extra inspanningen, die nodig zijn voor het bewerkstelligen van een werkelijke prestatie die groter is dan de geëiste prestatie, kunnen worden bepaald en verrekend.

Kwantificering van de geëiste prestatie

De kwantificering van de geëiste prestatie is mogelijk door de conceptoplossing als systeem op te vatten en te ontleden in specifieke deelsystemen. Die deelsystemen betreffen niet de elementen van het systeem, maar een aantal fase-systemen zoals bijvoorbeeld bouwfase of gebruiksfase en de voor deze fase-systemen relevante, specifieke aspect-systemen van gelijk gewicht en inhoud. Dergelijk aspect-systemen zijn, bijvoorbeeld, sterkte en stabiliteit.

Met inachtname van de relaties tussen deze aspect-systemen is het mogelijk om, met een eenvoudige transformatie, de geëiste prestatie uit te drukken als de som van de geëiste prestaties van de conceptoplossing gedurende de verschillende fase-systemen. De prestatie zelf wordt uitgedrukt in kengetallen voor de aspect-systemen.

Het meten van een verandering in de geëiste prestatie

Door het meten van de kengetallen van de aspect-systemen is het mogelijk om, met behulp van bovengenoemde transformatie, de veranderingen in de geëiste prestatie te meten ten opzichte van de initieel geëiste prestatie.

Mogelijkheid tot doelaanpassing

Indien geconfronteerd met een verandering van de geëiste prestatie, kan de opdrachtgever een besluit nemen tot het aanpassen van het doel. Daartoe wordt een geschikt aspect-systeem geselecteerd, meestal onderhoud of capaciteit, waarop kan worden bespaard. Met behulp van de transformatie kan de invloed van de aanpassing op de totaalprestatie worden bepaald.

Verrekening van een verandering in de geëiste prestatie

Verrekening van een verandering in de geëiste prestatie is mogelijk met een nieuw type contract, het Fixed-Price-Peformance-Reimbursement D&C-contract (FIPPER D&C). Zonder de niet te kwantificeren onzekerheden mee te nemen, wordt een vaste prijs afgesproken voor D&C met de conceptuele oplossing als referentie (initieel geëiste prestatie). Met een evenredigheidsbeginsel tussen prestatie en de daarvoor benodigde inspanningen, wordt een verandering in de prestatie t.o.v. de initieel geëiste prestatie, verrekenbaar gesteld.

Organisatievorm

De organisatievorm is gericht op het besturen van D&C met behulp van aspect-systemen. De opdrachtgever neemt de besturing tijdelijk over indien de initieel geëiste prestatie wordt overschreden, of een doelaanpassing gewenst is. Samen met de bovengenoemde contractvorm is het mogelijk om D&C volledig, dynamisch en continu te beheersen.

Case studies

De huidige D&C-situatie is geïllustreerd met een case study: de Stormvloedkering in de Nieuwe Waterweg. Het voorgestelde D&C-besturingssysteem is partieel geïllustreerd met drie case studies: (1) de Ekofisk Protective Barrier, (3) de Stormvloedkering in de Oosterschelde en (3) de Stormvloedkering in de Nieuwe Waterweg.

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ANNEXES

1. INTRODUCTION

1.1 On the realization process of large systems

Realization processes of large systems are associated with project management, contracts and last but not least overruns of costs and time. A study relevant to this subject is published by Morris[1]. Based on various sources, an outline is given of overruns of costs and overruns of time for many major projects. It is assumed that in all cases the project performance did meet the requirements. This is a realistic assumption, since most projects will come to an end, where eventually all "available" resources will have been mobilized to meet the defined requirements.

The outcome of the study is not encouraging. A large list of substantial overruns (up to 700 %) is given with corresponding principal reasons for those overruns. In the list of principal reasons the following categories can be distinguished: (1) underestimations (size, complexity, difficulty, quantity, technological advance,), (2) changes (scope, design, schedule, quantities), (3) financing (inflation, interests, financial problems), (4) management (poorly defined contracts, faults, strategy, resources) and (5) contracting (badly defined contracts). Not surprisingly, Morris characterized large projects as "those undertakings which are essential to the development of society but which are poorly understood and too often inadequately managed".

1.2 Civil engineering

General

In this paragraph the specific characteristics of civil engineering technology are discussed. In the context of this study no reason can be found for a fundamental treatment of characteristics of civil engineering technology and associated aspects. Therefore, an eclectic survey has been conducted to give a short overview of those characteristics which are most relevant with respect to the realization process of civil engineering systems. The following items are distinguished: (1) purpose and function, (2) technology and (3) developments.

Purpose and function

The following functions of civil engineering can be distinguished[2]:

- protection against floods, reclamation;
- water resources management (quantity and quality);
- infrastructure (construction and control);
- protection of characteristic landscapes and cities;
- environmental protection and rehabilitation;
- mining;
- science (CERN);
- defence.

Most of these functions have a strong economical impact. The economic significance of protection against floods, water resource management, infrastructure and mining does not require further explanation. At present, a growing notion is observed that the protection of landscapes and cities (cultural aspects) and environmental protection and rehabilitation represents economical value as well.

Developments

With respect to functions mentioned above, the following developments are expected requiring technological answers[3]. It is noted that these developments are interrelated:

- *Rise of the sea level:* This is a consequence of the green house effect, which requires advanced technology for: (1) inland drainage, (2) shore protection, (3) design criteria for estuary and rivers.

- *Scarcity of land:* Although the total land area in the world is very large, it is well known that the area which can be used for human life in all its varieties is rather limited. When combined with the fast increase of the world population[4], the civil engineering sector can probably provide answers: reclamation, underground construction, cultivation of land, water resources control, etc.

- *Increase of mobility:* With the growth of urban areas and the growth of the human activities within these areas, the mobility of urban population increases rapidly. Due to the limited possibilities with respect to space, complex solutions must be found for these infrastructural problems[5].

- *Pollution:* The increase of pollution makes it necessary to find rehabilitation techniques which: (1) can be applied on a large scale, (2) can be applied on location and (3) are relatively cheap;

- *Waste:* Due to the high rate of consumption not only a problem arises with minerals and the transformation technology for a wide spectrum of products with associated pollution, but also an increase is observed of waste material. New technology must be developed with respect to:(1) cleaning, (2) working up, manipulating and (3) re-using. A substantial part of this technology is based on civil technology;

- *Reduction of energy consumption:* Sooner or later, the energy consumption must be reduced. This development can lead to energy saving transport systems: (1) High Speed Railways and (2) Pipeline transportation systems.

Technology

With respect to specific technological characteristics, the following items can be distinguished:

- The civil engineering sector has a significant artisan character, strongly focused on the execution of works. This can be explained by the historically grown relation between the Client (in most cases the government) and the various production companies[6]. The governmental budgets were (and still are) mainly based on political motives and previous budgets, more than on motives of rentability.

- The strong relation between (governmental) Clients and production companies together with the budgeting strategy as described above, is probably the main reason for the passive attitude of most civil Contractors. The technical "state of the art" suffices to bring most projects to an end.

- The realization of a civil engineering structure is mostly a "one shot" realization process. It can be compared with the prototype development for other industrial products. The difference is that it has a unique character and the prototype will not be taken into production. In other words, civil engineering is certainly not mass-production but tailoring merely for purpose[7].

- Due to the prototype development character, a large civil engineering project must either be developed from nothing, or be developed based on existing technology. This makes estimation of the necessary realization process difficult, in contrast to the development of new industrial products based on: (1) product families, (2) product functions, (3) product modules or (4) products[8]. This is a possible explanation for the fact that hardly any research on product development is observed within the civil engineering sector. In relation to that, also a poor product and knowledge protection against innovation is observed within this industrial discipline.

- Since the prototype is not copied and subsequently sold in large numbers, the development budget is normally rather low. The available budget rarely exceeds 5 to 10 % of the total prototype costs (and thus project costs). It is interesting to compare this development cost percentage with the development budgets for electronic products, cars or airplanes. In that industrial sector, the quotient of development costs and the production cost of one single prototype is substantially larger than 1, at least 10, but can sometimes exceed 100[9].

- A large civil engineering project is always Client specific; it must provide a specific solution for a Client having a specific problem. As a result, a very close relationship exists between Client and Contractor. Two specific complicated factors can be distinguished[10]: (1) requirements of the product to be made are very specific, demanding a very precise inventory and specifically formulated specifications and (2) the more specific the product to be made is, the less the use of product standards can be, leading to performance and quality problems.

- Civil engineering structures have a strong interaction with many aspects of environment: soil, ground water, wind, currents, tides, morphology, waves, salt water, earthquakes, etc. In view of the limited development budget as mentioned above, the investigation of the environmental conditions in relation with the design of the structure is in most cases not sufficient. Therefore, most development processes of civil engineering structures are characterized by a fight against initially underestimated loads and against severe foundation problems. In particular the soil condition, despite soil investigations, whether they are intensive or not, remain uncertain. This uncertainty refers not only to the quality of the soil (rock, peat, clay, silt, sand, etc.) but also its uniformity over the relevant foundation area.

- In most cases transport of the civil engineering products is not possible. Therefore, civil engineering systems are installed and most of the time also constructed on location. In consequence, the realization process must cope with various temporary construction phases, characterized by difficult interactions with environmental conditions.

- Due to the massive character of civil engineering structures it can generally be stated that the added value per kg of product is rather low.

- A very important aspect of civil engineering products is the exceptionally long required lifetime which must be guaranteed[(11)] in contrast to the relatively short lifetime required for other industrial products. This demands very particular quality requirements of the materials to be used.

- Often, for civil engineering projects, the eventual User (Owner) of the realized structure is not the Builder. This adds another close relationship between two parties which requires precise inventory of requirements and a correct specification. This is a complicating factor with respect to utilization aspects and in particular the maintenance aspects[(12)].

- Given the function of civil engineering structures, that is, giving a particular solution for a general civil engineering problem, unavoidably certain groups of people exist, experiencing negative influences from the solution. Therefore, the realization process in the complex society of today will be surrounded by many affected parties, making the process complicated.

- A civil engineering system cannot function without components from other disciplines (electrical, mechanical, environmental, chemical disciplines). Given the unique character, it is hardly possible to decompose the total system into part-systems with separated development processes. Most disciplines operate parallel in the primary development process, requiring strong coordination.

1.3 Why "Design & Construct"?

Purpose of D&C Contracts

Until the middle of the previous century, the realization process of civil engineering systems was generally the responsibility of one single man, the master builder. Since then, the most common structure of an organization for the realization of such a system has consisted of a team of paid and independent designers and a Contractor for the work after the design is determined. In this context the Owner or Client deals with at least two separate organizations.

Recently, a change has come about in which organizations, able to cover both the design as well as the construct part of the overall realization process, have been awarded contracts to realize civil engineering systems. At first, this method was merely used for standard types of structures. At present, however, any project is undertaken with this type of contract(13). In the last decade even large, complex, civil engineering systems, with their particular difficulties, were realized in this way. This type of contract is mostly called "Design & Construct" when dealing with buildings and sometimes "Engineering, Procurement, Construction and Installation" when dealing with civil engineering systems. The term "Design & Construct", abbreviated as "D&C", is commonly known and is therefore used in this study.

In principle, the purpose of a D&C contract can be established from both the Contractor's as well as the Client's point of view. The purpose of a specific type of contract between two parties in order to solve a problem can be derived by considering the way the two parties are able to gain the respective advantages and to control the respective disadvantages. Therefore it is necessary to outline the advantages and disadvantages of D&C contracts.

Advantages of D&C Contracts for the Client (Owner)

The following advantages can be distinguished:

- The Client has to deal with only one organization for both design and construction. At least the relationship between the involved parties is simpler. In theory the one-team organization can be very effective and efficient.

- There are no disputed responsibilities. The D&C firm is solely liable(14). The clear separation of responsibilities between Client on one side and Contractor on the other is considered to be a main advantage of D&C(15).

- There is better constructability. Constructability is defined as the optimum use of construction knowledge and expertise in the phases of conceptual planning, detail engineering, procurement and field operations to achieve the overall project objectives (16). The integration of construction knowledge into all project phases as an effective means for reducing project costs and the completion time was formally realized in the mid 70's(17). Seven concepts of constructability are developed by the Construction Industry Institute(18):

  * Design and procurement schedules should be construction driven. The advantages of the construction driven schedule are significant(19): (1) project duration is reduced; (2) fewer delays are experienced in the field; (3) engineering and procurement activities are effectively prioritized; (4) work package is more effective; and (5) project personnel has an increased awareness of true schedule goals.

  * Designs should be selected to enable efficient construction. Illustrative principles for simplifying designs include(20): (1) using a minimum number of components, elements or parts for assembly; (2) using readily available materials in common sizes and configurations; (3) using simple connections, easy to execute, with minimum requirements for highly skilled labour and special environmental controls.

  * Standardization of design elements should be used as much as possible. The advantages of standardization include the following(21): (1) benefits of the learning curve from repetitive field operations and increased productivity; (2) volume purchase discounts from more of the same material; and (3) simplified material procurement and materials management from fewer differing materials.

  * Use of modularity and preassembly designs, which facilitate fabrication, transport and installation. Module/assembly fabrication concerns might include the following(22): (1) temporary structural supports; (2) dimensional accuracy; (3) minimization of scaffolding needs; (4) sequence of operations; and (5) design standardization wherever possible.

  * Designs should promote accessibility of all resources (manpower, material and equipment). Recommendations for increasing accessibility include(23): (1) establishing guidelines for minimum spacing of project elements; (2) specifying well defined access lanes; (3) dedicating clear spaces for pieces of equipment and linear runs; and (4) communicating accessibility related information to project designers and planners.

* Designs should facilitate construction and installation under adverse environments. Projects constructed on sites where weather conditions are adverse, present a greater challenge to both the designer and the constructor. Designers should investigate ways in which the exposure to temperatures, rain, wind, water, currents, waves, etc. may be minimized [(24)].

* Specifications should not impose unnecessary complex construction methods, building materials, installation tolerances, or other qualitative requirements concerning form, which hamper field operations. Special attention must be paid to tolerance requirements. In this respect, the most beneficial tolerance relaxations permit the use of less sophisticated equipment and procedures[(25)].

- Time can be shortened by overlapping later stages of design with early stages of construction[(26)]. This is a possible advantage, as the overlap is optional.

- Saving on consultancy costs[(27)].

- Estimations of duration and costs of construction have higher rate of reliability[(28)].

- Project harmony can be improved. Two areas of improved harmony can be distinguished[(29)]: (1) integration of design culture and construction culture, which should facilitate the coordination and should reduce conflicts between designers and construction engineers (workmen, engineers) and (2) the clear relation between only two participants should reduce conflicts.

Sometimes it is suggested that one of the Client's advantages of D&C for the realization of civil engineering systems is that the risk with respect to the overall project costs is shifted towards the Contractor. Hence, the Client can obtain a firm price at an early stage. This is not correct, since D&C refers only to the description of a task. Risk is certainly not only determined by the defined task but also by the type of financial contractual arrangements.

Disadvantages of D&C Contracts for the Client

The following disadvantages are distinguished[30]:

- The number of D&C firms competent to realize a particular project in a D&C contract is likely to be smaller than the number of possible teams which could be assembled in the traditional method with specifications and drawings prior to construction. This may have price consequences;

- The client may have to commit himself at an early stage to contractual and financial arrangements which he might prefer to consider only when the design is completed;

- A D&C firm is an entity. Hence, when one part of the firm mistakenly acts against Client's interest, it is difficult for another part to redress the balance.

- It is difficult to control the desired balance between capital costs and maintenance costs. This requires strict contractual clauses.

It can be concluded that Client's disadvantages refer to control problems.

Advantages of D&C contracts for the Contractor

The advantages of D&C contracts for Contractors are[31]:

- D&C may be a means to profile the firm for a strategic market position. The number of D&C competent firms is smaller than the number of traditional contracting firms;

- by undertaking projects with a D&C contract, the Contractor is able to upgrade his technological power.

Disadvantages of D&C Contracts for the Contractor

It is remarkable that disadvantages of D&C Contracts for Contractors are hardly reported in literature. This is strange since the task of the Contractor is extended in a D&C contract. This extension implies a change of responsibilities and risks, which should be reflected in a change of organizational structure and an adjusted type of contract.

In most cases, these changes and, in particular, the corresponding changes of culture induce control difficulties in most cases[32]. Hence it is assumed that the Contractor have some control problems as well.

1.4 Aim of the research

Given (1) the rich history of cost and time overruns of complex projects (see paragraph 1.1 of this book), (2) the trend to realize these projects with a D&C contract, (3) the changed responsibilities of the D&C task, (4) the reported control problems of D&C tasks and (5) the advantages of D&C, it is worthwhile to investigate the changed D&C situation in a more fundamental way. This is the main cause for this study.

It is evident that the advantages of D&C contracts for the Client as well as the Contractor can only be gained in case the realization process can be controlled respectively the induced risks will be controlled. Tentatively, the control problem as sketched in fig. 1.4.1 consists of two components:

- the changed primary process, which have organizational implications:
- the changed responsibilities, which have contractual implications.

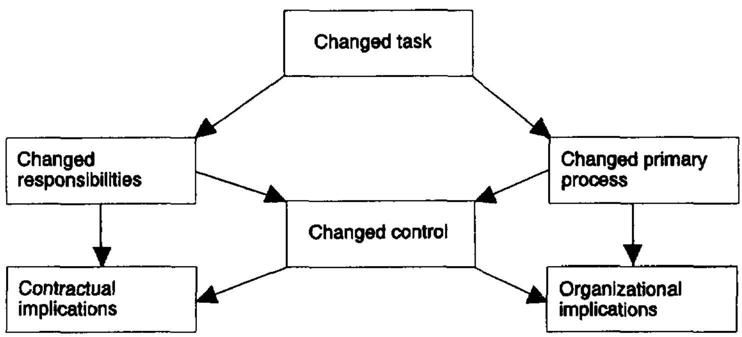

Fig. 1.4.1 The control problem of D&C contracts, which is induced by the change of task with respect to the task in the traditional contracting situation. Due to this changed task both contractual implications as well as organizational implications are incurred.

The aim of the research is to give a conceptual framework providing an organizational structure for Client and Contractor and a contractual concept, guaranteeing a satisfying realization process of complex civil engineering systems with a D&C contract. "Satisfying" in this context implies that both involved parties will reach their project goals.

As far as the conceptual framework is concerned as the aim of the research, it can be stated that in order to elaborate an organizational issue, the formation of a conceptual framework, that is a framework of consistently interrelated concepts, is recommended for the following reasons[(33)]:

- the organizational science is still in a pre-paradigmic stage, which would result in starting research on a pre-paradigmic conceptual level.

- scientific progress starts with the formation of concepts. Thereafter, the commonly known process for the formation of theory begins. As the organizational science theories do not have such a status it is logical to start at the conceptual level.

- The notion that organizational science is not interested in concepts but only in practical problem solving capacity is not correct. The development of practical problem solving methods cannot be realized without the backing of theoretical concepts.

1.5 Methodology

The subject of this study comprises various disciplines. The combination of the main ingredients makes that the research domain is relatively unexplored and complex. In that case, it is difficult to find and define a sharp, adequate and empirical scientific hypothesis. A hypothesis is defined as an open, supposed and general rule or law, which can be checked against new facts or observations. The forming of a hypothesis supposes a basis of findings or observations. This can be based on personal experience, registrations, observations or research of others. The forming of a hypothesis is only possible in case the facts or observations will be interpreted.

Given the aim of the research, an interpretive-theoretical methodology is adopted[(34)]. Interpretation is characterized by the following aspects: (1) it concerns a closed and clearly defined set of phenomena, (2) during the interpretation no new facts may be added, (3) it is assumed that the observed phenomena obeys a general law or rule which also applies outside the defined set of phenomena, (4) the applicability or validity of the rule or law is dubious.

The essence of this type of research is an interpretation and a theoretical evaluation of a given closed set of findings. The facts or observations are linked together by trying to derive them from a hypothesis, theory, vision or notion which is, from the researcher's point of view, possibly valid for the considered set of findings. This type of research is indicated by the impossibility to solve the problem by means of empirical research. In other words, the set of phenomena exists and is considered to be unique(35).

Interpretation contains some intrinsic difficulties (contamination and subjectivity). Normally, for closed sets of data, which require theoretical interpretation, many aspects and many variables play a role. Therefore, logically different interpretations can exist for the same set of raw materials. One of the difficulties is that interpretations of parts are mutually dependant. The interpretations of the whole is based on interpretation of the parts, but interpretation of the parts must be done in the total context.

The central question of theoretical interpretative research is whether an interpretation can be justified or not, that is, whether the interpretation is a substantial contribution to knowledge and insight of the observed set of data. The following justification is given for this theoretical interpretative study on D&C of complex civil engineering system: (1) the subject of study is unique and important enough, (2) the subject of this study is too complex and unique to find generally accepted laws which could give an explanation for the observed phenomena and (3) the subject of this study is objectively delimited;

The interpretation is based on convergency within the observed set of data. The set of data consists of complex patterns and structures. It is stated that the more details, facts, phenomena within the observed material are covered by one interpretative action, the better the mutual support and the support of the hypothesis is.

1.6 System Theory

During the fifties, biologists concluded that structure and activities of organisms could only be understood if that organism was studied as a whole system. From these notions, a system theory was initiated as a new scientific discipline. In the sixties, a system theory was also adopted for management thinking, economics and even for sociology(36). At present, the system theory is considered to be the main tool to the solution of complex problems(37). It becomes clear that there is a need for interdisciplinary scientists, who are able to achieve a goal-oriented coordination and integration of the activities of scientific specialists.

There are, however, some objections against system theory for organizational purposes[38]. System analyses have a number of endemic weaknesses[39]. The most important are:

- attachment to quantification;
- incapacity to handle conflicting non-commensurate values;
- requirement for clear-cut criteria;
- neglect of political feasibility;
- omission of adequate recognition for non-rational decision-making processes such as tacit knowledge, creativity and judgement;
- inability to deal with large complex systems;
- lack of instruments for taking account of motivations.

This list is certainly not in line with the claims for successful application of system theory. Dror[40] suggests that the successes were merely caused by brilliance and experience of the early pioneers of system theory then the theory itself.

In an organizational context however, the system theory is considered to be useful for the development of conceptual frameworks when also emphasis is laid upon[41]: (1) qualitative analysis, (2) innovative thinking, (3) use of tacit knowledge and (4) multiple criteria. Moreover, in consequence of the eclectic method in order to arrive at a conceptual framework for the realization of complex civil engineering systems with a D&C contract, a first survey on existing literature of organizational science pointed out that system theory is used frequently to develop conceptual frameworks: (1) systematic problem solving process[42], (2) systematic control of systems[43], (3) systematic decision making[44] and (4) systematic contracting strategy[45].

Given the practical aim of this study and the necessary choice to adopt a frame of reference which is mainly based on system theory, the main goal of this study is a contribution to practice, whereas a possible contribution to theory is not excluded.

1.7 Delimitation

General

In order to avoid misunderstandings it is important to clearly define the scope of the study. The subject of study refers to Contractor's participation in Client's realization process of large, complex, civil engineering structures with a D&C contract. In other words, the study refers to the roles to be played by participants in very specific project circumstances, which are indicated in figure 1.7.1.

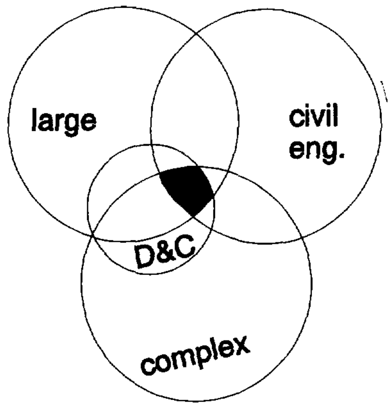

Fig. 1.7.1 *This figure represents the relevant subsets of particular project circumstances with respect to this study. The black spot in the middle of the subsets, is the union of all subsets and forms the subject of the study.*

Delimitation with respect to organizational aspects

As defined in section 1.4, a structure should be given for both the organization of a D&C project as well as the make up of an appropriate type of contract.

As far as the organizational issues are concerned, the active part, that is the management, falls outside the scope of study. The incorporation of management aspects is not necessary, since the aim of the study is to find out the most adequate organizational structure.

As far as the contractual issues are concerned, the active part, that is negotiation, does not belong to the scope of the study, since the aim of study refers to the structure of the D&C contract.

Delimitation with respect to participants in D&C projects

As far as the participants dealing with an D&C project are concerned, the number of participants is limited to two (2): The Client (Owner) and the Contractor. Hence, typical aspects concerning the roles to be played when conducting a D&C project with a Joint Venture, will not be discussed. In addition to that, the relation between Contractor and Sub-Contractor does not belong to the scope of study either.

Delimitation concerning financial and contractual matters

The financial part of D&C projects does not belong to the scope of study. As far as the contractual matters are concerned, emphasis is put on typically technical and administrative aspects of contract types. Consequently, a large number of terms and conditions of contracts will not be dealt with. Such terms and conditions are for instance: (1) general forms of contract, (2) standard terms of contract, (3) terms of payment, (4) liquidated damages, (5) delivery conditions, (6) defect arrangements, (7) insurances and indemnity, etc. etc.

Delimitation about Client's and Contractor's goal

Although different goals can be distinguished for Clients as well as Contractors when dealing with realization processes for large civil engineering projects, the starting point of this study for the goal concept of the Client and Contractor is a satisfactory performance of their respective part of the realization process. For the moment, a satisfactory performance is defined as the finding and implementation of an effective solution in an efficient way.

1.8 Synopsis

The study is divided into four parts.

Part 1: Theoretical aspects of the realization process of complex systems

In chapter 2, the methodology of the theoretical problem solving process as an abstraction of the "one shot" realization process is discussed. Milestones and criteria are defined. Notions on effectiveness and efficiency are given. The influence of complexity is investigated. In chapter 3 the control of the problem solving process is discussed at the highest possible abstraction level.

Part 2: Practical aspects of the realization process of complex systems

Given the theoretical aspects of the problem solving process, the practical implications with respect to organization and contracts are generally outlined in chapter 4. In chapters 5 and 6 the two main organizational issues, decomposition and coordination, are investigated in detail. In chapter 7 different types of contracts are discussed.

Part 3: The present Design & Construct situation

This part is divided into two chapters. In chapter 8, the actual D&C situation with respect to organizational structure and types of contracts is described. In chapter 9, a case study is presented as an example of the present D&C situation.

Part 4: The proposed control system of Design & Construct of complex civil engineering systems

This part is divided into four chapters. In chapter 10, the proposed control system for D&C of complex civil engineering systems is presented, comprising relevant, organizational and contractual issues.

After this theoretical part, three case studies will be presented.

The first case study, presented in chapter 11, gives a description of the design of the installation and offshore completion of the Ekofisk Protective Barrier, giving a practical application and illustration of the proposed goal control for large, complex, civil engineering projects. The case study is a validation of a part of the proposed control system.

The second case study is given in chapter 12 and refers to an ideal, one-aspect goal control model which is the tolerance control model as used in the realization of the Storm Surge Barrier in the Eastern Scheldt. This case is a validation of a part of the control system.

The last case study (chapter 14) consists of three showcases illustrating the possibilities of the proposed control system using actual control situations which occurred in the projects as described in chapters 9 and 11.

Notes

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   Bogue, D.J., Principles of Demography, John Wiley and Sons; New York, 1969.
5. Goode, H.H. and R.E. Machol, System Engineering, An Introduction to the Design of Large Scale Systems.
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7. Ibid.
8. Muntslag, D.R., "Kwaliteitsbeheersing van complexe klantspecifieke produkten", in: Kwaliteit in de ontwerpfase, Stichting Bedrijfskunde-Congres Industria, TUE, Eindhoven, 1992.
9. Obtaining information on real development cost of mass production goods is difficult. Nevertheless, sometimes some rough figures can be derived from various articles in newspapers and magazines. For instance, the development costs of the Fokker 100 and Fokker 50 aircrafts are estimated at Dfl 1.5 billion (personal opinion). The prices of the aircrafts are respectively Dfl 50 million and Dfl 25 million. From these rough figures, the ratio between development budget of the aircraft programme and the price of an individual aircraft can be derived (approximately 40).
10. Muntslag, D.R., "Kwaliteitsbeheersing van complexe klantspecifieke produkten", in: Kwaliteit in de ontwerpfase, Stichting Bedrijfskunde-Congres Industria, TUE, Eindhoven, 1992.
11. For two large projects in The Netherlands rather extreme lifetimes were required to guarantee: The Storm Surge Barrier in the Eastern Scheldt: 200 years (see chapter 11) and The Storm Surge Barrier in the Nieuwe Waterweg, Rotterdam: 100 years (see chapter 9).
12. This is a general problem. During project development, the building department is often confronted with cost and time overruns. In consequence, the natural response is to change the scope. The easiest way is to change the agreed balance between capital cost and maintenance cost in order to stay within the budget. This response causes difficulties between building department and utilization department. The problem becomes worse when dealing with a Design & Construct contract. In that case maintenance could be dealt with in a step-motherly way. This is shown by Rohde, A.A.J., Het Life Cycle Costing Concept en de Stormvloedkering in de Nieuwe Waterweg, Afstudeerscriptie Katholieke Universiteit Nijmegen, Faculteit der Bedrijfswetenschappen, 1992.
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O'Connor, J.T., S.E. Rusch and M.J. Schultz, "Constructability concepts for engineering and procurement" in: Journal of Construction Engineering and Management, ASCE, 113(2), 1987.
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21. Ibid. and O'Connor, J.T. and R.L. Tucker, Improving industrial project constructability, Report to Texaco, Inc. at University of Texas, Austin, Texas, 1983.

22. O'Connor, J.T., S.E. Rusch and M.J. Schultz, "Constructability concepts for engineering and procurement" in: Journal of Construction Engineering and Management, ASCE, 113(2), 1987.

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24. O'Connor, J.T., S.E. Rusch and M.J. Schultz, "Constructability concepts for engineering and procurement" in: Journal of Construction Engineering and Management, ASCE, 113(2), 1987.

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26. This advantage is mentioned by CIRIA (Construction industry research & information association), A client's guide to Design & Build, London, 1981. As will be shown in the next chapters, the option is only satisfactory under certain organizational and contractual conditions.

27. This advantage is mentioned by Doree, A., K. Veenvliet en H. Wind, Evaluatie van het ontwerpproces Stormvloedkering Nieuwe Waterweg, Vakgroep Civiele Techniek, Faculteit der Bedrijfskunde, Universiteit Twente, Enschede, 1991. As a matter of fact the consultancy task is taken over by the D&C Contractor, which will be paid anyway. Consequently, the saving of consultancy costs is not substantial.

28. This advantage is mentioned by Doree A., K. Veenvliet en H. Wind, Evaluatie van het ontwerpproces Stormvloedkering Nieuwe Waterweg, Vakgroep Civiele Techniek, Faculteit der Bedrijfskunde, Universiteit Twente, Enschede, 1991. The estimation of project efforts by the D&C Contractor is not necessarily more reliable than the estimation of the client. In the contrary, due to the competition the underestimation of efforts is expected to be larger than the underestimation of the client.

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    In 't Veld, Analyse van organisatieproblemen, Stenfert Kroese, Leiden, 1988.
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PART 1: THEORETICAL ASPECTS OF THE REALIZATION PROCESS OF COMPLEX SYSTEMS

2. METHODOLOGY OF THE "COMPLEX" PROBLEM SOLVING PROCESS[1]

2.1 General

In this chapter a theoretical description is given of the complex problem solving process, which is considered the abstraction of the "one shot" realization process of a complex civil engineering system[2].

This chapter is divided in three parts. The first part deals with the "problem", being the start of a problem solving process. Definition, classification and characteristics are given. In the second part the problem solving process is in first instance described with respect to effectiveness of the solution. Milestones, phases, activities and criteria are presented and the influence of complexity is investigated. Then, in the third part, the efficiency of the problem solving process is introduced, which is associated with costs and time.

2.2 The problem

2.2.1 Definition of a problem

In general, a problem is defined as the difference between the desired and the actual situation[3]. This definition does not exactly cover the practical problem situation, which would lead to the start of a problem solving process. Two objections can be given[4]:

- The objective character of the above definition is not correct. A problem is by definition subjective. For example, a severe problem of a certain individual is not necessarily a problem for another individual. Hence, there must be a group or an individual who is confronted with an undesired situation.

- The uneasy feeling as a consequence of the difference between the desired and the actual situation must be such that it causes a willingness to do something about it.

Given the two objections above, the following definition of a practical problem is proposed[5]:

- an individual or a group has a problem (Problem Owner);
- there is friction between the desired situation and the actual situation;
- this friction generates an uneasy feeling;
- the uneasy feeling is strong enough to activate the Problem Owner to do something about the actual situation;

2.2.2 Problem characteristics

Given the above definition, it will be clear that not only the actual situation but also the desired situation must be represented as clearly as possible. The representation of these situations is determined by the perception process[6]. With respect to perception, a problem can be defined as a dissatisfied need to change a perceived actual situation into a perceived desired situation[7]. This definition is graphically presented in figure 2.2.1.

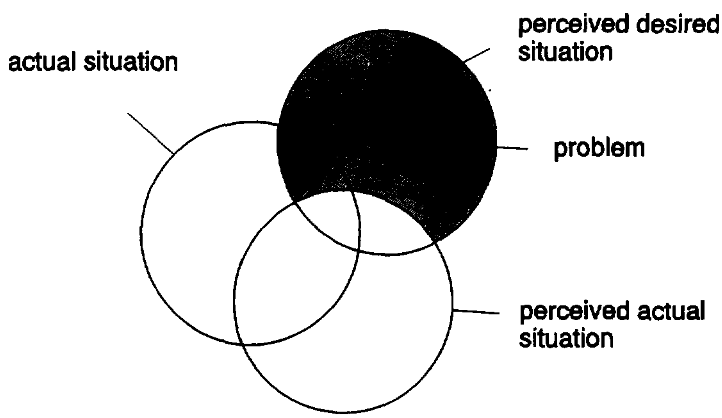

Fig. 2.2.1 This graphical representation of a problem shows the problem as the difference between the perceived desired situation and the perceived actual situation (shaded area). It is noted that the perceived actual situation does not correspond with the actual situation. This difference is a measure for the quality of the problem definition: the smaller the difference, the better the problem definition.

Obviously, the actual situation plays an important role. The smaller the difference between the actual present situation and perceived actual situation, the better the problem is defined. The perception process is influenced by three factors[8] (see intermezzo 2.1): (1) the rate of awareness of the "real life system", (2) the knowledge of scientific models and (3) the purpose of the representation of the "real life system".

Intermezzo 2.1

- The rate of awareness of the real life system

  A Problem Owner is not able to observe a certain part of the real life system in the case of complete unawareness of that part[9]. The rate of awareness is determined by skill, experience etc. and is not only a point of reference but also a pragmatic filter[10]. The better the awareness, the better the problem is defined and the better the control of the variety of possible solutions[11]. Even observations with sufficient awareness of the area of interest could be influenced by unknown factors, which affect the objectivity of the perception process[12]. Therefore, the perceived situations are subjective, due to the rate of awareness of the real life system.

- Knowledge of scientific models

  The application of scientific models specifies the variables to be considered. Therefore, the use of scientific models for the representation of the real life system is prescriptive. The specification of variables is also selective, meaning that the model is exclusive[13]. Due to the prescriptive and exclusive character of the use of models, the representation of the real life system can never be true and is related to the model which is used. Therefore, the perceived situations are relative, due to the knowledge of scientific models.

- The purpose of the representation of the real life system

  The purpose of representation of the real life system is to solve a problem. The first aim of model makers is to reduce the quantity of information. An effective reduction can be achieved by classification and description[14]. This reduction consists of two parts. The first part is realized by both the awareness of the real life system and the use of mathematical models. The second part is determined by the purpose of the initiator. Therefore, the perceived situations are partial, due to the specific purpose of the initiator.

Due to these three factors, the representation of the real life system is: (1) subjective, (2) relative and (3) partial. In consequence the problem perception is not correct.

2.2.3 Classification of problems

As stated before, a problem arises from the friction between the perceived desired situation and the perceived actual situation. Such a friction can be caused by a change of:

- the environment of the Problem Owner;
- the Problem Owner himself;
- the relation between Problem Owner and his environment.

Based on these cases of friction, the following ideal types of problems can be distinguished[15]:

- *Reality problems*, arising from a change in the perceived actual situation as a consequence of a change in the actual situation. The difference between the changed perceived actual situation and the perceived desired situation causes an uneasy feeling.

- *Goal problems*, arising from a change in the perceived desired situation, which causes an uneasy feeling when compared with the perceived actual situation.

- *Perception problems*, arising from the difference between perceived actual situation and actual situation. In this case the perceived desired situation is identical to the actual present situation.

A problem can also be composed of a mixture of the above ideal types of problems. In theory this leads to eight types of problems, each type being a combination of the three ideal types. Instead of this situational classification, a classification can also be made on how a solution could possibly achieved (see intermezzo 2.2). However, such a classification is not relevant in the context of this study.

Intermezzo 2.2

A classification of problems can be given by the following problem taxonomy[16]:

- *Conceptual problems*; for these problems, intellectual and cognitive ideas or theories are involved in their solution;

- *Empirical problems*; these problems require experience or experimental data for their solution;

- *Behavioral problems;* activities of a person or a group are a part of these problems. A substantial part of these problems is related to the empirical nature of human perception. The errors of such perceptions are increased and become more complex as the number of people involved in the problem increases.

- *Societal problems;* these problems incorporate the three other problems. Also social and cultural norms constitute important factors of this type of problem. In the above list, each type of problem is a partition of following problems. For example, a conceptual problem is a part of an empirical problem.

2.3 The effectiveness of the problem solving process

2.3.1 Definition and characteristics of the problem solving process

The problem solving process is defined as the set of necessary activities associated with the change of a problem state to a solution state. The effectiveness of the problem solving process is defined in paragraph 3.2. For the moment the problem solving process is considered effective if a solution to a problem is realized. A solution to a problem is realized when the perceived actual situation and the desired actual situations are perceived to be the same(17). Principally, a problem solution can be achieved in three ways(18):

- the perceived actual situation can be transformed into the perceived desired situation;
- the perceived desired situation can be transformed into the perceived actual situation;
- a solution is derived by some combination of the first two ways.

The direction of the problem solving process is determined by different influencing factors. It is important to realize that a relation between the elimination of a problem and the cause of a problem does not necessarily exist(19). It is preferable to determine the direction of the problem solving process by considering the type of problem. Then, the principle choice to be made is a change of(20):

- the Problem Owner, which is a change of goal;
- the environment, which is a change of the real life system;
- the relation between Problem Owner and the environment, which is change of perception.

It is noted that also a combination of the above changes can be considered. Moreover, it is even possible to change the direction of the problem solving process during the process itself. Besides these principles of changes, also some factors can be distinguished, influencing the direction of the problem solving process[21]:

- the skill and expertise of the participants in the problem solving process;
- available knowledge about the problem or about parts of the problem;
- possibilities available to Problem Owner to influence the environment;
- possibilities available to influence Problem Owner.

The above ways of problem solving do not cope directly with the influence of the actual situation. In most practical cases the difference between the actual situation and the perceived actual situation, enlarges the problem. This is graphically represented by the dotted area in figure 2.3.1. The ratio of the dark grey area and the light grey area is the rate in which the problem is underestimated.

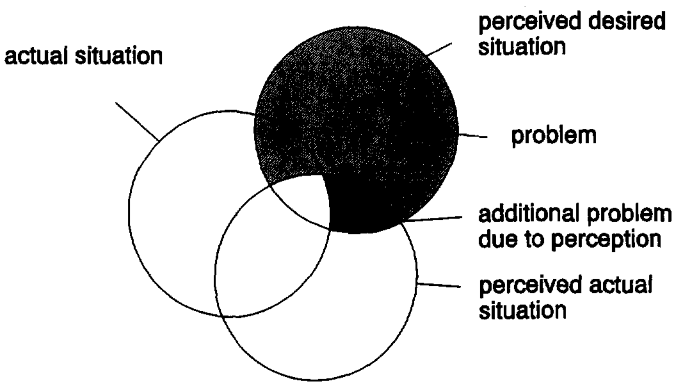

Fig. 2.3.1 *The problem, defined as the difference of two perceived situations (actual and desired respectively), is enlarged by the perception of the actual situation. The actual situation manifests itself during the problem solving process and the associated additional problem should be solved as well.*

2.3.2 The problem solving process; milestones, phases and criteria

At the highest abstraction level the problem solving process can be represented by four milestones and three phases in between them[22](see figure 2.3.2). The milestones are: (1) problem, (2) problem statement, (3) solution and (4) action. The phases are: (1) orientation, (2) design and (3) implementation.

Two criteria are given: (1) the action should solve the problem effectively and (2) the solution should always be true with respect to the problem statement.

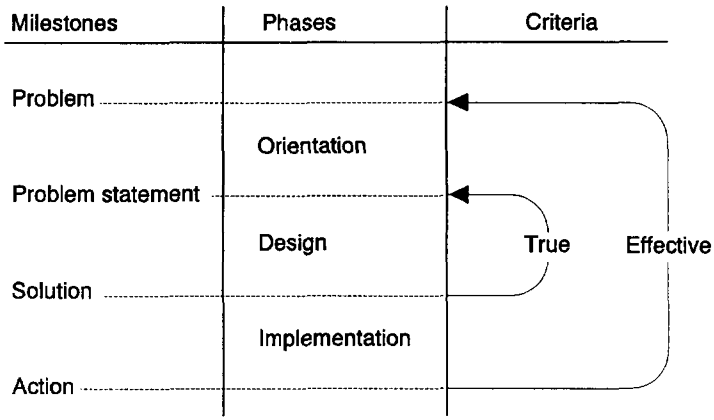

Fig. 2.3.2 *The problem solving process given in milestones, phases and criteria*

2.3.3 The transition from problem to problem statement (orientation)

The formulation of the problem statement is generally recognized to be difficult. Most research is aimed at "problem solving" rather then at "problem finding"[(23)]. This difficulty reflects itself in the variety of terminology for this phase in the problem solving process: identification, incubation, orientation, initiative, analysis, etc.

The transition from problem to problem statement is in fact a part of the design work, to be considered as a pre-design phase. In the context of this study, the ultimate objective of design is "form" (see section 2.3.4 for a detailed analysis of design work). The basic idea is that design is the set of efforts to achieve fitness between two entities: the form in question and its context. The context defines the problem and the form is the solution to the problem[(24)].

Using this definition of design, the problem statement can be determined by finding a conceptual solution (form), and listing the total friction between the problem (context) and that conceptual solution[(25)]. In this sense, the problem statement is the characterization of the fit between problem and solution. The main difficulty however is, that harmony is searched between two intangibles: a solution which is not yet designed, and a problem which cannot properly be described yet.

The search for a problem statement is mostly conducted with intuitive and discursive methods, which are applied with alternating steps: (1) establish the way the solution should function and (2) to determine the corresponding structure of the solution[26]. It must be realized, however, that the problem statement, consisting of (1) the problem, (2) a conceptual solution and (3) the description of the fit between problem and conceptual solution, that is a set of requirements, can never be correct[27].

2.3.4 The transition from problem statement to solution (design)

The iterative character of the design process

Design can be defined in many ways[28]. As explained in the previous section, the systematic architectural approach of Alexander[29] is preferred for further investigation of the design process: "a solution is reached in case the problem and the conceptual solution are put together into effortless contact or frictionless coexistence. The fit between solution and problem may be regarded as a condition for the ensemble, subject to disturbance in various ways, each one a potential misfit".

The design process consists of an analytical process which aims at a fragmentation of the total problem and a synthetic process which aims at bringing elements together in a solution[30]. Even for a simple design problem, the fit between problem and solution is given in a large set of conflicting, concurring[31] and independent requirements, which makes it difficult to meet them. With this respect, it is considered fruitful to think of requirements from a negative point of view[32]. Through misfit considerations the problem originally brings itself to the Problem Solver's attention. The state of each potential misfit is a variable. The task of design is not to create a solution which meets certain conditions, but instead to create such an order in the ensemble that all variables fit. This is what makes design difficult, what makes it a search process and what causes large iterations of trials and errors in most cases (see figure 2.3.3).

It is therefore important to realize that a design problem is not a straightforward optimization problem[33]. The meeting of any requirement in the best possible way is impossible. Instead it suffices to satisfy the requirements at a level which prevents misfits between solution and problem[34].

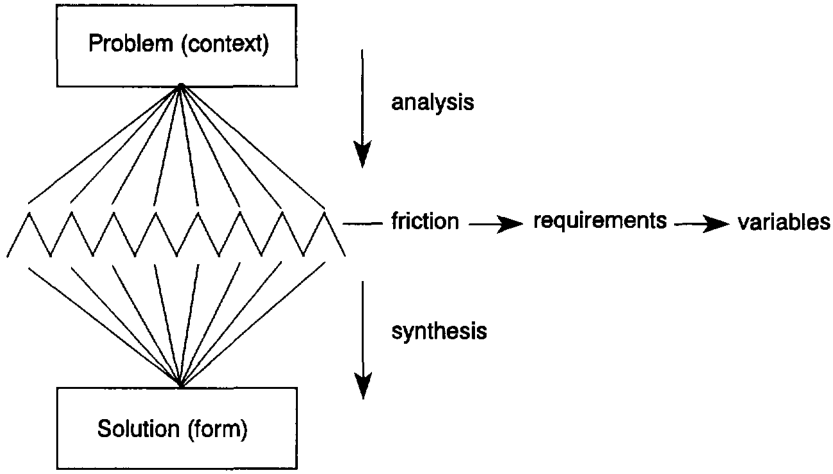

Fig. 2.3.3 *The analytical and synthetical part of a design process, aiming at frictionless coexistence of problem (context) and solution (form).*

The design process can basically be compared with the dynamic model of the development of science as given by Popper[35]. The principle is given in figure 2.3.4, dealing with one problem statement P_1. A number of tentative solutions (TS_i) will then be compared with each other in order to select the solution which is most effective. The tentative solutions are mostly generated from available knowledge, but the results cannot be predicted. The information derived from these results is selectively used to adjust the models of the problem and to improve the insight in the problem. This error elimination (EE) enables the Problem Solver to try more appropriate tentative solutions, being, in fact, a new problem statement P_2. This is a trial and error method, that is, trials for TS_i and error for the elimination of bad trials.

Although the evaluation of the tentative solutions on effectiveness is a selection process, the design process is like a search process, consisting of a number of operations to be performed on a problem situation (see intermezzo 2.3). This is the operational view on design work, which is inter-problem-focused[36]. In order to converge, it is necessary to use the information which is generated with each new step in the design process. This is the information processing view[37]. Both views are complementary and must be taken into account for design work.

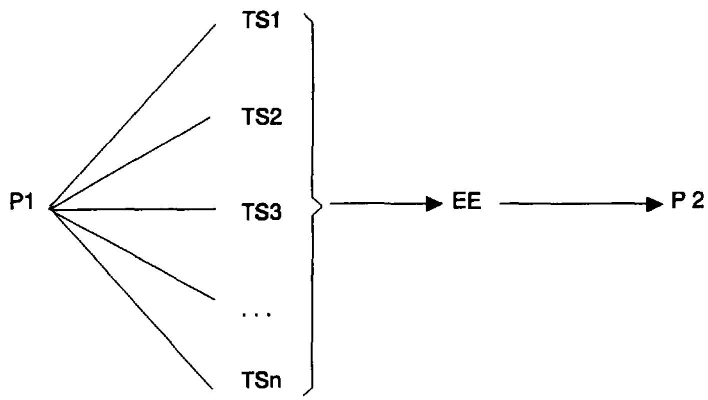

Fig. 2.3.4 *Dynamic transition from problem statement to solution which is mainly based on trial and error. For the problem statement P_1, a set of tentative solutions TS_i will be generated and evaluated on effectiveness. Then an error elimination EE defines the problem statement P_2 which is closer to the solution than the problem statement P_1.*

Intermezzo 2.3

The difference between a search process and a selection process is rather important, since both processes are needed in the problem solving process (search in the orientation phase and the design phase, selection in the implementation phase). Most people think, that all problems can be solved mechanically such as algebra, economics, administration, chess playing, etc[38]. The basic idea behind that is, that all problems can be turned into simple selection processes[39]. Two conditions however, are necessary to solve a problem by selection[40]:

- it must be possible to generate a wide enough range of possible alternative solutions symbolically;
- it must be possible to express all the criteria for a solution in terms of the same symbolism;

For a design problem these conditions are not met because:

- there is no symbolic way to generate alternative forms;
- criteria for success can not be expressed in a symbolic description of a form;
- construction of form also demands principles as simplicity, non-arbitrariness and clear organization.

A condition for finding an effective solution is that each last step must solve the initial problem. In this iterative process, each step is evaluated on effectiveness with respect to the initial problem. Converging iterations are obtained in case the transitions from problem statement P_i to problem statement P_{i+1} are adequate. The formulation of the problem statements should be more precise the later the stage of the problem solving process is. In this way an hierarchic structure of problem statements is created, which describes the overall problem statement at various aggregation levels, giving both the global problem statement as well as all details. The difference between a converging and a non-converging design process is given in figure 2.3.5. In an adequate design process the iterations are as small as possible. An interesting variant on the hierarchic structure of problem statements is given in intermezzo 2.4, showing a converging design process which initially does not take into account all details.

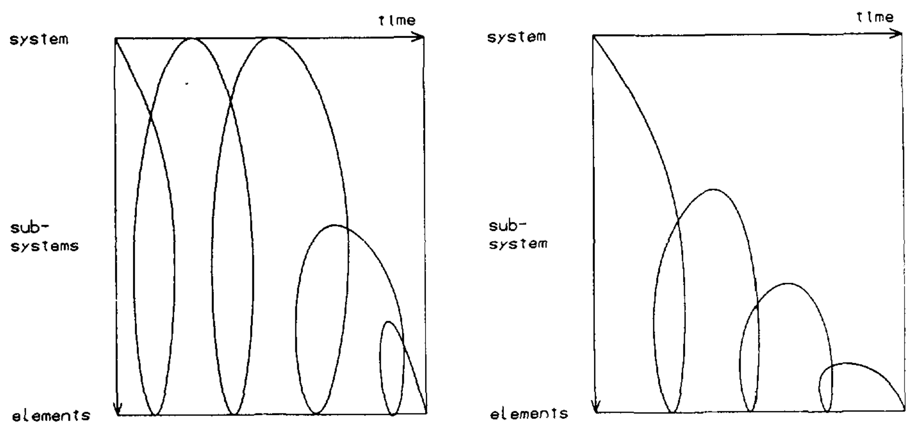

Fig. 2.3.5 *Convergence of the design process. The curved line of these problem solving processes represents frictionless coexistence between (sub-) problems and (sub-)systems which solve the problem. The design process sketched in the left part does not converge (inadequate steps), whereas the design process sketched in the right part converges (hierarchic structure of problem statements). In case of inadequate steps, the problem solving team must go back to the total system and start again. Consequently, the problem solving process makes negative progress at that moment.*

Intermezzo 2.4

The criterion for an adequate design process is that the iterations are as small as possible. This can be obtained in case not all details are considered at any time of the design process. Such a design process is sketched in figure 2.3.6.

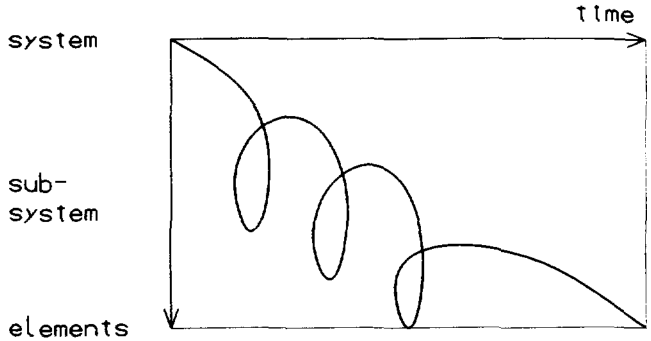

Fig. 2.3.6 *A converging design process with increasing attention for details as a function of time*

The basic aspect that makes a design process good or bad is adaptation. A good design process is possible in case it has an adaptation oriented, self-organizing (homeostatic) structure, producing fits even in the face of change[41]. On the other hand, in a non-adaptation oriented design process it is likely that the production of solution fails to *fit in the problem.*

The design variables (potential (mis)fits between solution and problem) are connected by causal linkages. Hence, the set of variables can be represented as indicated in figure 2.3.7, showing variables and inter-variable linkages. Since the variables are linked together, they cannot be adjusted independently. However, since not all variables are equally strongly connected, a formation of sub-systems of variables can be made such that sub-systems of variables can be adjusted fairly independently[42]. Three such sub-systems of variables are indicated in figure 2.3.8.

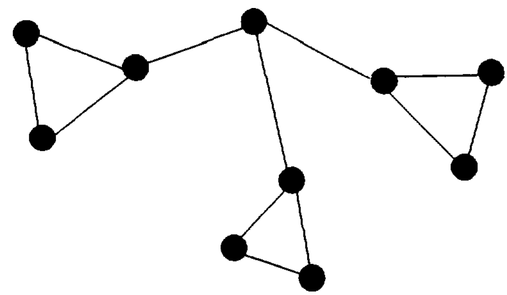

Fig. 2.3.7 *A graphical representation of potential misfits (variables) between problem and solution. Variables are indicated with dots and inter-variable linkages with lines.*

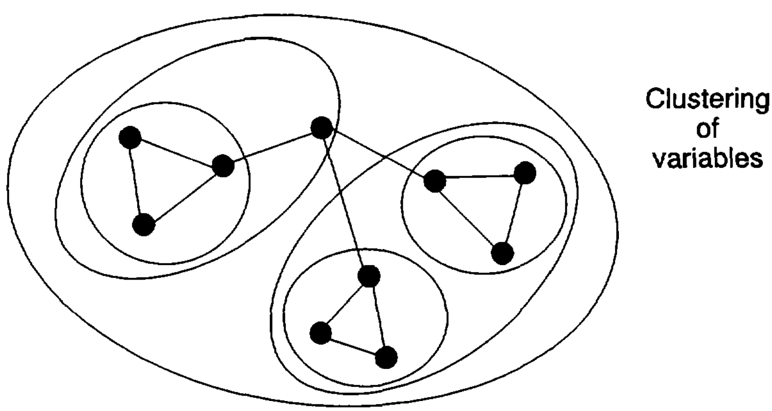

Fig. 2.3.8 *An example of a clustering of variables resulting in sub-systems of variables*

Given these sub-systems of variables, the design process can be defined as the subsequent adaptive action of a series of sub-systems of variables, all interlinked, yet sufficiently free to adjust independently in a feasible amount of time. In a design process these adjustments can take place in discrete steps.

The vital point that makes a design process good is that it responds to small changes in a way that allows the sub-systems of the misfit system to work independently during certain limited periods (see also chapter 5). Most designers make a classification of requirements, which results in a limited number of concepts, each of them being a general name for a number of specific requirements. In this respect, at the highest abstraction level, a design problem can be simply managed by two concepts: (1) its function and (2) its economics[(43)]. By making a hierarchy of concepts the designer thinks that he is able to face the overall problem at once. An example of such a hierarchy is given in figure 2.3.9.[(44)].

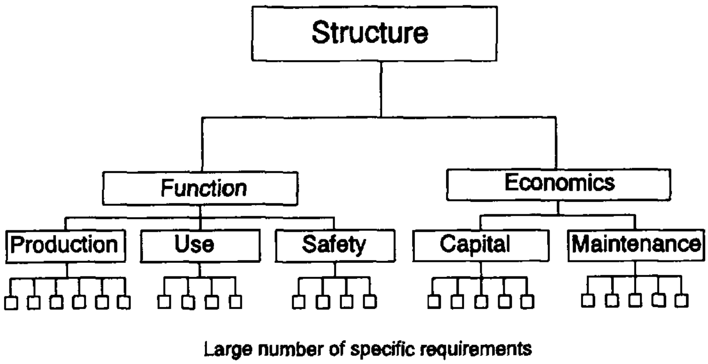

Fig. 2.3.9 *Hierarchy of concepts in which the overall problem is decomposed. Each concept identifies a certain set of variables (after Alexander, 1964).*

Each concept identifies a certain set of variables. It is stated that the arbitrarily chosen concepts do not help the designer in finding a well adapted solution unless they happen to correspond with the sub-systems of variables. In general, there is no reason to expect correspondence. In most cases the concepts identify different sub-systems of the system of variables (figure 2.3.10).

Due to this non-correspondence between sub-systems of variables and concepts, the designer encounters severe problems, causing large iterations[(45)].

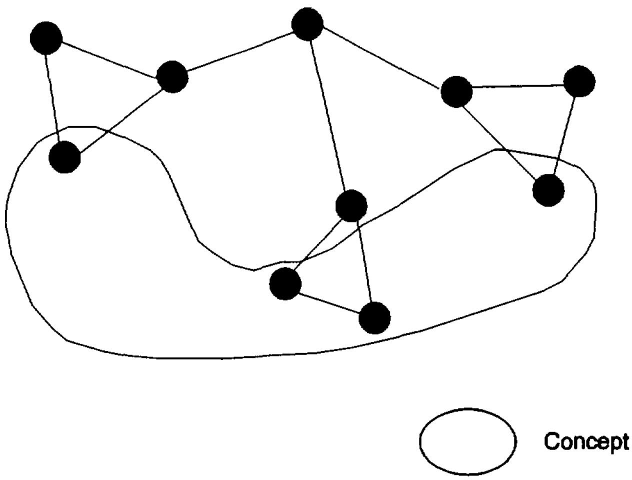

Fig. 2.3.10 *Non-correspondence between sub-systems of variables and concepts. This means that the requirements generally do not correspond with the simple concepts the designer wants to start with.*

The influence of complexity

Complexity with respect to the design process is related both to the designer as well as to the solution to be designed[(46)]. Complexity related to the designer is subjective, as it is experienced differently by various observers and it is relative, because experienced complexity is related to skill, experience, purpose, task, etc. The individual perception and the individual response to a complex environment plays an important role in the complex design process. This personal aspect, however, falls outside the scope of this study, dealing with organizational structure and contracts. Nevertheless, some personal aspects with respect to the problem solving process are discussed in chapter 6.

In most design processes complexity is introduced with the solution. For further analysis of complexity it is fruitful to consider a solution as a system. In that way, the solution is provided with structure and behaviour, which is tentatively connected with complexity[(47)]. For a better understanding of complexity related to systems, some elementary notions are given in annex 1.

The question is: what makes a system complex? When surveying literature, a large number of definitions and notions on complexity are observed. Obviously, the definition of complexity is rather complicated[48].

The level of complexity of a system is often connected to the number of elements and the interactions between them. Without a precise definition for the interactions, the interactions can be regarded as additive contributions to complexity, that is, for every partition of the whole system, its complexity should equal the sum of the interactions between the parts plus the sum of the complexities of the parts considered separately. This is demonstrated in the first part of annex 2.

With respect to elements and the relations between the elements, Simon defined complexity as follows[49]: "Roughly, by a complex system I mean one made up of large number of parts that interact in a non simple way". An extension to the behaviour of a complex system is made by the following definition[50]: "A system is complex, in case there are many components, linked by such large number of relations that the predictability of the behaviour of the system is low".

After these qualitative definitions of complexity, it would be interesting to have available a quantification method of complexity. This is rather difficult, however[51]. Given the definition of complexity, not only should the interactions be counted but also classified. In fact a measure must be assessed for the simplicity of interactions. An attempt is given in the second part of annex 2. Another measure of complexity is the number of functions to be fulfilled by the system.

Summarizing, it can be stated that objective measures of complexity are not available. In case a reference level of decomposition, which is subjective by definition, can be established, complexity could possibly be measured by:

- counting the number of functions at a certain decomposition level;
- classifying the interactions in quantitative sense, that is, the number of interactions at a certain decomposition level;
- classifying the interactions in qualitative sense, that is, whether the interactions are simple or not.

With respect to the design process, the influence of complexity can be sketched with the example of intermezzo 2.5[52].

Intermezzo 2.5

Consider a designer, who is to design a system determined by a large number of elements. These elements have to satisfy a large number of requirements. The chance that there is a system which meets all requirements to the full extent is negligible. The designer's strategy is to aim at maximizing the fulfilment of all requirements simultaneously. As the designer cannot pay attention to all elements at once, he starts an iterative design process by first solving subset E_1 of the elements with the corresponding subset R_1 of requirements. In that way he finds a provisional system and he proceeds to consider subset E_2 of elements with the corresponding subset R^2 of requirements. Two elements have mutual interaction, in case both are subjected to the same requirement (see figure 2.3.11).

When one of the elements is changed after the initial fulfilment of the requirement, the designer has to change the other element as well. In case of interactions the designer must make many new starts, together forming an iterative design process. It is noted that in case of weak interactions, the successive provisional systems become more satisfactory. It will be clear that in case of non-interaction between the elements, the provisional system will fully meet the requirements in the first step.

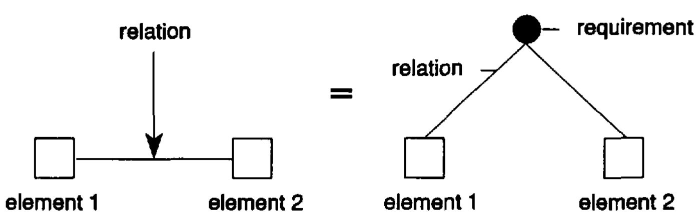

Fig. 2.3.11 Interaction between elements can be interpreted as a requirement for both elements

Based on the example of intermezzo 2.5, it is concluded that the design of an interactive system is difficult. Obviously, the interaction of elements requires a large number of iterations in order to find solutions. These iterations are added to the iterations already present for common design processes.

In general, designers in charge of a "complex" design problem develop one part of a functional program at the expense of another[53]. The driving force behind this method is the need for simple concepts[54]. Since the whole is more than the sum of the parts, it will be clear that this method does not lead to such an order in the ensemble that all variables fit. On the other hand, if designers try to consider all requirements equally, the result is absolute chaos.

In all, the design process is a difficult search process with three iterative factors:

- the poorly defined problem statement
- the non-correspondence between the large number of requirements and the concepts;
- the complexity of the solution (large number of elements and non-simple interactions)

When finding the right way, harmony is reached between problem and solution at the end of the design phase. Then the solution is completely fixed with: (1) specifications, (2) drawings and (3) quantities.

2.3.5 The transition from solution to action (Implementation)

Although the influence of the actual situation on the problem solving process is eliminated to a large extent at the end of the design phase, in most cases some "events of reality" will enter the problem solving process in the implementation phase. These events normally lead to relatively small problems with respect to the effectiveness of the action.

Given the fixed solution, the implementation process is a simple selection process. All alternatives for implementing the solution can be expressed with two symbols: (1) costs and (2) time. Consequently, these alternatives can also be evaluated with respect to these symbols.

2.4 The efficiency of the problem solving process

2.4.1 General

In the previous paragraph, the problem solving process is discussed fundamentally with respect to effectiveness, which was focused on particular attributes of the problem and associated difficulties to solve the problem. It must however be realized that the intention of the Problem Owner to do something about the actual situation is bound to certain limited efforts. This limitation of efforts is a part of the problem, which introduces efficiency as an additional criterion for the problem solving process. Efficiency is defined in paragraph 3.2. For the moment the problem solving process is considered efficient in case the initially estimated efforts are not exceeded.

2.4.2 The efforts needed for the problem solving process

With respect to the overall criteria (effectiveness and efficiency), the start of a problem solving process can be represented by the "triple constant"[(55)] (see fig. 2.4.1).

The cube of the "triple constraint" is spanned by:

- the requirements to be fulfilled for an effective solution, which is defined as the normative performance of solution;

- the costs of the efforts necessary to reach the normative performance of solution, which are defined as the normative costs (budget);

- the time needed for the efforts necessary to reach the normative performance of solution, that is the normative time (time schedule).

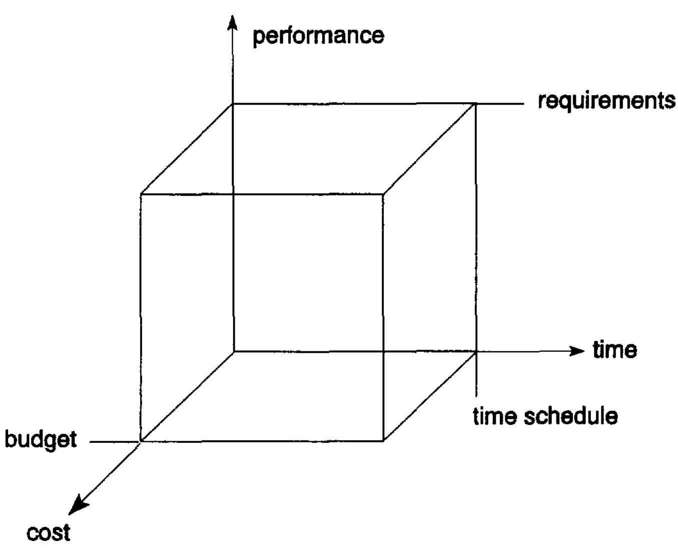

Fig. 2.4.1 The "triple constraint" for any type of realization process is spanned by the normative performance of solution which should be reached and the normative efforts (time schedule and budget), which are needed for reaching the normative performance of solution and may not be exceeded.

Together, the budget and the time schedule form the normative efforts. At the end of the problem solving process, the efforts will be totally absorbed in the normative performance of solution[56]. Consequently, there is a proportionality between performance of solution and efforts: the more performance of solution is required, the more efforts are needed. It is assumed that in the proximity of the normative performance of solution and normative efforts, the proportionality is fully linear.

Intermezzo 2.6

With the "triple constraint", the normative performance of solution of the problem solving process and the normative efforts needed, are defined at the highest abstraction level. It is obvious that time and money is not enough to solve a problem. The money and time available at the start of a project are used to solve the problem with an effective action at the end of the problem solving process. This transformation is realized using transformation technology. In the context of this study (civil engineering systems), the basic components of the transformation technology are Material, Energy and Information[57] (see figure 2.4.2).

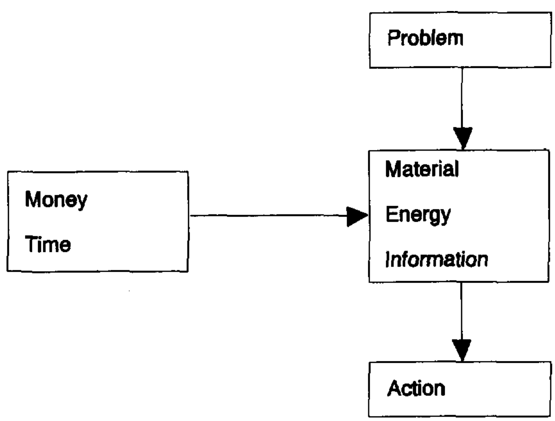

Fig. 2.4.2 Transformation technology for the realization process of civil engineering systems, consisting of material (concrete, quarry stone, steel, wood, etc.), energy (fuel, labour, etc.) and information.

2.5 Summary

The problem solving process can be considered the abstraction of a "one shot" realization process. The goal of the problem solving process is to find an effective solution for a problem which can be implemented efficiently.

The methodology of the problem solving process is roughly represented by three phases (orientation, design and implementation) and four milestones (problem, problem statement, solution and action).

With respect to effectiveness, the friction between problem and solution is in fact the problem statement and starting point for the design work, but in most cases poorly defined: (1) the perception of the problem situation is subjective, partial and relative and (2) the solution is not yet known. Consequently, design work is the most difficult part of the problem solving process as it is a search process to harmonize two intangibles. This search process must also cope with: (3) non-correspondence between requirements and concepts and (4) complexity of the solution. Due to these four aspects, design work has an iterative character.

Apart from the fact that the solution should be effective, it should also be implemented efficiently, meaning that the design of the solution must be such that initially estimated efforts may not be exceeded.

The solution which is developed at the end of the design period, can be transformed into an effective and efficient action during the implementation phase. This is a selection process which can simply be evaluated with respect to time schedule and budget.

Notes

1. The adjective "complex" is placed in quotation marks, since problems are rarely complex. Complexity in most cases is introduced with solutions. The title of this chapter could therefore be read as methodology of the problem solving process and the influence of the complexity of the solutions.
2. The problem solving process in this respect placed in a confined context (just the implementation of the solution). In fact, also the utilization and the elimination after utilization belongs to the problem solving process, but fall outside the scope of this study.
3. Jackson, K.F., The art of problem solving, London 1975.
4. Kramer, N.J.T.A., Systeem in probleem, Stenfert Kroese bv, Leiden/ Antwerpen, 1978. Kramer's book, dealing with a systematic approach of the problem solving process in a wide organizational context, is used as the main reference for this chapter. As will be shown later on in this study, in particular the approach in which a problem is considered to be a system, is rather fruitful in the problem solving process.
5. This definition is given by Kramer, N.J.T.A, Systeem in probleem, Stenfert Kroese bv, Leiden/ Antwerpen, 1978. It is noted that the definition originates from a rather liberal point of view. A lot of problems in the present world are characterized by the first three conditions of the definition only!
6. Kramer, N.J.T.A., Systeem in probleem, Stenfert Kroese bv, Leiden/Antwerpen, 1978.
7. Perception is rather important for both problem definition as well as problem solving. Bartee, E.M., " A holistic view of problem solving", in: Management of Science, vol 20 no 4, 1973.
8. Kramer, N.J.T.A., Systeem in probleem, Stenfert Kroese bv, Leiden/Antwerpen, 1978.
9. Veld, J. in 't, Analyse van organisatieproblemen, Stenfert Kroese, Leiden, 1975.
10. Kramer, N.J.T.A., Systeem in probleem, Stenfert Kroese bv, Leiden/Antwerpen, 1978.
11. Sitter, L.U. de, "Over het menselijk kompas: Normen, waarden en hun verandering", in: Wijsgerig Perspectief 17, 1977, 6
12. Unknown factors generally lead to uncertainties due to unawareness. Goemans, T., "Beleidsanalytische aspecten van het ontwerpproces" in: Ontwerpmethoden voor civiele en bouwkundige ontwerpproblemen, PATO, Delft, 1980.
13. Kramer, N.J.T.A., Systeem in probleem, Stenfert Kroese bv, Leiden/Antwerpen, 1978.
14. Bertels, K. and D. Nauta, Inleiding tot het modelbegrip, de Haan, Bussum, 1969.
15. This is a rather theoretical classification only based on the definition of a problem and given by K-ramer, N.J.T.A. en A.C.J. de Leeuw, "Probleemoplossend onderzoek, een benadering vanuit de systeemleer", Rapport no. 28, Afdeling der bedrijfskunde THE, Eindhoven 1976.
16. In this classification of problems also the person or group with a problem and some aspects of the problem solving process are taken into account. Bartee, E.M., " A holistic view of problem solving", in: Management of Science, vol 20 no 4, 1973.
17. Bartee, E.M., " A holistic view of problem solving", in: Management of Science, vol 20 no 4, 1973.
18. Ibid.
19. Kepner, C.H. and B.B. Tregoe, The Rational Manager, New York, 1965.
20. Kramer, N.J.T.A., Systeem in probleem, Stenfert Kroese, Leiden/ Antwerpen, 1978.
21. Some influencing factors of the problem solving process were given by: Elshout, J.J. van, "Ontwikkelingen in de Psychologie/5: Probleemoplossen", in: Intermediair 13, 1977, 24. Moreover, an important influencing factor is the relation between PO and a possible Problem Solver. Kramer, N.J.T.A., Systeem in probleem, Stenfert Kroese, Leiden/ Antwerpen, 1978.
22. The problem solving process as given here must be seen in a general context. The scheme originally was presented with the milestones "question" and "answer" for respectively problem statement and solution by Kramer, N.J.T.A., Systeem in probleem, Stenfert Kroese, Leiden/ Antwerpen, 1978.

23. Van der Zouwen, J.van der, De probleemstelling als probleem, Alphen aan den Rijn, 1971.
24. Alexander, C., Notes on the Synthesis of Form, Harvard University Press, Cambridge, Massachusetts, 1964.
25. " The form is a part of the world over which we have control, and which we decide to shape while leaving the rest of the world as it is. The context is that part of the world which put demands on this form". Alexander, C., Notes on the Synthesis of Form, Harvard University press, Cambridge, Massachusetts, 1964.
26. Kroonenberg, H.H. van den, Methodisch ontwerpen, Technische Hogeschool Twente, Enschede, 1978.
27. For a correct transition from problem to problem statement, it would be necessary to transform the subjective, partial and relative problem into a problem statement which is: (1) objective, (2) complete with respect to all relevant factors and (3) absolute. This is impossible because such a transformation would imply a full knowledge of all aspects and influencing factors of the problem, which normally is reached after the problem solving process has been ended.
28. Various definitions and notions of design are given by: Polak, B.M. and M.R. Beheshti, Systematisch Ontwerpen, Delft Technical University, 1991:
    - a goal-directed problem solving activity (Archer, 1965);
    - decision making in the face of uncertainty, with high penalties for error (Asimov, 1962);
    - simulating what we want to make (do) before we make (do) it as many times as may be necessary to feel confident in the final result (Booker, 1964);
    - the use of scientific principles, technical information and imagination in the definition of a mechanical structure, machine or system to perform prespecified functions with the maximum economy and efficiency (Fielden, 1963);
    - the performance of a very complicated act of faith (Jones, 1966);
    - the imaginative jump from present facts to future possibilities (Page, 1966);
    - a creative activity; it involves bringing into being something new and useful that has not existed previously (Reswick, 1965);

    Then a number of rather identical definitions:
    - finding the right physical components of a physical structure (Alexander, 1963);
    - relating product with situation to give satisfaction (Gregory, 1966).
    - the optimum solution to the sum of the true needs of a particular set of circumstances (Matchett, 1968). In this definition the adjective "optimum" is certainly not correct (see note no 34);

    Finally an opinion about the designing activity itself:
    "Creative design is an essentially personal achievement. There is nothing automatic about it" (Legg, G.L., The Science of Design, 1973; The selection of Design, 1972 and The Design of Design, 1969).
29. Alexander, C., Notes on the Synthesis of Form, Harvard University press, Cambridge, Massachusetts, 1964.
30. The analysis and synthesis as the essence of the design process is recognized by various authors:
    Wijnen, G., W. Renes, and P. Storm, Projectmatig werken, Het Spectrum, Utrecht, 1988.
    Kroonenberg, H.H. v.d., Methodisch ontwerpen, Technische Hogeschool Twente, Enschede,1978 and by:
    Stuip, J., "Methodische aanpak voor waterbouwkundige constructies aan zee", in : Ontwerpmethoden voor civiele em bouwkundige ontwerpproblemen, Stichting Postdoctoraal Onderwijs in de Civiele Techniek, Delft, 1981.
31. Concurring means that two requirements have mutual physical implications for the system to be developed. Alexander, C., Notes on the Synthesis of Form, Harvard University Press, Cambridge, Massachusetts, 1964.
32. Vickers, G.,"The Concept of Stress in Relation to the Disorganisation of Human Behaviour" in: Stress and Psychiatric Disorder, ed. J.M. Tanner, Oxford, 1960.

33. March, J.G. and H.A. Simon, Organizations, New York, 1958.
Simon, H.A., "Rationality and Administrative Decision Making", " A behavioral Model of Rational Choice" and " Rational Choice and the Structure of Environment" in : Models of Man, New York, 1957.

34. A design method often observed, is to write down a list of all possible relations between a form and its context, which should be required by good fit and start work. This is the list of requirements which designers want to write down. Such a list is potentially endless and it is obvious that the endless number of requirements must be compressed. Since a field description of the context does not exist, there is no intrinsic way to reduce the potentially endless list of requirements to a finite number of requirements.

35. Popper, K.R., Objective Knowledge, Oxford, 1972.

36. Elshout, J.J. van, "Ontwikkelingen in de Psychologie/5: Probleemoplossen" in: Intermediair 13, 1977, 24.

37. The practical problem solving process is linked with the development of science (described by Popper, K.R., Objective Knowledge, Oxford, 1972) by Kramer, N.J.T.A., Systeem in probleem, Stenfert Kroese, Leiden/ Antwerpen, 1978.

38. Newell, A., J.C. Shaw and H.A. Simon, "Elements of Human problem Solving" in: Psychological Review, 65, 1958.

39. Mirsky, M.,"Heuristic Aspects of the Artificial Intelligence problem", in Group Reports 34-55, Lincoln Laboratory, M.I.T., 1956.

40. Alexander, C., Notes on the Synthesis of Form, Harvard University Press, Cambridge, Massachusetts, 1964.

41. Ashby, W.R., Design for a Brain, New York, 1960.
Yovits, M. and S. Cameron, Self-Organizing Systems, New York, 1960.

42. Ibid.

43. Alexander, C., Notes on the Synthesis of Form, Harvard University Press, Cambridge, Massachusetts, 1964.

44. This figure is exactly taken from: Alexander, C., Notes on the Synthesis of Form, Harvard University Press, Cambridge, Massachusetts, 1964.

45. Ibid.

46. Alkemade, M.J.A, "Complexiteit, een verkenning", in: Inspelen op complexiteit: mens, techniek, informatie en organisatie, red: M.J.A. Alkemade, Samson, Alphen aan de Rijn, 1992, (in Dutch).

47. Kramer, N.J.T.A., Systeem in probleem, Stenfert Kroese, Leiden/ Antwerpen, 1978. Korthagen, J.N.M., Aanzet tot het ontwerp van een probleemklassificatie, Afstudeerverslag Afdeling der Bedrijfskunde THE, Eindhoven, 1977.

48. In general, there are various fields of complexity and their associated treatment. Two main fields are pattern recognition and numerical taxonomy, referring primarily to the classification problem based on similarity. Although these two fields do not contribute directly to a simple treatment of complex problems in the sense of looking for solutions, the principles of classifications can probably be fruitful.
The first field, dealing with complexity, is pattern recognition. This area is mainly developed in physics and electrical engineering. An overview on pattern recognition is given by Nagy, G., The state of the art in pattern recognition, Proc. Ieee 56, 1968.
The second field is the numerical taxonomy, focused on classification in a biological context and aimed at the understanding of systems. Numerical taxonomy deals with the numerical evaluation of similarity. The main aims are repeatability and objectivity of the resulting classification. Closely related to numerical taxonomy is plant ecology to characterize different types of vegetation. Sokal, R.R. and P.H.A. Sneath, Principles of Numerical Taxonomy, Freeman, San Francisco, 1963.

It is noted that in contrast to the biological sense of classification, mainly aimed at the classification of species, patterns, units, etc. to arrive at a better understanding, here the classification principles can be used to recognize specific characters of complex problems to improve the problem solving process.
When looking for any kind of solution for a complex problem, the criterion of a successful classification is the number of iterations required to attain a satisfactory solution.

49. Consider, for instance, a brick pavement. The number of bricks is tremendous and so is the number of interactions (direct contact). The brick pavement, however, is certainly not a complex system. Obviously the number of components combined with simple interactions is not enough to make a system complex. This is perhaps the reason that non simple interaction as additive condition for complexity was proposed by Simon, H.A., The Architecture of Complexity, in: Simon, H.A., The Sciences of the Artificial, MIT Press, Cambridge, 1982.
50. Alkemade, M.J.A, "Complexiteit, een verkenning", in: Inspelen op complexiteit: mens, techniek, informatie en organisatie, red: M.J.A. Alkemade, Samson, Alphen aan de Rijn, 1992, (in Dutch).
51. Maddox, J., "Complicated measures of complexity", in: Nature, Vol. 344, 1990.
52. Emden, M.H. van, An Analysis of Complexity, Mathematical Centre Amsterdam, 1971.
53. The typical western approach to find solutions for complex problems by decomposing a system into small parts in order to solve them and subsequently putting the sub-solutions together to understand the total system is criticized by Toffler, A., "Science and Change"; a foreword in: Order out of Chaos, Prigogine, I. and I. Stengers, 1984.
54. It is hardly possible to start a design problem without simple concepts. In this respect it is stated that "the designer should start with an overall concept which works and which can be realized", Vos, Ch.J., "De Wisselwerking tussen functionele eisen, constructief ontwerp en uitvoering bij constructies aan zee", in: Ontwerpmethoden voor civiele en bouwkundige ontwerpproblemen, Stichting Postdoctoraal onderwijs in de Civiele Techniek, Delft, 1981.
55. Shaines, M.J., Engineering management, Course by Intermediar, Amsterdam, 1989. Shaines defined the "triple constraint" for engineering design problems. However, there principally is no objection to applying the "triple constraint" for any type of problem solving process.
56. Dijk van P., "Gunther Anders: De geantiqueerdheid van de mens" in: Achterhuis, H., De Maat van de Techniek, Ambo, Baarn, 1992.
57. The three components of transformation technology e.g. matter, energy and information were given in a mechanical engineering context by Kroonenberg, H.H. van den, Methodisch ontwerpen, Technische Hogeschool Twente, Enschede, 1978. The same components were distinguished for building processes by Maas, G.J., "Vernieuwing te realiseren door te kijken naar totale bouwproces", in: De Ingenieur Van Kasteren (red), nr. 3, 1991.

3. CONCEPT OF GOAL CONTROL OF THE COMPLEX PROBLEM SOLVING PROCESS

3.1 General

In this chapter, the goal control of the complex problem solving process is dealt with at the highest possible abstraction level. Having outlined the methodological aspects of the complex problem solving process, it is now possible to discuss the goal concept and the corresponding goal control of the complex problem solving process. Control is outlined in detail in chapter 6. For the moment control is defined as any form of directed influence(1). This influence is used to control the direction of the problem solving process. Goals and goal concepts will be discussed in detail in various parts of this study. For the moment, goal is defined as an ordering of alternatives(2).

This chapter is divided into two principal parts. In the first part a general concept of goal control is given, based on the two criteria given in chapter 2, namely effectiveness and efficiency. In the second part, the concept of goal control is evaluated for the situation in which certain tasks of the problem solving process are delegated to other parties.

3.2 The performance of the problem solving process

Since the problem solving process must be effective as well as efficient, it is convenient to introduce the performance of the problem solving process, being the product of effectiveness and efficiency. The product of effectiveness and efficiency can be interpreted as an abstraction of the friction between problem and solution. In this sense a satisfactory performance of the problem solving process means that the friction between problem and solution is taken away effectively and efficiently. First of all, a few definitions will be presented(3):

- effectiveness is the quotient of actual performance of solution and normative performance of solution;
- efficiency is the quotient of normative efforts and actual efforts;
- productivity is the quotient of real performance and actual efforts.

The performance of the problem solving process is schematically sketched in figure 3.2.1(4).

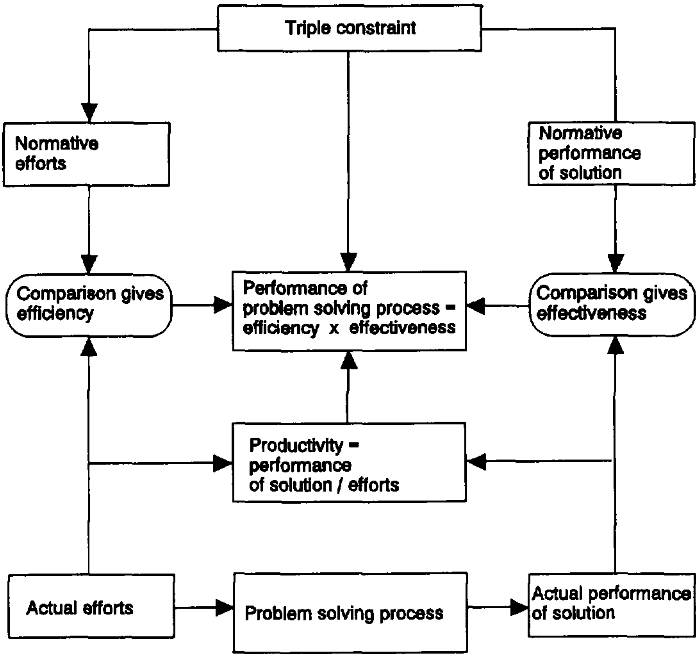

Fig. 3.2.1 *The performance of the problem solving process is defined as the product of efficiency and effectiveness. In case the normative performance is fully fixed, for instance for a production process, the problem solving process can mainly be controlled with the productivity. However, for an overall problem solving process, the normative performance is not fixed yet given in a set of requirements which makes control of the problem solving process difficult.*

The performance of the problem solving process can be written as follows:

$$P_{psp} = \frac{P}{P_0} * \frac{E_0}{E} \qquad (3.2.1)$$

in which:
P_{psp} = performance of the problem solving process
P = actual performance of solution
P_0 = normative performance of solution
E = actual efforts
E_0 = normative efforts

The parameters of equation 3.2.1 are given without dimensions (see intermezzo 3.1).

Intermezzo 3.1

The performance of solution cannot be given in a functional relation and can consequently not be expressed in a "performance dimension". Regarding the efforts, two basic components can be distinguished: time and money. These two components were presented in paragraph 2.4, forming the basis of the "triple constraint". In this constraint context, the product of budget and time schedule can in a way be interpreted as a product representing the normative efforts. When used as variables, however, time and cost cannot be interpreted as a product with the dimension (time * cost). Such an interpretation would suggest a possibility of linear exchange between these two effort components, which is certainly not the case. Therefore, all formulas containing the parameters "performance of solution" and "efforts" are presented without dimensions.

A satisfactory performance of the problem solving process is obtained for $P_{psp}>=1$. It is important to realize that equation 3.2.1 can only be used with respect to the whole system and not with respect to parts of the system (see intermezzo 3.2).

Intermezzo 3.2

Following the definition of complexity, it can be stated that the product of effectiveness and efficiency of the whole is less than the sum of the products of effectiveness and efficiency of the parts:

$$\frac{P}{P_0} \cdot \frac{E_0}{E} < \sum_{i=0}^{n} \frac{P_i}{P_{0i}} \cdot \frac{E_{0i}}{E_i} \qquad (3.2.2)$$

In which:

P	=	actual performance
P_0	=	normative performance of whole system
E_0	=	normative efforts of whole system
E	=	actual efforts of whole system
P_i	=	actual performance of i-th sub-system
P_{oi}	=	normative performance of i-th sub-system
E_{oi}	=	normative efforts of i-th sub-system
E_i	=	actual efforts of i-th sub-system
n	=	number of sub-systems

3.3 The general concept of goal control

3.3.1 Concept of goal control with fixed normative performance of solution

As shown in the previous chapter the normative performance of a solution for a problem cannot be established and therefore certainly not fixed at the start of the problem solving process. However, a situation which is close to a fixed normative performance of solution is the start of the implementation phase with the milestone "solution". Hence, the concept of goal control as presented in this section refers to implementation (production) processes.

According to equation 3.2.1 and for fixed P_0 and E_0, the Problem Owner has a few possibilities available to him in order to compensate a disappointing performance of the problem solving process ($P_{psp} < 1$). The choice between these possibilities are determined by Problem Owner's preferred direction of the problem solving process. The following directions can be distinguished:

A. No extra efforts ($E=E_0$)

In this particular case, two control possibilities are available to the Problem Owner in order to return to a satisfactory problem solving process.

- The first control possibility is the acceptance of a less than 100% solution ($P/P_0<1$). This is, in fact, an adjustment of the initial goal. At the start of the problem solving process, the goal of the Problem Owner is maximum fulfilment of all requirements against minimum cost. With the goal definition already given (ordering of alternatives), it can be stated that the ordering must be a weak and the set of alternatives should[5]: (1) consist of all relevant alternatives and (2) not be constrained to end states only, but also applicable to inputs, actions, states and outputs of the considered system. The choice between the alternatives can be based on the expected effect in the direction of reaching the goal. There is no need to require an explicitly defined or operationalized goal. This would imply a constant and complete goal which cannot be established due to the incorrect problem definition. Generally stated, goals: (1) change as a function of time due to changing circumstances, (2) are not complete and (3) are not explicit. Hence, it suffices to use the term goal in case an evaluation possibility exists[6]. Therefore, it is possible to adjust the goal when confronted with a disappointing performance of the problem solving process.

- The second control possibility can be visualized by rearrangement of the fixed values and variables of equation 3.2.1.

$$P_{psp} = \frac{E_0}{P_0} * \frac{P}{E} \qquad (3.3.1)$$

The problem solving process can simply be controlled by influencing the productivity (P/E).

B. *No reduction of performance ($P=P_0$)*

In this particular case the Problem Owner has two control possibilities available to him in order to return to a satisfactory problem solving process. The first is the increase of productivity (P/E) as described above. The second is an injection of extra efforts ($E>E_0$).

C. *Neither extra budget nor reduction of performance ($E=E_0$, $P=P_0$)*

In this particular case the Problem Owner can only increase the productivity P/E in order to return to a satisfactory performance of the problem solving process.

3.3.2 Concept of goal control with underestimated normative performance of solution

In contrast to the starting point of implementation processes, the normative performance of solution is not fixed for the total problem solving process. Although the conceptual solution for the problem is already known at the start of the problem solving process, the normative performance of solution is not exactly known due to the subjective, relative and partial character of the problem at the start and the required objective, absolute and total character of the solution at the end of the problem solving process. In fact, the description of the normative performance of solution has some intrinsic uncertainties, leading to underestimation. During the problem solving process most of the uncertainties will be eliminated, incurring a continuous increase of the normative performance of solution. This process is sketched in a qualitative sense in figure 3.3.1.

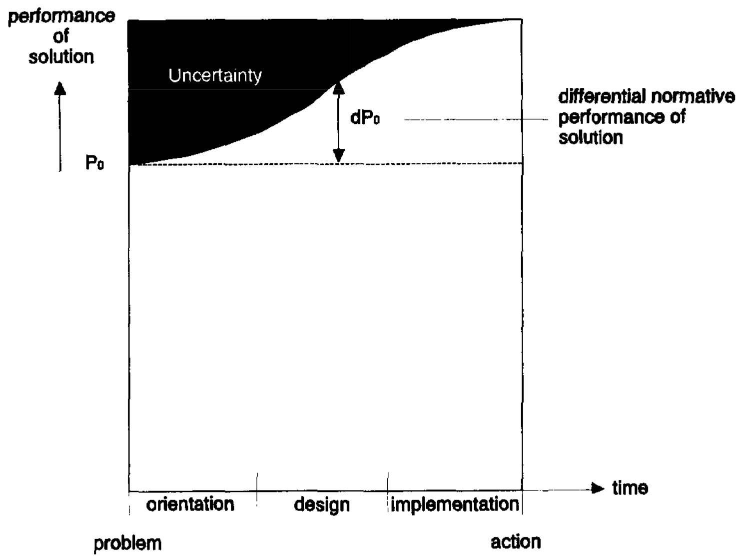

Fig. 3.3.1 *The problem solving process is aimed at finding and implementing an objective, absolute and total solution for a subjective, relative and partial problem. The difference between these characteristic descriptions of respectively problem and solution can be interpreted as uncertainty, in most cases leading to an increase of the normative performance of solution (dP_0). The S-curve originates from the fact that, particularly during the design phase, most uncertainties are converted into certainties.*

Due to the proportionality of the performance of solution and the efforts needed to reach that particular performance of solution, the differential normative performance of solution automatically leads to additional efforts with respect to the normative efforts (differential efforts). In fact, the uncertainty is the main reason for the initial underestimation of efforts. The estimated actual efforts are sketched as a function of time in figure 3.3.2.

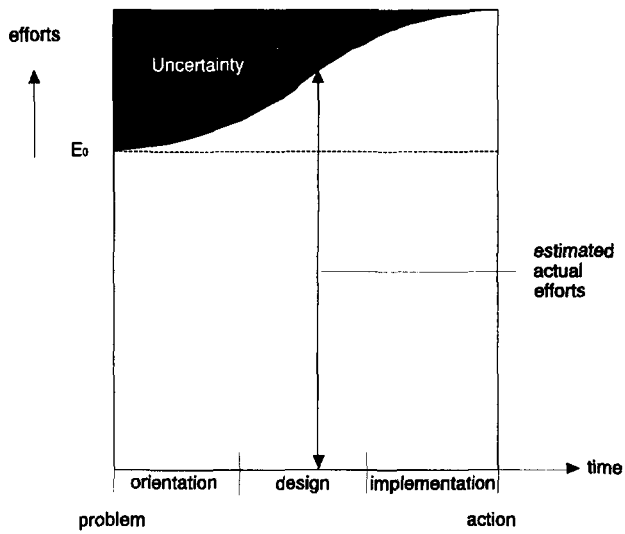

Fig. 3.3.2 *Estimated actual efforts as a function of time. This figure is similar to figure 3.3.1 due to the proportionality between performance of solution and efforts needed to reach the required performance of solution.*

Since most uncertainties will be attacked during the design phase, the influence on the underestimation of efforts is largest during the design phase and relatively small during the orientation phase and implementation phase.

It is noted that the estimated actual efforts are different from the actual efforts. The relation between estimated actual efforts and actual efforts is given in figure 3.3.3 in a qualitative sense(7).

Given the uncertainties about the normative performance of solution, it can be concluded that the problem solving process counts three variables: P, E and P_0. It is noted that the normative efforts are not variables, since the normative efforts can be expressed in firm dimensions as normative time (time schedule) and normative costs (budget). Consequently, the control problem is initially confined to three variables, making control of the problem solving process more complicated than the case described in the previous section (implementation of a fixed solution).

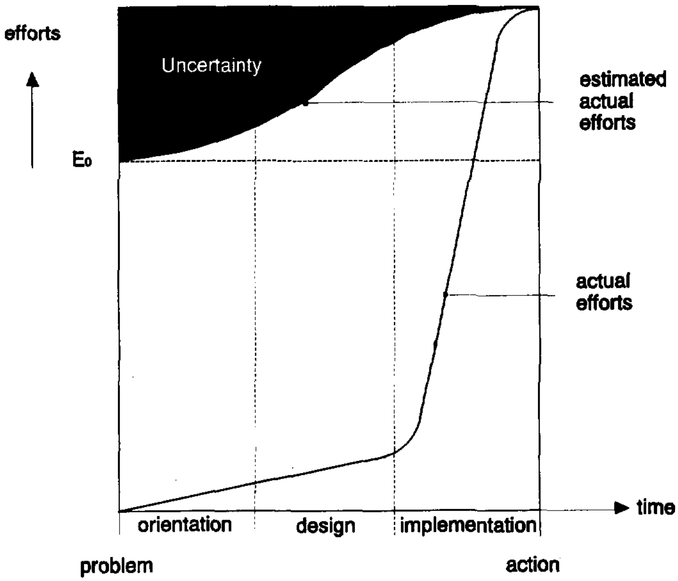

Fig. 3.3.3 *Estimated actual efforts and actual efforts as a function of time, showing (1) the large influence of design work on estimated efforts and low contribution to the actual efforts and (2) large influence of construction work on actual efforts and low contribution to the estimated actual efforts.*

In order to investigate the various control possibilities, the differential PSP is written as the sum of the partial differentials of the variables.

$$dP_{psp} = \frac{\partial P_{psp}}{\partial P} dP + \frac{\partial P_{psp}}{\partial P_0} dP_0 + \frac{\partial P_{psp}}{\partial E} dE \qquad (3.3.2)$$

or:

$$dP_{psp} = \frac{E_0}{E} * \frac{dP}{P_0} - \frac{P}{P_0} * \frac{E_0}{E} * \frac{dP_0}{P_0} - \frac{E_0}{E} * \frac{P}{P_0} * \frac{dE}{E} \qquad (3.3.3)$$

It will be clear that, for a satisfactory performance of the problem solving process, it is necessary to minimize the product of the negative differential performance of the problem solving process ($-dP_{psp}$) and the actual efforts (E). This product can, in some way, be considered as the risk involved with a problem solving process. The negative differential performance of the problem solving process ($-dP_{psp}$) is the undesired event with a probability of occurrence, whereas the actual efforts (E) represent the consequences[8]. In that way the risk is expressed in commonly known and used dimensions.

The risk can be visualized by rearranging equation 3.3.2:

$$- dP_{psp} * E = E_0 \left(- \frac{dP}{P_0} + \frac{P}{P_0} * \frac{dP_0}{P_0} + \frac{P}{P_0} * \frac{dE}{E} \right) \qquad (3.3.4)$$

or:

$$- dP_{psp} * E = E_0 * \frac{P}{P_0} * \left(- \frac{dP}{P} + \frac{dP_0}{P_0} + \frac{dE}{E} \right) \qquad (3.3.5)$$

The overall control of the problem solving process can be visualized by combining equations 3.2.1 and 3.3.5:

$$(P_{psp} - dP_{psp}) * E = E_0 * \frac{P}{P_0} * \left[1 + \frac{dP_0}{P_0} + \left(\frac{dE}{E} - \frac{dP}{P} \right) \right] \qquad (3.3.6)$$

In the left term of equation 3.3.6 the efforts to be put into the problem solving process are represented. The right term clearly shows the three control possibilities:

- The first possibility is represented by factor P/P_0 indicating the possibility of goal adjustment ($P/P_0<1$).

- The second possibility shows the proportionality between actual efforts and normative performance of solution ($E = E_0 \, (1 + dP_0/P_0)$). This term can be controlled by a description of the normative performance of solution which is to be as clearly as possible.

- The third possibility, represented by the term (dE/E - dP/P), stands for control of productivity, which is shown is in intermezzo 3.3.

Intermezzo 3.3

The productivity is satisfactory if:

$$\frac{dE}{E} - \frac{dP}{P} \leq 0 \qquad (3.3.7)$$

or:

$$lnP \geq lnE + C_1 \qquad (3.3.8)$$

$$\frac{P}{E} \geq C_2 \left(C_2 = \frac{P_0}{E_0} \right) \qquad (3.3.9)$$

The term dP/P in the differential productivity term, being the relative increase of the performance of solution, refers to the effectiveness of the problem solving process. A positive value of dP/P stands for a "smart" problem solving process.

The term dE/E in the productivity term, being the relative increase of real efforts, refers to the efficiency of the problem solving process.

With these three control possibilities, two fundamental types of control possibilities can be distinguished:

- The first type refers to the problem definition and the goal concept with the associated perception problems and shortcomings at the start of the problem solving process. This type of control possibility is aimed at the control of estimated actual efforts, determined by the terms P/P_0 and dP_0/P_0 in equation 3.3.6 and is sketched in figures 3.3.4 and 3.3.5 with respect to the two main criteria of the problem solving process: (1) effectiveness (performance of solution) and efficiency, e.g. estimated actual efforts.

- The second type refers to the problem solving process itself, with respect to the productivity aiming at the control of the actual efforts. This type is sketched in figure 3.3.5. with respect to efficiency (actual efforts).

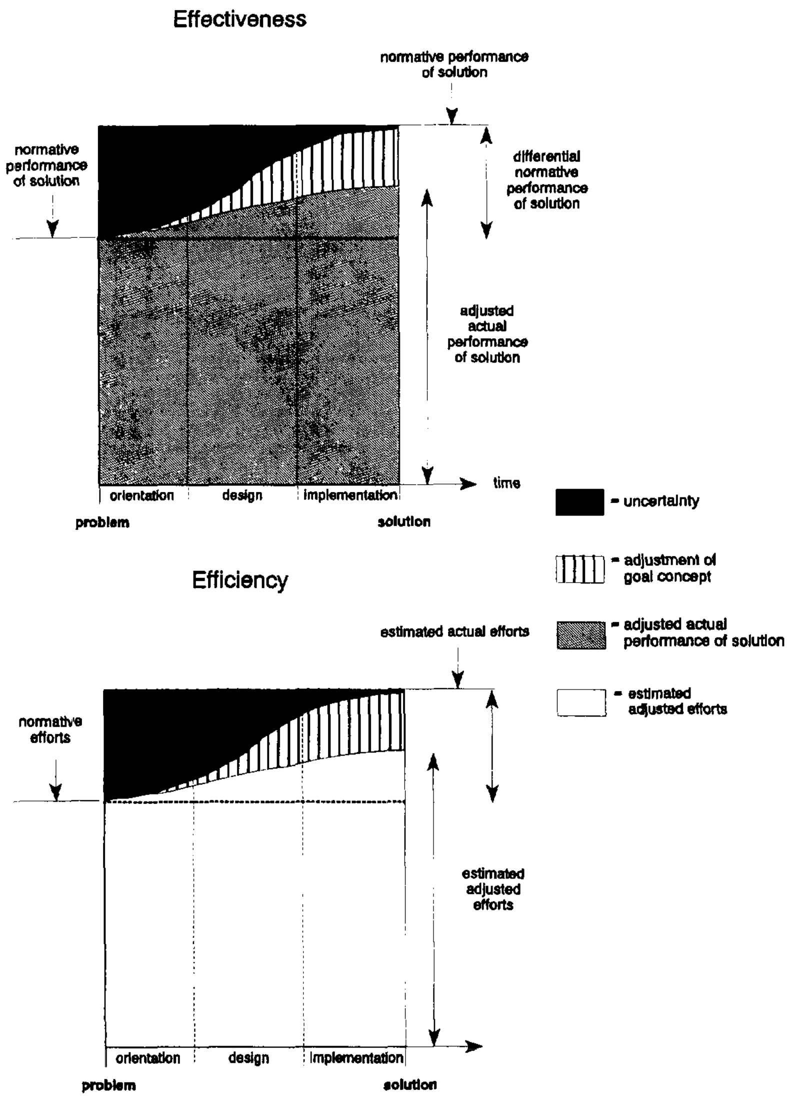

Fig. 3.3.4 Control of the problem solving process by goal adjustment

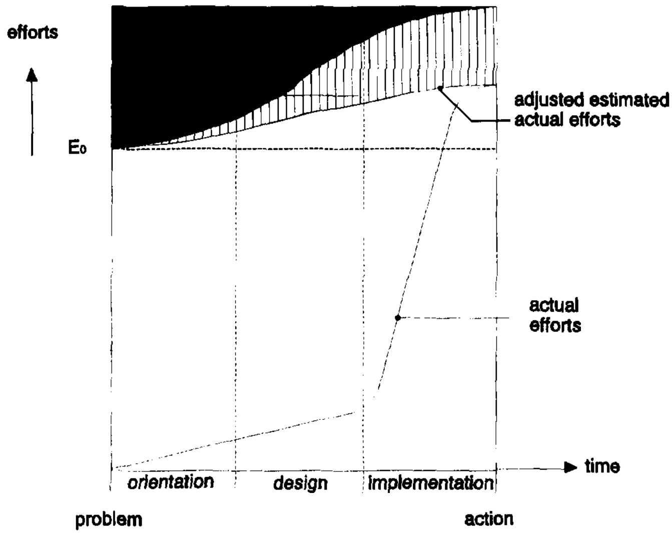

Fig. 3.3.5 Control of actual efforts given the adjustment of the goal concept

From figure 3.3.5, it is concluded that:

- The influence of "design work" on the efforts (represented by the increase of the black area as a function of time) is large, whereas the contribution of "design work" to the total efforts (represented by the "actual efforts" line) is small;
- The influence of "implementation work" on the efforts is small, whereas the contribution of "implementation work" to the efforts is large;
- Given the above influences and the definition of control (any form of directed influence), the design leader is the main controller of the problem solving process.

The eventual choice between all control possibilities mentioned, is determined by the type of problem to be solved, the efforts available and last but not least the parties involved with the arrangements made. This last aspect is dealt with in the next paragraph.

3.4 Control of task delegation

3.4.1 General

In this paragraph, the control of the performance of the problem solving process is considered in the case where the Problem Owner assigns a Problem Solver for a part of this process.

Sofar, the problem solving process has been considered from the point of view of the Problem Owner only. In most problem solving processes however, the Problem Owner does not have enough know-how, skill or opportunity to conduct the problem solving process by himself. In that case a Problem Solver is assigned. The agreement between the Problem Owner and the Problem Solver, with respect to tasks, responsibilities and risks, has influence on control of the realization process[9].

The main objective of this paragraph is to show what should be controlled in case two parties are involved. Control is considered in relation with: (1) tasks, (2) criteria and (3) risk.

3.4.2 Tasks of Problem Solvers

Based on the three basic phases of the realization process (orientation, design and implementation), theoretically there are six combinations. In the context of this study, dealing with "Design & Construct", only three combinations are relevant:

- design (transition from problem statement to solution);
- implementation (transition from solution to action);
- design and implementation (transition from problem statement to action).

3.4.3 Control in case of delegated design work

Delegated tasks and responsibilities

The task of a Problem Solver (PS), who is assigned for the design phase of a problem solving process, is to transform the problem statement into a solution. More specifically, using the criteria given in chapter 2, the task of the PS(design) is to develope a conceptual solution to an effective and fully specified solution, which can be implemented efficiently.

The definition of a task as given above has a very general character. Based on figure 3.3.5, it is possible to give a strict definition of the delegated task and the associated control goal of a PS(design) with respect to the problem solving process. As a matter of fact, the work of a PS(design) should be aimed at developing an effective solution while minimizing the difference between the estimated actual efforts and the normative efforts. This control goal is given in equation 3.3.6.

The minimization of the difference between normative efforts and estimated actual efforts can not be performed without restriction, since the PS(design) is responsible for a true transformation of the problem statement into a solution. Not only all influencing factors must be taken into account, the transformation must also be in accordance with national and international standards.

The task of the PS(design) can be divided into two parts:

- enable the Client to adjust the goal concept, which means: (1) finding a solution which meets P_0, (2) quantifying the differential normative performance of solution (dP_0/P_0) and (3) giving opportunity to reduce the actual performance of solution ($P/P_0 < 1$);

- find a solution which not only meets the normative performance of solution (P_0) but can also can be constructed with the largest amount productivity (minimum value for $dE/E-dP/P$).

It is noted that the PS(design) is neither responsible for the magnitude of the estimated actual efforts, nor for the actual efforts. Selfevidently the PS(design) is fully responsible for the quality of the estimation of actual efforts.

Risk

Although the PS(design) is not responsible for the actual efforts to be made in the problem solving process, the PS(design) is fully responsible for the actual efforts of his own design work. This is that part of the actual efforts which is delegated to the PS(design). His control goal can simply be derived by considering the design phase as a problem solving process (see intermezzo 3.4).

Intermezzo 3.4

The PS(design) should minimize:

$$(P_{des} - dP_{des}) * E_{des} = E_{0\,des} * \frac{P_{des}}{P_{0\,des}} * \left(1 + \frac{dP_{0\,des}}{P_{0\,des}} + (\frac{dE_{des}}{E_{des}} - \frac{dP_{des}}{P_{des}})\right) \qquad (3.4.1)$$

with:

$P_{0\,des}$	=	normative performance of design work, referring to the quality of design work such as approach, details, number of drawings, modelling, model testing, risk analysis, etc.;
$E_{0\,des}$	=	normative efforts of design work, referring to budget and time - schedule for design work;
P_{des}	=	actual performance of design work;
E_{des}	=	actual efforts of design work;
$dP_{0\,des}$	=	differential normative performance of design work, caused by an underestimation of the design work. In most cases, more drawings, more calculations and more model testing is necessary than initially estimated in order to develop a solution.
dP_{des}	=	differential actual performance of design work, which must be seen as a change of the quality of design work;
dE_{des}	=	differential actual efforts of design work, which can be interpreted as a change of design efforts needed.

As shown in intermezzo 3.4, the risk of the PS(design) is related to the normative design efforts $E_{0\,des}$ and is rather limited since $E_{0\,des} < E_0$. The risk components are:

- the productivity of the design work ($dE_{des}/E_{des} - dP_{des}/P_{des}$), which for instance is caused by unexperienced designers and poor coordination;
- underestimation of design work ($dP_{0\,des}/P_{0\,des}$);
- a very demanding Problem Owner (PO), who continuously asks for additional reports, etc. ($P_{des}/P_{0\,des}$).

Roles

The work to be done by a PS(design), is mostly conducted in a consultancy/advisory assignment. In this context two types of roles can be distinguished[10]: (1) a role aimed at the product (or action) to be realized at the end of the problem solving process and (2) a role aimed at the problem solving process itself.

Given these two types, four models can be derived for the relationship between PO and PS(design) in the problem solving process[11]:

Expert model	Product oriented
Acceptance model	
Action model	Process oriented
Learning model	

Table 3.4.1 Relation models between Problem Owners and Problem Solvers

In the expert model, the PS(design) takes over the whole problem from the PO and conducts all necessary activities in order to find the effective and efficient action to take away the problem.
The acceptance model is a particular form of the expert model: the PS(design) must convince the PO that the actions found will be effective and efficient.
In the action model the PS(design) assists the PO with the problem solving process.
The learning model is a particular form of the action model in which the Design Contractor acts as master Problem Solver with a learning task.

3.4.4 Control in case of delegation of implementation work

Delegated task and responsibilities

The task of the PS(implementation) who is assigned for the implementation phase of a problem solving process is to transform the solution, defined at the end of the design phase, into action. The solution is mostly given in fixed specifications and drawings. The action can be considered as the system which should be implemented in accordance with the specifications and drawings. The responsibility of the PS(implementation) is that the transformation of the solution into the action is in conformance with the specifications and drawings.

For implementation work, the following remarks can be made with respect to the terms of equation 3.3.6:

- The effort needed for construction are in most cases fixed in a contract ($E_{0\ constr} = E_0$).

- At the end of the design phase, most uncertainties disappear. The solution is fixed and is therefore a firm frame of reference. In theory, hardly any differential normative performance of solution is expected at the start of the implementation phase. Hence, $dP_0/P_0 = 0$. In case there are uncertainties left, the PS(implementation) can claim additional work, caused by change of scope. Such a change can be measured simply with respect to the firm frame of reference.

- In case the PO wants to change the actual performance of solution, the PS(implementation) can claim additional work, due to a change of scope. Such a change can simply be quantified with respect to the fixed frame of reference. Hence with respect to control, the ratio P/P_0 has a fixed fictive value of 1.

It is important to realize that in case the defined solution with the corresponding specifications and drawings at the end of the design phase is not correct (no effective solution to the initial problem), the PS(implementation) is not responsible. In all, the control of the construction process by a PS(implementation) is simplified to the minimization of:

$$(P_{impl} - dP_{impl}) * E = E_{0\ impl} * \left[1 + \left(\frac{dE}{E} - \frac{dP}{P}\right)\right] \qquad (3.4.2)$$

with[12]: P_{impl} = performance implementation process
dP_{impl} = differential performance of implementation process
$E_{0\ impl}$ = normative efforts at the start of the implementation period

As a matter of fact, the PS(implementation) should control the productivity (P/E) of his implementation process.

Risk

In case the contractual clauses with respect to additional work are adequate, the risk of the PS(implementation) is simply determined by the productivity of the implementation process:

$$Risk = - dP_{impl} * E = E_0 * \left(\frac{dE}{E} - \frac{dP}{P}\right) \qquad (3.4.3)$$

In fact, the implementation risk with respect to productivity is fully allocated to the PS(implementation). All remaining risks with respect to the overall realization process must be taken by the client.

Roles

The roles are to be played in a product oriented acceptance model. Each time a part of the totally fixed solution is transformed into a partial action, a conformity check with respect to specifications and drawings is carried out by the PO. In case of conformity, that part is accepted and paid for.

3.4.5 Control in case of delegation of design and implementation work

Delegated task and responsibilities

The task of a PS, who is assigned to transform the problem statement into an effective action with respect to the initial problem (PS(des/impl)), is to take over the full problem solving process from the PO, starting with the problem statement (defined by the PO) and ending with the effective and efficient action.

A design and implementation task implies, that the PS(des/impl) is responsible for an effective and efficient action. Furthermore, the PS(des/impl) is also responsible for a true transformation of the problem statement into a solution. In fact the PS(des/impl) should control the performance of the total problem solving process:

$$(P_{des/impl} - dP_{des/impl}) * E = E_0 * \frac{P}{P_0} * \left[1 + \frac{dP_0}{P_0} + \left(\frac{dE}{E} - \frac{dP}{P}\right)\right] \quad (3.4.4)$$

Since the PS(des/impl) is not authorized to change P/P_0 into values less than 1 and an increase of productivity ([dE/E-dP/P]<0) is normally not enough to compensate dP_0/P_0, both PS(des/impl) as well as PO have a serious control problem.

Risk

The PS(des/impl): (1) starts with a conceptual solution with corresponding (under-) estimated actual efforts, (2) faces substantial differential normative performance of solution, which can only be controlled by the PO, (3) is responsible for the actual efforts of the overall realization process. Hence, the task of PS(des/impl) is potentially risky as shown in figure 3.4.1. In fact, the PS(des/impl) should control the problem solving process, but is neither able to estimate the risks at the start of the problem solving process, nor authorized to apply the most powerful control, being an adjustment of the initial goal ($P/P_0<1$).

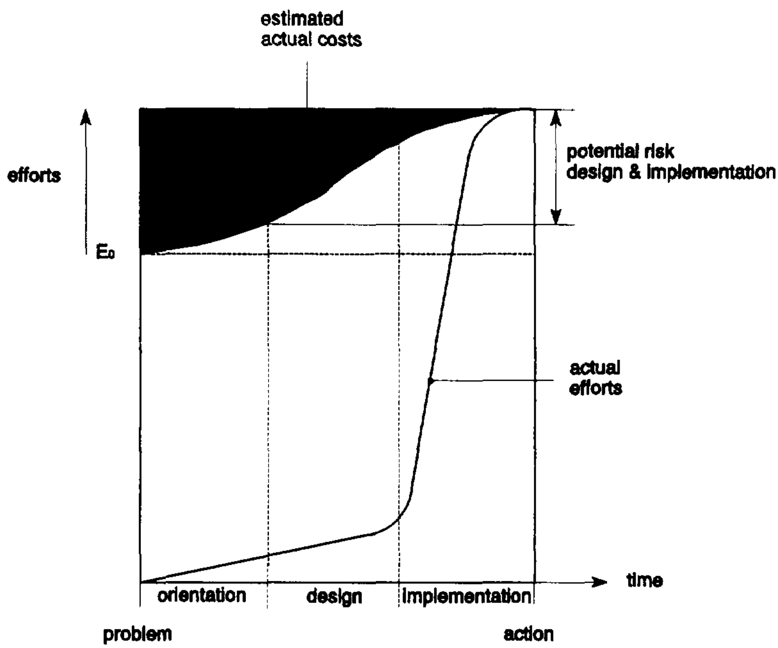

Fig. 3.4.1 *The potential risk of a Problem Solver assigned to a design and implementation task.*

For adequate control of the realization process aiming at minimization of waste of efforts, a special risk sharing principle is necessary. In section 3.3.2, two basic types of risk control have been distinguished. These two types can be used for a potential risk sharing principle. A general risk sharing principle is defined by Griffith [13]: Risk (consequences) should be carried by the party best able to either control the risk or estimate the risk. This allocation of risk can be determined by considering the various types of risk control.

- *First type of risk control*

  The first type of risk control is determined by control possibilities to cope with perception problems and control possibilities using the adjustment of the goal. The term dP_0/P_0 cannot be estimated at the start of the design and implementation process and originates from the poorly defined problem.

The more adequate the design and implementation process is conducted, the more uncertainties associated with the problem will be converted into certainties of the solution and the larger the differential performance of solution and corresponding efforts are. Without relevant and adequate contractual clauses, these additional efforts should be provided at the expense of the PS(des/impl). Since the PS(des/impl) can, in no way, be made responsible for perception problems prior to the start of his contribution to the design and implementation process, the PS(des/impl) should be protected against this consequence.

The term P/P_0 is, as explained earlier, a very important control variety as it enables the PO to adjust the goal. As explained, the PS(des/impl) will never have authority to use this control variety, which should therefore be allocated to the PO. Then PO's control goal is reduced to minimizing:

$$(P_{des/impl} - dP_{des/impl}) * E = E_0 * \frac{P}{P_0} * \left(1 + \frac{dP_0}{P_0}\right) \qquad (3.4.5)$$

- *Second type of risk control*

The second type of risk control, referring to the effectiveness and efficiency of the realization process typically belong to the responsibility of the PS(des/impl) and is given in equation 3.4.5.

$$(P_{des/impl} - dP_{des/impl}) * E = E_0 * \frac{P}{P_0} \left[1 + \left(\frac{dE}{E} - \frac{dP}{P}\right)\right] \qquad (3.4.6)$$

Equation 3.4.5 clearly shows that the risk to be carried by the PS(des/impl) refers to his own contribution to the problem solving process (effectiveness by dP/P, efficiency by dE/E). It is noted that the factor P/P_0 can only be changed by the PO.

Obviously, in a contractual relationship between the PO and a PS(des/impl) the "risk sharing principle" is rather important in order to control the problem solving process. In this context, it is more essential to allocate the risk rather than trying to estimate the risk. The main condition is that four parameters must be quantified:

- the normative performance of solution at the start of the design and implementation task ($P_{0\ des/impl}$). For the design and implementation situation, this is rather difficult since Po is not fixed in specifications and drawings.

Instead, P_0 is given in: (1) a description of the problem, (2) a description of a conceptual solution and (3) a description of the friction between the problem and the conceptual solution, which can be interpreted as the set of requirements.

- the normative efforts at the start of design and implementation task ($E_{0\ des/impl}$). For the determination of the normative performance as well as the normative efforts, both to be used as frame of reference for risk sharing, it is necessary to have a working concept available. $P_{0\ des/impl}$ and $E_{0\ des/impl}$ can not be quantified only with a set of requirements.

- the differential normative performance of solution (dP_0). This must be determined continuously during the design and implementation process. This is a difficult problem, since the performance of solution can not be given in a simple formula (see chapter 5). However, as the control is based on a relative differential performance of solution, the quantification can be given in a relative sense (dP_0/P_0).

- the real performance of solution (P). This must be done continuously during the design and implementation process. The quantification of P can be developed in analogy with the quantification of dP_0, since the actual performance of solution is also controlled in a relative sense (P/P_0).

In case the above quantifications can adequately be arranged, the PS(des/impl) is well able to minimize equation 3.4.3 and control his part of the problem solving process as described in equation 3.4.5.

Roles

The roles to be played by PO and PS(des/impl) should preferably be set in a product oriented acceptance model. The PO takes over control in case: $dP_0/P_0 > 1$ and is contractually authorized to adjust the initial goal ($P/P_0 < 1$).

3.5 Summary

The performance of a problem solving process can be expressed in the product of effectiveness and efficiency of implemented solution to the initial problem. The performance of a problem solving process is satisfactory in case the product of effectiveness and efficiency is larger than 1. A value of 1 or more is, in fact, the goal of the problem solving process.

Given the underestimation of efforts in order to take away the friction as derived in chapter 2, three different possibilities have been derived for adequate control: (1) the adjustment of the initial goal, which is the most powerful control and mainly applicable in the design phase, (2) an increase of the productivity, which is limited and mainly applicable in the implementation phase and (3) an acceptance of more effort in order to reach an effective solution.

For problem solving processes which are relevant to this study, three types of tasks are distinguished which can be delegated to Problem Solvers: (1) design, (2) construction and (3) design and construction. For a design task only the first control possibility can be applied in dialogue with the Problem Owner. The implementation task is well defined with respect to a fixed frame of reference which is the solution (specifications, drawings and quantities). Thus, with adequate contractual clauses on additional work beyond the defined scope, the Problem Solver assigned for implementation is easily able to control the productivity of the implementation construction process.

The combined design and implementation task is more complicated. The Problem Solver takes over full responsibility for the effectiveness of the solution and the efficiency of the design and implementation process. The uncertainties at the start of the design phase with respect to the conceptual solution, lead to an increase of efforts needed to solve the problem. This increase of efforts can only be controlled by the Problem Owner via adjustment of the goal concept. In order to avoid substantial waste of efforts, it is necessary to apply a risk sharing principle which enables the Problem Solver to optimally control his own design and implementation process (goal-control in dialogue with the Problem Owner and productivity control only by the Problem Solver).

Notes

1. Leeuw, A.C.J. de, Systeemleer en organisatiekunde, Stenfert Kroese, Leiden, 1974.
2. Kramer, N.J.T.A., Systeem in probleem, Stenfert Kroese, Leiden, 1978.
3. For industrial production processes effectiveness, efficiency and productivity were defined by: In 't Veld, J., Analyze van organisatieproblemen, Stenfert Kroese, Leiden, 1988. There is no objection to using these definitions for development processes as well.
4. This figure is taken from Lee, A. van der, R. Okhuysen and M. Karthaus, "Produktiviteit in industriële organisaties" in: Bedrijfskundig Vakblad, September 1993. The relations between the various notions are derived for industrial processes but can be used for development processes as well.
5. Kramer, N.J.T.A., Systeem in probleem, Stenfert Kroese, Leiden, 1978.
6. Ibid.
7. Kroonenberg, H.H. van den, Methodisch ontwerpen, Technische Hogeschool Twente, Enschede, 1978
8. Vrouwenvelder, A.C.W.M and Vrijling, J.K., Probabilitisch Ontwerpen, Faculteit der Civiele Techniek, Technische Universiteit Delft, 1986.
9. Kramer, N.J.T.A., Systeem in probleem, Stenfert Kroese, Leiden, 1978.
10. Ibid.
11. These models are developed in a general organizational context with respect to advisory services by Zwart, C.J.,"De verscheidenheid in de rol van de organisatie adviseur" in: Organisatiewetenschap en Praktijk, opstellen aangeboden aan prof. ir. T.J. Bezemer, Leiden, 1975.
12. The other symbols used are already explained in paragraph 3.2.
13. Griffiths, F. "Project Contract Strategy for 1992 and beyond", in International Journal of Project Management, Vol 7, no. 2, 1989.

PART 2: PRACTICAL ASPECTS OF THE REALIZATION PROCESS OF COMPLEX SYSTEMS

4. THE REALIZATION PROCESS OF A COMPLEX SYSTEM AND RELATED ORGANIZATIONAL ISSUES

4.1 General

In this chapter, an outline is given of the main organizational issues needed for a satisfactory performance of the realization process of a complex system. The outline of organizational issues is based on the theoretical aspects of the problem solving process, being the abstraction of the realization process of complex systems. This abstraction was necessary in order to find connections with existing theories and literature. In this chapter, however, a start is made towards the practical and specific approach. Therefore, in order to avoid misunderstandings, from now on:

- "problem solving process" becomes "realization process"
- "implementation phase" becomes "construction phase"
- "Problem Owner" becomes "Client"
- "Problem Solver" becomes "Contractor"

The organizational issues to be outlined in this chapter, are given in a general sense and will be worked out in detail in chapters 4, 5 and 6.

4.2 The realization process of a complex system and the contingency theory

The realization process of a complex system can roughly be divided into two main phases: (1) design phase (orientation and design) and (2) construction phase. These phases have completely different characters, illustrated in table 4.2.1.

The purpose of this study is that an organizational structure and an appropriate type of contract must be found for the combined design and construction task, e.g. the total realization process to be conducted by one Contractor. Given the differences between the two main phases, it is apparent that both the organizational structure as well as the type of contract should have enough flexibility. For the introduction of flexibility into organizations, the contingency theory is often used[1].

Characteristics	Design phase	Construction phase
Type of process	Search process	Selection process
Goal	Effectiveness x efficiency	Effectiveness x efficiency
Contribution to the actual costs	Small	Large
Influence on actual costs	large	Small

Table 4.2.1 Characteristics of the two main phases of the realization process of a complex system

In organizational science the contingency theory is developed. The contingency theory firstly aims at prescription. Secondly, it uses a pluralistic vision on organizational theories. Thirdly, the starting point is that the structure and the functioning of organizations is determined by the specific situation(2). With these three specific points, the contingency theory gives a basis for the organization of a realization process. In the context of the contingency theory, a situational model, in which the relevant organizational issues are linked together, is developed by Staehle(3). This model is sketched in figure 4.2.1.

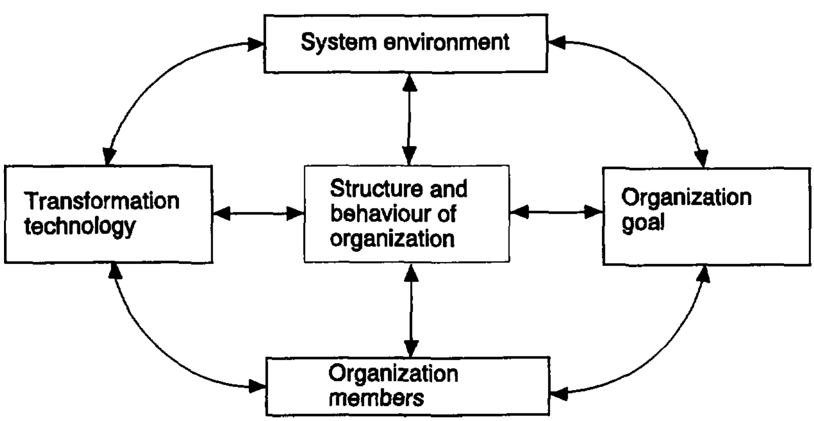

Fig. 4.2.1 Situational model based on the principle that structure and functioning of organizations are determined by the specific situation.

The four organizational issues in the outer ring of figure 4.2.1 are discussed in the next paragraphs. Obviously, these issues are related to the structure and behaviour of the organization.

4.3 System environment

In a system theoretical meaning, the system environment can be interpreted as the context. According to chapter 2, the context is in fact the problem which should be solved and which is starting point for any realization process. Since the problem is poorly defined, the system environment plays an important role in the realization process. In chapter 3 the relation between the problem on one hand and the following issues on the other have been discussed: (1) organizational goal with three specific control possibilities and (2) transformation technology in relation with efforts. Given these two relations, it is not surprising that the model of figure 4.2.1 also indicates a relation with structure and behaviour of organization.

4.4 Organizational goal and organizational structure

As shown in chapter 2, the organizational goal of the realization process is a satisfactory performance of that realization process. Such a satisfactory performance is only possible in case the product of effectiveness and efficiency is continuously controlled. The realization process of a complex system can be considered a primary process. A primary process is defined as the process in which characteristic products or services are produced for the organization[4]. A primary process is also defined as the set of various activities necessary for a realization process[5]. Obviously there is a relation between: (1) primary process, (2) goal and (3) control.

For the development of complex information systems, Bemelmans[6] presented a diagram for structuring an organization starting from the primary process (see fig. 4.4.1). Since the notions used in the diagram refer to general organizational issues, there is no objection to use the diagram in a more general context.

Obviously the following issues have mutual relationships: (1) primary process, (2) control, (3) organization and (4) information. The relation between control, organization and information can be illustrated by considering two important aspects of an organization, e.g. autonomy and coordination. As will be shown in chapter 6, the control of the development of complex systems can be interpreted as a form of coordination.

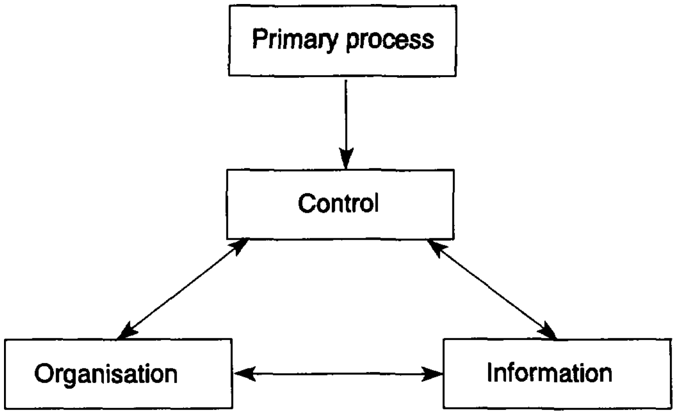

Fig. 4.4.1 *Relation between primary process and three main organizational issues: control, organization and information.*

Any organization consists of autonomous components and coordination between them[7]. Coordination is only possible with information exchange. Hence, control, information and organization are strongly interrelated. The relation is based on the quality of both. As will be shown, the better the quality of the organizational structure, the better the information transmission and the less effort for information processing is needed. In the context of communication theory, information is associated with the amount of freedom of choice we have in constructing messages. If an information source is not characterized by a large degree of randomness or choice (that is low information or "entropy") then the situation is highly organized[8].

For obtaining a highly organized realization process with low entropy, the autonomous components must be chosen in such a way, that coordination is facilitated. Therefore, it is necessary to decompose the total system with corresponding tasks into part-systems with corresponding partial tasks. Since any method of decomposition induces a coordination problem, decomposition and coordination are strongly interrelated. This interrelation is simple: decomposition should facilitate coordination. This is the reason that a simplification step is recommended between the primary process and control[9]. Such a simplification step aims at a reduction of complexity and is in fact a smart decomposition. As will be shown in chapters 5 and 6, the reduction of complexity is mainly determined by the way decomposition and coordination is arranged. An appropriate arrangement automatically leads to an optimal organizational structure.

Since the subject of this study refers to the delegation of a primary process to a Contractor, another aspect of organizational structure is the type of contract. As a matter of fact, an appropriate type of contract is essential for adequate control.
As indicated in figure 4.4.2, the "information" plays a central role in the relation between simplification, control, organization and contract.

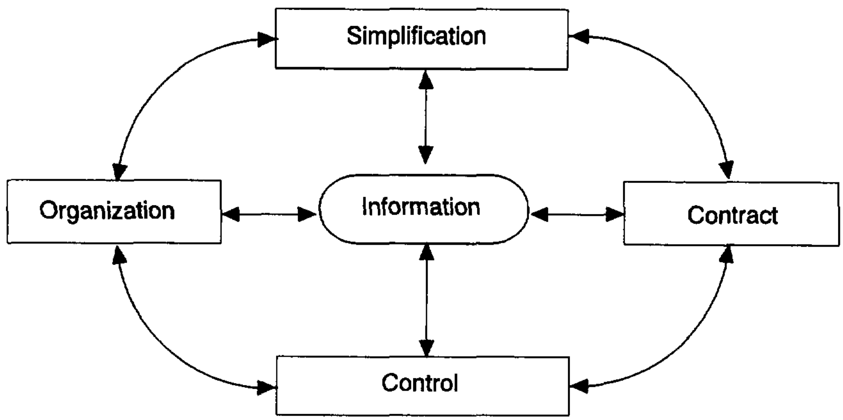

Fig. 4.4.2 *The crucial role of "information" in the relation between simplification, control, organization and contract.*

The extended diagram with both the simplification step as well as the type of contract is given in figure 4.4.3.

The simplification to be applied for the realization process of complex systems is given in chapter 5, the corresponding control models are outlined in chapter 6 and the contractual aspects are dealt with in chapter 7.

4.5 Transformation technology and organizational structure

The transformation technology necessary for the realization process (material, energy and information) covers two main phases: (1) design and (2) construction. Generally, these two phases must not only be taken into account elaborating the organizational issues of figure 4.4.2, but also in relation with the members of the organization (see paragraph 4.6).

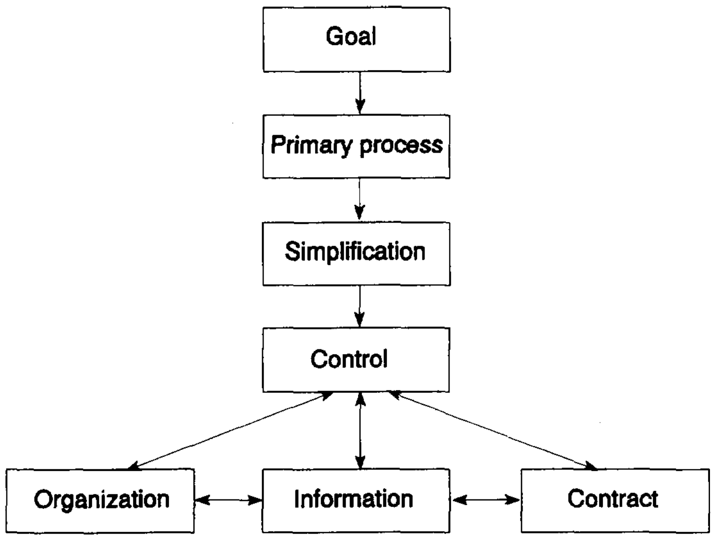

Fig. 4.5.2 *Most relevant issues necessary for the structuring of organizations dealing with complex systems*

However, since this study is delimited to develop an organizational structure and an appropriate type of contract at the highest abstraction level for a certain primary process using a particular transformation technology, a separate treatment of transformation technology falls outside the scope of study.

4.6 Members of the organization and organizational structure

Similar to the considerations of paragraph 4.5, a discussion on members of the organization also falls outside the scope of study. However, the control of the realization process is not only guaranteed with an adequate organizational structure and an appropriate contract, but also depends on the active part of control, that is, decision making. This active part of control and coordination is conducted by the members of the organization.

From figure 4.2.1, it can be seen that with respect to members of the organization, the following relations can be distinguished:

- Relation with transformation technology; the organization must contain people able to cope with either design work or construction work. The coordination staff must be competent to coordinate these two different activities such that the organizational goal is eventually reached.

- Relation with organizational goal; the joined activities of all organizational members should lead to an effective solution of the problem, implemented in an efficient way.

- Relation with behaviour and structure of organization; the basic principle here is to make the organizational structure in such a way that the organizational members can control their delegated task. For instance, designers should not actively deal with construction, whereas construction managers should never coordinate design work.

Aspects related to members of the organization working on the realization of complex systems are discussed in chapter 6 in relation with the organization of decision making.

4.7 Summary

- Based on the specific characteristics of the realization process of a complex system, it is fruitful to use the contingency theory in order to introduce a flexible, organizational structure, which is able to control the realization process.

- Contingency theory relates the structure and behaviour of organizations to: (1) system environment, (2) organization goal, (3) transformation technology and (4) members of the organization.

- As far as the organizational structure is concerned, the primary process (design and construct) with the defined goal (product of effectiveness and efficiency) should start by a simplification step, resulting in an adequate decomposition, which facilitates control.

- Simplification and control are strongly related to organization and information. Since control must be guaranteed with two involved parties (Client and Contractor), the type of contract is essential. In this respect, information plays a central role in the organizational structure linking together simplification, control, organization and contract.

Notes

1. Kramer, N.J.T.A., Systeem in probleem, Stenfert Kroese, Leiden, 1978.
2. Ibid.
3. Staele, W.H., "Der situative Ansatz in der Organisations und Fuhrungslehre" in: Mackarzina, K. und W.A. Vechsler (eds), Personal Management, Band 1: Mitarbeiterfuhrung und fuhrungs-organisation, Wiesbaden, 1977.
4. Leeuw, A.C.J. de, Organisatie: Management, analyse, ontwerp en verandering, Van Gorcum, Assen, 1988.
5. Vorstman, H.R., Produktmarktbeleid en kwaliteit: relaties, rekenschap en raakvlakken, Samson Bedrijfsinformatie, Alphen aan de Rijn, 1990.
6. This diagram is presented by Bemelmans, Th.M.A. in the presentation of: "Complexiteit en de beheersbaarheid van software-lectuur" (co-author: Heemstra, F.J) during the conference on complexity, held in Utrecht, 1992.
7. Kickert, W.J.M., Organisation of decision making, North holland publ. Cy, New york, 1979. Kieser, A. and H. Kubicek, Organisation, de Gruyter, Berlin, 1977.
8. Weaver, W., Recent Contributions to the Mathematical Theory of Communication; in: Shannon, C.E., and W. Weaver, The Mathematical Theory of Communication
9. This simplification step is introduced by Quist, H.G., (Fokker Aircraft Holland) on the Conference on Complexity, held in Utrecht, 1992.

5. SIMPLIFICATION: THE DECOMPOSITION OF COMPLEX SYSTEMS

5.1 General

In this chapter, a decomposition method is developed to enable adequate control of the realization process. More specifically, the decomposition method should give reduction of complexity without loss of insight into the performance of the whole system. With the definitions from chapter 3, the performance of the whole system should be read as the performance of solution. Hence, it must be realized that the decomposition methods to be developed initially, refer to the effectiveness of the realization process. Efficiency, however, is implicitly incorporated. Efficiency can never be achieved without control of effectiveness and control on efficiency is rather simple when effectiveness is properly controlled.

Based on the goal concept for the realization process of complex systems as developed in chapter 3, the decomposition should facilitate the control of: (1) effectiveness of the action (implemented solution) with respect to the initial problem, (2) estimated actual efforts during design and (3) actual efforts during construction.

As mentioned in chapter 4, decomposition is strongly related to coordination. Both issues together form the key to organizational simplification. Due to this interrelationship, the coordination aspects cannot be ignored when dealing with the decomposition of problems, tasks, resources, etc. The more adequate the decomposition, the smoother the coordination can take place and the better the realization process can be controlled.

For the understanding of decomposition, it is necessary to use some notions of system theory. A brief summary of the most relevant notions of system theory, with respect to the content of this study, is given in annex 1.

5.2 Definition and goal of decomposition

Decomposition is defined as the formation of part-systems of a system(1). Instances of part-systems are sub-systems, aspect-systems and phase-systems.

From a system's theoretical point of view, it is very difficult to define a goal for decomposition. The difficulty is how to relate the system-theoretical parameters (elements, relations, behaviour, etc.) to practical, organizational aspects. These practical organizational aspects can either be subjective or objective.

Examples of such practical organizational aspects are competence of employers, desired number of elements in a cluster, organization of coordination, etc. With an eclectic exploration of literature, only three goals of decomposition were deduced.

The first goal is defined in relation to decomposition of problems[2]. The essence is, that a problem solving process (realization process) is stimulated by a systematic description such that the problem is simplified. This systematic description is realized by decomposition aiming at the reduction of complexity. The corresponding decomposition goal is to obtain a better insight into the critical problem areas.

The second goal is given by In't Veld[3], stating that joining functions, tasks or actions can be beneficial in terms of economic rationality. The result is "internal differentiation". In case the economic rationality is related to the products to be made, the result is "internal specialization".

The third goal is to work simultaneously on a realization process with a number of people in order to reduce the time to pass the various phases. This is necessary due to the fact that most realization processes must be conducted under time pressure. It is clear that this goal is also based on economic rationality[4].

Combining the goals, it can be stated that decomposition is necessary from a rational economic point of view as well as for a reduction of the complexity. It is important to realize that the goal of decomposition is not to find the smallest parts (elements) of a system. In general, every decomposition strategy or method (top-down or down-top), results in a set of smallest parts. The main problem of decomposition however, is to define working clusters. These clusters consist of part-systems which, in turn, consist of (or refer to) a number of elements and/or relations. The relation between part-systems are called intrarelations and the relations within a part-system are called interrelations.

5.3 Types of decomposition

The first type of decomposition of human activity originates from the experience that all necessary actions in order to reach a certain goal cannot be done simultaneously. Hence, time and sequence of activities can be considered as the most elementary decomposition method. Another type of decomposition originates from the division of labour, resulting in specialisms. During the industrial revolution the division of labour formed the framework on which the "economy of manufacture" was based. Founded on this principle "Scientific Management" was developed in the second decade of this century, leading to the founding of a school in industrial management (Taylorism)[5].

Besides these divisions in individual tasks, examples can also be given of decomposition in larger organizational divisions[6]. This type of decomposition is generally defined as departmentalization. Generally, a number of dimensions can be given which play a role in the formation of working units or clusters[7], such as organizational functions, products, locations, customers, processes, equipment, etc. Also the dimension of authority can be applied to form a departmentalizational structure. In that case, the rate of autonomy is the governing factor, resulting in a certain amount of decentralization[8].

5.4 System-theoretical aspects of decomposition

When considering the relation between the part-systems as the outcome of decomposition and the organizational issues to be dealt with, it can be stated that[9]:

- sub-systems refer to "things" and are related to members and/or groups of an organization. A sub-system can be considered as a cluster of elements and/or individuals;

- aspect-systems refer to the issues or the topics of a system. Aspect-systems are clusters of relations between elements and/or individuals. Examples of an aspect-system are weight and maintenance;

- phase-systems refer to the relevant phases of a system. Phase-systems can be considered clusters of time (periods). Examples of a phase-system are, for instance, temporary construction phase and utilization phase;

The structure of a system is determined by the mutual relations between sub-systems, aspect-systems and phase-systems. Each relation gives insight and information about a particular organizational issue:

- relations sub-sub : interactions, communications
- relations aspect-aspect : system behaviour, functional coordination issues, relations between issues
- relations phase-phase : sequence
- relations sub-aspect : who does what
- relations sub-phase : who acts when
- relations aspect-phase : what is dealt with when

It can be concluded that, with the above systematic decomposition method, the considered system and organizational issues are modelled as a path in the three-dimensional space spanned by sub-systems, aspect-systems and phase-systems. Generally, it is difficult to visualize such a three-dimensional structure. Mostly it is preferred to graphically present the various relations between part-systems in two dimensions. Instances of two-dimensional relation diagrams are given in figures 5.4.1, 5.4.2 and 5.4.3.

Unfortunately, the above decomposition methods do not straightforwardly lead to an ideal and unique decomposition strategy resulting in optimal clusters. The decomposition strategy is governed by a dilemma induced by the desired simultaneous development of the system in relation to coordination:

- on one hand, it is important to split up the system into a large number of part-systems in order to enable simultaneous development and hence to limit the development period (economical rationality);

- on the other hand, it is necessary to limit the number of part-systems in order to maintain coordination.

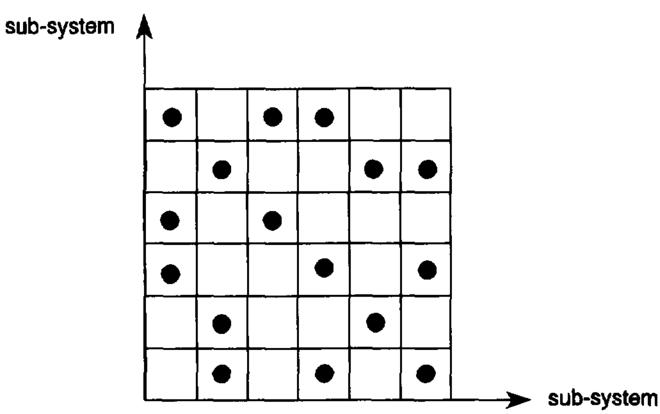

Fig. 5.4.1 *This diagram is a two-dimensional graphical representation of symmetrical relations. The indicated diagram refers to the interrelation between sub-systems. Similar diagrams can be made for the mutual relations between aspect-systems and for the mutual relation between phase-systems.*

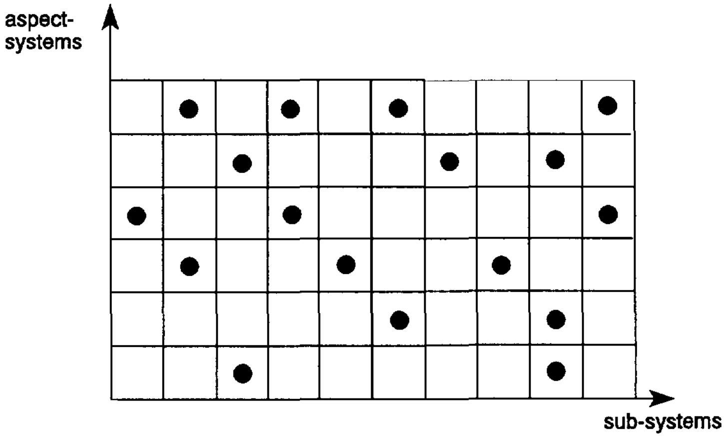

Fig. 5.4.2 *This diagram is a two-dimensional graphical representation of relations between aspect-systems and sub-systems. Obviously, not all aspect-systems are related to all sub-systems. For instance, a sub-system can be free of maintenance.*

This leads to two important aspects of decomposition, namely (1) the autonomy of the part-systems when dealing with their development tasks and (2) the structure of mind.

Regarding the autonomy of the part-systems, Simon's hierarchical decomposition strategy, is useful[(10)]. The decomposition strategy must be such that at any level of observation the whole system will be correctly represented. This is the condition for partial autonomy of the various departments.

Earlier, Simon developed the "nearly-decomposability rule"[(11)]. The essence is that the behaviour of the considered sub-systems on short term basis is only determined by internal coherence, whereas the long term behaviour of the considered sub-system is determined by external coherence between the sub-systems. The consequence of the above rule in terms of decomposition is that relationships inside the part-systems are maximized and relationships outside the part-systems are minimized.

With respect to the structure of mind in relation to decomposition, Graicunas[(12)] defined the "span of control", that is, that one leader can control 6 to 7 subordinates at maximum. This point of view originates from the idea that control possibility is also determined by the complexity of the considered system.

In't Veld[13] defined the "span of attention" in which the number of subordinates depends on the situation, namely the number of problems, the need for coordination, the quality of the subordinates etc.

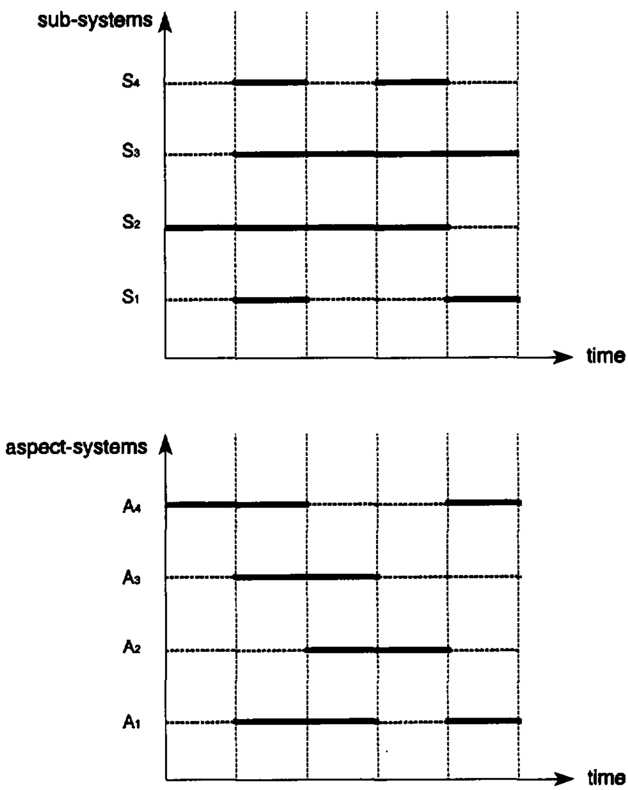

Fig. 5.4.3 *This diagram is a two-dimensional graphical representation of the relation between phase-systems on one hand and both aspect-systems and sub-systems on the other. Obviously, not all sub-systems are necessary for all phase-systems and not all aspect-systems are relevant to all phase-systems. For instance, the aspect-system maintenance is not relevant for a relatively short construction phase.*

5.5 Methods of decomposition for the realization of complex systems

Following the considerations on types of decomposition and aspects of decomposition as given in the previous paragraphs, three formal methods of decomposition can be distinguished(14).

- The first method is related to departmentalization. The predominating decomposition rule is similarity in operations, processes, functions, tasks, individuals, etc. The main goal is directed to form part-systems or clusters as homogeneous as possible. In that way homogeneity is characterized by a high degree of similarity. Consequently, the part-systems show a high degree of mutual dissimilarity. The main disadvantage is that due to the dissimilarity, very strict coordination requirements apply, as the part-systems cannot operate autonomously. Autonomy can only be given in case all functions or tasks can be performed within the part-system or cluster. This implies the absence of any relation between the distinguished part systems.

- The second method deals with autonomy of sub-systems. Given the nearly decomposability rule, the decomposition is predominantly based on interrelationships and intrarelationships. It is based principally on the coordination possibilities and is therefore in full contrast with the first method.

- The third method deals with coordination and is based on a particular form of relationship, namely communication and information transmission flows.

When considering these three decomposition methods, it is not difficult to find instances of application. Departmentalization and the associated homogeneous task clusters are applied in production processes at shop-floor level in the industrial sector. An important aspect of production is that the design phase is finished and that people know what to produce. Production processes hardly require coordination of relationships between the elements, but in most cases coordination of time (tuning). Decomposition aimed at autonomy and coordination based on interrelation or on information flows is rarely found at execution level. These methods are found at management level and/or design organizations.

For a realization process of a complex system, the main decomposition criteria follows from the defined goals. Given the required product of effectiveness and efficiency to be controlled, all three discussed decomposition methods must be applied.

- The large set of requirements, together forming the friction between solution and problem, cannot be handled adequately without clustering. Such a clustering should give a compressed and correct insight into the behaviour of the "solution" in the "context" during the design period of a realization process. This clustering method based on information transmission flows is discussed in paragraph 5.6.

- When dealing with a complex system, the design of (sub-) systems cannot take place directly from the set of requirements. Design work always starts with simple concepts of elements. Due to the large number of elements of a complex system, the design of such a system cannot be controlled without clustering the elements into working clusters. However, such a cluster must take into account all relations between the elements. This clustering method based on relationships is discussed in paragraph 5.7.

- *Due to the various typical disciplines needed for the implementation of most* complex systems, which often should work on different locations, the implementation phase of the realization process cannot be controlled without construction clusters. This clustering method based on (dis)similarity is discussed in paragraph 5.8.

5.6 Decomposition of the friction between solution and problem: clustering of requirements

5.6.1 The decomposition of the design problem

This section is mainly based on the fundamental work of Alexander[15]. The design problem starts with the list of requirements or variables. For the design of complex systems, the number of variables is large and the information needed for the design process is tremendous and confusing. As shown already in chapter 2, a mechanic approach of design work is not recommended. The question then is, how should the design process be adequately organized.

As shown in the previous section, for a good design process, the adaption must take place independently within fairly independent sub-systems of variables. For further elaboration it is considered fruitful to describe the variables in terms of set theory. Suppose there are m misfit variables: $x_i ... x_m$. Then the set of misfits is defined as:

$$x_i \in M \text{ (for all } i = 1 \text{ to } m) \qquad (5.6.1)$$

Since the variables could interfere, conflict or not interact at all, the variables are interrelated. The set of interrelations is defined as L, containing the non-directed, signed, one-dimensional elements called links. Each link joins exactly two elements of M. The two sets together form a linear graph G (M,L)[16]. An example of such a graph is given in figure 2.3.7 (see chapter 2), showing the structure of the variables.

It is important that graph G (M,L) gives an accurate picture of the behaviour of the variables. Only in that way the design process can be controlled. In order to give this accurate picture, graph G (M,L) must meet three formal requirements[17]:

- Set L must describe all interactions between the variables. Since the elements of L are links representing a two-variable correlation, this means that three-variable and higher order correlations must be prevented. Consequently, any pair of variables must be independent of the states of other variables. The only way to achieve that, is to make the variables as specific as possible.

- Even the two-variable correlation must be as small as possible, meaning an attempt must be made to make the variables as independent as possible.

- The variables must show a certain symmetry, meaning that the proportion of all solutions satisfying a requirement, should be about the same for each requirement. In other words, all variables should be roughly comparable in their scope and significance.

Having defined graph G (M,L), the question is how to decompose set M into a number of subsets in the most appropriate way. It will be clear that set L plays an important role in this decomposition.

A possible clustering method is given in figure 2.3.8 (see chapter 2) in which most links of set L are within the defined clusters and only a few links of set L intersect the cluster boundaries. A totally different decomposition method is indicated in figure 5.6.1. This method results in a hierarchical tree of (sub-)sets of variables.

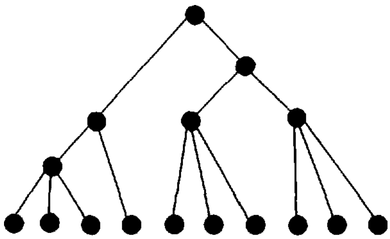

Fig. 5.6.1 *Clustering of variables resulting in a hierarchical tree of sub-sets of variables.*

It will be shown that the most proper decomposition is substantially different from the decomposition most designers want to use. Alexander stated[18]: "A proper decomposition of set G (M,L) results in significant "pieces" yielding major aspects of the problem the design organization should apply herself to". Then the point is reached in which the design work must be divided into two parts:

- the first part is the analysis; the total set of requirements is decomposed in a tree of sets of requirements, together forming a design program.

- the second part is the synthesis, starting at elementary level with a number of diagrams of concepts and ending with a tree of concept diagrams together forming the solution of the initial design problem.

The most ideal decomposition method is to bring together the analysis with the synthesis such that each set of program requirements corresponds with a concept diagram. In other words, it should be possible to derive the rough structural components from graph G(M,L). Therefore, the requirement diagram must contain elements of the concept diagram, while the concept diagram must contain elements of the requirement diagram. In this most ideal situation the concept diagram is a requirement diagram and vice versa. These are "constructive diagrams"[19] (see figure 5.6.2).

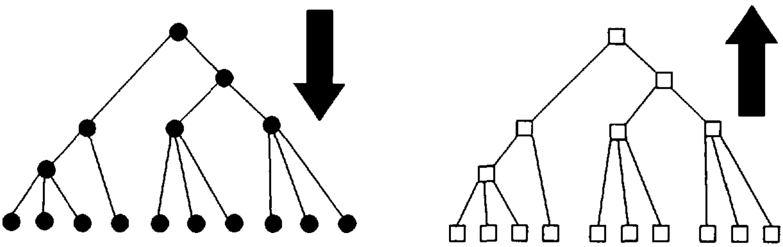

Fig. 5.6.2 *Constructive diagram, which is composed of a design program of sets of variables and a diagram of concepts (elements, sub-systems and systems). In an ideal constructive diagram, the design program is identical to the diagram of concepts.*

5.6.2 The decomposition method

The basic decomposition problem is illustrated by imagining a diagram of requirements, S_1 and S_2 being two different sets of requirements, whereas S_3 contains all requirements of S_1 and S_2. The designer must then do two things:

- find constructive diagrams for S_1 and S_2 individually, meaning that the possible misfits which S_1 contains, somehow cohere and suggest a physical aspect of the considered concept. The same applies to S_2. This is highly dependable on the internal structure of the sets S_1 and S_2.

- derive a constructive diagram for S_3 in some simple way from the constructive diagrams of S_1 and S_2. This depends highly on the relations between the sets S_1 and S_2.

It is clear that making the diagram depends on interactions and that it is important to realize that interactions between requirements originate from physical properties and dimensions. In case the requirements should deal with totally different aspects, there could be no basis for conflict or concurrence.

The traditional design way, that is: (1) successively and separately treat each separate variable, (2) find a constructive diagram and (3) superimpose all constructive diagrams at the end, will lead to iterations.

The reason is that the physical characteristics demanded by one requirement can conflict with the physical characteristics demanded by another. However, sometimes during the fusion of diagrams the conflict will be encountered. The later the conflict occurs in the design process, the worse possible implications can be coped with. Hence, it is stated that the later conflicting diagrams have to be integrated in the design process, the more difficult the integration is. This implies that the fewer links there are between the subsets of the decomposition the better. In that case conflicts will immediately be dealt with in the subsets. Consequently, the decomposition rule is maximization of internal interactions of the sets of variables and a minimization of external interactions of the sets of variables.

Intermezzo 5.1

In a formal sense the decomposition rule is as follows[20]:

At a certain decomposition level, some set S must be parted into disjoint subsets (S_1, S_2, S_3....S_a.....S_n). The issue is to choose S_a in such a way that the constructive diagram S_1 can be made such, that it does not severely contradict with one of the other S_a's to be made, which has to be repeated for S_2, S_3, etc.

This process is rather difficult as each variable which has links with other variables exercises constraint over the state of those variables. In other words, values of variable S_1 give information about the value variable S_a can take. Hence, S_a should be chosen such that the variables in different subsets of the partition will have as little information constraint on each other as possible.

The three conditions for graph G (M,L), as specified in section 5.6.1, define a unique probability distribution $p(\lambda)$ over the states λ of any set of variables S. Furthermore, it is shown that given any partition p_i of a set S into subsets, $\pi(S_1, S_2....S_n)$, a measure of information transfer can be established among these subsets: R (π). As $R(\pi)$ is defined for all possible partitions of any S, the desired decomposition of set M is obtained by minimizing $R(\pi)$ for successive partitions.

In a more practical sense, the existence of information constraint can be considered an ordinary relation. In that case, the decomposition method is identical to the decomposition of a system into sub-systems based on interrelationships. This decomposition method is given in annex 3, together with a simple example.

5.6.3 The practical significance

With the described decomposition method, it is possible to make a constructive diagram for a design problem bringing together the design program and the diagram of concepts.

These constructive diagrams can be obtained for infrastructural and even architectural problems, which are characterized by concepts more than by typical structural properties. For problems however, which could only be solved with forms governed by structural properties, most designers think and work with simple concepts. In that particular case, there is a difference between what is in the designers mind (simple concepts) and what comes out of a proper decomposition (design program). The difference is illustrated in figure 5.6.3.

The difference can be bridged with help of system theory. A complex design problem, fully decomposed into sub-systems, aspect-systems and phase-systems may be an adequate alternative for the constructive diagrams. Therefore, the design work is split into: (1) work on concepts (elements or sub-systems) and (2) control by subsets of requirements (based on intermezzo 2.5 and given the definition of an aspect-system, it is obvious that a sub-set of requirements can be considered an aspect-system). In that way, it is not necessary to decompose the total set of requirements into a tree of sets of requirements, but to confine the decomposition to a higher level of abstraction. Such a decomposition would lead to a number of aspect-systems containing the whole set of requirements as well as its physical implications.

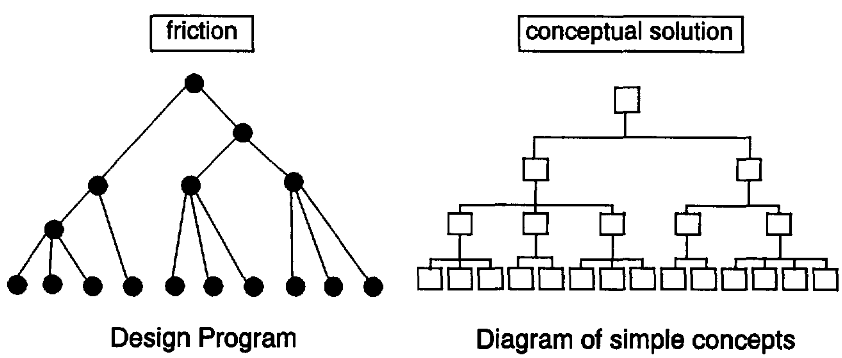

Fig. 5.6.3 *Difference between a decomposition of the set of variables (design program) and what is in a designer's mind (diagram of simple concepts).*

Using the above decomposition method it is possible to use simple concepts at the most elementary level and fuse the elementary concepts into complex constructive diagrams. In such a way, it is guaranteed that by subsequent fusion at the various levels, all misfit variables will be dealt with.

The final diagram at the end of the design process represents the required effective performance of solution and consequently is very useful to control the design work on performance of solution[21]. When strictly using the decomposition rule, the design manager can avoid the development of one part of the functional program at the expense of another. Consequently, he is able to avoid large iterations, since he has a continuous insight into the state of the design with respect to performance of solution. The fusion is sketched in figure 5.6.4.

Obviously, a decomposition of the design program must stop at a high level of abstraction in order to enable appropriate overall control. This means that for most complex problems, a small number of aspect-systems is obtained.

For practical use, it is important to realize that the clustering of conflicting requirements can be simplified by converting the specific requirements into a neutral, physical dimension. A clear example is a system with two conflicting requirements: (1) it should be heavy enough and (2) it should not be too heavy. The clustered requirement (aspect) in this case is the variable "weight".

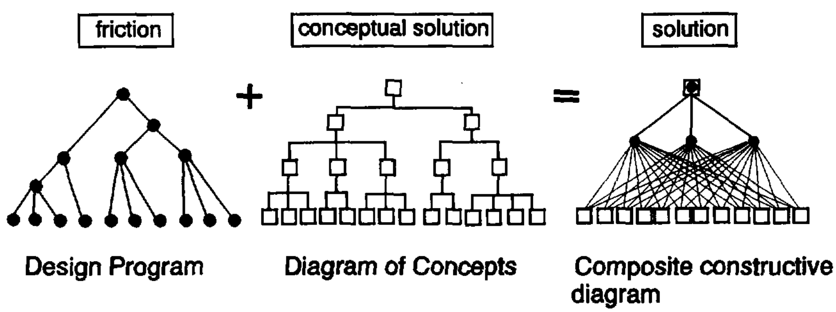

Fig. 5.6.4 *This figure gives the fusion between the design program consisting of sub-sets of variables and the diagram of concepts on which most design work is based. The indicated fusion is necessary for complex systems and results in a separation between specialist work on concepts on one hand and coordination of complexity by a few sub-sets of variables (aspect-systems) on the other.*

5.7 Decomposition of concepts: clustering of elements

5.7.1 General

In the previous paragraph, the decomposition of the set of requirements has been discussed, resulting in aspect-systems to be used for control of the performance of solution at the highest possible abstraction level during the design phase. These aspect-systems automatically take into account the main characteristics of complex systems: (1) the large number of requirements, c.q. functions, (2) the large number of elements and (3) the large number of non-simple interactions (relations) between the elements. The important control function of aspect-systems is sketched in figure 5.7.1.

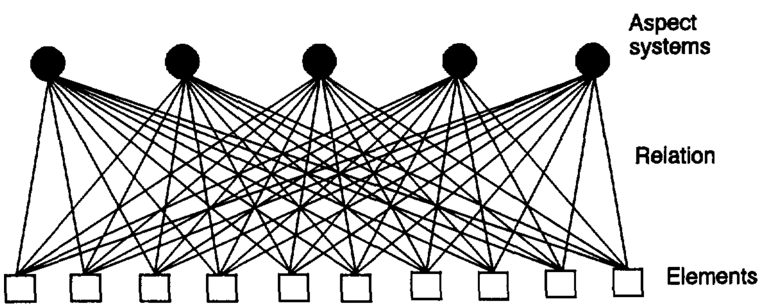

Fig. 5.7.1 Control function of aspect-systems covering: (1) the set of requirements, (2) all elements and (3) all relations between the elements.

For systems with a large number of elements, however, this control method is rather cumbrous. This is demonstrated by considering two elements (figure 5.7.2).

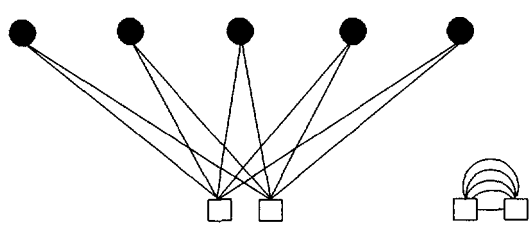

Fig. 5.7.2 Centralized control of two elements by aspect-systems versus direct control between elements.

Obviously, a rigid and centralized control of elements by aspect-systems is not the easiest way for design work. The opposite control method however, does not lead to an insight in the overall performance. This is illustrated in figure 5.7.3 showing direct control of relations between the elements without using aspect-systems for goal control.

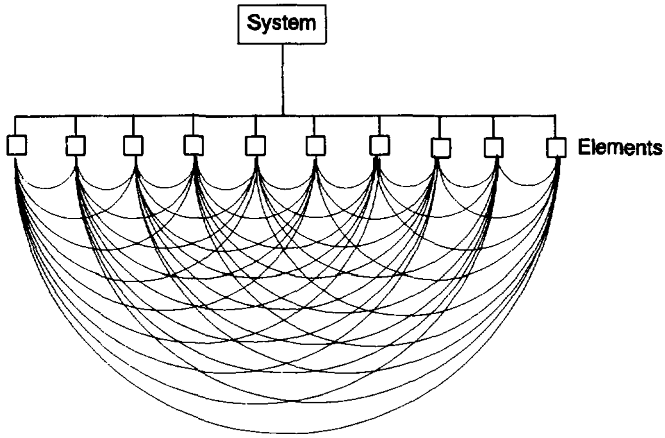

Fig. 5.7.3 *Diagram representing the elements of a system and the relations between those elements. The set of lines represents the control problem.*

When a rigid centralized control is prescribed, the probable result would be two control systems working in a parallel way: (1) a formal and indirect control circuit via aspect-systems and (2) an informal direct control circuit between the elements. This situation is sketched in figure 5.7.4.

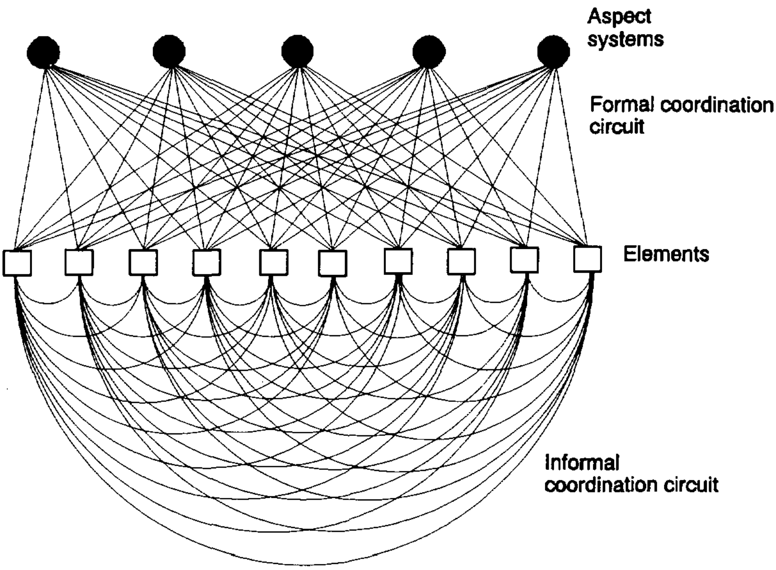

Fig. 5.7.4 *The "structural" control of a system split up in a combined goal and structural control (formal circuit) and an informal structural control directly between the elements.*

It will be clear that this parallel control system is not recommended. Besides the goal control (performance of solution) by means of the set of aspect-systems, an additional decomposition is needed to simplify structural control (relations between the elements).

5.7.2 Relations and the decomposition rule

The objective of this paragraph is to provide a simple control system for the structure of the solution. Structure is defined as the set of relations between the elements of a system. This implies, that it would be useful to decompose the system in such a way that the relations between the system elements are taken into account. In other words, decomposition must be aimed at facilitating control[22].

This approach to the decomposition problem, that is, an approach from the point of view of the relations between the elements, is theoretically described by the decomposition rule of Simon (see paragraph 5.4).

As shown in paragraph 5.4, the short term behaviour of the part-systems of the system is determined by the internal coherence of the considered part-system (intrarelations), while the long term behaviour is determined by the coherence between the part-systems (interrelations)[23]. This characteristic enables the designer to draw attention to part-systems for a certain relatively short period without concerning the rest of the system. The rest of the system will have long term consequences only. As shown, the long term behaviour can easily be represented by the aspect-systems as derived in the previous paragraph. Obviously, when a complex system is decomposed according to the nearly-decomposability rule, the control efforts are minimized.

The decomposition method of systems, resulting in a clustering of elements based on relations, is given in annex 3, presenting the most relevant theoretical backgrounds as well as a simple example. This example has an hierarchical character. Other decompositions, however, are also possible. Obviously, the "nearly decomposability" rule does not automatically lead to an unambiguous optimum of sub-systems. It is concluded that additional requirements are needed for a general decomposition rule. The following additional requirements are suggested[24]:

- specification of the desired number of elements in a sub-system;
- specification of the desired number of sub-systems;
- specification of the maximum number of steps between the elements of a sub-system (distance = length of a path, see paragraph 5.8).

The most important additional requirement would be the introduction of the strength of the relations. However, the use of graph theory, which is based on binary Boolean relations, implies that the strength of the relations cannot be incorporated in the decomposition directly. Polak[25] introduced an analogue method to incorporate the strength of the relations. He developed a program for the operation of a graphical relation matrix. It is graphical because the strength of the relations is proportional to the graphical symbols. In that way, it is possible to take into account the weighted density of graphical symbols.

5.7.3 Practical significance

The decomposition method, as described in the previous section, is a very important tool to organize the design and engineering work. In fact, the formal and informal control circuits, as indicated in figure 5.7.4, are replaced by an adequate control system for both goal control as well as structural control (see fig. 5.7.5).

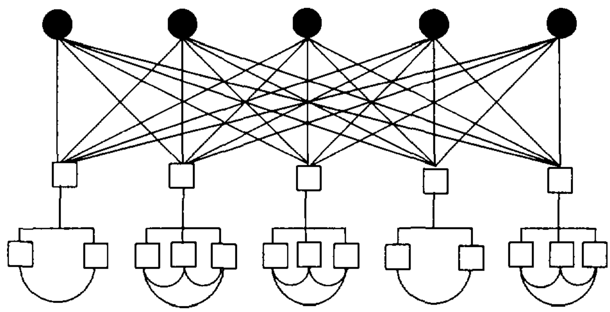

Fig. 5.7.5 *Simplified goal coordination and structural coordination as a result of two clustering operations: (1) clustering of requirements yielding aspect-systems for goal coordination and (2) clustering of elements yielding sub-systems for structural coordination.*

It is noted that with the two decomposition methods of paragraphs 5.6 and 5.7, figure 5.6.4 is substantially simplified (see fig. 5.7.6).

Although it is mathematically possible to decompose a system in a number of sub-systems such that control is facilitated, it must be realized that the final choice of the sub-systems must not only be made by the results of a mathematical decomposition method but also depends on practical considerations.

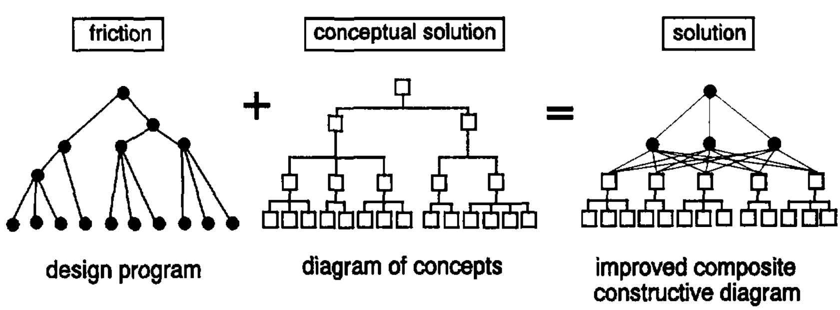

Fig. 5.7.6 *The decomposition of a complex system with respect to variables (requirements) and sub-systems. The clustered variables represent the total friction between solution and problem. The clustered concepts (sub-systems) simplify structural control.*

5.8 Decomposition of system construction: clustering of elements

5.8.1 General

Having discussed the decomposition of the design work, now the decomposition of the construction task, being the next step in the realization solving process, is discussed. Construction work is related to production, location, equipment, processes, etc. As discussed already in section 5.5, for production processes, the predominating decomposition rule in order to facilitate coordination is departmentalization which should be based on (dis)similarity considerations. In this section the decomposition method based on (dis)similarity considerations is presented.

5.8.2 The decomposition on (dis)similarity

The basic problem is to decompose a system into sub-systems in such a way that the elements inside the sub-systems are as similar and the elements of different sub-systems are as dissimilar as possible. This problem can be solved mathematically by cluster analysis on which a large number of publications is available. A unified exposition of cluster analysis is given by Duran(26), which is used for the theoretical background of the section. The most relevant, most necessary and main principles are given in annex 4, showing that cluster analysis provides a basis for the measuring of similarity. Based on that, methods for clustering algorithms can be developed.

5.8.3 Methods for clustering algorithms

Three different practical methods for clustering algorithms can be distinguished(27):

- *one-to-one method*: take the distances between the elements and require that the mutual distances inside a cluster should be minimal or should not exceed a certain threshold;
- *one-to-group method*: take the average distance of one element to all elements from a cluster and add the element if the similarity is maximal or above a certain threshold;
- *group-to-group method*: maximize the average distance of all elements of one group to all elements of another.

In addition to that, many other clustering algorithms have been described. An interesting typology of cluster algorithms is given by Hartigan and Kickert[28]:

- *sorting*: part the elements according to the most important variable, then part the elements inside these clusters according to the next important variable (not too many variables).

- *switching*: given an initial partition, new partitions will be created by switching elements from one cluster to another (not always converging to optimal result, depends on good start);

- *joining*: find closest pair of elements and join them in a cluster; repeat this procedure until all elements are in one cluster (not too many elements);

- *splitting*: part the elements in a number of clusters; then part each cluster into a number of smaller clusters and so on;

- *adding*: given a certain clustering structure, an element typical of each cluster is selected and each element is added to the cluster to whose typical elements it is closest;

- *searching*: if many clusters are ruled out by a certain criterion then search the remaining clusters.

5.8.4 The hierarchical clustering method

Many clustering procedures are hierarchical[29]. As stated before, the production process requires a more or less hierarchical structure. Hence it would be convenient if a simple hierarchical clustering method could be found. In fact, the joining method as described in the previous section can be called a hierarchical clustering. Implicit in the hierarchical clustering method is the concept of distance between an element and a cluster and distance between two clusters.

Moreover, inherently to the cluster problem is an optimality criterion (objective function). In other words, there must be a measure of homogeneity within a cluster and disparity between two clusters. These measures can depend on distance between two clusters, whereas various possibilities can be distinguished[30]. A formal example of the hierarchical clustering method is given in intermezzo 5.2.

Intermezzo 5.2

The hierarchical clustering is as follows[31]:

Consider $I = \{I_1, I_2,....,I_n\}$ as a set of clusters:

$\{I_1\}, \{I_2\}, ...\{I_n\}$.

Select two clusters I_i and I_j which have closest distance to each other and fuse them into one cluster. The new set of n-1 clusters is:

$\{I_1\}, \{I_2\}....\{I_iI_j\}.....\{In\}$.

This procedure must be repeated until there is only one cluster (=whole system) left. This hierarchical clustering method can be represented graphically by a "dendogram" (fig. 5.8.1).

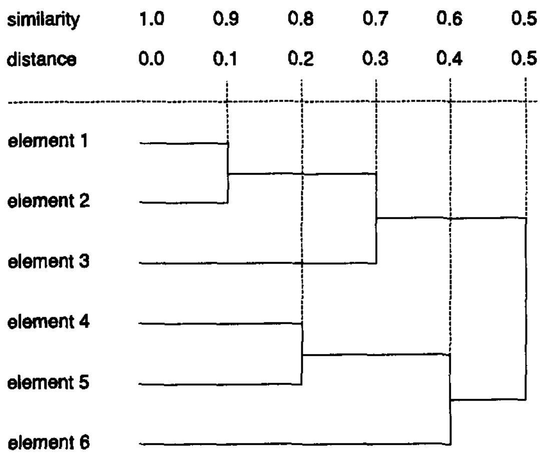

Fig. 5.8.1 *An example of hierarchical clustering resulting in different clusters with different similarities and distances at various hierarchical levels.*

5.8.5 Practical significance

The decomposition method as presented in this paragraph is very suitable for the decomposition of a production task. An experienced engineer is able to stop the repeated decomposition at a level which is characterized by (in his opinion) an optimum between the number of clusters and the number of elements in a cluster.

5.9 Summary

Decomposition is aimed at facilitating control and is closely connected to it. For the realization process of complex systems, three decomposition methods are presented.

With the first method, the friction between problem and solution is decomposed. Since the friction is given in a set of requirements, the decomposition of the friction is, in fact, a clustering of requirements. The clusters of requirements are aspect-systems, defined as a part of the set of relations of a system, taking into account all elements of a system. The set of aspect-systems represents the behaviour of the system and can be used for goal-control on effectiveness.

With the second method, the solution consisting of a set of elements is decomposed for facilitating structural control during the design phase, resulting in clusters of elements. Without structural control, goal-control is not possible. The relations inside the clusters are maximized whereas the relations outside the clusters are minimized.

With the third method, the solution found at the end of the design phase is decomposed to facilitate control during the construction phase. Based on (dis-) similarity of process parameters, the most appropriate working clusters are determined.

Notes

1. Kickert, W.J.M, Organisation of decision making, North Holland Publication Company, 1979.
2. This definition is particularly given with respect to the theoretical problem solving process by: Kramer, N.J.T.A., Systeem in probleem, Stenfert Kroese, Leiden, 1978.
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15. Alexander, C., Notes on the Synthesis of Form, Harvard University Press, Cambridge, Massachusetts, 1964.
16. The most relevant issues on graph theory in relation to decomposition and relationships between elements of a system were presented by: Kickert, W.J.M., Organisation of decision making, North Holland Publ. Cy, New York, 1979.
    A theoretical discussion of graph theory can be found in: (1) Harary, F. and Z. Norman, Graph Theory as a Mathematical Model in Social Science, Ann Arbor, 1955 and (2) Even, S., Graph Algorithms, Computer Science Press Inc. Rockville, Maryland, 1979.
17. Alexander, C., Notes on the Synthesis of Form, Harvard University Press, Cambridge, Massachusetts, 1964.
18. Ibid.
19. Ibid.
20. Ibid.
21. In principle, cost and time can be considered aspects as well, but do certainly not represent a misfit variable between form and context. Cost and time do belong to the efforts needed to solve the total set of misfit variables between form and context. As shown in chapter 2, there is a relation between efforts and performance.
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23. Ibid.
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25. Polak, B.M. and M.R. Beheshti, Systematisch Ontwerpen, Delft University, Civil Engineering, Delft, 1991.
26. Duran, B.S. and P.L. Odell, Cluster Analysis, A Survey, Springer-Verlag, New York, 1974.
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29. Duran, B.S. and P.L. Odell, Cluster Analysis, A Survey, Springer-Verlag, New York, 1974.
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31. This example is given by: Kickert, W.J.M., Organisation of Decision Making, North Holland Publ. Cy, New York, 1979, and by: Duran, B.S. and P.L. Odell, Cluster Analysis, A Survey, Springer-Verlag, New York, 1974.

6. CONTROL OF THE REALIZATION PROCESS OF COMPLEX SYSTEMS

6.1 General

Control of the realization of complex systems is the main issue of this study. As shown in chapter 5, decomposition should be arranged such that control is simplified. The other organizational issues such as organization and information are determined by the way control is arranged. In this chapter, control is generally discussed in three parts.

The first part deals with theoretical considerations on control. In accordance with the main decomposition methods as derived in chapter 5, system theory is again used as the theoretical frame of reference.
In the second part, an extension is made to meta-control which can be used to structure the control/coordination of the realization process of complex systems.
The third part deals with the active part of control, that is, decision making. Since this active part is beyond the scope of the study, only a short outline of main issues is given, obtained in an eclectic survey on relevant literature.

6.2 Control paradigm

With the definition of control (any form of directed influence), it is possible to approach control in two ways(1): (1) control of social systems and (2) cybernetical control of technical processes by feedback and feedforward control. Obviously, for the realization process of complex systems, consisting of a search process followed by a selection process to be performed by one and the same organization, both ways should be applied.

The question is how control should be arranged. Consequently, control is dealt with in a prescriptive sense, resulting in a set of control rules. This set of rules is derived from a control paradigm as developed for the control of systems(2). The control paradigm is defined as a class of abstract systems, each consisting of a controlled system, an environment and a controller(3). The notion "paradigm" is used as the best way empirical reality can be considered(4). The starting point is, that the class of abstract systems for each interesting phenomenon contains a system which can be used as a model for that phenomenon(5). Hence, control situations can be represented schematically as sketched in figure 6.2.1.

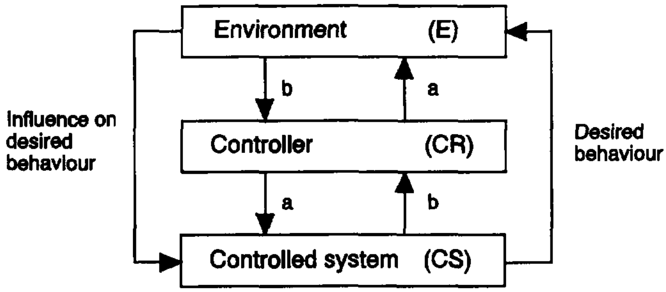

Fig. 6.2.1 *Graphical representation of the control paradigm, showing the system to be controlled (CS) by the controller (CR) taking into account the direct environment (E) in which the system exists and should show a desired behaviour. The arrows (a) stand for influence relations while arrows (b) stand for information relations.*

The controlled system (CS) can be considered a generator of behaviour, showing behaviour as a function of intervenience of the controller (CR) and/or influence from the environment (E). The environment can also be considered a generator of behaviour as it is influenced by both the controller as well as the controlled system. This implies that two types of control can be distinguished:

- the first type is internal control aiming at influence of the controlled system.
- the second type is external control aiming at influence of environment.

Hence, given the relation between controlled system and environment, it is possible to control the behaviour of the controlled system indirectly as well. The relations between E, CR and CS, as indicated in figure 6.2.1, refer to influence relations (a) and information relations (b).

6.3 Conditions for effective control

6.3.1 General

Given the control paradigm of the previous paragraph, the conditions for effective control are[6]:

- CR should specify a goal with respect to the CS;
- CR should have a model of the CS available;
- CR should have information available about the situation of the system parameters and influencing parameters of the environment as specified by the model;
- CR should have sufficient control variety available.

These conditions will be discussed in the next four sections.

6.3.2 Goals and control

Given the definition of control, there can be no control without a goal. Control actions will be chosen with respect to the impact on the system in the direction of the defined goal. For realization processes, it is recognized already that the reflection of reality, being partial, relative and subjective, plays an important role. The reflection of reality results in a certain vision of the controller on the situation. Hence, the goal discussion with respect to solutions is governed by visions of the participants. As solutions can be considered as systems, this goal discussion also refers to systems. In most cases, discussions about goals have a chaotic character. The most common misunderstanding is that systems "have" a goal. In fact the goal of a system is determined by the interest of the person or group has in the system[(7)]. Consequently, it is recommended to speak about goals in relation to the vision on the system, since a goal is not a system property but a model property[(8)]. For a control situation the goal for the controlled system is determined by the controller. In this sense the goal has two functions[(9)].

- Goal as criterion for effectiveness of control. The goal determines the desired behaviour of the system. A comparison with the actual behaviour of the system gives insight into the effectiveness of control.

- Goal as criterion for the quality of the process of modelling. The goal is a guideline for which choices are made with respect to parameters and relations to be included in the model. The goal oriented modelling can be evaluated by considering the effectiveness of control.

The goal of the problem solving process can be achieved in various ways. In case the solution is considered as a system, then, within the control paradigm, the goal is defined as arranging pairs of input and output or arranging combinations of mutually associated inputs, outputs and control actions[(10)] (see intermezzo 6.1).

Intermezzo 6.1

The behaviour of a system can be described by means of input, output, control and the state of the system as a function of time (figure 6.2.2).

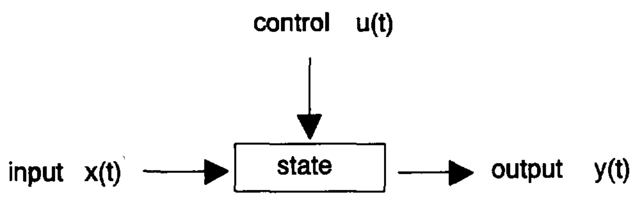

Fig. 6.2.2 *Schematic representation of a dynamic system. The state of the system can be influenced by input, control, output and all possible combinations.*

In this way, the complete goal concept of a system is given by combinations of x_i, u_i, y_i, provided with a preference of ordering, for instance (x_1, y_1) above (x_2, y_2). Hence, various types of goals can be recognized. These types are classes of the complete goal.

Production companies often identify the goal with the arrangement of outputs, that is, optimization of profit only(11). Another approach is that the profit at output side is limited due to the competitive market, giving a reason to concentrate control activity to the input side(12). From a more system theoretical point of view it is recommended to incorporate all three distinguished classes for control purposes(13).

A possible decomposition of the total goal can be considered after the decomposition of the total system into part-systems, aspect-systems and phase-systems. This is discussed later on in this chapter.

6.3.3 Models

The need for models for control purposes

Since effective control is based on directed influence on the system in order to create the desired system behaviour, it is necessary to compare the actual behaviour with the desired behaviour. This can only be done by means of a model(14). Such a model predicts the behaviour of the total system and may therefore not be confused with static structural models of elements of a system.

The effectiveness of control is, to a great extent, determined by the quality of the models. The necessity of a model for the control of a controlled system is shown by Conant[(15)]. For the selection of models used for control, it is important to analyze different types of models. In general, models can be classified with respect to[(16)]: (1) type of system to be described and (2) function. In addition to that, the role of models can be considered with respect to application and principles. These various aspects of models are given in annex 5.

The basic principles of the use of models

The basis of any use of models is the abstraction principle as for instance given by Rosenblueth[(17)]: "Abstraction consists of replacing the part of the universe under consideration by a model of similar but simpler structure". When reasoning in terms of generalization and abstraction, the direction of isomorphous modelling is from concrete systems via conceptual systems towards formal systems. As far as the formation of models is concerned the following relevant aspects can be distinguished[(18)]:

- isomorphy between model and reality should be shown;
- model and reality should not be identified with each other;
- models should not be too precise in an early stage;
- factors not initially included should be investigated at a later stage;
- a limited model has advantages as well as disadvantages;
- models are useful, but should never directly be used for decisions.

The use, the function of different types of models and the associated working principles are given in annex 5.

With respect to application of models in relation with the realization process, there is a relation between models and phases of the realization process[(19)]: (1) scale models, structural models and mathematical models are used for all phases and (2) ideal models and analogy models are used for the pre-design phases. However, the choice of an appropriate model is eventually a matter of inventivity and creativity of the user (see paragraph 6.6).

6.3.4 Information

Processing of information

The third condition for effective control is that the Controller should have enough information on relevant system data and environmental data. Given the dynamic character of the control models, the data, as specified by the models itself, should include both the actual value as well as the time dependant change of it. This is the only way to describe the behaviour of the system.

About the quantity of information (should be enough, but not too much), the current mechanic approach in most realization processes generates too much information. In this respect, Conant[20] has derived the following formula:

$$F = Ft + Fb + Fc + Fn \qquad (6.3.1)$$

in which:

F	=	the total information rate, that is, the sum of all the individual capacities to handle information;
Ft	=	the throughput information rate, that is, input-output flow of the considered system;
Fb	=	the blockage information rate, that is, the rate at which information on input side is blocked within the considered system, given the kind of information that is relevant for the output;
Fc	=	the coordination information rate, that is, the measure of the coordination of all elements of the considered system;
Fn	=	the noise rate, that is, a measure for the information at the output side which has no correlation with the information at the input side.

For the realization of complex systems, Ft is the only relevant information rate. Ft is the information component of the transformation technology. Regarding the other components of the total information rate, it can be stated that: (1) Fb is, for instance, large in case people in an organization withhold information (2) Fc is large in case the system consists of a large number of components and many workers are needed for the realization process, (3) Fn is large in case no input is added to the system and (4) Fc, being a measure for the necessity of coordination, can be reduced by means of adequate decomposition of CS[21]. With high values of Fb, Fc and Fn it is obvious that development managers tend to increase the total information rate F (for instance more people and more computers).

Such a measure, however, automatically increases Fc as well. This often leads to bureaucracy and inflexible organizations. Generally, it is more effective to reduce information itself[22].

Information with respect to models

In the classical decision theory (decision making is the active part of control), three cases are distinguished with respect to information[23]: (1) certainty, (2) risk, and (3) uncertainty. The distinction between the three cases follows from the difference in knowledge about the states of the system which would occur and the associated models[24]. These information cases refer to the occurrence of the states but none to the states themselves[25].

- certainty assumes a deterministic model; with the information available, it is exactly known what will occur;
- risk assumes a conditional probability function; with this information available it is known what can be expected, but not what will occur;
- uncertainty implies absence of knowledge about the model; it is not known what can be expected, let alone what will occur.

Intermezzo 6.2

The second case is confusing with respect to the common notions of risk. When considering risk in a qualitative and general context, it can be stated that risk is also connected to uncertainties. In such cases risk is experienced as "consequence". For a quantitative analysis of risk, three definitions can be distinguished using: (1) probability of occurrence of an undesired event and (2) consequences of the undesired event[26]:

1. Risk = probability of occurrence;
2. Risk = probability x consequence
3. Risk = probability x $(\text{consequence})^n$

The second definition of risk is commonly used.

In particular for the modelling of complex systems with respect to control purposes, it is important that the three classical cases are not mixed up when using one control model. The reason is that each case has its particular decision making process: (1) linear programming for the certainties, (2) risk analysis for the quantifiable uncertainties and (3) sensitivity analysis for the real uncertainties. Therefore, a strict separation with respect to information with a mixed decision making process, is recommended.

6.3.5 Control variety

Control variety is developed for operational control with cybernetic models[27]. Based on these models, a set of control possibilities were developed with the following areas[28]: (1) the system itself (internal control variety) and (2) the environment (external control variety).

The relevant control dimensions are: (1) routine control, which is bound by the process variable of the system itself, (2) adaptive control, which is based on a change of the structure of the system and (3) goal control, which is based on a change of the performance of the system. Together, the control areas and control dimensions give six control possibilities. This set is called the control characteristic[29]:

- internal routine (IR) : process variables within the system;
- internal adaptive (IA) : change of structure of the system;
- internal goal (IG) : adaption of goal given the system possibilities;
- external routine (ER) : better use of environment;
- external adaptive (EA) : change of structure environment;
- external goal (EG) : change of goal of system in environment.

Obviously, a certain hierarchy exists in this set of control varieties. For the practical application of hierarchical control, the meta-control concept is very useful.

6.4 Meta-control and multi level meta-control

6.4.1 Concept of meta-system

The meaning of the Greek word "meta" is "after". Nowadays meta is used for the notion "above" in the sense of a higher level[30]. Especially in organizational science, the concept of meta-systems is frequently used. Beer[31] recognized the need for meta-systems in the sense of higher logical levels for the control of lower level systems. Mathematics, for instance, is considered to be the meta-language of science, that is, the language in which higher order generalizations can be expressed[32]. In this sense, probability theory is sometimes called the meta-language of uncertainty and fuzzy set theory sometimes the meta-language of ambiguity[33].

As far as concrete applications are concerned, meta-systems are used for policy making[(34)] and planning theory[(35)]. The basic principles of meta-control will be outlined in this paragraph.

6.4.2 Meta-control configurations

Meta-control is defined as control of the control, that is, the directed change of the controller itself in order to improve its control. Meta-control is also applied in case control is out of its competency[(36)]. The meta-controller controls the controller, which gives two levels of control: (1) control at object level and (2) control at meta-level (see figure 6.4.1).

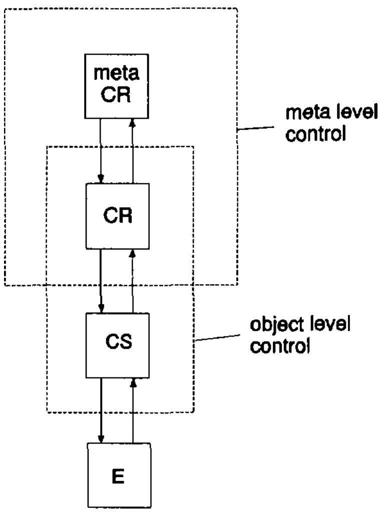

Fig. 6.4.1 Diagram showing control and meta-control configurations: meta-control is applied: (1) to improve object control or (2) when object control is out of its competency.

For effective meta-control, both the control paradigm as well as the conditions for effective control are valid. In figure 6.4.1 the controller CR becomes a controlled system, whereas the original environment E of the control system CR + CS will generally change. Since meta-control incorporates control of CS, CR and E, both internal meta-control as well as external meta-control can be distinguished. Hence, in analogy with section 6.3.5, six meta-control possibilities are available:

- internal routine meta-control
- internal adaptive meta-control
- internal goal meta-control
- external routine meta-control
- external adaptive meta-control
- external goal meta-control

With respect to meta-control configurations, three possibilities can be distinguished (fig. 6.4.2)[37]:

- pure meta-control of the controller, CS is then controlled by CR and meta-CR;
- "support" meta-control and "take over" meta-control both incorporating directed influence of the originally controlled system;
- meta-control of the relation between CR and CS, which consists of internal meta-control of CR and external meta-control on CS.

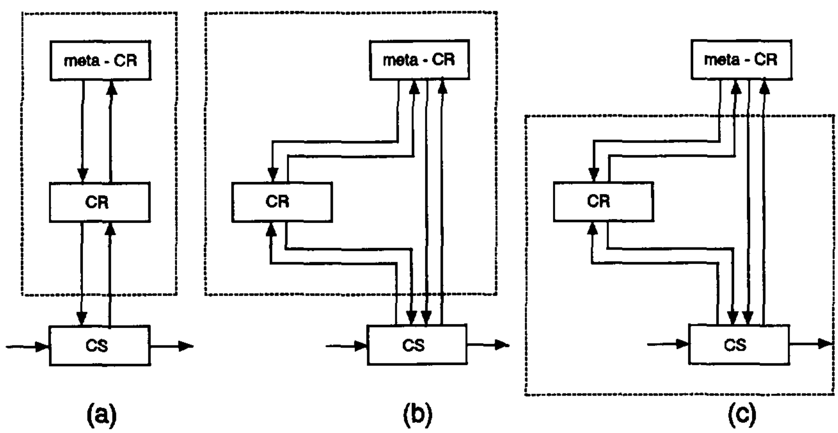

Fig. 6.4.2 Various meta-control possibilities: (a) pure meta-control of controller, (b) "support" and "take-over" meta-control and (c) meta-control of relation between CR and CS.

6.4.3 Multilevel systems

A control system does not stop at the meta-control level. It is clear that more steps can be distinguished in control: object control, meta-control, meta-meta-control, etc.

At first sight, the number of control levels has something to do with the number of aggregation levels as a result of decomposition, that is, in a quantitative sense. However, also a qualitative difference in control levels can be recognized[38]. In this case, the aspects of concern differ per control level. This is important with respect to coordination (see next paragraph). An example of a meta-meta-control configuration is given in figure 6.4.3.

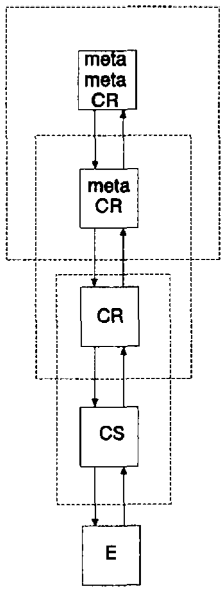

Fig. 6.4.3 *Diagram showing a meta-meta-control configuration. In this particular control situation, the controller is controlled by the meta-controller and the meta-controller by the meta-meta-controller.*

6.5 Coordination and meta-control

6.5.1 Concept and definition of coordination

According to Mintzberg[39], the two basic aspects of an organization are: (1) the way the work to be done is divided and (2) the way the required coordination is arranged. In other words, the most essential organizational issues are decomposition and coordination.

Since decomposition is already defined as the formation of part-systems, it seems rather trivial that coordination should cover the interrelations between the part-systems. Hence, it may be concluded that coordination is aimed at maintaining relationships, which can be interpreted as structural coordination[(40)].

The question is whether coordination is limited to the structure of systems only. Although coordination is recognized as the main issue of organizations, the notions of coordination itself are rather vague. Consequently, it is hard to find an unambiguous definition of coordination. A literature survey conducted by Kickert[(41)] indicated two main ingredients of the concept of coordination: (1) the mutual adjustment of the parts, in order to (2) attain some common (organizational) objective[(42)]. Hence, coordination should also deal with a goal concept.

It is concluded that two coordination modes can be distinguished: (1) goal coordination and (2) structural coordination. With the introduction of a goal concept, coordination can be defined as the control of a system of part-systems[(43)].

The division in two coordination modes is in full agreement with the first and second decomposition method as presented in chapter 5. The first decomposition method simplifies goal coordination whereas the second decomposition method simplifies the structural coordination. However, due to the fact that aspect-systems cover all relations between the elements, the main issue of both goal coordination as well as structural coordination is relationships. Both coordination modes take into account all elements and relations. In this sense, goal coordination is meta-coordination of structural coordination.

6.5.2 Coordination and meta-control

As mentioned in the previous section, coordination is control of the part-systems. In case a system is decomposable in two or more aggregation levels and considering the lowest decomposition level i, coordination is then at least control of the controller CR_i of the controlled (part)system CS_i (figure 6.5.1). The same situation applies to the i-1th decomposition level. Control of the controller of a controlled system is by definition meta-control. Consequently, meta-control is strongly related to decomposition level.

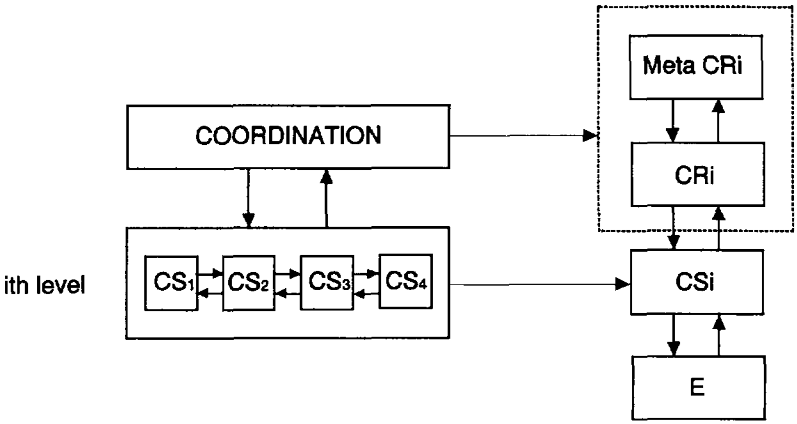

Fig. 6.5.1 Coordination and meta-control

6.6 Control and decision making

6.6.1 Definition of decision making

The clearest definition of decision making is the choice between alternatives[44]. However, such a definition is not sufficient to cover the decision making process. The decision making process needs both some preparatory work prior to the choice between alternatives, as well as some work after the choice has been made in order to ensure implementation. The concept of decision should at least consist of the following elements[45]:

- a choice between alternatives;
- the conscious drawing of conclusions from premises;
- a learning process of search, development, evaluation, etc.;
- an action commitment for implementation.

As far as the last element is concerned, it is evident that the decision making process must be situated at the lowest level possible in order to avoid a situation which is observed too often: a decision maker who enters a decision situation, takes a decision and leaves the situation for what it is.

6.6.2 Relation between decision making and control

Given the definition, it is stated that decision making is the determination of the choice which prefaces all action. In this sense, a decision maker can act as a controller. The analogy between decision making and control is given in figure 6.6.1[46].

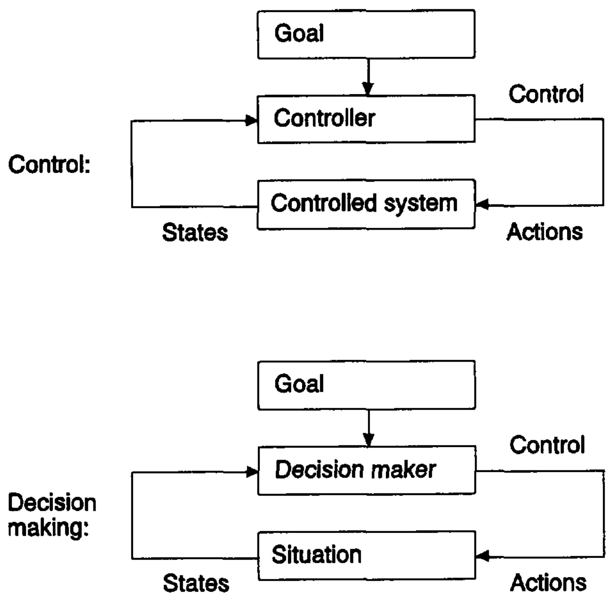

Fig. 6.6.1 *The analogy between control and decision making, clearly showing that control is not possible without decision making and that decision making is, in fact, control.*

The decision maker is the controller, the control actions are the decisions to improve the situation of the controlled system. The model of the controlled system is a relation between actions and states. The goal is a preferred ordering of states. Control and decision making cannot really be separated. The control model gives insight into conditions for effective control and the way this effective control can be carried out. The decision making process gives tools to change and improve some situations of a system by means of control. From this, it is concluded that control is not possible without decision making and that decision making is, in fact, control.

6.6.3 The classical model of decision making (Homo economicus)

The "homo economicus" model is the basis for the modern theory on decision making processes in organizations[47]. The rational homo economicus:

- has complete information about the decision situation;
- knows the decision alternatives;
- knows the present situation;
- knows exactly what profits each alternative can offer him;
- strives at maximization of that profit.

The above model can be described in a formal sense (see intermezzo 6.3).

Intermezzo 6.3

Assume a controlled system and the rational homo economicus as decision maker. Available is:

- a set of actions A;
- a set of states S;
- a model M of the decision system indicating the consequence of a certain action: M: A x S;
- a preference ordering of states: the value function V(s);

Given a situation s_j, the rational homo economicus chooses action a_i, resulting in a maximum of V(s), that is, Max V (s_k) in which $s_k = M(a_i, s_j)$.

Three main assumptions of the model can be distinguished[48]: (1) information, (2) the preferred ordering arrangement and (3) the decision rule.

Assumption about information

The model presupposes complete information about actions, states and model. The classical decision theory gives three particular cases with respect to information (see section 6.3.4). These three cases suggest a difference in the total information. This is not the case, since the three types assume full knowledge about the set of possible actions, the set of possible states and the preferred ordering. The distinction between the three types originates from the difference in knowledge about the model. For instance, a decision maker with complete uncertainty about the model he uses, often knows what states can possibly occur, yet he knows nothing about the probability of occurrence.

Assumption about the preferred ordering

In the classical model the decision maker should be able to order all possible states according to his preference, which is possible in case of a weak ordering. This means that for each two states s_1 and s_2, the decision maker either prefers s_1 to s_2, or s_2 to s_1 or has no preference at all (indifferent). The above preference rule implies that the decision maker has only one goal and that it concerns decision making under certainty. In order to provide a preferred ordering for decision making under risk and uncertainty, a basic set of assumptions has led to a utility function[(49)]. Due to its limited relevance with respect to this study, the utility function will not be further explained.

Assumption about the decision rule

The assumption of the homo economicus model is its decision rule to choose optimal alternatives. Here again the three different "information cases" can be distinguished.

- The decision maker under certainty chooses that action which will maximize his utility. The most appropriate tool is provided with operation research and linear programming.

- The decision maker under risk chooses that action which will maximize his expected utility. In this case, a risk analysis is the most appropriate tool to use.

- The decision maker under uncertainties can use various rules[(50)], which will not be discussed here. The most interesting rule is the minimax rule[(51)].

However, the decision rule to be used for the control of the realization process of complex systems must be a mixture of the three rules.

6.6.4 Extensions of the classical model

The homo economicus model is based on: (1) one decision maker, (2) who has one goal and (3) who decides in one step. Obviously, in most decision situations, particularly in the decision situations during the realization process of complex systems, this model is not correct. These situations are characterized by: (1) several decision makers, (2) several goals and (3) several phases.

These extra dimensions of decision making are treated in mathematical decision theory, which will not be discussed further. The main reason for mentioning these extra dimensions is to show that the decision making becomes more difficult in case the abstraction level, at which the decision should be taken, is higher. Consequently, it is recommended to make decisions at the lowest possible level. The various hierarchical decision levels are determined by the multi-level control system.

6.6.5 Limited rationality

Simon and March have criticized the rational homo economicus model[(52)]. They stated that due to the limited information processing capacity of the decision makers:

- not all alternatives are known;
- not all effects of alternatives are known;
- which alternative have what effect is not known
- not optimal but only satisfactory decisions can be taken

Simon developed his "Bounded Rationality", which is characterized by two aspects:

- alternatives and effects are not available but should be discovered and developed in a search process;
- optimal decisions cannot be taken, instead the decision maker will be content with satisfactory solutions.

It is noted that this bounded rationality is conform the characteristics of a design process, being a search process by definition. The principle of satisfactory solutions have been discussed in chapter 2. The discovery and development is described by the methodology of the problem solving process. An example of a discovery and development model is given by the following phases[(53)]: (1) problem identification, (2) information gathering, (3) development of possible solutions, (4) evaluations of these solutions, (5) selection of strategy for performance and (6) actual performance of an action.

Although many models are developed with respect to the rationality of decision making[(54)], the two most essential parts, e.g. the bounded rationality as basis for decision making in search processes and the phasing in decision making, have been discussed. The bounded rationality is the basis of the proposed control system as will be presented in chapter 10.

6.6.6 Decision making and decision makers

As already mentioned in chapter 5, a study on the members of the organization and on their typical profiles does not belong to the scope of study. Nevertheless, some indication is given of how the decision makers contribute in the control of the realization process.

Both from the control paradigm as well as the models of decision making, it is concluded that decision making (action) is only possible with information (knowledge). When dealing with realization processes of complex systems both the gathering of knowledge as well as the decision making, can not be done by one person, but must be delegated and distributed. As far as knowledge and action is concerned there is an interesting analogy with scientific strategy. Scientific research and work can be classified according to the strategy adopted. In between pure knowledge and pure action, the following types of scientific research can be distinguished[(55)] (see figure 6.6.2): (1) formal, (2) theoretical/experimental, (3) applied, (4) evaluation/diagnostic and (5) action.

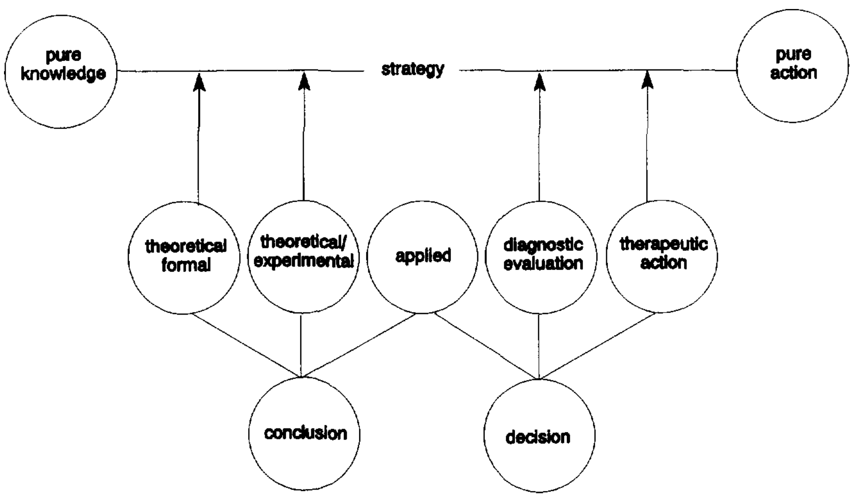

Fig. 6.6.2 Scientific work and strategy from pure knowledge to pure action

This classification can also be used for placing members in the structure of the organizations dealing with realization processes. Having two main phases, with significant differences in process, influence and goals, the classification is used to compose a design team and a construction team. A suggestion is sketched in table 6.6.1.

	Design		Construction		
Strategy	Member	Goal	Member	Goal	Task
Formal	Scientist	Truth	Bookkeeper	Truth	↑
Theoretical/ empirical	Specialist	Effectiveness	Controller	Efficiency	Distributed gaining of knowledge ↑
Applied	Design coordinator	Effectiveness x efficiency	Construction coordinator	Effectiveness x efficiency	Decision making
Evaluation/ diagnostic	Designer	Effectiveness	Manager	Efficiency	↓ Distributed action
Action	Artist	Effectiveness	Engineer	Efficiency	↓

Table 6.6.1 *Members of the organization dealing with design and construction in a realization process and their respective tasks in the decision making process.*

Obviously, both the design as well as the construction coordinator has overall control on the realization process. Given the respective influence on the total costs of the problem solving process, the design coordinator should be hierarchically placed above the construction coordinator. Moreover, the difficulties encountered with a complex search process are completely different from the difficulties encountered in a selection process. Hence, the design coordinator plays an important role in the decision making process. This is the reason that some personal views on the desired thinking profile of the design coordinator are given in annex 6.

6.7 Summary

With respect to the realization of complex systems, a system-theoretical control paradigm is available, consisting of: (1) controlled system, (2) controller, (3) environment and (4) relations between these three components. For effective control, there should be: (1) a goal, (2) a model of the system, (3) information about that model and (4) control variety.

A meta-control principle is introduced in case control is not adequate or is not competent. When using this principle, a multi-level meta-control model can be defined, adding extra control variety for each higher level of meta-control. Such a model can be used for structural control and goal control.

Although outside the scope of work, a paragraph is devoted to the active part of control that is decision making.

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7. TYPES OF CONTRACTS

7.1 General

In this chapter, an outline is given of various types of contracts together with criteria for application. Such an outline is necessary in order to investigate the existing possibilities for the contractual part of a D&C task.

This chapter is divided into two parts. In the first part, some general aspects of contracts are given, resulting in an outline of various types of contract. In the second part, influencing factors for the selection of contract types are described.

Legal aspects of contracts are not discussed. The emphasis is put on the technical, administrative and financial side of contracts with respect to related aspects such as information, complexity, tasks, control and risk. Another aspect, e.g. the contract strategy of Clients, is beyond the scope of this study. The matter of interest concerns the contract type itself and not how the decision to use a certain contract type is reached.

7.2 Definitions and types of contracts

A contract is defined as an agreement between two parties, where one party commits itself to deliver (clearly specified) goods, software, services or a combination of these to a second party, within a certain delivery time and for an agreed price(1). The contract party delivering goods is called the Contractor and the contract party ordering the goods is called the Client.

Given this definition, a few essential conditions can be defined(2): (1) competent parties, (2) a specified subject matter, (3) an offer and acceptance thereof (agreement between two parties) and (4) mode and terms of payment.

It is evident that there is a basic conflict of interest for each type of contract. The Client would aim for a perfect product at a minimum price and within a minimum delivery time, whereas the Contractor tries to deliver an acceptable product (just meeting the specifications) with a maximum profit at a convenient time. In this extreme context, the Client would prefer a Firm-Fixed-Price contract, which gives a minimum budgetary risk, whereas the Contractor would prefer a Cost-Reimbursement contract in which his efforts will automatically be paid. Therefore, traditionally two ways can be distinguished in which the contract price may be expressed(3):

- A Cost-Plus-Fee-Price contract, in which all justified costs are paid along with a fee as a fixed percentage. In this case, the final price is determined by postcalculation.

- A Firm-Fixed-Price contract, not allowing adjustments. In this case, the final price is determined by pre-calculation.

In reality, the conflict of interest and the associated contracts are not as extreme as indicated above, since contracts are agreed upon, meaning that consensus is reached on the contract type. In fact there are numerous contract types in between the two extreme types above, examples being:

- the "schedule of rates or remeasurement" as an intermediate way in which the contract price may be expressed(4).

- the "Lump-sum and variations" contract between the Firm-Fixed-Price contract and schedule of rates or remeasurement(5).

- "cost plus" possibilities: (1) target costs, (2) fixed fee and costs and (3) cost plus(6).

Intermezzo 7.1

An interesting (just for purpose) type of contract was drawn up between the two participants involved in the realization process of the Storm Surge Barrier in the Eastern Scheldt. The contract between Client and Contractor was a unique contract, dealing with integration of design and construction with the two parties. This is totally different from a delegated D&C task. With this particular type of contract no more risk was allocated to the Contractor than he could initially carry. The essence of the contract was that rules were agreed on for the determination of the contract sum of the parts of the whole system once these parts had been properly detailed. The most relevant issues are given in annex 9.

These contract types and all other intermediate types belong to two principal families of contract types: (1) Cost-Reimbursement contracts and (2) Fixed-Price contracts. It is important to realize, that these two contract types are not necessarily mutually exclusive(7). In most construction and installation projects it is common to use lump-sum for the supply part and cost-reimbursement for the installation part.

The intermediate types of contracts can only be obtained when both participants are able (or thought to be able) to control the realization process. In such a case, the contract establishes the risk to be carried by each party.

The general principle suggested earlier in this study (chapter 3) is, that risks should be carried by the party best able to either control the risk, or estimate the risk, meaning that both parties should have contractual incentives to arrive at the required performance, within the agreed time schedule and within the agreed cost limits. The contract should include adequate incentives to meet both the Client's as well as the Contractor's main objectives, preferably by attempting to align the objectives of the Client with those of the Contractor(8).

Given the fact that no Client will have any objections to paying allowable, allocatable and reasonable costs which the Contractor can demonstrate to have made, the most appropriate contractual incentive is the fee of the Contractor. With the Contractor's fee as the most important variable, Peeters(9) gives a systematic treatment of the two families of contract types, which is briefly outlined in the next paragraph.

7.3 Contract types

7.3.1 Cost-reimbursement contracts

In cost-reimbursement contracts the Client is required to reimburse all allowable and reasonable costs which the Contractor can demonstrate to have made. In this context, it is noted that the schedule of rates or remeasurement is not a particular type of contract but a certain method to establish and reimburse costs. There are three possibilities characterized by the method of fee determination. The differences will be discussed hereafter by considering cost aspects only and assuming a 10 % fee on a contractual sum of 100 US dollars.

Cost-Plus-Percentage-Fee Contract (CPPF)

From a Contractor's point of view, this is the most beneficial type of contract. All demonstrated costs are paid and the fee is paid according to a fixed percentage. The target cost is the estimated contractual cost to completion. The target fee is paid when the actual cost equals the target cost. This type of contract is sketched in figure 7.3.1.

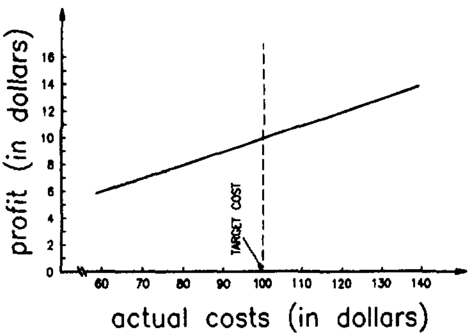

Fig. 7.3.1 *A Cost-Plus-Percentage-Fee type of contract (CPPF). Starting point is a 10% fee on the target cost (after Peeters, 1987)*

Cost-Plus-Fixed-Fee Contract (CPFF)

In this type of contract, the costs are reimbursable but the fee remains constant (figure 7.3.2).

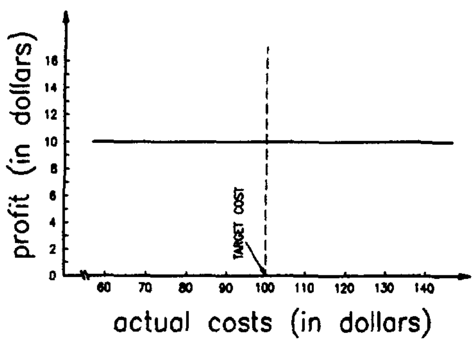

Fig. 7.3.2 *A Cost-Plus-Fixed-Fee contract (CPFF). Starting point is a 10% fixed fee (after Peeters, 1987)*

Cost-Plus-Incentive-Fee contract (CPIF)

In this type of contract, the fee varies within set limits as a function of actual allowable costs. Two elements can be identified: (1) sharing formula, that is, the basis of Client's and Contractor's cost-sharing arrangements and (2) range of Incentive Effectiveness, that is, the range between upper fee limit (maximum) and lower fee limit (minimum) (figure 7.3.3).

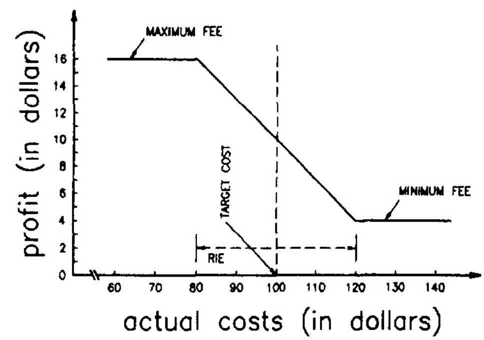

Fig. 7.3.3 A Cost-Plus-Incentive-Fee contract (CPIF). Starting point is a 10% target fee (after Peeters, 1987)

It is noted that:

- the sharing formula can be non-linear;
- in most cases the sharing formula for overrun is different from sharing formula for underrun;
- in order to avoid many discussions, a neutral zone in the first track of the overrun formula is often introduced [10].

7.3.2 Fixed-Price contracts

With a Fixed-Price contract (lump-sum contract), the Contractor is obliged to deliver a product for a specified price. In case of a Fixed-Price contract, the risk for the Contractor is high and profit is speculative. Overruns can only be paid if a change in the scope of deliveries or requirements can be demonstrated. This is not always evident. Two types of contracts can be distinguished in this category.

Firm-Fixed-Price-contract (FFP)

The fixed price as agreed in this type of contract is not subject to any adjustment unless the scope of work is changed. Note that the profit can be negative (figure 7.3.4).

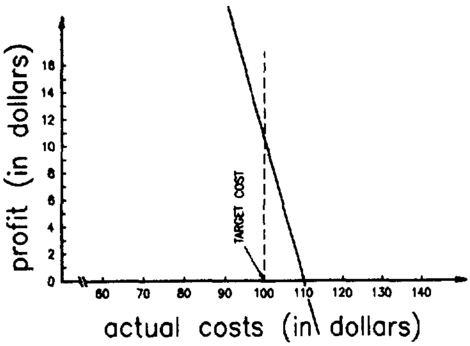

Fig. 7.3.4 *A Firm-Fixed-Price contract (FFP). Starting point is a 10% fee (after Peeters, 1987)*

Fixed-Price-Incentive contract (FPI)

In this type of contract, a target price is agreed, whereas the fee is dependant on actual costs. There are two special arrangements for fee determination. In general, a maximum is agreed on for the fee and a ceiling price is accepted by the Client. Costs exceeding this ceiling price nor fees over these costs will be paid (figure 7.3.5). In order to reach the ceiling price in case of increasing actual costs, the sharing ratio must be adjusted (Point of Total Assumption; PTA).

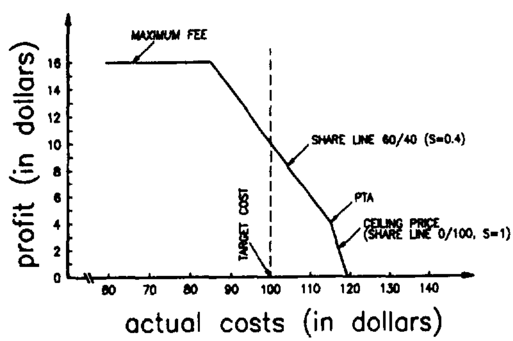

Fig. 7.3.5 *Fixed-Price-Incentive contract (FPI). Starting point is a 10% fee (after Peeters, 1987)*

7.3.3 Some other variants

Adjustments-for-Escalation contract

In most contracts there are provisions for escalation, that is, upward adjustment in price if there are allowable changes in materials or labour cost. The adjustment is usually arranged with predetermined escalation formula.

Performance-Incentives contract

In this type of contract the fee is made dependant of obtaining a certain technical performance (figure 7.3.6). It is noted that such a performance should be measurable. In the example of figure 7.3.6 the performance is measurable (mass). It is noted that this type of incentive should preferably be combined with cost incentives in order to prevent Contractors from incurring costs.

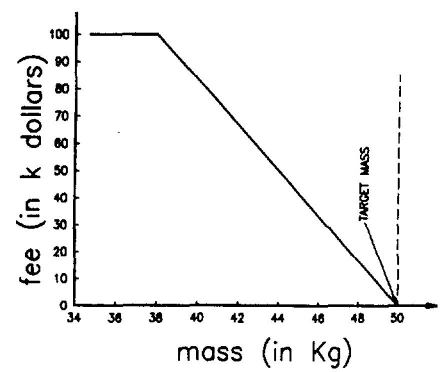

Fig. 7.3.6 A Performance-Incentive contract (after Peeters, 1987)

Delivery-Incentives contract

In case delivery time is very critical, sometimes stepwise incentives are incorporated in the contract (figure 7.3.7). In analogy with performance incentives, here the delivery incentives should also be combined with cost incentives. The combination of cost, delivery and performance incentives is called multiple incentives.

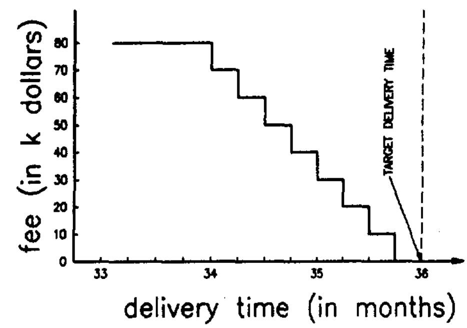

Fig. 7.3.7 A Delivery-Incentive contract (after Peeters, 1987)

Award-Fees contract

A part of the contractual sum is determined for awards. The project is divided into evaluation events. These evaluation events are subjectively measured. The Contractor can earn awards or part of the awards at each evaluation event. The award system is usually found in combination with cost-plus types of contract. The common form is Cost-Plus-Award-Fee contract (CPAF).

7.3.4 Summary of types of contract

For the types of contract discussed above, it is possible to derive a general mathematical expression for the profit of the Contractor[11]:

$$P = BF + AF + s(TC - AC) + DI + PI \qquad (7.3.1)$$

which:

P	=	profit	AC	=	actual cost
BF	=	basic (fixed) fee	DI	=	delivery incentive
s	=	sharing ratio	PI	=	performance incentive
TC	=	target cost	AF	=	award fee

Given the formula above, the distinguished types of contracts are:

Cost-Plus-Incentive-Fee for : $0<s<1$, AF = 0, DI = 0, PI = 0

$$P = BF + s(TC - AC) \tag{7.3.2}$$

Cost-Plus-Fixed-Fee for : s = 0, AF = 0, DI = 0, PI = 0

$$P = BF \tag{7.3.3}$$

Firm-Fixed-Price for : s = 1, AF = 0, DI = 0, PI = 0

$$P = BF + (TC - AC) \tag{7.3.4}$$

Cost-Plus-Award-Fee for : s = 0, DI = 0, PI = 0

$$P = BF + AF \tag{7.3.5}$$

Cost-Plus-Multiple-Incentive for : $0<s<1$, AF = 0

$$P = BF + s(TC - AC) + DI + PI \tag{7.3.6}$$

7.4 Influencing factors for the selection of contract types

The main consequence of a certain type of contract for a certain type of project is the risk for both parties. As far as the Client's risk is concerned, Corrie[12] gives the relation between Client's risk and the following influencing factors: (1) contract type, (2) information available at the start of the contract period, (3) Client's control and (4) Client's control effort required (figure 7.4.1).

In figure 7.4.1, the incentive fee contractual form is absent. An overview of contract types with motivations for selection and an indication of Contractor's risk and required control by the Client is given in figure 7.4.2[13].

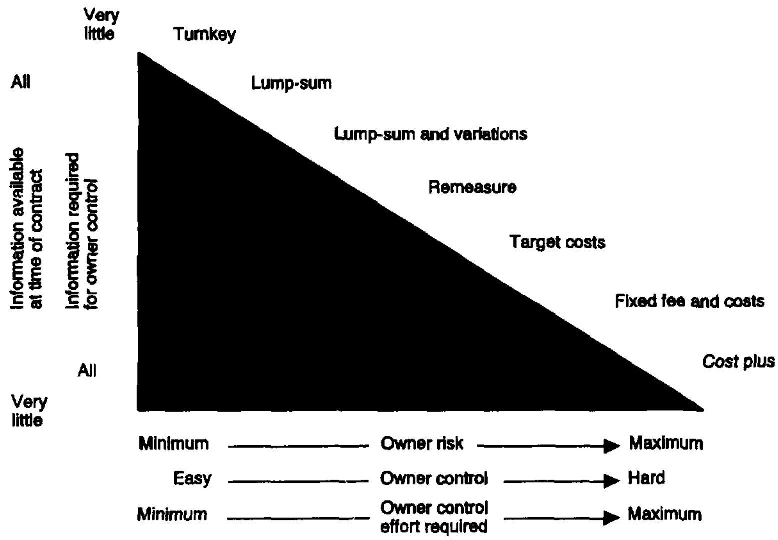

Fig. 7.4.1 *Client's (Owner's) risk and control possibilities as a function of contract type and information (after Corrie, 1991)*

Herten[14] stated that, from the Client's point of view the choice for a certain contract is sometimes based on both the risks and the degree of control which is required. In extremely difficult control situations, the Client prefers an easier type of contract, implying extra risk (table 7.4.1).

Criteria	Type of contract
High risk, high control	Cost-Plus-Fixed-Fee
High risk, low control	Cost-Plus-Incentive-Fee
Low risk, high control	Fixed-Price with Incentive
Low risk, low control	Firm-Fixed-Price

Table 7.4.1 *The relation between control, risk and type of contract*

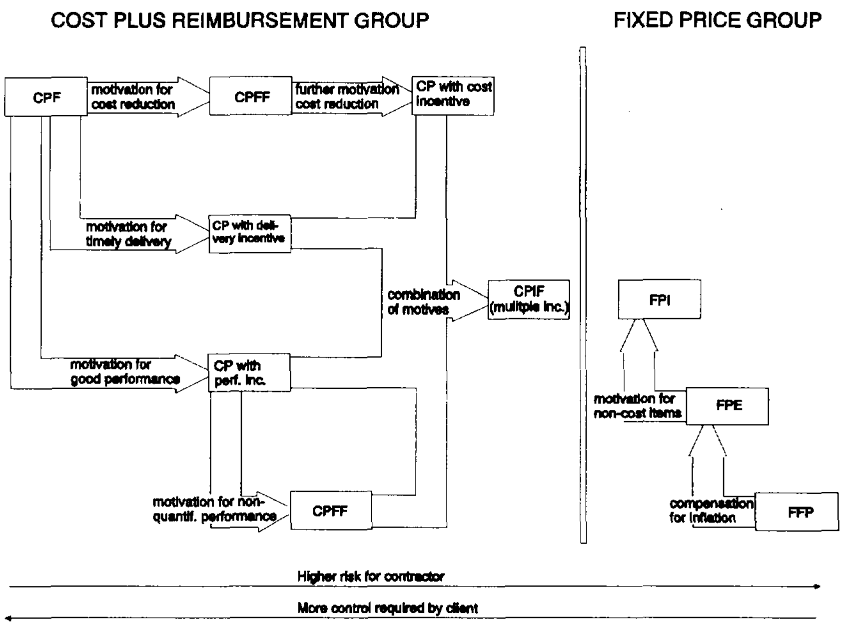

Fig. 7.4.2 *All distinguished contract types with respect to control required by the Client and the risk of the Contractor. For each type also the motivation is indicated (after Peeters, 1987)*

Since the incentive fee is recognized as an interesting risk sharing contractual factor, it is worthwhile to consider managing contracting arrangements which are typically fee-based contracts. Corrie[15] gives fee arrangements as a function of: (1) briefing information available at the time of appointment, (2) scope of variations and (3) complexity (figure 7.4.3).

In a more general sense, Wubbenhorst[16] emphasized the strong relation between contract type and project stage. In his opinion, the type of contract can only be chosen when the following three criteria have been evaluated:

- degree of uncertainty
- efficiency required
- availability of means of control

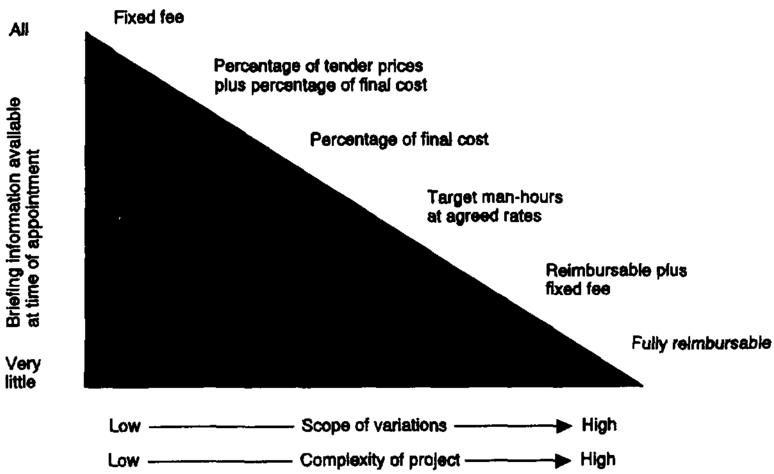

Fig. 7.4.3 *Fee arrangements with respect to information, complexity and variations (after Corrie 1991)*

It is rather important to link the degree of uncertainty to the project stage. However, with this linkage the question is raised that real uncertainties as defined in chapter 6 (which cause most of the control troubles and consequently most of the risks) cannot be quantified and therefore cannot be evaluated as well.

Summarizing, the type of contract to be chosen depends on various influencing factors and criteria. In this paragraph the relation between type of contract (with cost and fee arrangements) and the following factors and criteria has been established:

- risk Client
- risk Contractor
- control Client
- information available
- information required for Client's control
- scope of variations
- complexity
- uncertainty
- project stage

This set of relations can be helpful to select appropriate contract types but certainly does not lead to an unambiguously determined choice. The main constraint for such a determined choice is two-fold:

- for the choice of a type of contract, two parties are involved who must both cope with internal and external project factors:
- the contract type depends on the agreements made for the risk sharing, which also is the result of internal and external project factors.

7.5 General considerations on suitability of contract types

In this paragraph the suitability of contract types is discussed in a general context. A relation exits between specific tasks and project characteristics on one side and types of contracts on the other. For the application of award fees, most authors agree that contracts with award fees should only be used in exceptional cases, when performances cannot directly be quantified[17]. For the choice of a contract type, the following guidelines can be used, relating specific types of contract to typical programmes[18]:

Firm-Fixed-Price (FFP):

- production or construction with clear specification
- short program duration or profitable currency effects
- training

Fixed-Price with Escalation (FPE):

- same categories as FPP, but longer program duration

Fixed-Price with Incentive (FPI):

- development programs using existing technology

Cost-Plus-Incentive-Fee (CPIF):

- prototype development
- development of new machines or devices

Cost-Plus-Fixed-Fee (CPFF):

- research and study programs

As far as the program category is concerned, a Design & Construct task of a complex civil engineering structure can be considered:

- a typical development program using existing technology, which should preferably be arranged by a Fixed-Price with Incentive contract,
  but also;
- a typical prototype development program, which should preferably be arranged by a Cost-Plus-Incentive-Fee contract.

Obviously, the incentive aspect is rather essential for development programmes. The two types are not directly suited to arrange the contractual part of the necessary control system, based on a particular risk sharing principle. As shown in chapter 10, however, the most appropriate type of contract is a mix of the two types of contracts mentioned above, containing an incentive contract type, including both the fixed-price as well as the cost-plus element.

7.6 Summary

Traditionally two types of contracts can be distinguished: (1) Fixed-Price contracts and (2) Cost-Reimbursment contracts. In between these extreme types of contracts various interesting variants are possible. Variants are characterized by different incentive arrangements.

Based on various influencing factors such as risk, information, scope, complexity, uncertainty and project stage, two types of contracts are, in principle, eligible for Design and Construct of complex systems: (1) Fixed-Price with Incentive and (2) Cost-Plus-Incentive-Fee.

Neither type 1, nor type 2 however is suitable for the particular risk sharing principle as condition for a satisfactory D&C process. As shown in chapter 10, a combination of the two types approaches an appropriate D&C contract.

Notes

1. This definition is given by Peeters, W.A., The appropriate use of contract types in development contracts, European Space research and technology Centre Noordwijk, The Netherlands, 1987, and also by Vorstman, H.R., Produktmarktbeleid en kwaliteit, relaties, rekenschap, raakvlakken, Samson/Nive, 1990.
2. Ibid.
3. Peeters, W.A., The appropriate Use of Contract types in Development Contracts, European Space Research and Technology Centre, Noordwijk, 1987.
4. Marsch, P.D.V., Contracting for Engineering and Construction Projects, Gower Publishing Company Limited Aldershot, Hants, England, 1981.
5. Corrie, R.K., Project evaluation, Thomas Telford LTD, London, 1991.
6. Ibid
7. Marsch, P.D.V., Contracting for Engineering and Construction Projects, Gower Publishing Company Limited Aldershot, Hants, England, 1981.
8. Griffiths, F., "Project contract strategy for 1992 and beyond", in: International Journal of Project management, Vol 7 no 2, 1989.
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10. Kahn, S.G., Partners in Risk- Cost Incentives in development Contracts, ESA bulletin 26, 48, Paris, 1981.
11. Peeters, W.A., The appropriate Use of Contract types in Development Contracts, European Space Research and Technology Centre, Noordwijk, 1987.
12. Corrie, R.K., Project evaluation, Thomas Telford LTD, London, 1991.
13. Peeters, W.A., The appropriate Use of Contract types in Development Contracts, European Space Research and Technology Centre Noordwijk, The Netherlands, 1987.
14. Herten, H.J. and Peeters, W.A.R., "Incentive Contracting as a Project management Tool" in: International Journal of Project Management, 4(1), 34, 1986.
15. Corrie, R.K., Project evaluation, Thomas Telford LTD, London, 1991.
16. Wubbenhorst, K.L., Konzept der Lebenszykluskosten, Darmstadt, 1984.
17. Jenkins, G.H., Decision Criteria in Cost-Plus-Award-Fee Contracts in Major systems Acquisitions, M.S. thesis, Naval Postgraduate School, Monterey, California, 1979.
    Peeters, W.A. The appropriate Use of Contract types in Development Contracts, European Space research and technology Centre Noordwijk, The Netherlands, 1987.
18. The DOD/NASA Incentive Contracting Guide (1969) is often used to determine which type of contract is used for development contracts. These guidelines are elaborated on by Peeters, W.A., "Is een juiste keuze van contractvormen een oplossing voor kostenoverschrijdingen?" in : Bedrijfskunde 86/3 september, 287, 1986.

PART 3: THE PRESENT DESIGN & CONSTRUCT SITUATION

8. THE PRESENT SITUATION: D&C MERELY PERCEIVED AS CONSTRUCTION

8.1 General

The subject of this part of the study, e.g. the determination of the present D&C situation, contains some theoretical and practical difficulties. Such determination would require an extensive study towards all D&C projects in relation with the organizational and contractual issues as described in chapters 5, 6 and 7. This is not only outside the scope of the study, but it is also questionable whether a complete and compressed picture can be derived from the available project information, which inevitably shows a wide spectrum of issues, phenomenae and circumstances, all related to each other. Interpretation is difficult since, as already mentioned in section 1.5, an ordering of causal-variables and effect-variables is hardly possible when various related phenomenae occur simultaneously.

The delegation of a combined design and construction task with one contract is a rather new phenomenon, where in former days the design task and construction task were strictly separated. Therefore, the present D&C situation could possibly be described by assuming a traditional approach which is characterized by a strict separation of tasks. In that case, it is important to find out what type of professional organizations deal with D&C tasks. Principally, there are two possibilities: (1) a design organization extending the design work with construction work and (2) a construction organization extending the construction work with design work.

It is not likely that a design organization will conduct D&C. The main reason is that an important advantage of D&C, namely a better constructability, is only induced by bringing construction experience into the design phase. Another reason is that a design organization is not able to take responsibility for the actual efforts of construction. Therefore, it is assumed that the D&C organization is a construction organization extending the construction work with design work. This assumption is confirmed by a number of civil engineering projects(1).

In this context the D&C task is perceived to be a construction task only. The characterization of the present D&C situation is then a simple description of what happens in case a Client and a Contractor agree on a D&C contract for the realization of a complex civil engineering system, thinking that it concerns a construction contract and thus without changing the organizational and contractual structure.

In the next paragraphs this theoretical and hypothetical D&C situation is determined in relation with the relevant control issues: (1) goal control concept, (2) simplification, (3) control, (4) organization and (5) type of contract. For each issue the theoretical and practical D&C approach according to chapters 3 to 7, will be compared to the typical "construction" approach of D&C.

8.2 Goal control concept

8.2.1 D&C in theory

The goal concept of D&C has been clearly defined in chapter 3. On the highest possible abstraction level the goal concept is a value of at least 1 for the product of effectiveness and efficiency. On a lower abstraction level the goal concept contains two components:

- the actual performance of solution should meet the normative performance of solution;
- the actual efforts should be less than the normative efforts.

Since the efforts needed to reach the normative performance of solution are generally underestimated, the goal must be changed during the realization process. Consequently, the main component of the goal control concept is a changing goal.

8.2.2 D&C perceived as "construction"

At the highest abstraction level, the goal concept of "construction" does not differ from that of "D&C". In both tasks, the product of effectiveness and efficiency must be at least 1. At a lower abstraction level, however, the goal concept of a construction task is quite different:

- the construction work should meet the specifications;
- the actual efforts during construction should be less than the initially estimated efforts.

The "construction" goal concept implies that the problem statement (not correct, see chapter 2) at the end of the orientation phase is perceived to be the fixed solution at the end of the design phase.

Consequently, the goal concept with respect to efficiency is defined with respect to the estimated actual efforts at the end of the orientation phase. The basis for goal control is the indicated actual efforts line (figure 8.2.1).

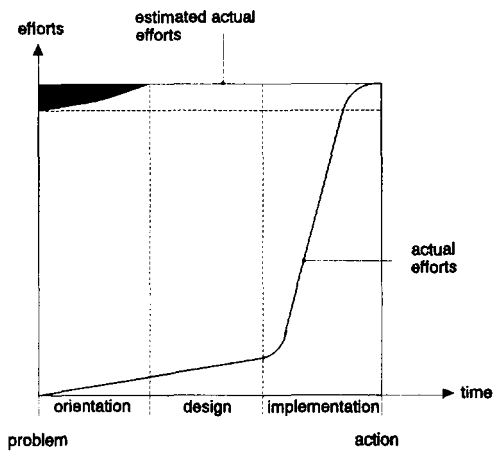


Fig. 8.2.1 *The "Design & Construct" goal concept perceived as a "construction" goal concept. The problem statement at the end of the orientation phase is perceived to be the fixed solution at the end of the design phase. The goal concept is represented by the "actual efforts" line.*

With respect to the consequences of the wrong goal concept, the present D&C situation is given in figure 8.2.2, showing the potential risk (hatched area) of a Contractor, who considers a D&C task to be a construction task. As shown in paragraph 8.6, the type of contract is the main variable in turning the potential risk into a real risk, involving the Client as potential risk carrier(2).

It must be realized that the potential risk (hatched area) as indicated in figure 8.2.2. is a function of the point in time during the realization process at which a D&C contract is awarded. Particularly the orientation and design phases of a realization process are not sharply defined (see annex 7). In general, the later D&C is commenced, the smaller the potential risk.

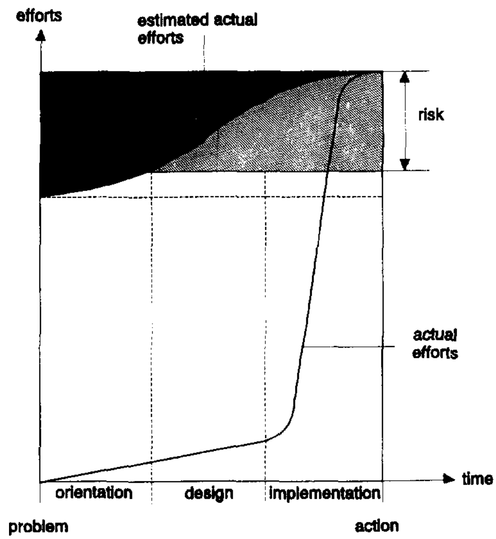


Fig. 8.2.2 *The difference between the perceived D&C situation and the actual D&C situation expressed in efforts. The hatched area is the potential risk of Contractor and Client.*

8.3 Simplification

8.3.1 D&C in theory

According to chapter 5, three decomposition methods were developed in order to facilitate control of D&C. The first method refers to goal control, which is made possible by the clustering of the requirements, or the decomposition of the friction between problem and solution into a quantifiable set of aspect-systems. Main characteristic of this decomposition of friction is that the behaviour of the total system (even a complex system) is represented correctly. The second method is the clustering of elements, or the decomposition of the total system into sub-systems, in order to control the structure (relations between elements) of the system. The third method refers to the control of construction and is based on similarity of processes, materials, locations, etc.

8.3.2 D&C perceived as "construction"

It will be clear that only the last decomposition method mentioned in section 8.3.1, is used by the Contractor who perceives D&C as "construction". In such a "construction perception", the conceptual solution as the concrete part of the problem statement is fully fixed with specifications and drawings. The only thing lacking is some design work on minor details, which can possibly lead to savings on the actual costs. The basic assumption of this decomposition method is that the whole is equal to the sum of the parts and that the whole system can simply be decomposed into small parts. The total task, defined by the triple constraint, is decomposed into partial tasks, with partial specifications, partial budgets and partial time schedules. Optimization of the construction of sub-systems automatically leads to optimization of construction of the whole system. This dominant decomposition method is sketched in figure 8.3.1.

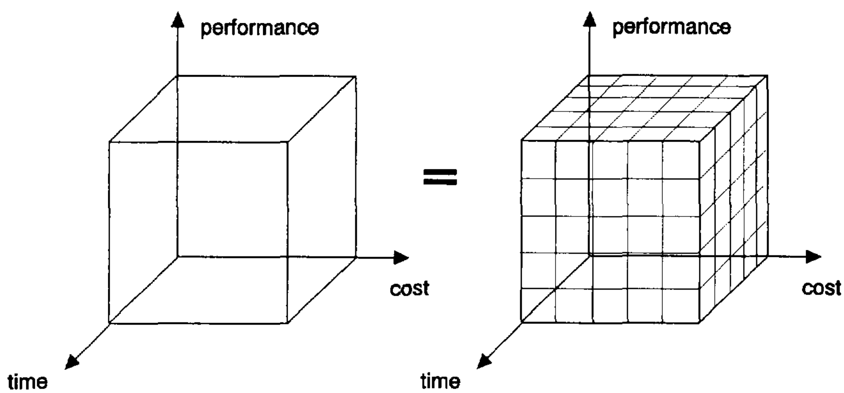


Fig. 8.3.1 The traditional decomposition method, based on the notion that the system is completely fixed in drawings and specifications, implying that these can be decomposed in drawings and specifications of elements. In such a perception the corresponding costs and time can be decomposed in the same way.

The indicated decomposition in the right part of figure 8.3.1, is the basis of the commonly used CTR-decomposition method[3]. In that way the total task is simply decomposed into small tasks, described in three dimensions: (1) Costs, (2) Time and (3) Resources (CTRs).

It is clear that decomposition method for construction is not adequate for D&C.

8.4 Control

8.4.1 D&C in theory

In chapter 6, firstly the conditions for effective control (goal, model, information and variety) and secondly the meta-control concept for goal control and structural control have been given. Both components are briefly discussed below.

Effective control

Goal : the goal concept for D&C is already given in section 8.2.1

Model : the model to be used for D&C should provide a dynamic insight into the performance of solution. In addition, the model should also visualize both the estimated actual efforts as well as the actual efforts.

Information : the model as described above, needs specific information about the system to be developed and the environment of the system.

Variety : the most essential variety of D&C is the adjustment of the goal concept. Additionally, the productivity of construction work is also a control variety, which however is of minor importance in comparison with the goal adjustment.

Meta-control concept

The meta-control concept is necessary to deal with the design problems of complex systems. Starting with the lowest element level, the successive levels are structural control dealing with relations and goal control dealing with effectiveness and efficiency of the realization process.

8.4.2 D&C perceived as "construction"

The control goal of construction work is: (1) efficiency of the construction process and (2) conformity with drawings and specifications. The performance of solution is certainly not a subject of concern to the construction Contractor.

In case the solution, as fixed in specifications and drawings, does not provide enough performance (effectiveness < 1), the Client changes the specified solution generating additional work for the construction Contractor. For construction work, the control issues are as follows:

Goal	:	see section 8.2.2
Model	:	drawings and specifications for the control of effectiveness; cost control model and planning model for the control of efficiency.
Information	:	specifications, costs and delivery time of elements.
Variety	:	productivity of construction process

In all, it can be stated that control is arranged by a description of the processes, the input and the output. The three relevant dimensions in information transfer are: (1) time (delivery time, production time, etc), (2) cost (interest, procurement, stock, production, renting equipment, etc.) and (3) specifications of (sub) systems.

Given the necessary control issues as mentioned in section 8.4.2, it is concluded that the control system of the construction Contractor is inadequate to control D&C tasks.

8.5 Organization

8.5.1 D&C in theory

Theoretically the organization of D&C should be based on the two main organizational issues e.g. decomposition and control. Since the performance of solution is the most important control variable, the organization must be able to continuously visualize the performance of solution. As shown, such a control requirement results in a strong meta-control system, based on the processing of information. The blueprint of the organizational structure is given in figure 8.5.1.

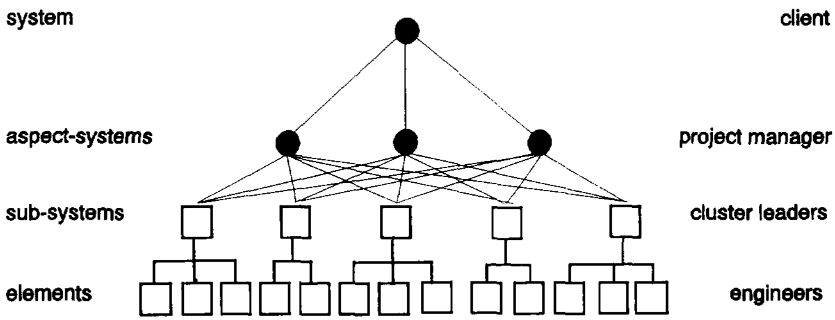


Fig. 8.5.1 *A blueprint of the theoretical D&C organization based on the relation between the system to be developed and the project team members with their specific tasks.*

8.5.2 D&C perceived as "construction"

Due to the specific production aspects, the construction Contractor arranges a particular project organization which is characterized by: (1) an hierarchical structure and (2) functional structure. Both structure principles lead to an organization which consists of operative islands as sketched in figure 8.5.2[4].

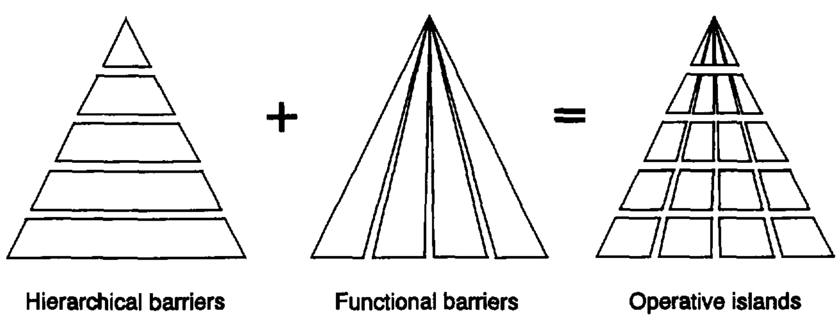


Fig. 8.5.2 *Project organization of construction Contractors, characterized by a large number of operative islands as a result of hierarchical barriers and functional barriers.*

Due to the relatively simple realization process, the general disadvantages of such an organizational structure, which are: (1) filtering of information, (2) "not invented here" syndrome and (3) severe control problems, are not critical.

As mentioned in the previous section, the organization and associated information transmission of D&C should be in accordance with the necessary control activities. The organizational structure should therefore cope with both relations and information transmission between the sub-systems as well as typical production aspects. It will be clear that the organizational aspects of design work are totally different from the organizational aspects of construction work. Consequently, it can be stated that a typical design organization (aimed at the search for effectiveness in an efficient way) cannot be applied for construction (aimed at an optimization of efficiency only) and that a typical construction organization cannot be applied for design.

In all, the application of the functional and hierarchical organizational structure, with the two dimensional information blockage, typically applied to construction work, is not adequate for D&C.

8.6 Type of contract

8.6.1 D&C in theory

Given the most important control variety of D&C, e.g. a continuous adjustment of the goal concept and the associated risk sharing principle as proposed in chapter 3 for effective control, the D&C contract should provide possibilities to arrange that particular risk sharing principle. As derived in chapter 7, a D&C contract should contain some incentives.

8.6.2 D&C perceived as "construction"

Since in a construction task it is exactly known what should be constructed, the dominant contract type is a Fixed-Price contract. The basis of a Fixed-Price contract type is given by:

- *Specifications*; it is evident that no fixed specifications, such as dimensions and volumes, are available for D&C tasks. Instead the starting point and contractual basis for D&C is a problem statement, which is not correct.

- *Time schedule*; since the design work is perceived to be of minor importance, the period reserved for design work is very short and not realistic (in most D&C cases 6 to 10 months, see chapters 9 and 11).

- *Fixed-Price*; it will be clear that the Contractor who offers D&C for a complex system in competition against a Fixed-Price, brings himself in a severe risky position.

With a Fixed-Price contract, both participants involved in a D&C task have only one goal: stay as closely as possible to the contract. When, during the design period, the Contractor is confronted with an increase of the normative performance leading to an increase of estimated actual efforts, he has a severe control problem due to the Fixed-Price contract. The Contractor initially denies the increase of normative performance of solution. This makes the situation worse, since design work must guarantee a true transformation from problem statement into a solution, taking into account the governing standards and taking away all remaining uncertainties. This attitude hinders a fundamental search for good solutions, decisions cannot be made anymore and design rapidly becomes a time consuming process. With the very short design period reserved in the already time schedule, the early construction phase will overlap the late design phase. Together with sub-optimization (= optimization of elements, which for complex systems leads to a reverse effect with respect to the whole system), this overlap prevents finding effective solutions and results in a disproportional increase of actual efforts, which is more than the normally expected increase of efforts due to perception. This effect is roughly sketched in figure 8.6.1.

Selfevidently, the Contractor claims extra efforts due to additional work. During the design process, however, there is no fixed frame of reference and, in most cases, the Client is not willing to relax the contractually fixed conceptual specifications. In this situation, the D&C participants are faced with substantially increasing actual efforts, which can neither be controlled by the Client, nor by the Contractor.

Even in the absence of a fixed frame of reference, the overrun will eventually be claimed by the Contractor. In that particular situation the overrun is a substantial risk for both participants of a D&C project. Even in case the overrun is settled on a fifty-fifty basis, the Client would probably spend more efforts than he would have spent in the ideal theoretical D&C situation with the proposed control by goal adjustment.

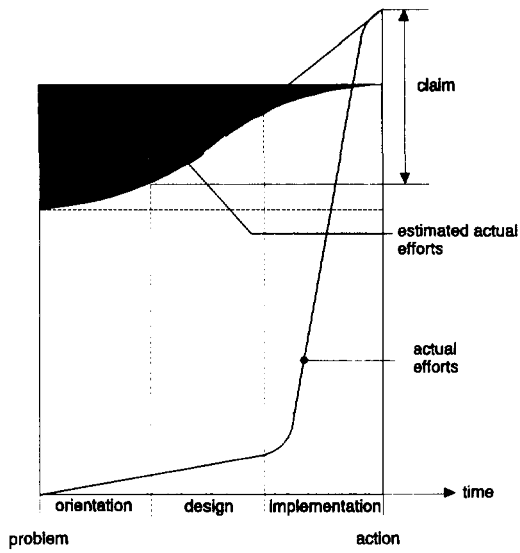


Fig. 8.6.1 *The consequences of a Fixed-Price Design & Construct contract. The Fixed-Price contract forces the Contractor to stay as close to the concept as possible which hinders adequate design and construction work, leading to excessive overrun of efforts. This overrun will be claimed, becoming a substantial risk for both Contractor as well as Client.*

8.7 Summary

A description of the present D&C situation is hardly possible due difficulties with the ordering of causal-variables and effect-variables when various related phenomenae occur simultaneously. Instead, a characterization of D&C is presented with the assumption that a D&C task is perceived to be a construction task, with just a minor part of design work to be done prior to the "real" construction work. With this assumption, the consequences with respect to the arrangement of the relevant organizational and contractual issues are described.

The goal concept is conformity with specifications and efficiency of construction instead of effectiveness and efficiency of the action using the goal adjustment as main component of the goal concept.

The decomposition is purely based on construction processes and does not take into account the adaptive and information processing character of design work.

The control is mainly based on cost and time control with respect to budget and time schedule respectively, instead of on the multi-level meta-control concept which copes with goal control, structural control and substantive control.

The organizational structure is characterized by functional and hierarchical barriers hindering information transfer, instead of a flat organizational structure allowing for optimal coordination and communication.

The Fixed-Price contract forces Contractor and Client to stay as closely to the problem statement as possible, hindering the development of fundamental solution, eventually leading to a non-satisfactory performance of the realization process.

It is concluded that a typical "construction" approach of D&C, with all associated arrangements with respect to organization and contracts, does not lead to satisfactory performance of D&C.

Notes

1. This statement is confirmed with a 100% score of all D&C projects in which the two largest civil engineering contractors in The Netherlands (Hollandsche Beton Groep and Koninklijke Volker Stevin) participated: (1) Dunlin A Platform (1973-1977), (2) Lac Nord de Tunis (1985-1989), (3) Ekofisk Protective Barrier (1988-1989), (4) Storm Surge Barrier Nieuwe Waterweg Rotterdam (1989-1997) and (5) NAM F3 Platform (1991-1993).
2. The risk is principally determined by the combination of responsibility and contract. Therefore, this paragraph deals with potential risk, which could be read as conditional risk with the type of contract as variable.
3. The CTR-decomposition is described by many authors and is presently used for almost all large civil engineering projects.
4. Hurkmans, J.F.G.M., "Multidisciplinair projectmanagement: randvoorwaarde voor toekomstig succes" in: De Ingenieur, nr. 7- 8 1992.

9. CASE STUDY: THE STORM SURGE BARRIER IN THE NIEUWE WATERWEG

9.1 General

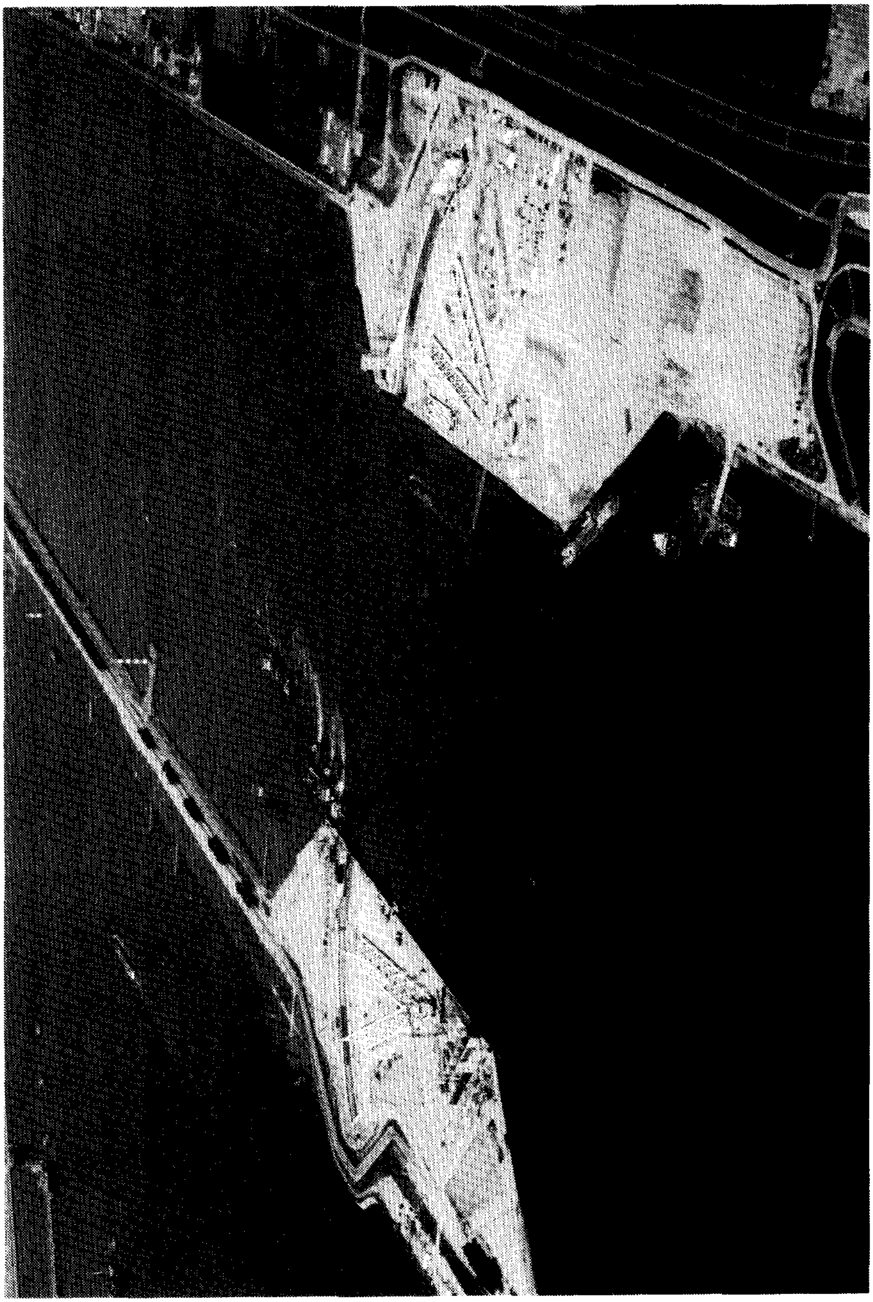
This case study is considered to be a representative illustration of the present D&C situation for the realization of large complex civil engineering systems. Both by the Client as well as by the Contractor, the D&C task of the Storm Surge Barrrier in the Nieuwe Waterweg, Rotterdam (abbreviated from now on as SSBNW) was perceived to be a traditional construction task with a minor part of engineering prior to construction.
First of all background, history and start of the project are given. After that, the type of contract and the special circumstances of this project are outlined. Then, the most relevant organizational issues are dealt with. Finally, some organizational measures are discussed and evaluated.

9.2 Background[(1)]

The flood disaster of February 1st, 1953 forced the Netherlands to face the facts. Only a few weeks after the disaster the Delta Commission was set up, and a year later it issued a report which formed the basis for the Delta Project, an ambitious project aimed at damming the inlets in the Delta area. The entrance to the port of Rotterdam, the Nieuwe Waterweg and the Western Scheldt remained open.

An extensive programme was launched to strengthen the water-control structures in the lower reaches. The work was regulated by the Delta Act, which laid down a flood protection standard for each area. The dyke-strengthening programme was aimed at ensuring that the standard was met, by heightening or strengthening existing dykes or building new ones. High priority was assigned to this programme and at the time money was no problem. A spirit of reconstruction prevailed and all these factors together ensured that the programme was implemented at a rapid pace. Not surprisingly, the easiest work (closure of some small branches of the Eastern Scheldt and the Storm Surge Barrier in the Hollandsche IJssel) was carried out first.

The dyke-strengthening programme was delayed by many problems encountered in the urban areas of Rotterdam, Dordrecht and Sliedrecht (see figure 9.2.1). In addition to the tremendous expenses involved, the impact on the local population was enormous. A great deal of demolition work was necessary to achieve the desired result.



The Storm Surge Barrier in the Nieuwe Waterweg under construction

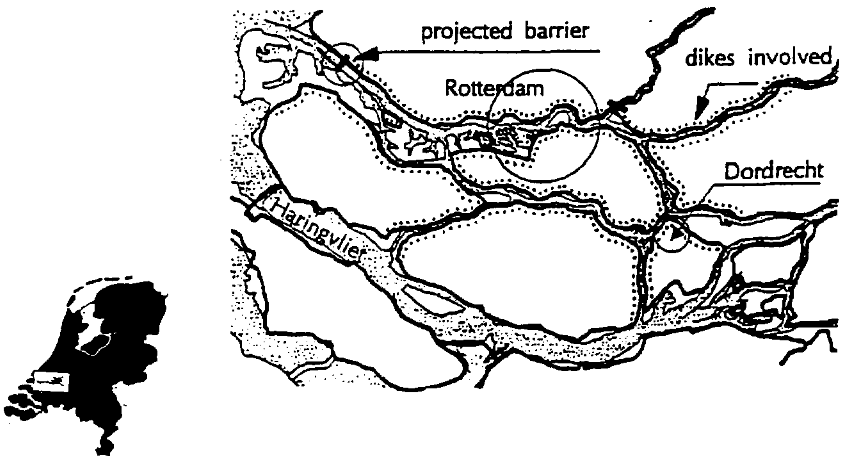


Fig. 9.2.1 *The urban areas of Rotterdam and Dordrecht which would be subject to an extensive dyke strengthening programme as consequence of the Delta Act and an open connection between Rotterdam port and the North Sea.*

Already in the fifties, consideration was given to the possibility of building a storm surge barrier in the Nieuwe Waterweg. Such a barrier could be an alternative to heightening the dykes along the Nieuwe Waterweg and the adjacent tidal rivers. This was ruled out, however, by the vigorous development of the port of Rotterdam consequently and the idea was not further developed. The difficulties began in the 1970's when the time came to tackle the urban areas. By then memories of the flood disaster had largely faded. The authorities were struggling with a lack of funds and trying to make cut-backs. People had become much more outspoken and the Public Works Department was not simply left to make all the decisions itself. Increasing attention was also devoted to the environment and to Dutch cultural heritage. This was particularly true for the people living in houses which were to be demolished in order to enable the dyke-strengthening programme.

Updated calculations in the early 1980's showed that the flood levels needed to be further adjusted in order to meet the flood protection standards. The dykes would have to be strengthened even more, which in turn entailed greater expenses and problems. Not surprisingly, the idea of a storm surge barrier in the Nieuwe Waterweg soon surfaced again. A study of the protection of the lower reaches was launched in 1987, focusing on the relative merits of a storm surge barrier and stronger dykes. An important starting point in this study was that open access to the port of Rotterdam should be preserved. Eventually, a storm surge barrier situated in the Nieuwe Waterweg near Hoek van Holland was opted for.

The choice for a storm surge barrier meant that only a limited dyke-strengthening programme needed to be carried out. The final step in the protection of South Holland was the construction of a water defense through the Europort area, forming the missing link between the storm surge barrier and the Voorne/Putten dyke.

9.3 The problem (context) as basis for the D&C contract

9.3.1 Description of the desired situation

With the construction of the SSBNW at a point just west of Maasluis, extremely high water levels in the tidal areas around Rotterdam and Dordrecht was to be prevented. The SSBNW aimed at reducing the design water levels at Rotterdam with 1.60 m and at Dordrecht with 0.60 m. The required reduction of design water levels is given in figure 9.3.1, showing the decreasing influence of the SSBNW for locations upstream.

At present, the design water levels at both places are determined by a set of combinations of (high) water levels in Hoek van Holland and the Rhine discharges. From this set of combinations, isolines of water levels as a function of both parameters can be composed (see figure 9.3.2).

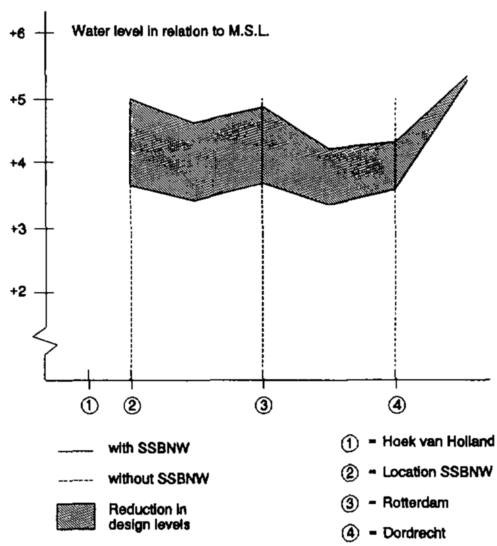


Fig. 9.3.1 *The required reduction of design water levels. The uninterrupted line represents the design water levels without SSBNW, the dotted line with SSBNW and the hatched area is the reducing effect of the SSBNW*

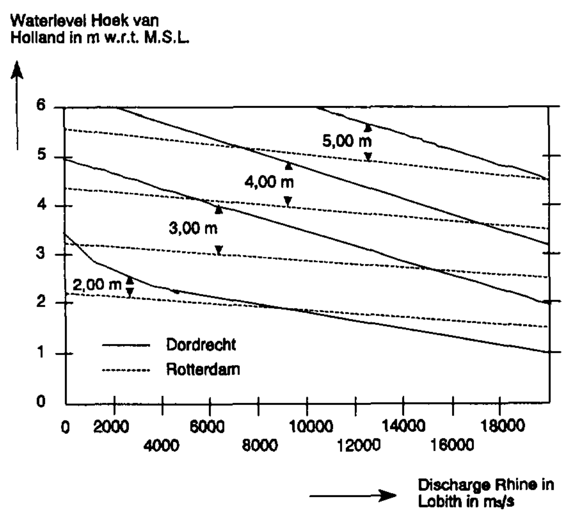


Fig. 9.3.2 *Isolines of water levels in Rotterdam and Dordrecht as a function of water levels in Hoek van Holland the Rhine discharge.*

As mentioned above, the purpose of the SBBNW is to reduce the contribution of the extreme water levels at Hoek van Holland to the design water levels at Rotterdam and Dordrecht. This reducing influence is sketched in figure 9.3.3 for Rotterdam, showing the isolines of extreme water levels for the situation with and without an SBB, again as a function of the two main parameters.

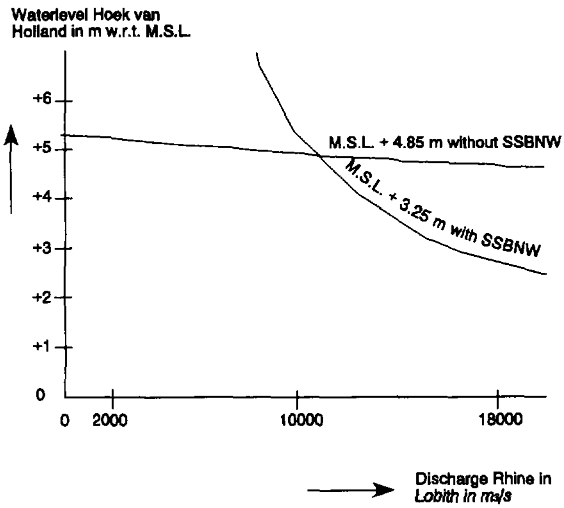


Fig. 9.3.3 *Effect of the proposed Storm Surge Barrier in Rotterdam, showing clearly the reduced contribution of high water levels at Hoek van Holland to the design water levels in Rotterdam.*

9.3.2 Description of the actual situation

The actual situation is described by isolines of water levels at Rotterdam and Dordrecht. Moreover, statistical data of the following parameters is available:

- storm surge levels and storm durations at Hoek van Holland;
- tidal information at Hoek van Holland;
- Rhine discharge;
- wind forces, wind directions, wind velocities and wind verticals;
- current velocities;
- sediment transport;
- shipping frequencies and distribution functions;
- and some information on soil condition.

9.3.3 The attempts reaching a contractual agreement

In 1987, six joint ventures of contractors were invited for a competition in order to find, develop and realize a solution for the problem as described in this paragraph. Five months were available to competitors to analyze the problem and to make a realization plan which was to be arranged with a D&C Fixed-Price contract[(2)].
The proposals, being in fact, conceptual solutions with associated products of effectiveness and efficiency, as submitted by the competitors, did not only vary substantially, but also suffered from a large number of uncertainties. Apparently, a competition based on a problem only leads to totally different solutions. The solutions are sketched schematically in figure 9.3.4. After the first competition round the Client was not able to evaluate the proposals properly[(3)]. Two extra competition rounds were necessary for the Client in order to be able to develop a conceptual solution which could be used to define the set of requirements. These requirements form the total friction between problem and solution.

In 1989, BMK (a Joint Venture of four Dutch Contractors: Hollandsche Beton- en Waterbouw, Koninklijke Volker Stevin, Dirk Verstoep and Hollandia Kloos) was awarded the D&C contract with a Fixed-Price. The part of the contract dealing with effectiveness of the project consisted of:

- the problem as described in this section
- the conceptual solution as described in section 9.4;
- the set of requirements as given in section 9.5.

The part of the contract dealing with the efficiency of the project is given in paragraph 9.6.

9.4 The selected conceptual solution

9.4.1 System (see figure 9.4.1)

The SSBNW consists of two box-shaped sector gates, each forming the segment of a circle. The length of the arc of each gate is 210 m and the gates are 22 m high. When expecting storm tides exceeding the closing criterion, these gates can be swung across the Nieuwe Waterweg and subsequently lowered on a concrete underwater sill, which is sill is composed of concrete blocks placed on a granular filter bed. On either side of the sill, quarry stones will be placed and dumped to protect the river bed against scouring by water flow underneath the gates. A stable riverbed is necessary to guarantee the stability of the sill and the abutments.

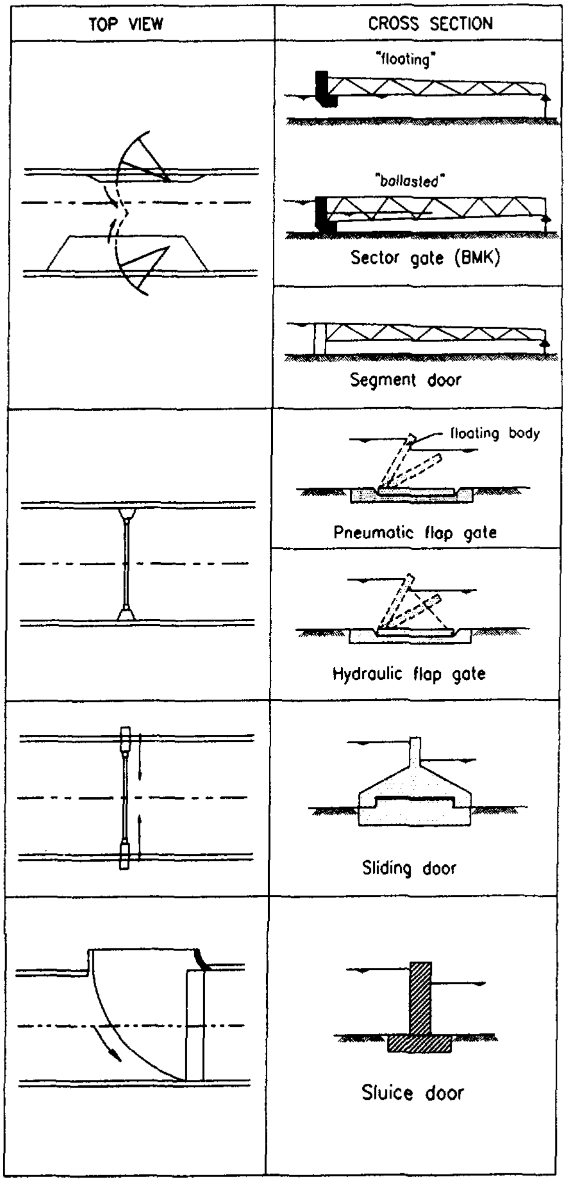


Fig. 9.3.4 *The presented conceptual solutions as a result of the competition between six contractors.*

The cross-section of the box shaped gates has been designed to provide the best possible combination of hydronamic stability and buoyancy. The ballasting system is capable of controlling the vertical position and the trim of the gates, is carried out by ballasting the gate's compartments separately.

The forces acting upon the gates due to the head difference over the gates, are transferred via a trussed steel framework, which has a free span of 240 m, to a ball-and-socket joint embedded in a large concrete block of 70 x 70 m^2, bringing the force to the earth. The total load on each gate is transferred to a ball-and-socket joint with a 10 m diameter. These joints, which have to take forces up to 330,000 KN, allow the sector gates to be turned in all directions.

When the Barrier is open the gates are parked in docks, built into the river banks. They guarantee the required 360 m full width of the Nieuwe Waterweg for shipping.

9.4.2 The closing and opening procedure (see figure 9.4.2)

During the mobilization period, the SSBNW is prepared for closure by allowing the parking docks to become flooded and the gates to float. Once the decision for closure has actually been taken, the dock gates are opened and the sector gates are swung horizontally across the river. The operating units situated on the abutments are connected to "loco-mobiles" which grip a rail on top of each sector gate and have been designed in such a way that they can follow any movement of the gates.
Once the gates have been fully swung across the river, they are ballasted with water and immersed. The gates will rest on a flat sill 17 m below MSL. In this position, the top of the gates will be 5 m above MSL. The whole closure procedure, which takes a maximum of 2.5 hours, is electronically controlled. Opening of the SSBNW takes place by: (1) water being pumped out, which causes the gates to rise and (2) the gates being swung back horizontally into the parking docks.

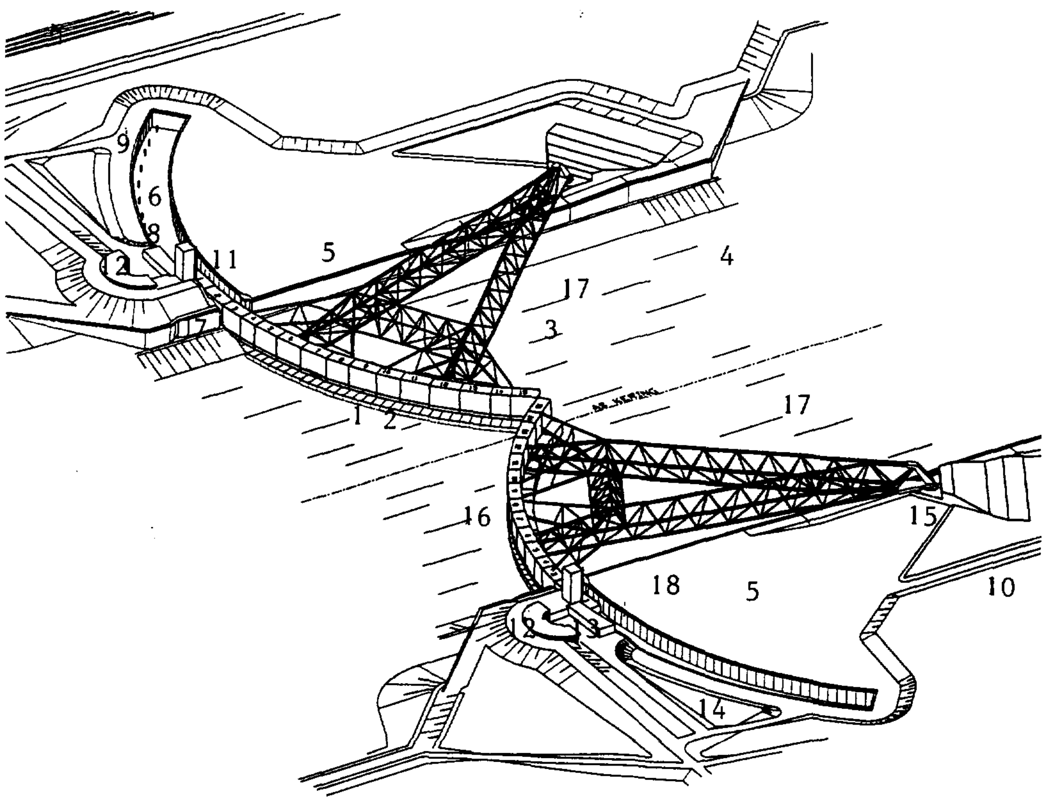


Fig. 9.4.1 *The system of the Storm Surge Barrier consists of the following sub-systems:*

(1) filter
(2) sill
(3) bed protection
(4) bed protection
(5) abutment
(6) dock
(7) dock gate
(8) building
(9) platform
(10) concrete block
(11) guiding tower
(12) building (control)
(13) building (generator)
(14) connection dyke
(15) ball & socket
(16) gates
(17) frame work
(18) locomobile

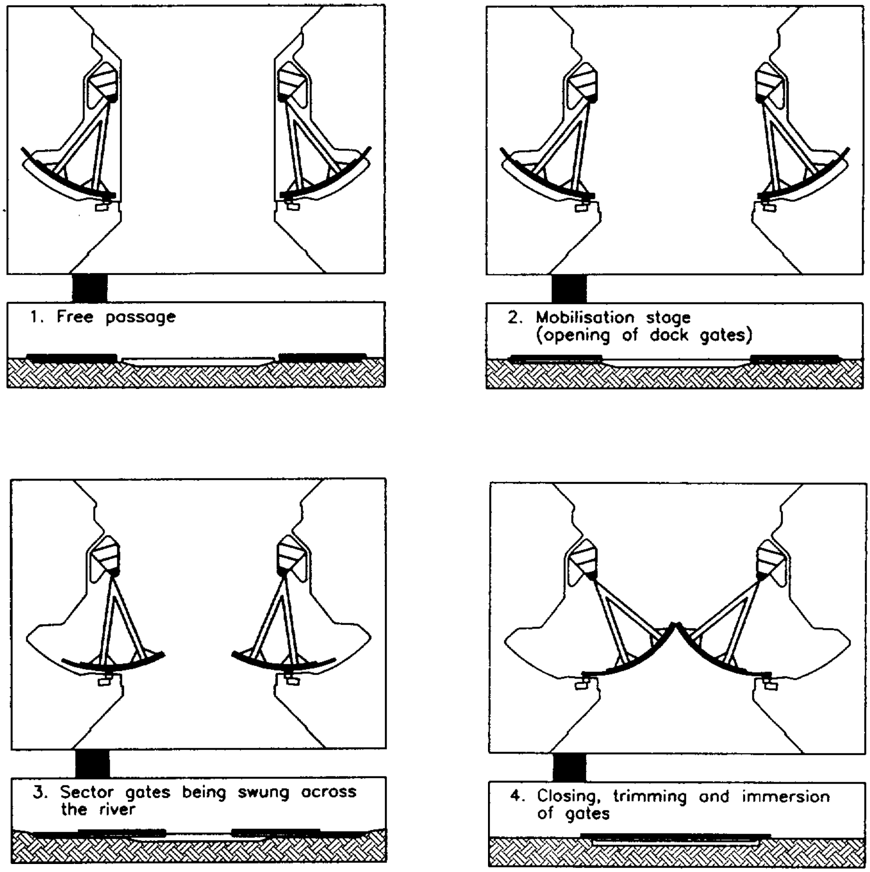


Fig. 9.4.2 *The closing and opening procedure. After mobilization, the following procedure is followed: (1) dock floated; gates floating (2) dock gates open (3) gates swung across the river (4) gates immersed on to the sill (5) functioning of gates (6) gates deballasted (7) gates back in the dock (8) dock gates closed*

9.5 The requirements (friction between problem and conceptual solution)

The way the reduction of extreme water levels is accomplished by the SSBNW is sketched in figure 9.5.1. As can be seen the head difference (main dimensioning parameter) over the SSBNW is strongly related to the leakage. The larger the leakage, the less the head difference c.q. the forces.

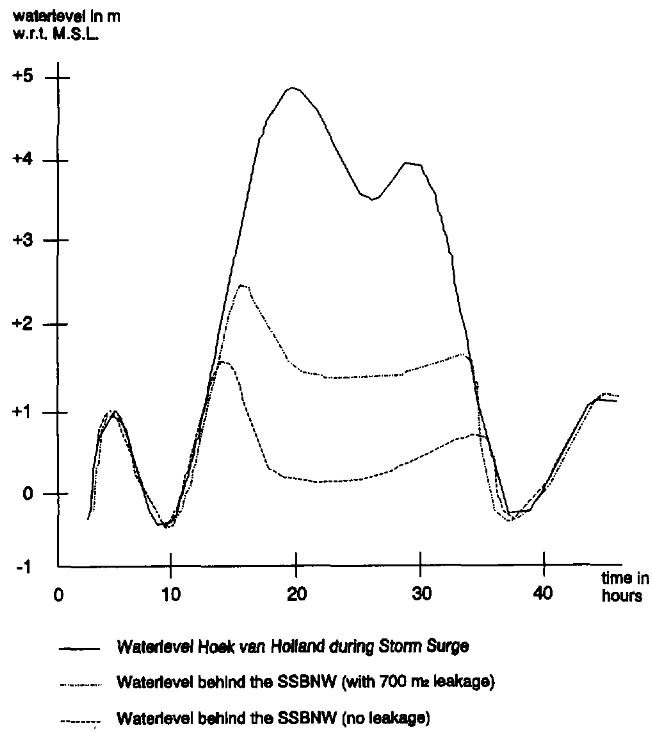


Fig. 9.5.1 *The effect of the Storm Surge Barrier without leakage (uninterrupted line) and with 700 m^2 leakage (dotted line)*

The decrease of water level behind the Barrier as a function of time is limited due to maximum berthing forces. Consequently, the closing period may not be too short. This is in conflict with a requirement for a fast closing operation in order to guarantee enough reduction capacity of design water levels.

In order to confine the Contractor to a certain solution (limiting design freedom) the Client defined the following set of requirements:

Functionality

- closure scenario (start at MSL + 2 m, 80% closure in 1.5 hour, 100% closure in 2.5 hours);
- opening scenario;
- maximum leakage (100 m^2);
- minimum cross-section (width between abutments without obstacles 360 m, minimum depth MSL - 17 m);
- maximum translation wave;
- outlet possibilities for river discharge;
- height of barrier (MSL + 5 m);
- maximum increase of current velocities in rest situation (5%);

Reliability[(4)]

- probability of failure of closing operation: 10 E-3 on demand;
- probability of failure during functioning: 10 E-6 /year;
- probability of failure of opening operation: 10 E-4 after use.

Requirements concerning durability

- lifetime; 100 years

Temporary construction phases

- minimum width for shipping (160 m)
- limited anchoring possibilities
- switch over of shipping canal

Exploitation and utilization

- control systems
- maintenance
- lightning protection
- drainage etc.

9.6 Contract

9.6.1 Contract type

The Contract type is a Design & Construct Fixed-Price-Contract with escalation. The rock material for filter and bed protection is reimbursable.

9.6.2 Contractual normative performance of solution

The contractual normative performance of solution is described by: (1) the problem, (2) the conceptual solution and (3) the requirements, being the friction between the conceptual solution and the problem. These three components are described in paragraphs 9.3 to 9.5.

The D&C Joint Venture signed for the responsibility of maintenance during a period of five years after commissioning.

The Design and Construction work should be conducted under Quality Assurance and Quality Control, according NEN ISO-9000 and NEN ISO-9001 standards.

The D&C Joint Venture was obliged to conduct model tests in order to: (1) investigate the floating behaviour of the gates and (2) support the design of the bed protection.

9.6.3 Contractual normative efforts

Time schedule

The time schedule for Design and Construction work is given in figure 9.6.1.

Costs

The total cost was put at 688 million Dutch Guilders. For filter material and bed protection material unit rates were agreed.

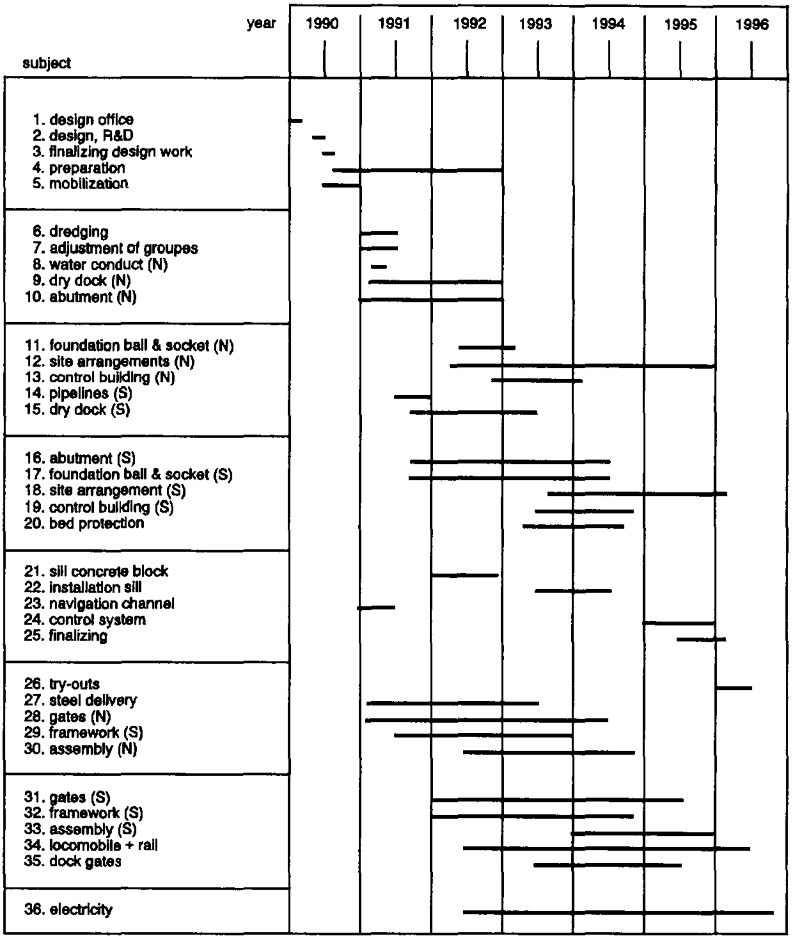


Fig. 9.6.1 *Time schedule for the Design and Construction work of the Storm Surge Barrier in the Nieuwe Waterweg. Note the short period (7 months) for design work (point 1, 2 and 3).*

9.6.4 Contractual issues and complications

Optimization during the design period

A rather remarkable contractual clause was devoted to "optimization efforts" which were agreed on between both participants. Obviously both participants had ideas about possibilities for optimization. Feelings about optimization possibilities originated from the full probabilistic approach, which was perceived to be less conservative than the usual standards. It is already shown that optimization in complex design work is not possible. The full probabilistic approach, however, had the reverse effect (see section 9.7.3).

The optimization should have been done in the design period, resulting in a design report, which at that time would become part of the Contract. This is of course in line with the "construction" perception of D&C, in which optimization is beneficial for both participants. From chapter 3, it is known however, that the normative performance of solution is underestimated, resulting in an proportional underestimation of normative efforts.

This situation (facing extra costs instead of expecting savings), caused a lot of discussions between Client and Contractor. These discussions became more difficult when model tests revealed instable floating behaviour of the gates (see next point: "change of concept"). Since the submission (not the acceptance) of the design report was connected with the first (substantial) periodic payment, the Contractor submitted the design report with a number of uncertainties, which could not immediately be accepted by the Client.

Hence, what initially started with firm commitments on optimization ended in a large number of interpretation difficulties, resulting in serious design delays and leading to overlaps of design phases and construction phases.

Change of concept

The concept of the Barrier gate was fundamentally changed (omission of auxiliary gates) a few weeks prior to the awarding of the contract in order to reduce project costs (see fig 9.6.2). Such a sudden conceptual change introduces a substantial uncertainty of dynamic behaviour during closing. Nevertheless, the change was included in the contract without: (1) an adequate check on dynamic behaviour, (2) a clause in the contract for possible consequences.

The idea behind this is that possible problems are a matter of design only, which can hardly influence the total project costs (see intermezzo 9.1).

Intermezzo 9.1

A sudden pre-contractual design change fits perfectly well in the "construction" perception of D&C. As shown in chapter 3 the costs of the design process are negligible when compared with the cost of the construction process. However, both the Client as well as the Contractor were obviously not aware of the fact that the influence of design work on the estimated project cost is substantially larger than the influence of construction on the estimated project cost. Hence, with D&C under one and the same contract the "low cost" design process has disproportional influence on the total cost of the realization process. With this knowledge, the conceptual change was probably never effected!

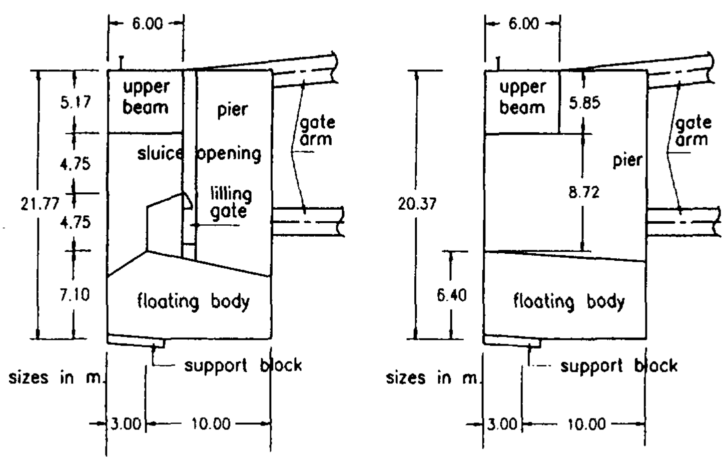


Fig. 9.6.2 *The fundamental change of the concept a few weeks prior to the awarding of the contract. The concept changed from a "semi-sub" with hardly any head difference during the closing operation into a barrier with head difference during the closing operation.*

Short design period

The engineering period was fixed at six months, which is rather short for a large complex civil engineering project. The idea behind this is that engineering work needed to be compressed in a fixed period of time in order to limit engineering costs.

In the "construction" perception of D&C, all design engineers should leave the project at the start of the construction works.

Client as partial sub-contractor

In order to reduce the cost, the decision part of the operations was shifted towards the Client, causing the Client to become sub-Contractor of the Contractor, a rather strange contractual situation.

Claim for additional work

A few months after contract awarding the Contractor notified the Client that a claim for additional work was to be expected. The additional work was mainly caused by perception problems causing delays in engineering work. In 1993, the Contractor substantiated the claim at approximately Dfl. 90 million, including the reimbursable part of the bed protection. This claim, a cost overrun of 13 %, was accepted by the Client.

9.7 Decomposition and control

9.7.1 General

In the "construction" perception of a D&C project, the whole is equivalent to the sum of the parts (see chapter 8). In the first two parts of this study it is clearly shown, that this perception is not correct and that the difference between the whole system and the sum of the parts equals the total set of relations[5].

Neither taking into account the relations between the elements nor the relations between the requirements, the decomposition of the system to be developed with associated efforts was rather easy. Two basic decomposition methods are given: (1) the CTR decomposition of tasks aimed at the control on efficiency and (2) the fault- tree decomposition as a basis of the full probabilistic design approach, aimed at the control of effectiveness.

With the knowledge of the previous chapters, it is obvious that the control is difficult with a decomposition, not taking into account the relations. This is shown in this paragraph.

9.7.2 CTR-decomposition of task

The total D&C task was split up in a large number of sub-tasks. These sub-tasks were defined by Cost, Time and Resources (CTRs). The list of CTRs is given in table 9.7.1. In principle, the CTR decomposition is aimed at controlling efficiency, but has some important disadvantages:

- by not taking into account the relations between the CTRs, the sum of all effective part-systems, as described by CTRs, does not automatically lead to an effective overall system. Due to the proportionality between performance of solution and efforts, this leads to inefficiency, since extra efforts are needed to integrate the different CTRs.

- the CTR decomposition does not lead to an organizational structure which facilitates control, because line functions and staff functions are mixed up;

- problems occurring at the interfaces between CTRs are: (1) often not recognized and (2) if recognized not solved. The CTR leader is mainly interested in solving the internal CTR problems instead of solving the problems associated with other CTRs. More generally, it can be stated, that for the control of complex systems the individual benefit is in conflict with the overall benefit.

It is concluded that the main characteristics of complex systems, e.g. the large number of requirements and the large number of relations between elements of the system are not taken into account with a CTR decomposition.

CTR no.	Description	CTR no.	Description
2010	Project management	2154	Site arrangement
2015	Document control	2155	Ball and socket system
2020	Administration	2161	Box shaped sector gates
2025	Project control	2162	Trussed steel framework
2105	Contr. requirements/	2165	Locomobile and rail
	boundary conditions	2166	Dry-dock gate
2111	Description of utilization	2170	Ballasting system
2115	Lay out and tolerances	2185	Electr. install. and Energy
2116	Hydraulic model of Rhine Delta	2186	Electr. install. control building
2117	Wave loads	2190	Design report
2118	Math. Model of Probabilistic loads	2216	Steel construction work
2120	Design loads	2217	Civil engineering construction work
2125	Failure modes analysis	2230	Planning
2127	Ship collision analysis	2240	Budgeting civil eng. constr. part
2135	Standards and codes	2245	Budgeting steel construction part
2140	Sill	2290	Construction and installation report
2141	Dredging work	2404	Quality plan total design
2142	Bed protection	2405	QA/QC system
2143	Morphology	2490	QA/QC report
2144	Impact SSB on river	2505	Hydro-dynamic and hydraulic scale
2145	Abutments and dry-docks		models
2146	Control system dry-dock gate	2506	Scale models bed protection
2147	Dry-dock pumps and discharge sys.	2507	Filter models
2150	Foundation of ball and socket joint	2508	Mathematical models
2152	Guiding tower	2509	Wind models
2153	Control building	2510	Soil investigation

Table 9.7.1 List of CTRs (Cost, Time Resources of elements and processes

The list of CTRs is interesting, as it clearly shows the a-systematic decomposition. In a way, the first set of CTRs (2010 to 2105) deals with overall control. The next set from 2111 to 2135 deals with coordination issues (aspects and loads). Then a set describing the elements of the SSBNW can be distinguished (2140 to 2186). However, morphology (2143), dredging work (2141) and impact SSB on river (2144) can hardly be considered elements. After one single CTR (design report; 2190), the next set of CTRs deals (typically) with construction work (2216 to 2290). After a set of quality related CTRs (2404 to 2490) the CTR list ends with a set of models and an investigation issue(2505 to 2510).

9.7.3 Fault-tree method for decomposition of required performance of solution

The control goal of the Client is to meet all defined requirements as perfect as possible. Given the Fixed-Price contract, the Client does not have a cost reducing incentive which would counteract the urge to strive for perfection. The control goal of BMK is to meet (and possibly optimize) the contractual normative performance of solution, which is defined in paragraph 9.5 and to minimize the cost given the fixed time-schedule. Obviously, the performance of solution plays a crucial role in the conflict of interest between the Client and Contractor (as perfectly as possible versus just enough).

BMK did not have a model which was able to describe the performance of the system, needed for the evaluation with respect to the normative performance of solution. This means that the conceptual solution should continuously be checked on all contractual requirements. The operational power of a design organization without a model for goal control is not large, since for each change of the conceptual solution it should be demonstrated that the concept meets the total set of requirements.

The BMK design organization used the three probabilistic requirements of failure for the three distinguished phase-systems (closing, functioning and opening) as the basis for the control of effectiveness(7). However, only three requirements are covered with such an approach, whereas a number of other requirements had to be fulfilled as well (see paragraph 9.5).

The model used for the control of effectiveness is the fault-tree with full probabilistic quantification. The use of a fault-tree as a guideline for the probabilistic design of a complex system is based on the notion that failure of the total system can be decomposed into failure of the sub-systems, which in turn can be decomposed into failure of sub-sub-systems, etc. In that context, the sub-systems and element function (perform) either in a serial or in a parallel way. In the full probabilistic approach, each element should have enough strength to withstand the loads on that element. The principle of the fault tree is sketched in figure 9.7.1.

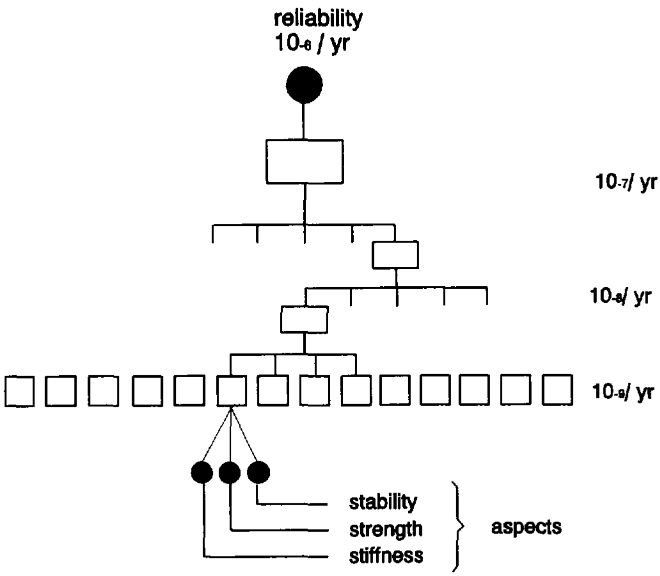


Fig. 9.7.1 *Principle of the fault-tree for analyzing the failure of systems. Down to the smallest elements, the faulttree is a one-dimensional (failure) analysis, resulting in extremely small probabilities of failure required for elements. Only at element level, the relevant aspects such as strength, stiffness and stability, are taken into account, making it impossible to take into account the relations between these aspects.*

For the description of the behaviour of complex systems however the fault-tree is not preferable for a few theoretical and practical reasons. The theoretical reasons are:

- a fault-tree concentrates only on the reliability (one clustered requirement) of a system. In fact, the concentration of a goal control model should be aimed at the friction between problem and solution. Failure in that context occurs in case at least one requirement of the total set of requirements is not fulfilled. The one-dimensional fault-tree however, is not equipped to cope with more than one requirement. At first sight, the only way to cope with this multi dimensional failure problem is to quantify a fault-tree for each failure requirement. However, even in that case failure is not correctly described since the requirements representing the friction between problem and solution are interrelated.

Intermezzo 9.2

The BMK design team faced two particular problems: (1) how to deal with the various requirements on elementary level, and (2) how to deal with remaining requirements.
As far as the requirements on element level are concerned, each recognized failure mechanism was considered to be a serial failure mode. This reduced the required probability of failure of the elements and has led to over-dimensioning.
With respect to the remaining requirements, the aspects functionality and durability were coped with at elementary level inducing, however, practical design problems (see next page). Maintenance was dealt with separately.

- a fault-tree does not automatically take into account the relations between the elements. Consequently, a lot of efforts are needed to incorporate relations, correlation etc. In case relations are not taken into account, the system will be over-dimensioned (see formula 2.5.2);

- the subsequent division into smaller part-systems is not subject to an objective stop-criterion. Some designers stop further decomposition when the behaviour of the sub-system can be described by a simple model (see figure 9.7.2a). Other designers cannot, as a matter of speaking, stop before they observe the molecules (see figure 9.7.2b);

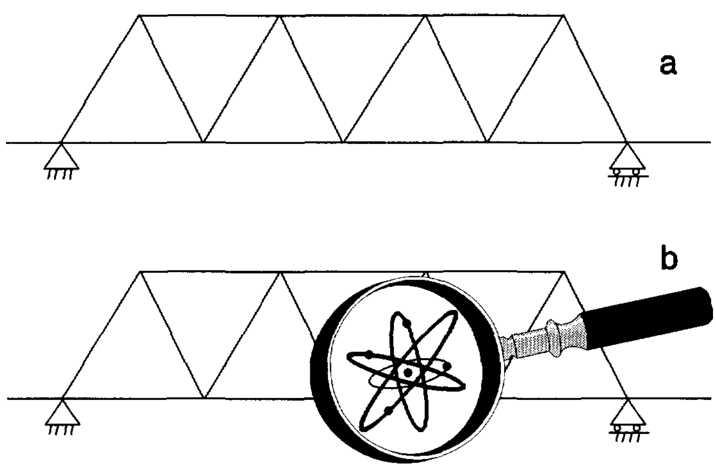


Fig. 9.7.2 Different stopcriteria for decomposition of systems

- decomposition of the performance of the system into partial performances of sub-systems, being the basis of the faulttree, is not possible. Requirements and sub-systems do not correspond(7). For the phase system "functioning" the non-correspondence between requirements and (sub)-systems is illustrated in figure 9.7.3;

The practical reasons are:

- a fault-tree is a tool for analysis and cannot be used for synthesis. Control of a search process by analyzing hundred or even more possibilities of failure does not lead to success(8);

- since the fault-tree does not consider relations between elements, it amplifies the wrong perception that optimization of elements automatically leads to optimization of the whole system;

- a fault-tree allows designers to concentrate on the smallest elements, however, without taking into account the relations between the elements. The subsequent partition of the total system into smaller parts yielded corresponding strict requirements. Starting with a probability of failure of 10 E-6, the required probabilities of failure for elements in this way became 10 E-9 or 10 E-10 (see figure 9.6.4). Such small probabilities of failure cannot be determined, nor demonstrated, nor guaranteed. Therefore, the distributed probability of failure for control of the design of elements is not the easiest way. The designer is obliged to determine both the probability distribution function of the loads as well as the probability distribution function of the resistance of each element. Therefore, the usual standards in which long term statistics on resistances in particular is compressed cannot be used. In this way the design work becomes research and development work and sometimes even scientific work. Since design work is a difficult search process, it must certainly not be made more difficult than it already is(9). Consequently, the design work must be based on standards instead of scientific research with respect to negligible probabilities and tails of invalid and unchecked distribution functions(10).

- decomposition is mainly aimed at simplifying coordination. The fault-tree decomposition of a system, however, has the reverse effect. First of all the dimensions are not familiar (a probability of failure is strange when compared with the usual design dimensions such as "meters" and "Newtons". Secondly, control is difficult due to the strongly non-linear character of the probabilities of failure (for instance an increase of 10 % of resistance can reduce the probability of failure with a factor thousand!);

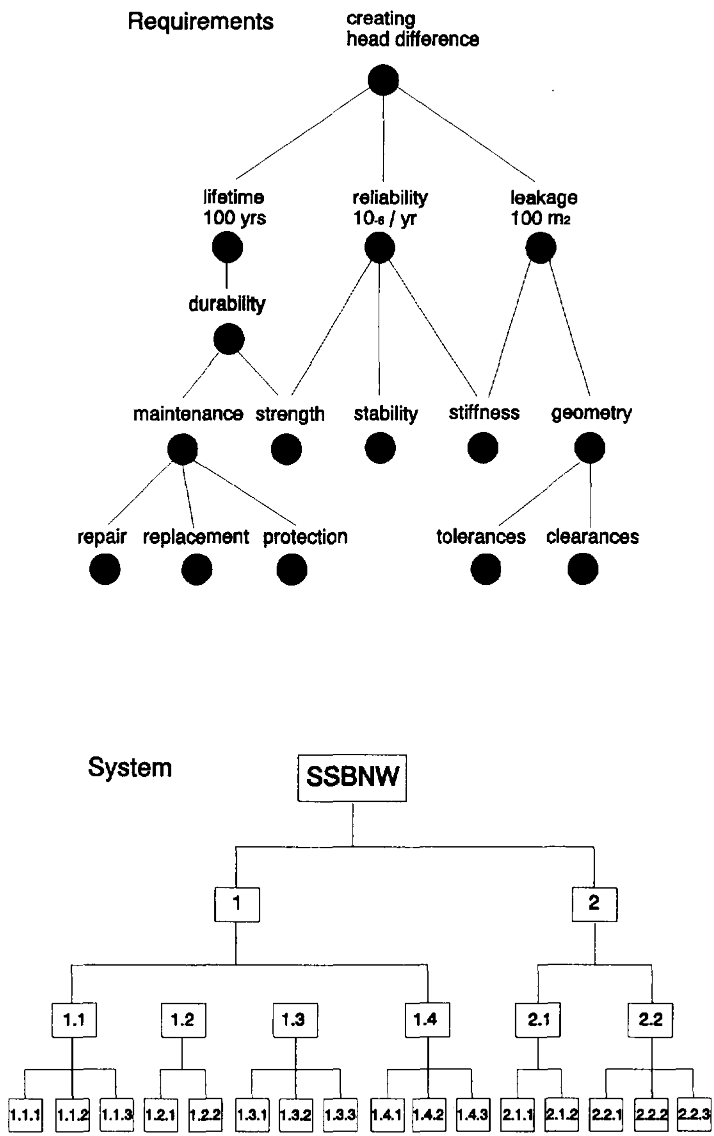


Fig. 9.7.3 *Non-correspondence between requirements and sub-systems for the phase system "functioning". 1 = system needed to create head difference actively (1.1 = gate, 1.2 = framework, 1.3 = ball & socket, 1.4 = concrete block). 2 = system needed to create head difference passively (2.1 = abutment, 2.2 = sill). The sub-numbers (..i) refer to elements.*

The above list refers to practical objections against application of fault trees for the design of elements of systems. The main objection however, is the lack of insight in the behaviour of the system. In other words, the fault tree does not provide a dynamic control model of the system.

The consequences of the fault-tree as main decomposition method to enable the control on effectiveness are sketched in figure 9.7.2 for the phase-system "functioning". As indicated, the three basic requirements for this phase-system are: (1) reliability (10E-6/year), (2) durability (100 years lifetime) and (3) leakage (100 m^2).

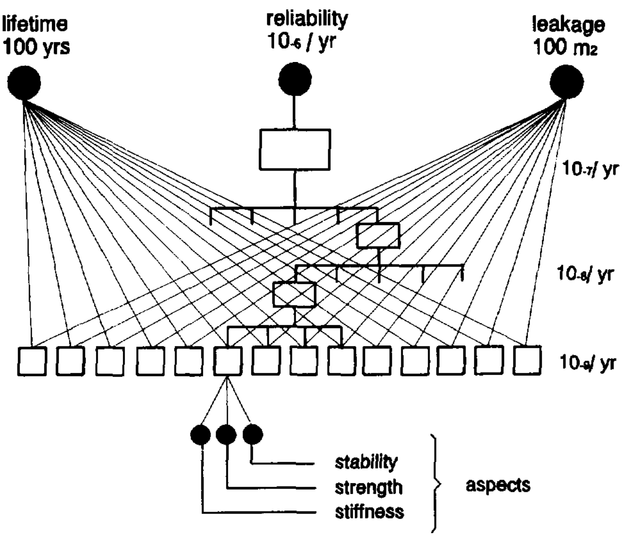


Fig. 9.7.4 *Fault-tree for phase-system functioning and the design coordination on other requirements. It can be seen that the one-dimensional failure analysis of systems (reliability) leads to small required probabilities of failure at elementary level, making it difficult to meet the other requirements.*

Due to the unlimited progressive decomposition into very small elements, the required probabilities of failure became extremely small. Not only the design on reliability became very difficult, but also the fulfilment of the two other requirements (durability and leakage).

Together, the fault-tree as the main framework for the control of effectiveness and the CTR decomposition for the control of efficiency, provided tools for the control of sub-systems c.q. elements, but certainly not for the control of the whole system.
Due to the lack of an overall control system, the design work suffered large iterations. Consequently, the reserved design period of 6 months extended to 4 years, causing an overlap of design activities and construction activities. Given the typical character of the decomposition aimed at sub-optimization of elements, this overlap resulted in an extension of only one year.

9.8 Organization and information

9.8.1 General

Contractor's control problem started with the absence of an overall goal control model as described in the previous paragraph. The associated control problem was amplified by the typical "construction" based organizational structure. This is shown in the following paragraph.

9.8.2 Organizational structure

As said before the project was mainly perceived to be a construction project with a small amount of design work prior to construction (just a few details). In such a context, the total structure can be decomposed at a high abstraction level on similarity of processes and materials to be used, resulting in two main construction disciplines: (1) civil engineering and (2) steel construction. This was the reason that the joint venture was divided into two sub-joint ventures: BMK-Steel and BMK-Civil Engineering, with a rigid demarcation of work content. Since the Client can not accept two joint ventures as participant, the two joint ventures were hierarchically placed under the overall joint venture BMK. The organizational structure at the start of the project is given in figure 9.8.1.

It is concluded that the BMK organization was not only characterized by the normal functional and hierarchical barriers resulting in the operational islands of figure 8.5.2, but in addition had a rigid functional barrier between two commercial parties within one problem solving situation. Such a functional barrier leads to sub-optimization, which is acceptable to a construction process, yet certainly not to a D&C process.

9.8.3 Amplification of the control problem due to the absence of design clusters

According to the demarcation, the design organization was also divided into two main departments (Civil Engineering and Steel). However, not all tasks could be brought within these two disciplines. Therefore a third (General) design department was placed in between the two other disciplines, dealing with all items and issues not belonging to typical Civil Engineering work or typical Steel work.

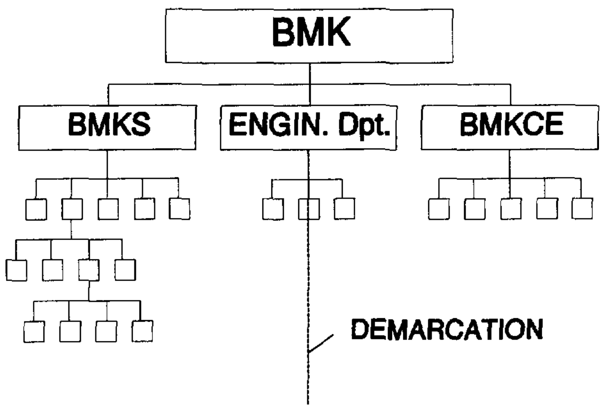


Fig. 9.8.1 *Organizational structure at the start of the project. This structure is typically based on functional and hierarchical principles associated with construction work*

As far as the relations between the elements were concerned, a severe difficulty was caused by the interaction between the elements. Since the essence of design work is maintaining relations under the change of elements, the structural control is of vital importance. The organization, however, did not contain clusters of elements (sub-systems) in which the interrelations are automatically coped with. The design management, confronted with this control problem, introduced a relations-book, containing all relations between the elements. This, however, is a rather static control approach. The dynamic component consisted of four different indications of the status of the relations between the elements: (1) recognized, (2) preliminary, (3) one-way fixed and (4) two-way fixed. The control problem is sketched in figure 9.8.2.

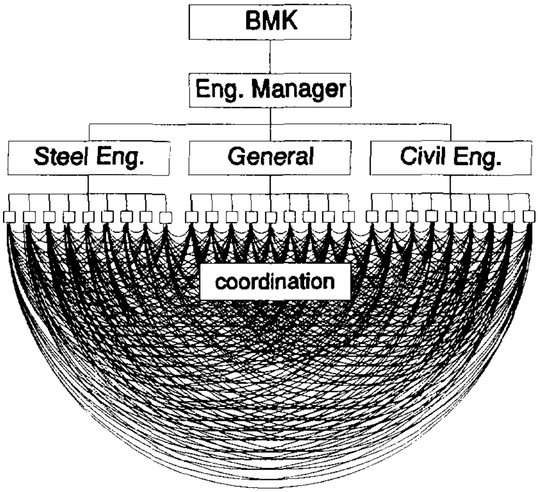


Fig. 9.8.2 *The control problem of the design organization. Each line represents at least one relation.*

As can be seen, the organizational structure of the Design department does not allow for continuous dynamic insight into the overall performance of the system. Neither the relations between the elements, nor the fulfilment of all requirements could be simply controlled.

Consequently, the required BMK meta-control on effectiveness and of course the meta-meta-control on effectiveness by the Client is difficult. Each line represents one or more relations. An improvement would probably have been achieved by placing the "general group" as a staff group under the design manager. This is sketched in fig. 9.8.3, however, not implemented. As can be seen, the number of relations is substantially reduced, but the remaining relations to be controlled by both Steel Engineering Manager and Civil Engineering Manager still does not provide a satisfying span of control.

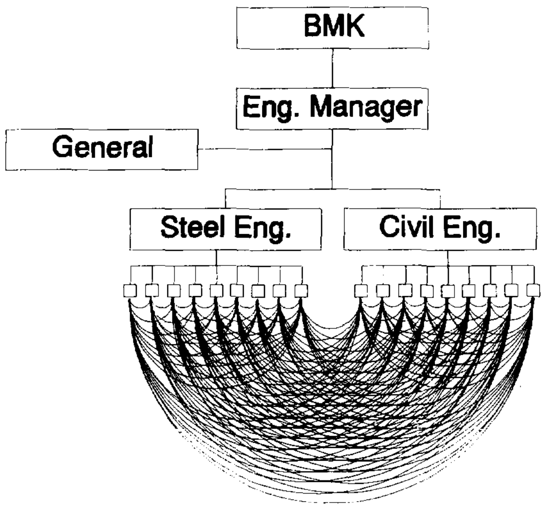


Fig. 9.8.3 *A proposed but not implemented alternative design organization with a staff group for goal control, aimed at reducing the number of relations.*

9.8.4 Amplification of the control problem due to the demarcation between BMK-Steel and BMK-Civil Engineering

The demarcation between BMK-Steel (BMKS) and BMK-Civil Engineering (BMKCE) resulted not only in a separation of the construction organization, but also in design groups: (1) "Steel Engineering" and (2) "Civil Engineering". As shown in the previous chapters, the goal control in a D&C project should be aimed at satisfactory performance of the realization process, which is the product of effectiveness and efficiency. This goal control should be applied to the whole system and not to the part-systems. In the BMK situation, however, the control of the performance of the realization process was split up into two levels:

- One part of the goal control (the efforts) was controlled by the two sub-joint ventures BMKS and BMKCE. This was possible due to the link between the two structural design departments and the associated sub-joint ventures (see figure 9.8.4). Self-evidently this meta-control of efficiency was not only applied for the design activities but also for construction.

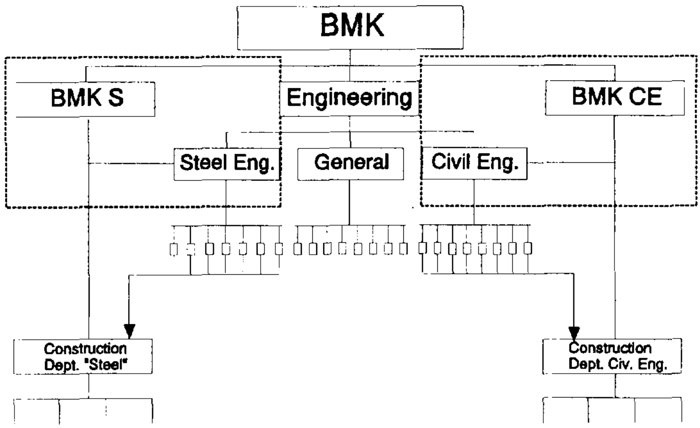


Fig. 9.8.4 *Meta-control of efficiency of the design organization by the two construction clusters "Steel" and "Civil Engineering".*

- The other part of the overall control was delegated to BMK Joint Venture, who was responsible for the overall performance of solution (see figure 9.8.5).

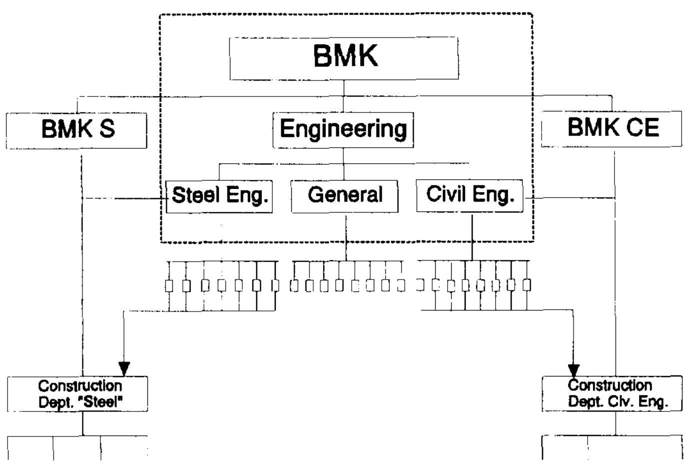


Fig. 9.8.5 *Meta-control of effectiveness at BMK*

In all, the BMK meta-control goal was in total conflict with the meta-control goal of BMKS and BMKCE, whereas both control goals together should theoretically have formed the overall goal (satisfactory performance of the realization process). Hence, there was a substantial conflict within Contractor's organization.

Obviously, the BMK organization had three goal controllers operating at different control levels, each controlling a part of the goal. In that way, it was difficult to develop a complex system. In a more general sense it can be concluded that a complex problem cannot be solved with two equivalent parties each dealing with a sub-problem. In that case, the problem solving process suffers from sub-optimization which certainly does not lead to overall optimization, and often prevents finding an adequate solution.

The demarcation also resulted in a blockage of the information flow in the design department. Each potential move of the design groups across the demarcation line was meta-controlled by the sub-joint ventures. The effect is sketched in figure 9.8.6. This blockage initially resulted in a large number of unsolved problems at the interface between BMKS and BMKCE.

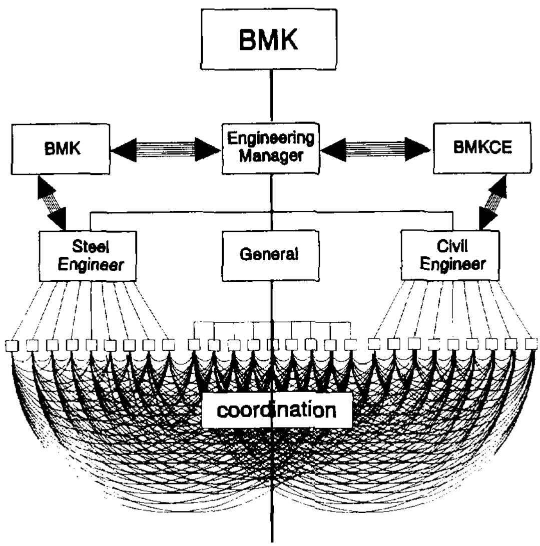


Fig. 9.8.6 *Information blockage due to the demarcation between BMKCE and BMKS. Information is filtered on efficiency by these two meta-controllers.*

9.8.5 Client's control problem

An important contractual clause was that construction of elements was allowed to start in case the specifications and drawings were accepted by the Client. Consequently, the control possibility of the Client had a passive character. Since the Client could only accept the design of an individual element in case the overall performance was known and the relation between the whole system and the considered element is visualized, BMK should have provided a continuous insight into the performance of the whole system. As shown in the previous section such an insight was not available. Consequently, the design of a simple element had to be accompanied by a number of documents covering the relations with: (1) requirements, (2) other elements and (3) environment. This caused bureaucracy, resulting in a large quantity of documents.

The only way the Client could influence the realization process was by non-acceptance of design documents. The delays due to non-acceptance of documents, however, appeared to be an effective control tool. Given the fixed price, BMK tried to avoid delays (even elements were designed with probability of failures up to 10 E-7). As already said, such small and unrealistic probabilities of failure required for the design of elements have led to overdimensioning and thus extra costs.

9.9 The organizational adjustments and the effects

Two years after the start of the project, it became apparent that the enormous information flow (procedures, documents, memo's, etc) in order to control the engineering work, could possibly be reduced by installing a few design clusters in order to reduce the efforts needed for structural control of the system. The structure of a system is given by the relations between the main sub-systems. The relation matrix of sub-systems representing the structure of the SSBNW is given in figure 9.9.1.
At that moment the organization contained two clusters of elements e.g. "Steel-elements" and "Civil Engineering Element". These two clusters are sketched in figure 9.9.2.

In fact, a few months after the start of the project, the civil engineering cluster was decomposed into two parts: (1) a cluster containing all civil engineering works on land and (2) a cluster containing all civil engineering on the river. This partition is sketched in figure 9.9.3.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1. sill	●	●	●		●		●							●					
2. filter	●	●	●		●														
3. bed protection	●	●	●	●	●														
4. river works			●	●															
5. abutment	●	●	●		●	●	●		●	●	●	●			●		●		
6. site arrangements					●	●	●												
7. dry dock	●				●	●	●	●		●		●		●	●		●	●	
8. dry dock pumps (CA)							●	●									●		●
9. foundation (B&S)					●				●				●	●	●				
10. guiding tower					●		●			●		●		●		●			
11. control building											●	●							●
12. power station							●			●	●	●				●		●	●
13. ball & socket system									●				●	●	●	●		●	●
14. gates									●	●			●	●	●	●		●	●
15. framework					●				●				●	●	●				
16. locomobile + rail										●		●	●	●		●			●
17. dry dock gate	●				●		●	●									●		●
18. ballasting system												●	●	●				●	●
19. power supply								●			●	●	●	●		●		●	●

Fig. 9.9.1 *Structure SSBNW: relations sub-systems/sub-systems*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1. sill	●	●	●		●		●							●					
2. filter	●	●	●		●														
3. bed protection	●	●	●	●	●														
4. river works			●	●															
5. abutment	●	●	●		●	●	●		●	●	●	●			●		●		
6. site arrangements					●	●	●												
7. dry dock	●				●	●	●	●		●		●		●	●		●	●	
8. dry dock pumps (CA)							●	●									●		●
9. foundation (B&S)					●				●				●	●	●				
10. guiding tower					●		●			●		●		●		●			
11. control building											●	●							●
12. power station							●			●	●	●				●		●	●
13. ball & socket system									●				●	●	●	●		●	●
14. gates									●	●			●	●	●	●		●	●
15. framework					●				●				●	●	●				
16. locomobile + rail										●		●	●	●		●			●
17. dry dock gate	●				●		●	●									●		●
18. ballasting system												●	●	●				●	●
19. power supply								●			●	●	●	●		●		●	●

Fig. 9.9.2 *The design clusters "steel" and "civil engineering" as result of the organizational structure*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1. sill	●	●	●		●		●							●					
2. filter	●	●	●		●														
3. bed protection	●	●	●	●	●														
4. river works			●	●															
5. abutment	●	●	●		●	●	●		●	●	●	●			●		●		
6. site arrangements					●	●	●												
7. dry dock	●				●	●	●	●		●		●		●	●		●	●	
8. dry dock pumps (CA)							●	●									●		●
9. foundation (B&S)					●				●				●	●	●				
10. guiding tower					●		●			●		●		●		●			
11. control building											●	●							●
12. power station							●			●	●	●				●		●	●
13. ball & socket system									●				●	●	●	●		●	●
14. gates									●	●			●	●	●	●		●	●
15. framework					●				●				●	●	●				
16. locomobile + rail										●		●	●	●		●			●
17. dry dock gate	●				●		●	●									●		●
18. ballasting system												●	●	●				●	●
19. power supply								●			●	●	●	●		●		●	●

Fig. 9.9.3 The non-official three design clusters in the real working situation

The basic idea behind the decomposition of relations is to minimize the external relations and maximize the internal relations. A main condition then is, that the cluster leaders have full responsibility of the clustered elements.

This step towards fully responsible cluster managers, however, was too large for the centralized and hierarchically organized project organization, which was set up by Client and Contractor. The main reason was a psychological reluctance to change the initial hierarchical structure. Instead of hierarchical clusters with delegated authority, five coordination clusters were installed without authority. The difference between hierarchical clusters and coordination clusters is sketched in figure 9.9.4. The effect of coordination clusters is sketched in figure 9.9.5.

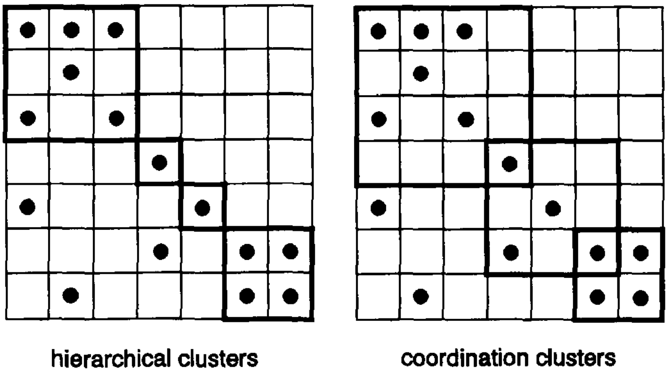


Fig. 9.9.4 *Difference between hierarchical and coordination clusters*

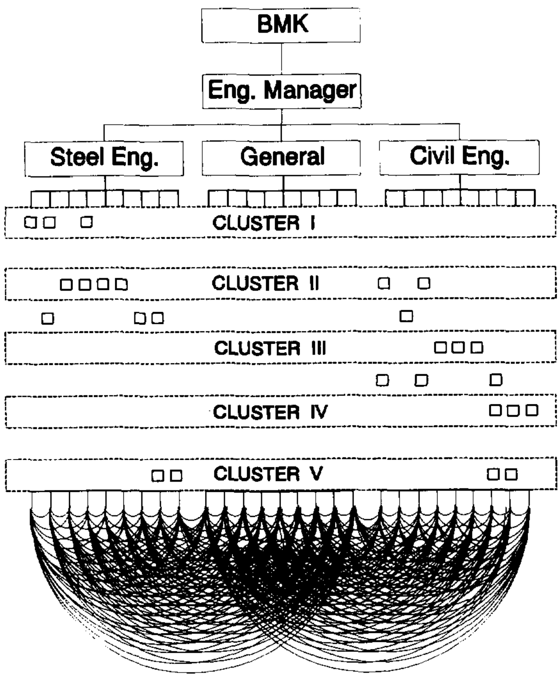


Fig. 9.9.5 *Effect of coordination clusters*

The cluster leaders were not held responsible for the internal interfaces within the clusters. Therefore, the aimed reduction of information transmission flow needed for structural control turned out to be an amplification of the existing information transmission flow. It is concluded that the total information transmission flow needed to coordinate the engineering work was increased by the coordination clusters instead of reduced.

9.10 Conclusions

The Storm Surge Barrier in the Nieuwe Waterweg is a complex civil engineering system. The realization process is arranged in a Fixed-Price D&C contract. The D&C task was by both Client as well as Contractor perceived to be a construction task with a minor part of preceding engineering work on details. This perception is demonstrated with the following facts:

The control goal was optimization of the contractual concept, which would result in more benefit for the Contractor. This is possible for a construction task but certainly not for a D&C task.

The decomposition in order to enable control was oriented on the elements. Both the decomposition of tasks (CTRs) as well as the decomposition of the system (faulttree) did not take into account the relations between the elements.

The control on effectiveness and efficiency was concentrated on the elements and not on the system as a whole, which is anyway in harmony with the decomposition methods. This has led to sub-optimization which is quite acceptable for construction tasks, but however for D&C tasks leads to less performance (product of effectiveness and efficiency < 1).

The control was based on actual efforts, which is common practice for construction tasks, but inadequate for the control of D&C tasks. As shown, the control of D&C task should be based mainly on estimated actual and in a lesser degree on actual efforts.

The organization was based on a strict hierarchical and functional principle which normally apply for construction tasks. Even a strict demarcation was made in the organization dividing the Joint Venture in two sub joint ventures (Steel Construction and Civil Engineering). This organization structure is not suited for a D&C task.

The Fixed-Price type of contract is suitable for construction tasks but certainly not for D&C tasks.

Notes

1. This general description is based on a Public Relations sheets of BMK, Bouwkombinatie Maeslant Kering and RWS (Dutch Ministry of Public Affairs). Hoek van Holland, 1991.
2. This approach clearly shows that Client and Contractors in the present situation are not aware of perception problems at the start of such a complex project and of the impossibility to give a fixed price for a realization process starting with just a rough conceptual solution. In other words, in the present perception of Client and Contractor, the normative performance of solution and the associated efforts can be determined fully and precisely at the very start of the project and will not change significantly. Such a normative performance of solution is considered to be specifications and drawings. This fully corresponds with the traditional contracting situation.
3. Evaluation report
4. It is noted that the required probabilities of failure of the operational phase-system are quite correct, because these operations should be guaranteed with certain reliability in order to mobilize the SSBNW for functioning. This in contrast to defined probability of failure for the phase-system functioning (gates resting on the sill withstanding extreme sea water levels). It would have been preferable to define the probability of exceedance of the governing load cases and to determine the strength of the system with the governing standards.
5. As mentioned earlier in this study, relations are connected to the system which is to be developed as solution to the problem. Elements and requirements are related. As will be shown in the next chapter the loads on the system operating in its environment are interrelated as well.
6. This makes sense since the full probabilistic approach was perceived to be less conservative than the usual standards and thus satisfied the optimization goal as agreed between Client and Contractor.
7. Correspondence of sub-systems and requirements (variables) is the main basis of Client's systematic approach. Roermund, A.J.G.M. van, Plan van aanpak ontwerpfase SVKW, SVKW-KWA-90005 rev 3, 1990, and also became the basis of Contractor's approach.
8. For the design of complex systems, two interesting types of approach were recognized by Wagenaars, W.A. at the symposium: "De Schijn van kans", held in Delft, April 1993. The first approach is resilience, based on resistance against undesired influences (illness hardly threats a healthy person). The second approach is anticipation, based on the continuous check of what could go wrong (taking a large number of pills against a large number of potential illnesses). This last one is identical to the fault-tree approach.
   This basic difference in approach is also recognized by the Spanish philosopher Fernando Savater (NRC, 3/6/93):
   "A cooking book writer does not mention the thousands way the preparation of a "tortilla de patates" can fail. Instead he describes the way the tortilla must be prepared in the best way". Therefore he is not necessarily an idealist or an optimist"
9. In this respect the traditional saying about "scientific design work" is clear: an engineer is not a scientist and a scientist can never be an engineer.
10. The existing theories on probability are not valid anymore when dealing with these extremely low probabilities of failure. Moreover, statistical data on strength is not available to cover these extreme probability areas. Hence, acceptance of elementary documents could only be discussed with regard to opinions and to arguments. Although the fault-tree is not recommended for the design of elements of a system, it can be used perfectly for the design of operations, since in most cases operations consist of serial and/or parallel sub-operations.

PART 4: THE PROPOSED CONTROL SYSTEM OF DESIGN & CONSTRUCT OF COMPLEX CIVIL ENGINEERING SYSTEMS

10. THE PROPOSED CONTROL SYSTEM FOR "DESIGN & CONSTRUCT" OF COMPLEX CIVIL ENGINEERING SYSTEMS

10.1 General

In this chapter proposed control system of "Design & Construct" of complex civil engineering systems is presented.

After the fundamental treatment of the realization process of complex systems yielding the principles for a satisfactory performance of a delegated Design & Construct task, it is now possible to develop the general control principles into a more specific control system for D&C of complex civil engineering systems. Following the general control principles, the D&C control system should, given a certain problem statement (problem + conceptual solution + set of requirements), be able to quantify the:

- normative performance of solution at the start of a D&C project (P_0);
- normative efforts needed to realize the normative performance of solution (E_0);
- differential normative performance of solution (dP_0) continuously during the D&C period;
- real performance of solution (P) continuously during the D&C period.

Furthermore, the D&C control system must contain a contractual part which satisfies the need for the specific risk sharing principle (perception risks for the Client and process risks for the Contractor).

Firstly, a system-theoretical framework is given for the overall realization process indicating the proposed control model with the roles of Client and Contractor and associated methodology of the realization process. This is the framework of the organizational part of the control system. Based on this system theoretical framework, the various organizational components will be discussed with respect to function, structure, primary process, decomposition, control, meta-control, models, information and organizational structure. Secondly, the contractual part of the control system is presented.

10.2 The systematic approach

As previously mentioned, system theory is adopted as the basis for control of the realization process of large civil engineering systems with a D&C contract. As far as the organization is considered, the systematic approach is sketched in figure 10.2.1, giving the organization at the highest abstraction level.

The basic idea behind the systematic approach is that any realization process starts with a problem and ends with a Controlled System (CS), operates in an Environment (E) and to be controlled by a Controller (CR). The start is in the left bottom corner of figure 10.2.1 where the end is on the right hand side. Along the horizontal axis, the time line of the realization process is given.

Although the realization process for complex civil engineering systems is often controlled by another party than the eventual user, it is assumed, following the delimitation of the study, that there only one party controls the overall realization process(1). This party is the Client, who is: (1) Problem Owner, (2) controller of the realization process and (3) user after commissioning. Given this context the Client is the highest controller throughout the realization process up to commissioning. This is indicated by the large horizontal bar at the top of the figure. The second bar at the top of the figure represents the control function of the Problem Solver (the D&C Contractor) during the realization process upto the commissioning. The Client is meta-controller of the D&C Contractor.

The D&C Contractor controls his part of the realization process using the control paradigm as described in paragraph 6.2. Although figure 6.2.1 and the part of figure 10.2.1 which represents the system analysis are not identical, the difference is negligible. The main difference is the addition of the friction-source between controlled system and environment which, in fact, can be considered to be the desired function of the system to be developed.

The outcome of the orientation phase is the basis for a D&C contract. The form, friction and context are worked out in starting points, requirements and boundary conditions respectively. The D&C task starts with a system analysis using the conceptual solution (fixed with starting points) as the controlled system and the boundary conditions as environment. With this approach the set of requirements represents Client's wishes with respect to construction and utilization.
The system analysis eventually results in a system which is capable of effectively and efficiently solving the initial problem. The "design part" of figure 10.2.1 (aspects, loads, risk analysis specifications and drawings) will be discussed further in this chapter.

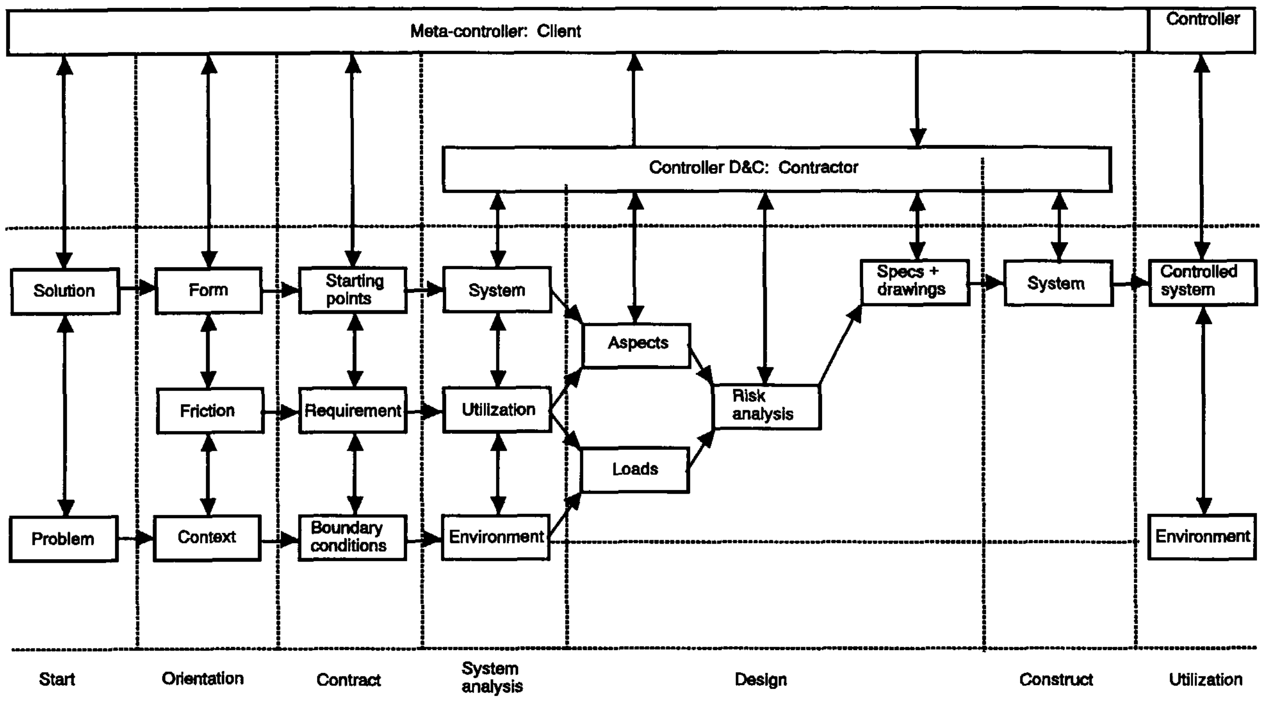


Fig. 10.2.1 *The system theoretical approach of the overall realization process at a high abstraction level. The diagram shows two important issues: (1) the roles of both Client (Problem Owner, meta-controller and user/controller of the system) and Contractor (Problem Solver) and (2) the systematic transformation of the friction between solution and problem into a controlled system operating in its environment.*

10.3 Decomposition

10.3.1 General

In chapter 5, three different decomposition methods have been presented corresponding with three specific control issues:

- goal control with respect to fulfilment of all requirements being the condition for sufficient performance of solution;
- structural control during the design process which should cover all relations between the elements;
- control of the construction processes, which is related to processes, locations, etc.

The first two control issues cover the overall realization process, and simplify the control of the performance of solution, which is the "effectiveness part" of the realization process. The third coordination problem only refers to the last part of the realization process, e.g. the effectiveness and the efficiency of construction, mainly determined by the constructability of the solution. Once the effectiveness part and the constructability are under control, the efficiency of the construction work can easily be controlled with the commonly known cost control techniques and planning models.

The decomposition methods result in three mathematical formalisms for the clustering of two items: (1) clustering of requirements resulting in aspect-systems and (2) clustering of elements resulting in sub-systems. Apart from sub-systems and aspect-systems, a system can also be decomposed into phase-systems. Phase-systems have not been discussed in a formal way. In fact, phase-systems are obtained by the clustering of time. As will be shown in section 10.3.4, a formal treatment is not necessary. The formation of phase-systems can be derived from a detailed consideration of the various phases in the realization process. Theoretically three phases have been recognized. For the civil engineering practice, however, 8 phases can be distinguished (see annex 6).

The mathematical formalisms for decomposition, as given in chapter 5, have provided a show case for clustering methods and permitted a comparison of the relative merits and demerits of the various distinguished methods[2]. In fact, the "best" clustering methods have been chosen, where the selection was based on a comparative analysis of objective criteria. The eventual choice of the clustering method is, however, strongly affected by non-objective factors (see intermezzo 10.1).

Intermezzo 10.1

For data analysis, the following subjective factors play an important role for the selection of a clustering method: (1) matching algorithm to data type, (2) the desired type of output, (3) the availability of the algorithm and (4) the acceptance of the clustering method in the methodology of the application. For the eventual choice of the clustering method for data analysis, the following sequence of analysis is proposed: (1) cluster tendency, (2) clustering method and (3) cluster verification(3).

The clustering in the context of this study is aimed at coordination. Therefore, the analysis is limited to the selection of the clustering method only. The only purpose is simplification of the coordination of the realization process of large complex civil engineering projects. Cluster analysis can be helpful for such a simplification as the objective of a cluster analysis is to uncover natural groupings.

It will be shown that the specific characteristics of the type of systems under consideration provide dominant criteria for the clustering. In other words, for the realization process of most large complex civil engineering systems, the main part of the preferable decomposition can be given. In the next section, the decomposition methods are discussed in coherence with, respectively, the goal coordination, the structural coordination and the coordination of the production processes.

10.3.2 Decomposition in aid of goal coordination: the formation of aspect-systems

The goal of the realization process is the product of effectiveness (sufficient performance of solution = fit of all variables = meeting all requirements) and efficiency (determined mainly by constructability) of the action. For adequate goal control, paragraph 5.6 gives the three formal properties of variables which will be repeated here:

- variables must be as specific as possible;
- variables must be as independent as possible;
- variables must be comparable in their scope and significance.

The first step (or at least the second step) in the decomposition of the total set of variables results in a set of aspect-systems representing the total friction between solution and problem. An aspect-system is a cluster of requirements. Given the decomposition rule, the formal properties of variables are by definition also valid for the aspect-systems. An aspect-system is in fact a criterion for effectiveness and should therefore be quantified.

It is noted that control with a set of aspect-systems is totally different from the well known multi-criteria analysis as often is used for evaluation of alternatives. The difference is that multi-criteria analysis is used in orientation phases of the realization of (sub)-systems without quantification of criteria, whereas the goal control as discussed above takes place after a concept is already selected.

For goal control of a design process, quantification of the set of aspect-systems is absolutely necessary. As shown later on, the quantification requires an additional property of an aspect-system: linearity.

Without the application of various algorithms for elaboration on the mathematical formalism of the selected clustering method, it is possible to distinguish a set of aspect-systems of civil engineering systems, which meet the formal properties[(4)] above (see figure 10.3.1).

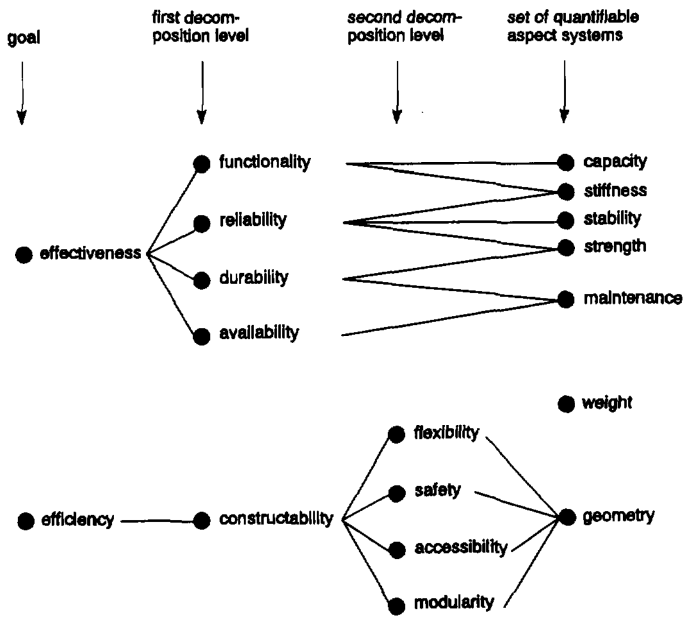


Fig. 10.3.1 *The decomposition of the goal defined as the product of effectiveness and efficiency, leading in three steps to a set of aspect-systems which are: (1) quantifiable, (2) linear, (3) equal in scope, (4) equal in significance, (5) as independent as possible and (6) as specific as possible.*

Starting with the two goal criteria for the realization process, e.g. effectiveness and efficiency, the first decomposition level leads to five aspect-systems, which can however not be quantified: (1) functionality, (2) reliability, (3) durability, (4) availability and (5) constructability. It is noted that efficiency is not only determined by constructability. As a matter of fact a lot of other aspects have influence on efficiency (prices, procurement strategy, choice of equipment, etc.). However, the above decomposition is aimed at a quantification of performance of solution with respect to goal control and with respect to the perception problems. Often the perceived constructability is quite different for the actual constructability.

The second decomposition level leads to a fragmentation of constructability, leading to the following aspect-systems which can still not be quantified: (1) flexibility, (2) safety, (3) accessibility and (4) modularity.

The third decomposition level yields the desired set of aspect-systems which can be used for the goal control of the realization process of complex civil engineering systems. Further decomposition is not necessary. It is noted that the aspect-system weight is not obtained from a decomposition of the goal. However, weight is an important implicit aspect-systems, also subject to underestimation due to perception. The aspect-systems are:

- *Weight;* not requiring further explanation;
- *Strength;* referring to a wide spectrum of notions with respect to direct resistance to loads, meaning that it should give resistance to various mechanisms (rupture, breakage, fatigue, corrosion etc.);
- *Stability;* referring to various types of stability: stability of foundation, structural stability, floating stability, etc);
- *Stiffness;* determining deformations, displacements and deflections;
- *Geometry;* covering dimensional problems and to be expressed in critical clearances and tolerances;
- *Capacity;* dealing with the performance of the system in various phases. Examples are berthing capacity, bearing capacity, throughput capacity, lifting capacity for utilization phases. For construction phases the following examples apply: ballasting capacity, concreting capacity, cooling capacity, sand suppletion capacity, lifting capacity, pumping capacity, floating capacity, etc;

- *Maintenance;* an important aspect-system due to the exceptional lifetime requirements. Maintenance can easily be expressed in protection, inspection, repair and replacements.

Although the aspect-systems are as independent as possible, there are still mutual relations. For instance "weight" interacts with "stability", "strength" interacts with "stiffness" and "durability", "weight" interacts with "capacity", etc.

The main question is whether the list of aspect-systems represents the total friction between problem and solution. In other words: (1) are all possible aspect-systems recognized and are all variables incorporated? The answer is no for two reasons. The first reason is that the list of aspect-systems do certainly not pretend completeness. It is difficult however, to find more than seven aspect-systems of equal scope and significance for civil engineering systems. The second reason is that regarding the variables, there will always be a minor requirement which cannot be clustered in an aspect-system. This is not a constraint for the goal coordination, since an unusual singular requirement can be dealt with separately, independently from the set of aspect-systems.

Intermezzo 10.2

With the set of aspect-systems, the control-system for the realization of the SSBNW (see chapter 9) during the phase-system "functioning" would have been as sketched in figure 10.3.2. The three requirements (lifetime, reliability and leakage) are decomposed in five specific aspect-system of equal scope and significance (see figure 9.7.5 for comparison).

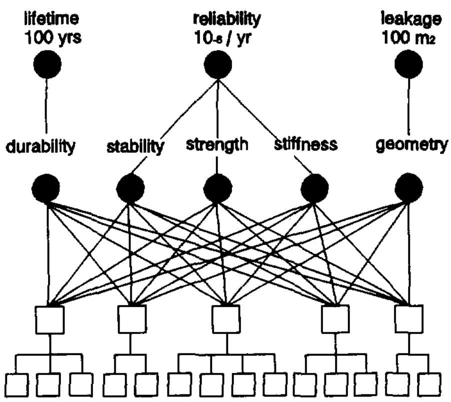


Fig. 10.3.2 An ideal goal-control model for the realization of the SSBNW

10.3.3 Decomposition in aid of structural coordination: formation of sub-systems

Two decomposition methods have been recognized for the formation of sub-systems. The first method is based on the interrelations between the elements, simplifying design work in particular. The second method is based on similarity, simplifying construction in particular. When applied rigidly, both methods would lead to totally different clusters of elements due to the basically different character of both activities.

Design is a search process which should cope with (1) a large number of elements, (2) a large number of requirements which do not correspond with the elements and (3) a large number of non-simple relations between both elements as well as requirements. Design work is preferably conducted with a limited number of people and the clustering method is based on the relations, resulting in communication clusters.

Construction is a selection process, which should cope with (1) a large number elements, (2) a large number of corresponding requirements and (3) a large number of simple relations between the elements. Construction work is mostly conducted with a large number of people and the clustering method is based on (dis)similarity, resulting in a few construction clusters: foundation, marine, steel, concrete, mechanical & electrical.

Since the subject of this study refers to both design work as well as construction work with one and the same contract, it would be convenient to find a clustering method satisfying both clustering methods as much as possible.

The basic ideas behind such a method are:

- the number of design clusters for a complex system is larger than the number of construction clusters;

- the transition from design clusters to construction clusters should be as smoothly as possible, without loss of control possibilities and information. This condition is fulfilled in case the design clusters are considered to be subsets of construction clusters, where each design cluster belongs to only one construction cluster.

The decomposition result is sketched in figure 10.3.2, showing the basic idea behind the formation of design clusters and construction clusters.

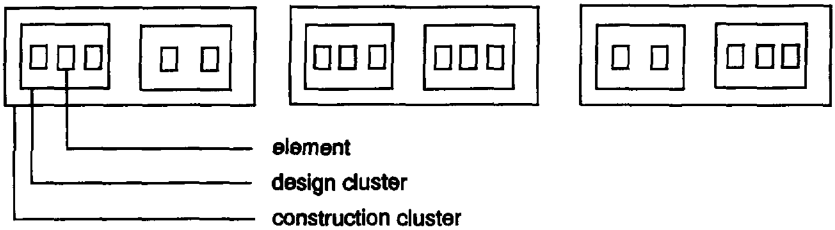


Fig. 10.3.3 Relation between design clusters and construction clusters. The condition for a smooth transition from design to construction is that design clusters are subsets of construction clusters

10.3.4 The formation of phase-systems

As mentioned in chapter 1, an important aspect of the realization of large civil engineering projects is that the temporary phases can be dominant in the design. Hence, the temporary construction phases must be recognized as a phase-system. Sometimes a division can be made in a construction phase-system and an installation phase-system (see the case study in chapter 11).

Civil engineering systems sometimes have an operational function. In that case, the system is actively used. For these types of systems, a division in an operational phase-system and a non-operational phase-system is necessary (see the case study of chapter 9). As a result, the following phase-systems are generally recognized for civil engineering systems(5):

- temporary phase-system : - construction phase-system
  - installation phase-system
- utilization phase-system : - operational phase-system
  - non-operational phase-system

10.4 The multilevel control-model

10.4.1 General

The framework of the proposed control system is a multilevel control-system which is sketched in figure 10.4.1 and qualitatively discussed below with respect to goals only.

10.4.2 Object level control

The lowest part of figure 10.4.1 is object level control, often called substantive control. At this level the overall realization process of individual elements as smallest parts of the system is controlled. This is the level at which the work is actually carried out. All other levels deal with coordination. It is noted that control should cover design, engineering, procurement and construction of elements. The goal of object level control is the realization of elements: (1) in accordance with standards, (2) taking into account the relevant context and (3) within the reserved budget and time schedule.

10.4.3 Structural control (meta-control)

Structural control deals with the interrelations between the elements. The structure of the system is controlled in design/engineering clusters during the design phase, which can change smoothly into construction clusters during the construction phase (see figure 10.3.1). The corresponding clustering methods have been discussed in the previous paragraph. It must be realized that not all relations are covered at this first meta-control level. Relations outside the cluster will always remain. These interrelations between the clusters however, are controlled at the next meta-control level.

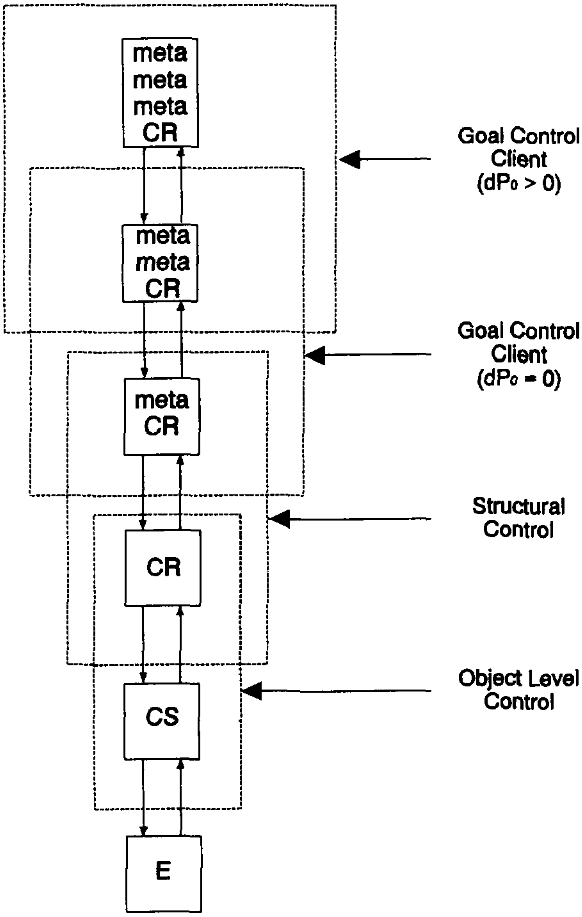


Fig. 10.4.1 The multi-level control system based on the meta-control concept and showing the different levels of control

10.4.4 Goal control D&C Contractor (meta-meta-control)

D&C Contractor's goal is an optimal performance of his part of the realization process (= maximum of effectiveness x efficiency). The D&C Contractor should minimize (d/E/E - dP/P). Preferably, for maximizing the profit, the D&C Contractor should even strive towards a negative value of (dE/E - dP/P).

Implying that the D&C Contractor should simply control his productivity (see chapter 2). Obviously for effective goal control, the variables P and E should be known during any time in the realization process.

As shown in the previous section both the normative as well as the real performance of solution can be established with aspect-systems. Aspects-systems play a crucial role in the goal control of the D&C Contractor. Given the definition of aspect-systems (see annex 1), it is concluded that at meta-meta-control level the overall performance of solution including the total structure of the system (structural control within clusters plus remaining interrelations between the clusters) is controlled. Or, in other words, the system behaviour is reflected correctly.

10.4.5 Goal control Client (meta-meta-meta-control)

Client's goal is an optimal performance of the overall realization process (= maximum of effectiveness x efficiency). In contrast to the D&C Contractor's goal, the Client's goal is not related to the contractual normative performance of the realization process, but to an unknown, yet actual, normative performance of the realization process, adequately solving the initial problem at the end of this process. As shown previously in this study, it can be expected that the unknown actual normative performance of the realization process is larger than the contractual normative performance of the realization process.

Given the risk sharing principle between participants, as developed in chapter 3, the Client's control is started in case: 1) the actual normative performance of solution at a particular in time point exceeds the contractual normative performance of solution, (2) the Client wants to adjust his initial goal. In those particular cases, the D&C Contractor cannot control his part of the realization process any more and the Client becomes meta-controller of the D&C Contractor[(6)]. As shown, the Client should only minimize the term $P/P_0\ (1 + dP_0/P_0)$, since the control of the productivity of the realization process is fully delegated to the D&C Contractor.

When confronted with an increase of normative performance of solution with respect to the contractual normative performance of solution (dP_0/P_0), the Client is now able to control the overall realization process on: (1) effectiveness (full effectiveness $P/P_0 = 1$ with acceptance of more efforts: $E_0 \times dP_0/P_0$) or (2) on efficiency (acceptance of less performance of solution: $P/P_0 <= 1$).

This is a very important advantage of the proposed control system. The Client is able to evaluate his initial set of requirements continuously. As stated in chapter 2, the Client's initial goal concept is certainly not correct. The proposed D&C control system enables the Client to adjust his goal concept in accordance with the increasing insight into the real problem situation.

For illustration of Client's meta-control possibilities, three different and arbitrarily chosen control scenarios for the performance of the realization process are given in figure 10.4.2. (see also chapter 3). Starting point for this figure is full proportionality of P and E.

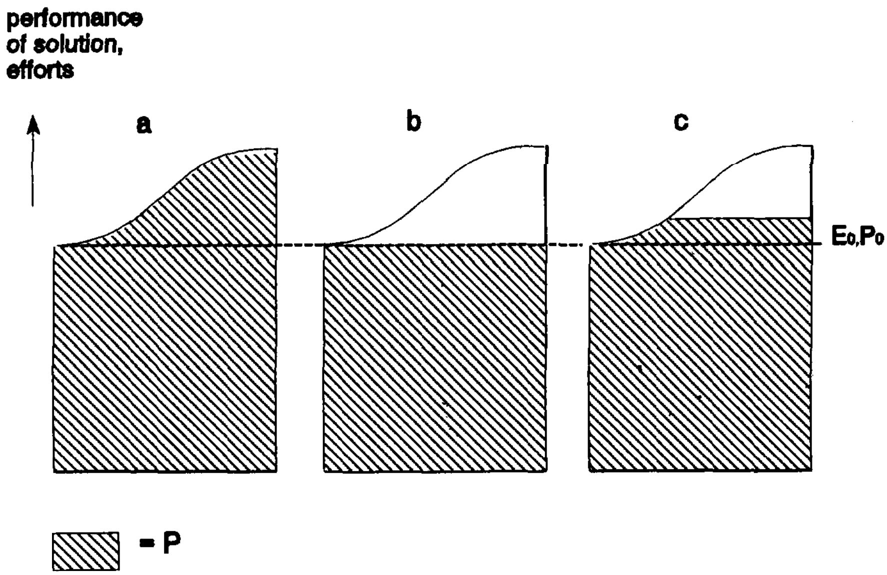


Fig. 10.4.2 *Three different meta-meta-meta-control scenarios. In scenario (a) the Client is not able or willing to adjust the goal (P/P_0 = 1) resulting in 40 % overrun of efforts. In scenario (b) the Client is not willing to accept any effort overrun, consequently he should accept 77 % performance of solution (P/P_0 = 0,77). In scenario (c) the Client defines a maximum effort overrun (10 %), consequently he should accept 80 % performance of solution (P/P_0 = 0,8).*

Having explained the way the different control levels relate to each other and which goals should apply, now the defined requirements for control can be quantified with respect to the remaining conditions for effective control (models, information and variety) for each distinguished control level. This is to be done in the next paragraphs.

10.5 Object level control (elements)

10.5.1 Goal and diagram

The goal of object level control is the realization of elements. The object level control is schematically sketched in figure 10.5.1 indicating the relation between the control paradigm and elements.

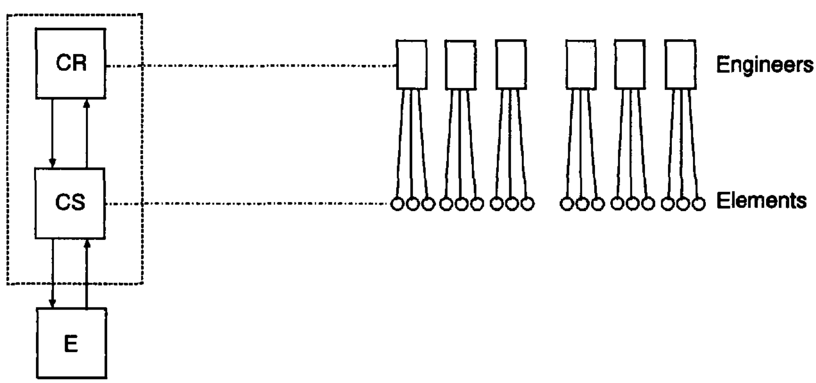


Fig. 10.5.1 Diagram of object level control in the context of the control paradigm.

10.5.2 Model

The models to be used for the control of effectiveness are empirical models of concrete systems (see annex 4). The type of models are: (1) scale models, (2) analogy models, (3) cybernetic models, (4) ideal models, (5) application of structural models and (6) realizations of mathematical models. For the control of efficiency two additional models should be used: a planning model and a cost control model. As far as efficiency control is concerned, the models to be used do not differ from the commonly known cost control models and planning models.

10.5.3 Information

The information input consists of the following components:

- relevant boundary conditions (context)
- starting points (simple concepts)
- standards for construction and design
- budget and time

Particularly for boundary conditions, the three information cases must be distinguished, e.g. certainties (for instance location), uncertainties with conditional probability functions (for instance wave climate) and real uncertainties (for instance soil condition).
It will be clear that for the active part of control, namely the decision making, the object level control should cope with these information cases. For uncertainties with conditional probability function, a risk analysis should be used and for real uncertainties a sensitivity analysis should be applied. The information output at the end of the design phase is a full description of the element (materials, properties, dimensions, etc.) and at the end of the realization process an as-built file.

10.5.4 Control variety

The control variety is limited. The control variety matrix is given in table 10.5.1.

	Internal	*External*
Routine		
Adaptive		-
Goal	-	-

Table 10.5.1 Substantive control variety matrix at object level defining the authority of the designer/engineer.

Examples of the indicated control varieties are:

- internal routine; the designer/engineer is allowed to change materials and dimensions;

- external routine; the designer/engineer is free to further study soil parameters or wave climate;
- internal adaptive; the designer/engineer is free to change the internal structure of the concerned element (relations between subelements).

In case the designer/engineer, dealing with elements and exercising substantive control, cannot solve the design and construction problems with the three defined control varieties, he should appeal to meta-control, which is structural control in the proposed control system.

10.6 Structural control (meta-control)

10.6.1 Goal and diagram

Structural control is aimed at maintaining all relations between the elements, guaranteeing the structure of the system. The proposed structural control is schematically sketched in figure 10.6.1.

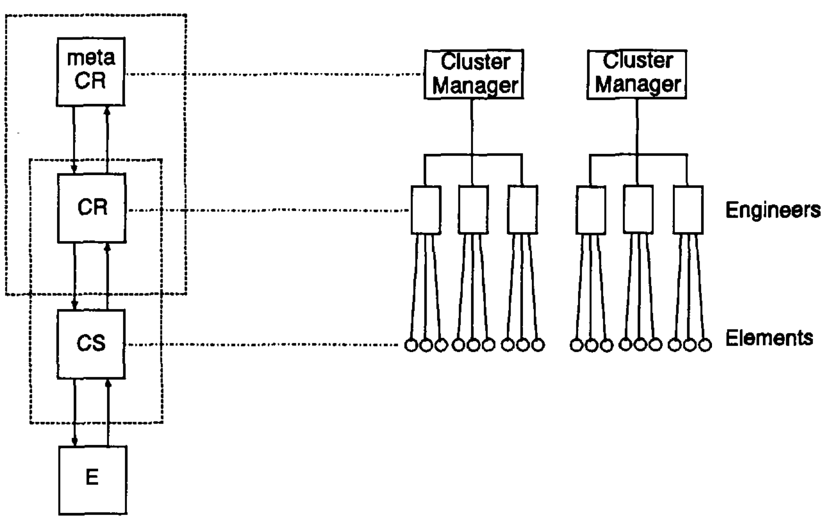


Fig. 10.6.1 Diagram of structural control as the first meta-control level

10.6.2 Model

The models to be used are structural models (see annex 4). Structural control is exercised by cluster managers. Structural control is a matter of dynamic communication. The cluster manager should be aware of all relevant relations inside the cluster and should be able to control them.

10.6.3 Information

The information refers to "starting-point boundary condition" relations. A starting point for one element becomes a boundary condition for another. It is important to realize that the structural control does not have direct interactions with the environment. Information can be processed in various ways. It is strongly recommended to process this information in an informal way during the design, and to make a design report of the cluster each for 1 or 2 months (see chapter 9, for an illustration of the induced bureaucracy as a consequence of a static and formal approach). Formally, the information is given in design reports, specifications and drawings.

10.6.4 Control variety

The control variety refers to the realization of elements which cannot be conducted within the three previously (in section 10.5.4) defined control varieties. The structural control provides two additional varieties to the varieties already defined for substantive control of elements (see table 10.6.1):

- externally adaptive, meaning that the relation with other elements and hence, the internal structure of the cluster can be changed in order to solve a problem;

- internal goal, meaning that the functions of the elements inside the cluster can be changed without changing the overall goal of the cluster. In this respect it should be realized that a change of the overall goal of the cluster (external goal) is not within the competence of the cluster leader (structural meta-controller).

	Internal	*External*
Routine		
Adaptive		
Goal		-

Table 10.6.1 Structural control variety defining the authority of the cluster manager. When compared with table 10.5.1, it can be seen that the cluster manager has two more control varieties available: external adaptive and internal goal.

10.7 Goal control Contractor (meta-meta-control)

10.7.1 Goal and diagram

Contractor's goal control is aimed at sufficient performance of solution with respect to the contractual normative performance of solution to be reached in the most efficient manner. Contractor's goal control is schematically given in figure 10.7.1 showing the meta-control configuration, the decomposed system and the project members.

The aspect-systems to be used for goal control refer to the performance of solution. It will be clear that the project manager should also control the efficiency part of the realization process. For cost control and time control however, the D&C Contractor can simply use the commonly known cost control models and planning models.

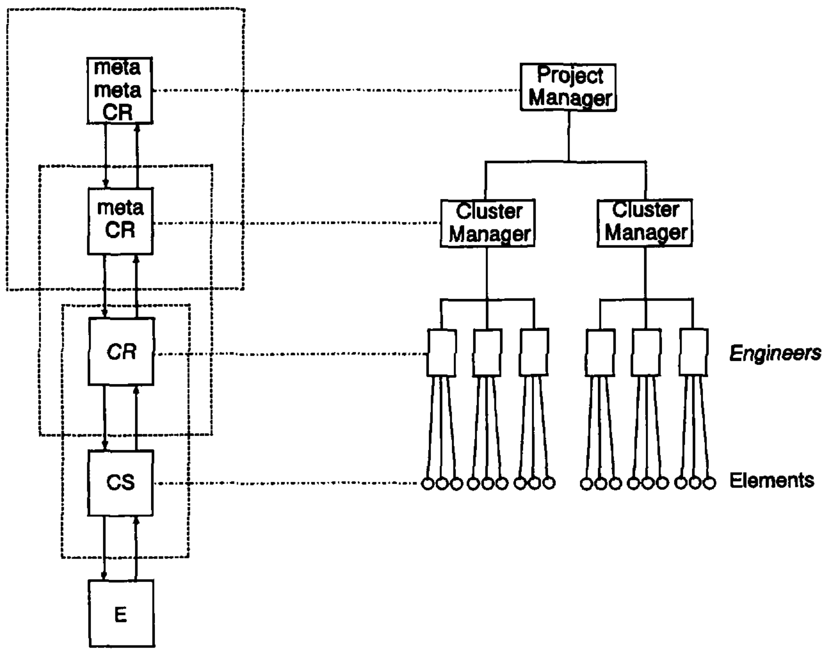


Fig. 10.7.1 Diagram of Contractor's goal control of effectiveness of performance of solution.

10.7.2 Model

General

The model to be used for the goal control of a D&C Contractor should be able to control both effectiveness as well as efficiency of the realization process.

- control of effectiveness: actual performance of solution ≥ normative performance of solution;
- control of efficiency: actual efforts ≤ normative efforts.

In order to give the Client his meta-control function with respect to potential goal control all performances of solution must be quantified:

- contractual normative performance of solution with associated normative efforts (at the start of D&C);
- actual normative performance of solution (dynamically);
- actual performance of solution (dynamically).

System analysis

As said before, the control on effectiveness is rather important. Once the performance of solution is controlled, the cost and time needed to reach that performance of solution can also be controlled. The model to be used to establish the performance of solution is based on system analysis (see figure 10.7.2).

The basis for the system analysis is given by the contract: (1) boundary conditions, describing the problem (context), (2) starting points, describing the solution (form) and (3) the set of requirements, describing the friction between problem and solution. When placed in a system theoretical framework, the boundary conditions can be interpreted as environment (E) and the starting points can be interpreted as the system (CS). The friction between (E) and (CS) determines the use and respective function of the system to be controlled by the controller (CR). It will be clear that the system (CS) when used and placed in function in its environment (E) should withstand loads. For instance, a sluice gate should withstand forces due to head differences.

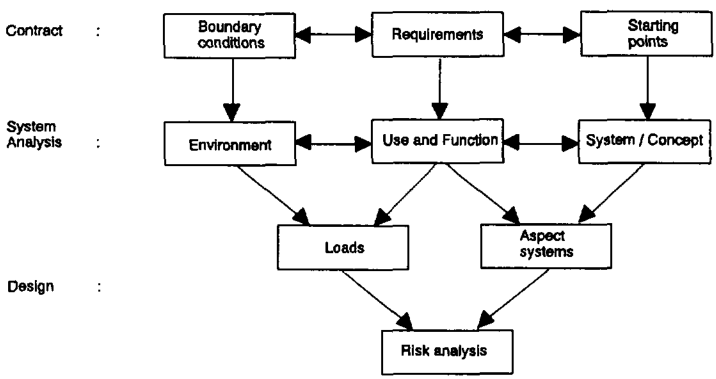


Fig. 10.7.2 System analysis contractual normative performance

As shown earlier in this study, the capacity to withstand loads, that is overall resistance, is represented by the set of aspect-systems. In this context, the loads should be read in the widest sense of the word. In case the set of aspects-systems on one hand and the loads on the other are brought in frictionless coexistence, an effective solution is achieved or, in other words, sufficient performance of solution is reached.

It is noted that for reaching the proper balance between the aspect-systems and the loads, the risk analysis is indicated as main tool. Such a risk analysis should be conceived in a very broad sense. Possible forms are: a detailed risk analysis, safety factors, sensitivity analysis for real uncertainties, etc. It must be realized, that the risk analysis must be applied to the whole system, meaning that for complex systems all relations must be taken into account. Therefore the risk analysis should be performed at high abstraction level with aspect-systems.

Performance of solution and phase-systems

Together with the loads the set of aspect-systems represents the overall performance of the solution. In particular for the realization of civil engineering systems however, the performance of solution refers to the utilization phase with possible sub-phases, as well as temporary phases. Hence, when talking about performance of solution it should be clear that adequate performance of solution should be provided for all relevant phases. Therefore it is necessary to know which aspect-systems determine the performance of solution of a certain phase-system. This relation is given by the relation diagram of aspect-systems and phase-systems (see figure 10.7.3).

The diagram in figure 10.7.3 is an important tool to determine the performance of solution per phase-system. Consequently, the overall performance of solution is given by a set of performances of solution per phase-system:

$$P = \{Pps_1, Pps_2, ...Pps_i....Pps_n\} \qquad (10.7.1)$$

in which P = overall performance of solution
Pps_i = performance of solution of i-th phase-system

In the next part of this model description for goal control, the performance of solution should be read as the performance of solution of a certain phase-system.

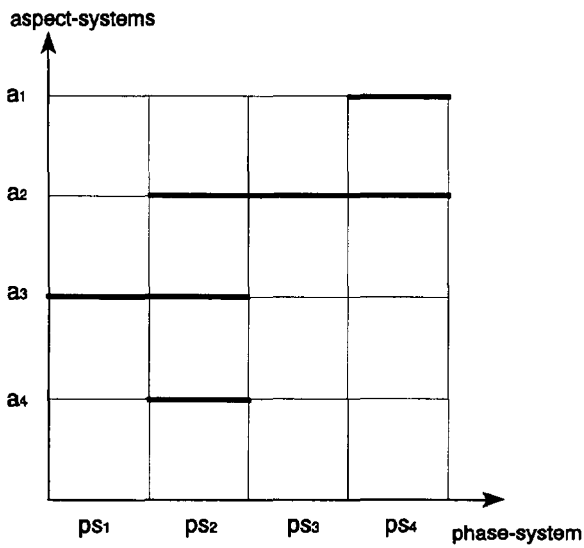


Fig. 10.7.3 Relation between aspect-systems and phase-systems

Performance of solution and the description (modelling) of the behaviour of the system

The model of each aspect-system or ensemble of aspect-systems should describe the behaviour of the system. Consequently, it is certainly not a static model of the concrete system to be realized. The model should include the system, the utilization of the system and the relevant environment. The type of model which is able to describe the behaviour of a system in this way is a quantitative mathematical model.

Principally, two different types of system behaviour can be distinguished:

- static system behaviour; the output depending on the input at any given time;
- dynamic system behaviour; the output depending not only on the input at any given time but also on the history of the input.

Apart from this distinction, the behaviour can be either deterministic or stochastic. Deterministic behaviour can be precisely predicted. A stochastic behaviour follows from stochastic input. In case the probability functions of the stochastic input does not change, the behaviour is called steady state stochastic.

All of the above types of behaviour can be described with analytical and statistical mathematical models. In case the probability functions of the stochastical input changes, the behaviour is called transient stochastic and cannot be described by means of the above models. In this particular case, a simulation model must be applied to describe the behaviour.

The quantification of performance of solution

As far as the quantification of the performance of solution is concerned, it is known that the state of each individual aspect-system has a specific, more or less independent and equivalent influence on the state of the total system. Despite the fact that the aspect-systems are as independent as possible, the aspect-systems can still be: (1) conflicting or (2) concurring, that is, having common physical implications.
With the theory in paragraph 5.6 it is explained that the overall performance of a system is determined by the state of the individual aspect-systems. It is also explained that there is no possibility to find a function in which the performance of a system is unambiguously expressed in values of the aspect-systems.

For the determination of the contractual normative performance of solution, it is enough to quantify the aspect-systems to be derived from the contractual concept. At the start of the contract period these aspect systems are brought in frictionless coexistence with the loads on the system. In that case the contractual normative performance of solution consists of a set of contractual normative aspect-system values.

$$P_0 = [a_{0\,1}, a_{0\,2}, a_{0\,i}, \ldots\ldots\ldots\ldots, a_{0\,q}] \qquad (10.7.2)$$

in which P_0 = contractual normative performance of solution
$a_{0\,i}$ = ith contractual normative aspect-system
q = number of aspect-systems

Experienced engineers with "integrator skills" (see annex 6) are able to quantify the aspect-systems based on system analysis. It is helpful, however, to give a checklist of loads and mechanisms which are often encountered with civil engineering systems (table 10.7.1).

Loads	Mechanisms	Aspect systems
Forces Moments Impacts Pressure Amperage Radiation Temperature	Breakage Deformation Fatigue Corrosion Fluidisation Solution Wear Emission	Strength Stiffness Stability Weight Geometry Capacity Maintenance

Table 10.7.1 Checklist of loads, mechanisms and aspect-systems

It is also helpful to give a few practical and measurable key figures which enable quantification of aspect-systems. In table 10.7.2, some examples are given.

Aspect system	Key figures
Strength	Allowable loads (see also table 10.7.1)
Stiffness	Allowable deformations, allowable deflections, allowable displacements
Stability	Allowable loads, no dynamic amplification
Weight	Allowable tonnes
Geometry	Clearances, tolerances, dimensions
Capacity	Floating capacities, lifting capacities, etc.
Durability	Lifetime, but also need for repair, protection, replacements, inspections

Table 10.7.2 Key figures of aspect systems.

Quantification of actual performance of solution

For the establishment of the actual performance of solution, the same quantification method as used for the establishment of the contractual normative performance of solution can be used.

Dynamic character of the model formed by the set of aspect-systems

Since the models of aspect-systems have a control function, the model should not only be composed of the clusters of elements, but should also provide boundaries of external goal control with respect to the control variety of elements. In that sense, the aspect-systems should not be presented by a fixed value associated for one state in one unique and fully specified environmental condition, but as a function of variable environmental conditions (variable loads). In other words, the set of aspect-systems should give the performance solution in a dynamic way(7). In some cases, however, such situations cannot be achieved (for instance sheet piling, with a large number of load cases in various phases). Then, the aspect-system-value must be chosen with engineering judgement, meaning that the value should have some reserve, in order to cope with unexpected future events associated with design work.

It must be avoided to incorporate too many aspects in one and the same model. Since the model is used for control purposes, it is not necessary to strive for perfect reflection of reality. On the contrary the dynamic aspect-system models must be available at the very start of a realization process and can even be very helpful in a rough conceptual form in the early design phases. The simpler the model the better(8).

An example of Contractor's goal coordination of the realization of a system with "transient stochastic behaviour" using two "dynamic mathematical simulation models" of five "aspect-systems" is given in the Case Study described in chapter 11 (Ekofisk Protective Barrier).

Quantification of efforts

Being able to quantify the performance of solution both in a dynamic sense as well as for the contractual starting position, it is possible to control the efficiency of D&C as well.

At any moment in the realization process the performance of solution is known and therefore the corresponding technical data is known; dimensions, tolerances, requirements, etc. With this technical data the total cost and time schedule can be controlled simply with the commonly known techniques.

As far as the contractual normative efforts is concerned, it is noted that with the proposed control system it is not necessary to incorporate uncertainties in the estimation of normative efforts. This is an important advantage since such an incorporation is logically impossible (efforts for uncertain tasks cannot be estimated)[9].

10.7.3 Information

The information is essential for the frictionless coexistence of loads on one hand and the set of aspect-systems on the other. As defined already for substantive control three specific information cases can be distinguished: (1) certainty, (2) uncertainty and (3) risk.

For civil engineering systems all three cases play a role. Loads have a stochastical nature (information case "risk"). Concepts with their dimensions and material belong to the information case "certainty". The information case "uncertainty" refers for instance to soil conditions. Due to the essential influence of loads it is recommended to focus the model and information case on a quantitative risk analysis which can cope with statistical and stochastical data.

The certainties can easily be used for the core of the risk analysis, whereas the uncertainties can be dealt by means of a sensitivity analysis to be incorporated into the risk analysis (see chapter 11 for a practical example: Ekofisk Protective Barrier).

As far as information is concerned it must be realized that the input of the aspect-systems is the output of the design clusters. However, due to the coordination function, the output of the aspect-system must, after interpretation and evaluation, be used for input of the design clusters. This cyclic information exchange is sketched in figure 10.7.4.

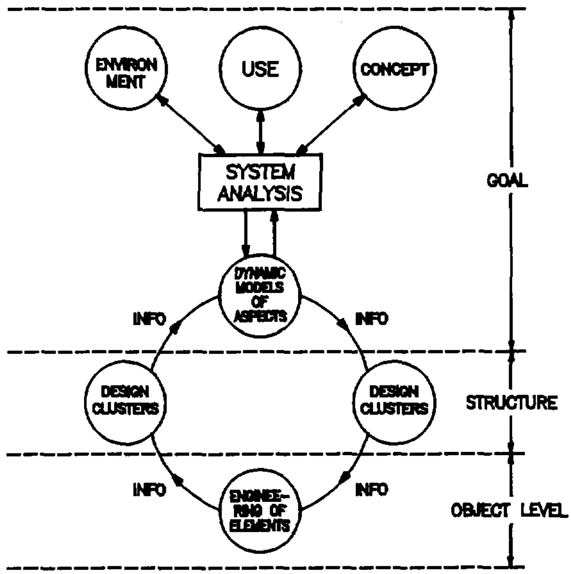


Fig. 10.7.4 *Information exchange and the role of aspect-systems. Evidently the aspect-system does not only provide information for goal control (down-top), but also provide information for coordination purposes (top-down).*

10.7.4 Control variety

Up to the structural control level, five of the six possible control varieties with respect to the development of elements can potentially be used (see table 10.6.1). The remaining control variety refers to external goal control. Since the control variety is defined with respect to the elements, the Contractor is the highest level fully authorized to change the goal of the elements. This is in fact a conceptual change of the system without changing the overall goal. Hence, with respect to the elements of the system, all control varieties can be used at the meta-meta-control level (see table 10.7.3).

	Internal	*External*
Routine		
Adaptive		
Goal		

Table 10.7.3 Goal control of the Contractor, using all internal and external control varieties, defined with respect to the realization of elements. Changing the goal of an element is in fact changing the concept of the total system, without changing the goal of the total system.

10.8 Client's control (meta-meta-meta-control)

10.8.1 Goal and diagram

The goal of the client is a satisfactory performance of the realization process, given by a sufficient actual performance of solution against minimum efforts. Client's meta-meta-meta-control is schematically given in figure 10.8.1 on the next page.

10.8.2 Model

General

In the proposed control system, the Client should be fully able to control the performance of the realization process. Client takes over control in two situations in which Contractor's control is no longer competent:

- a differential normative performance of solution with respect to the contractual normative performance which theoretically result in extra efforts to be put in the realization process.

- an adjustment of the initial goal ($P/P_0 < 1$) either as consequence of better insight in the system or for the compensation of extra efforts needed due to the differential performance of solution.

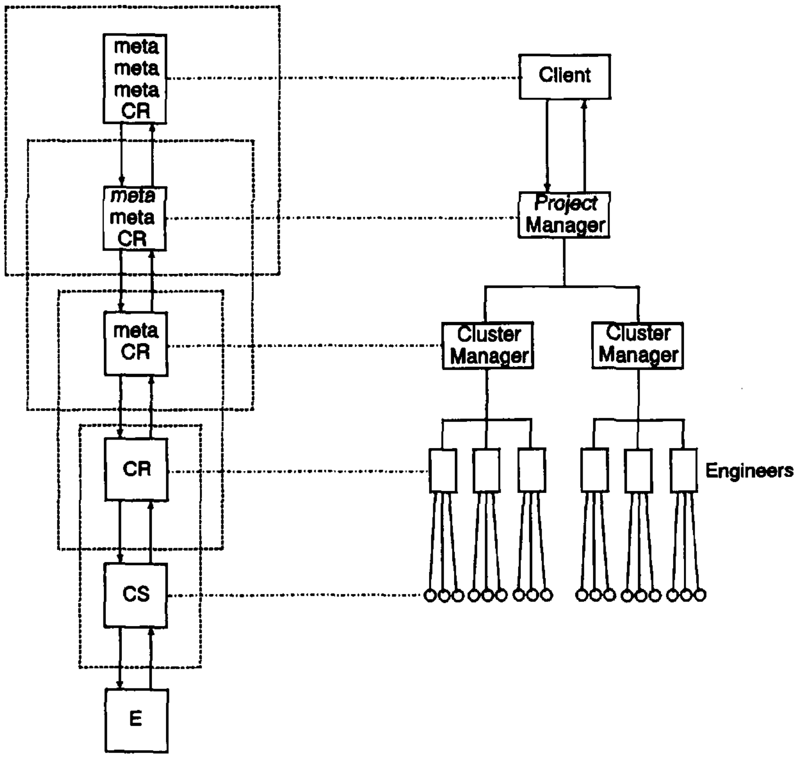


Fig. 10.8.1 Clients meta-meta-meta-control

For effective control the Client should have insight into: (1) the actual normative performance of solution in a differential way with respect to the contractual normative performance and (2) the consequences of a less than 100 % solution ($P < P_0$).

Quantification of differential normative performance of solution

As previously shown the performance of solution can only be given with the set of aspect-systems and not with a function of aspect-systems. Therefore the above problem cannot be solved directly. However, because the main interest is the differential normative performance of solution dP_0, the quantification can be aimed at the determination of dP_0 in a relative sense.

Hence, it is not necessary to quantify both performances of solution in an absolute sense first and then establish the difference.

Since the differential values of aspect-systems with respect to the contractual normative values of aspect-systems (see previous section) can easily be determined, a method must be found to express the differential normative performance of solution in differential values of aspect-systems. The only way is to look for a transformation of actual normative aspect-system values into an actual normative performance of solution. This can be done by linear vector transformations [(10)]. A short outline of linear vector transformations associated with the most relevant theoretical backgrounds is given in annex 7.

Considering the performance of solution spanned in a linear euclidian vector space by a number of vectors, each vector represents a value of an aspect-system. The basis of such a vector space is a set of vectors having two properties at once[(11)]:

- it is linearly independent;
- it spans the space.

Given the conditions for the clustering of variables, which in fact leads to the formation of aspect-systems, it is stated that the set of aspect-systems as defined above, fulfil the conditions to form a basis of a vector space[(12)]. Such a vector space is ske-tched in figure 10.8.2.

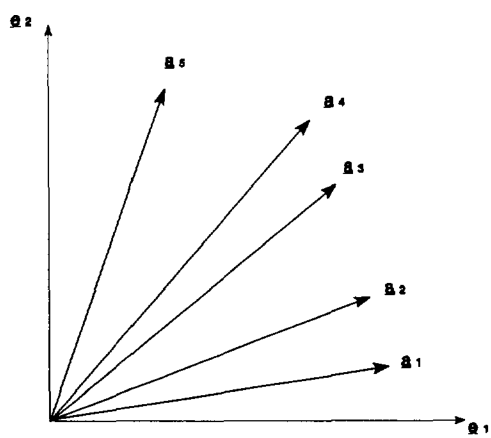


Fig. 10.8.2 The linear vector space spanned by a linear basis formed by a set of aspect-systems.

Given this linear basis, spanned by the set of aspect-systems, it is theoretically possible to establish the differential normative performance of solution (dP_0) with respect to the normative performance of solution (P_0). This is shown below.

From annex 7 it is concluded that in case a linear independent basis is given in both the linear vector space Rn as well as in the linear vector space Rm every m x n matrix A can be considered as the transformation matrix of a linear transformation A of R_n into Rm with respect to the given bases. The linear transformation x' = A x can be written as follows:

$$\begin{pmatrix} x'_1 \\ x'_2 \\ . \\ . \\ x'_m \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & . & a_{1n} \\ a_{21} & a_{22} & . & a_{2n} \\ . & . & . & . \\ . & . & . & . \\ a_{m1} & a_{m2} & . & a_{mn} \end{pmatrix} \times \begin{pmatrix} x_1 \\ x_2 \\ . \\ . \\ x_n \end{pmatrix}$$

The associated set of equations is given below:

$$x'_1 = a_{11} * x_1 + a_{12} * x_2 + \ldots\ldots a_{1n} * x_n$$

$$x'_2 = a_{21} * x_1 + a_{22} * x_2 + \ldots\ldots a_{2n} * x_n$$

$$. \quad . \quad . \quad .$$

$$. \quad . \quad . \quad .$$

$$x'_m = a_{m1} * x_1 + a_{m2} * x_2 + \ldots\ldots a_{mn} * x_n \tag{10.8.1}$$

For practical application, the following remarks can be made.

- The linear independent basis of the vector space Rn as well as the vector space Rm is spanned by the aspect-system-vectors. Since the number of aspect-systems is 7 at maximum (but for the various phase-systems probably less), it is stated that:

  $m = n$ with $m \leq 7$

- The transformation matrix corresponds with the above set of transformation equations. It can be seen that the transformation matrix represents the relations between the various aspect-systems. Hence, the transformation matrix can be made by considering the relation diagram of aspect-systems, which is often, but not necessarily, a symmetrical matrix. The relations are indicated with "0" in case the aspects are independent, with "+1" in case the aspects are concurrent and with "-1" in case the aspects are conflicting.

- Since the main purpose of the transformation is aimed at the mapping of the differential performance of solution, given the values of the various distinguished aspect-systems at the start of the contract period, it is possible to transform the linear independent basis into a linear independent basis of unity vectors. The length of the basis vectors in that case is:

  length $= \underline{a} \; / \; | \; \underline{a} \; | \; = 1$

- For the realization process of complex systems it is assumed that the differential measures of aspect-systems are always differential increases. This is due to the fact that the realization process of complex systems is systematically underestimated. Hence, the differential aspect-system matrix is filled only with values larger than 1. If an aspect-system measure is lower than was initially estimated, a "1" is given.

The differential normative performance of solution for each distinguished phase-system can be established as follows:

1) Establish the relation matrix of aspect-systems for each phase-system.

2) Establish the contractual normative performance of solution given by the "conceptual values" of aspect-systems.

3) Establish the length of the contractual normative performance of solution vector. Since the basis of aspect-systems is transformed into a normal linear independent basis with unity vectors, the length of the vector corresponding with the contractual normative performance of solution is established by multiplying the aspect-system relation matrix by the vector of contract values of aspect-systems (point 2 of this procedure), resulting in a product vector. The length of this vector represents the contractual normative performance of solution and is given by:

$$a = \sqrt{(a_1^2 + a_2^2 + \dots . a_i^2 \dots . a_n^2)} \qquad (10.8.2)$$

with: a_i = normative value of i^{th} aspect-system (i = 1 to n)

4) Establish the actual normative performance of solution by multiplying the aspect-system relation matrix by the vector representing the actual normative values of all considered aspect-systems. The length of the product vector represents the actual normative performance of solution.

5) Subtract the value of the contractual normative performance of solution vector from the value of the real normative performance of solution vector, giving the differential performance of solution with respect to the contractual normative performance of solution.

The above procedure is illustrated by considering a simple example. Suppose the following relation matrix of 4 aspect-systems is given:

	a1	a2	a3	a4
a1	1	0	-1	1
a2	0	1	1	1
a3	-1	1	1	0
a4	1	1	0	1

The contractual normative performance of solution is represented by a unit vector of aspect-systems (in this case a "4 x 1 matrix") filled with "ones". The contractual normative performance of solution is established by multiplying the relation matrix by the unit vector matrix:

$$\begin{pmatrix} 1 & 0 & -1 & 1 \\ 0 & 1 & 1 & 1 \\ -1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 1 \\ 3 \\ 1 \\ 3 \end{pmatrix}$$

The length of the product vector is (P_0):

$$P_{0\,ref} = \sqrt{(1^2 + 3^2 + 1^2 + 3^2)} = 4.47$$

The actual normative performance of solution at any given time, is represented by the actual values of normative aspect-systems. Suppose the aspect-systems 1, 2, 3 and 4 are increased with respectively 20 %, 10 %, 30 % and 10 % the actual normative aspect-system vector is:

$$A_A = \begin{pmatrix} 1.2 \\ 1.1 \\ 1.3 \\ 1.1 \end{pmatrix}$$

The actual normative performance of solution can now be determined by multiplying the actual normative aspect-system vector by the relation matrix of aspect-systems:

$$\begin{pmatrix} 1 & 0 & -1 & 1 \\ 0 & 1 & 1 & 1 \\ -1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1.2 \\ 1.1 \\ 1.3 \\ 1.1 \end{pmatrix} = \begin{pmatrix} 1.0 \\ 3.5 \\ 1.2 \\ 3.4 \end{pmatrix}$$

The length of this actual normative performance of solution vector is:

$$P_{0\ realiz} = \sqrt{(1^2 + 3.1^2 + 1.2^2 + 3.4^2)} = 5.12$$

The differential performance of solution (dP_0) is in percentages:
(5.12/4.47-1) 100 = 15 %.

When using the linear vector transformation for establishing the differential normative performance of solution based on the differential normative values of aspect-systems, the Client is able to control the overall realization process according to figure 10.4.2.

The model to be used by the Client for this part of the meta-meta-meta-control is in fact a two step model. Initially, the dynamic models of aspect-systems are used to form a linear basis for a vector transformation. Secondly a simple mathematical model is used to determine the differential normative performance of solution.

The above method to deal with differential normative performance of solution is the first step towards a satisfactory performance of the realization process. It prevents the Contractor from trying to hide, neglect or deny problems with effectiveness. Therefore it is probably the most important component of the proposed control system.

Adjustment of the goal concept

The other aspect mentioned at the beginning of the paragraph is the possibility of goal adjustment ($P/P_0 < 1$). For goal adjustment, the basics of the transformation method above must be used as well, as it is not possible for the Client to prescribe a 70 % normative performance of solution without an indication how this adjustment should be achieved. In fact, there are numerous ways to adjust the goal. The Client should select an aspect-system which, in his opinion, can be adjusted and should subsequently calculate the benefits of such an adjustment. However, the Client is not fully free to select any aspect he wants. Some aspects can not be freely reduced as it would not be in line with national or international standards. In a way, those standards can therefore be considered a meta-controller of the Client.

The adjustment of the goal concept can be shown with the example given earlier in the section. Imagine that the Client finds out that one aspect-system shows too large an increase with too large a corresponding increase of efforts in relation to the relative importance of the aspect-system. The aspect-systems which are usually selected for goal adjustment in case of a disappointing realization process, are maintenance and capacity. These aspects are not meta-controlled by standards! Capital costs can be reduced by accepting more maintenance. A reduction of capacity is a straight forward reduction of the eventual performance of solution.

It is assumed that in the example previously given in this section, aspect-system no. 3 shows an increase of 30 % with respect to the contractual value. The Client wants to go back to the contractual value of that particular aspect-system. Hence, this aspect-system returns to a 100 % value and is denoted as "1" in the actual aspect-system vector:

$$A_A = \begin{pmatrix} 1.2 \\ 1.1 \\ 1.0 \\ 1.1 \end{pmatrix}$$

The "new" actual normative performance of solution can now be determined by multiplying the actual aspect-system vector by the relation matrix of aspect-systems:

$$\begin{pmatrix} 1 & 0 & -1 & 1 \\ 0 & 1 & 1 & 1 \\ -1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1.2 \\ 1.1 \\ 1.0 \\ 1.1 \end{pmatrix} = \begin{pmatrix} 1.3 \\ 3.2 \\ 0.9 \\ 3.4 \end{pmatrix}$$

The length of the "new" actual normative performance of solution vector is:

$$Pr = \sqrt{(1.3^2) + (3.2^2) + (0.9^2) + (3.4^2)} = 4.93$$

The normative performance of solution vector was 4.47. Hence, with the adjustment of one aspect, the differential normative performance is:

$$(\frac{4.93}{4.47} - 1) * 100 = 10\%$$

instead of the calculated 15 % without goal adjustment.

Practical application of the model

Since the performance of solution is proportional to the efforts needed, both the quantification of differential normative performance of solution as well as the adjustment of the goal concept are considered strong and simple control varieties, showing clearly the effect of the control action. The main question is, however, how this rather theoretical model of the concrete system should be converted into a more or less practical control model of the concrete system. For this conversion three practical problems must be solved.

The first problem is the way in which the differential performance of solution must be compensated. As assumed, the differential performance of solution is fully proportional to differential efforts. The efforts, however, are expressed in two dimensions, e.g. time and cost, giving three principles for the compensation of efforts: (1) costs only, (2) costs and time and (3) time only.

According to Quist[13], the major project success factor for complex development projects is strict time control rather than pure cost control. Hence, when having performance problems, it is recommended to use accelerators instead of adjusting time schedules. It is a matter of efficiency yet, also a matter of discipline, involvement and motivation. This is the main reason that the compensation principles "costs and time" and "time only" are rejected. Hence, compensation should always be expressed in costs, the question is how to express "efforts" in "costs".

Generally, a differential normative performance shows up in the design phase. Since design work is, in fact, a continuous search for harmony between the poorly defined problem and the yet unknown solution, a change in the friction between these two intangibles can be considered daily design work. The most important condition is that the design work must have enough time. In this respect, the minimum design period for complex civil engineering systems is 1,5 year under the condition that the proposed control system is used.

The second problem is that, for instance, one aspect-system is initially not recognized or not adequately expressed in clear and relevant key figures. At first sight, it might be concluded that in that particular case the contractual normative performance of solution becomes worthless as a basis for the risk sharing principle. However, it is quite possible to express the contractual aspect-system value after the discovery of such an aspect-system (see chapter 11, regarding the claim for additional work due to unforeseen problems with the floating stability of the gates of the Storm Surge Barrier in the New Waterway Rotterdam). In order to avoid misunderstandings, it is important to incorporate a contractual clause with respect to the problem of an unrecognized aspect-system.

The third problem is a fundamental change of the concept. In such a case the above compensation can not be applied. Instead a new agreement must be made.
It is difficult to define a fundamental change. For the Eastern Scheldt the change of the foundation of the piers was experienced as a fundamental change of the whole system. The same feelings appeared when the pile foundation of the concrete blocks of the Storm Surge Barrier in the Nieuwe Waterweg was replaced by a foundation without any piles.

The definition of a fundamental change of the concept must be agreed between the two parties and be fixed in the contract. Suggestions for the definition are:

- a fundamental change occurs in case more than 20 % of the total costs must be compensated;

- a fundamental change occurs in case the concepts of at least two sub-systems (=first decomposition level of the system) must be changed fundamentally. Such a change is defined as a changed working principle, with respect to the function of that particular sub-system.

10.8.3 Information

It will be clear that for effective meta-control of the Client, the information is rather essential. In contrast to Contractor's control situation, the information on differential performance of solution cannot be given with risks and/or uncertainties. The linear vector transformation is not able to handle non-linear functions.

Each value of an aspect system, however, can be given in the three classical information cases certainty, uncertainty and risks. It is therefore quite well possible to give Client insight into those information cases and select minimum, maximum or average values for the transformation.

For providing extra efforts to compensate the Contractor for developing extra performance of solution, these information cases however are not relevant. It is quite simple to establish the normative performance of solution at the end of the project and calculate the corresponding normative efforts for a detailed settlement of efforts.

This is an important advantage of the control model. For decision making in order to select the best possible direction for the realization process, a rough insight into the differential performance of solution and differential efforts is sufficient.

10.8.4 Control variety

As previously mentioned, the Client is not fully free to adjust the normative performance. For instance, standards (national and international) give guidelines which cannot be neglected. The control variety therefore, is limited to the aspect-systems capacity and maintenance.

10.9 The control model and the corresponding organization and information

After having discussed the decomposition and control of the realization process of large complex civil engineering projects, the next question is how to organize this.

As shown in chapter 4, organization is strongly related to decomposition, control and information. These three issues have been discussed extensively in the previous paragraphs. The only thing to do is to link the outcome with respect to decomposition, control and information towards an organizational structure.

The organizational structure is connected with the indicated control and meta-control possibilities with corresponding control varieties. The basic principle is that each organizational level should correspond with a meta-level control variety. In that way the organizational structure is as flat as possible. A flat organizational structure: (1) enlarges the problem solving power and (2) is able to anticipate rapidly changing environments [14]. The proposed organizational structure is sketched in figure 10.9.1, together with the multi-level control system and the information exchange. The following remarks can be made:

- the most important aspect of the proposed D&C organization is that the Contractor's construction cluster managers are recruited from the design cluster managers. In that way the knowledge about the controlled system remains operational.

- during the design phases, the line organization consists of three levels only: (1) project manager, (2) cluster managers and (3) element engineers (designers, draughtsmen, etc).

- during the construction phase the line organization counts four main levels: (1) project manager, (2) cluster managers (3) chief executioners and (4) labourers.

  The staff organization is rather heavy. During the design phases, the project manager (coordinator) is assisted by a staff which consists of:

  - aspect-system model makers;
  - planners and time controllers;
  - cost controllers.

- as far as the information is concerned, the lowest level information is the common project information: specifications and drawings. At cluster levels more information is generated about the system and the relations between the sub-systems and elements respectively. The elements and the relations between the elements within the cluster represent (and give information of) the short term behaviour of the sub-system covered by the cluster. The goal coordination integrates the sub-systems, resulting in information of the long term behaviour of the total system.

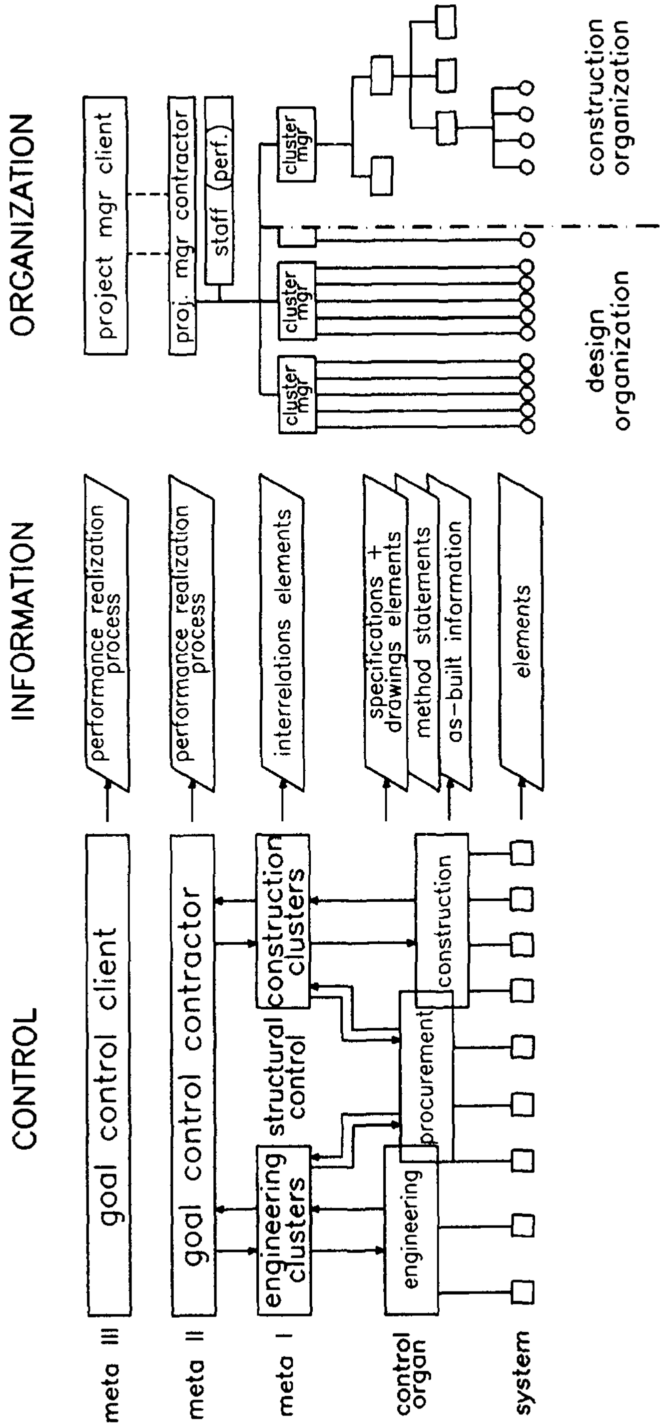


Fig. 10.9.1 The proposed organizational structure for D&C

- having discussed the organizational structure for satisfactory performance of the realization process of large complex civil engineering systems, the next question is what kind of people should run D&C tasks. Although beyond the scope of this study a rough outline of organizational members and their specific skills and tasks is given in chapter 6.

10.10 Type of contract

Given the clearly defined risk sharing principle, with the associated system to allocate the risk components, it is clear that the type of contract can neither be a Fixed-Price contract nor a Cost-Reimbursement contract. Hence, none of the types of contracts as mentioned in the previous paragraph, are suitable for the proposed D&C control system.

Intermezzo 10.3

An interesting (just for purpose) type of contract was drawn up between the two participants involved in the realization process of the Storm Surge Barrier in the Eastern Scheldt. The contract between Client and Contractor was unique, dealing with integration of design and construction within the two parties. This is totally different from a delegated D&C task. With this particular type of contract no more risk was allocated to the Contractor than he could initially carry. The essence of the contract was that rules were agreed on for the determination of the contract sum of the parts of the whole system once these parts had been properly detailed. The most relevant issues are given in annex 9.

The proposed contract type is a Fixed-Price-Performance-Reimbursement contract (FIPPER-D&C contract).

The fixed price refers to the contractual normative performance of solution to be agreed on. The contractual normative performance of solution is based on the available knowledge of the system and environment at the start of the project (starting points, boundary conditions and concept). This is a very important aspect of the proposed type of contract. The Contractors should estimate the normative efforts based on the concept without allowances for uncertainties. Obviously their prices should include the D&C risk with respect to the design process and construction process, but certainly not reservations for all sort of real uncertainties. Such a clear cut estimation of normative efforts simplifies the evaluation of proposals by the Client.

The reimbursement of the performance of solution refers to the risk sharing principle with respect to any change of the performance of solution referring to the contractual normative performance of solution. The Client carries the consequences of these type of changes. The most relevant contractual issues and clauses are given by means of an example in annex 10.

10.11 Summary

The proposed control system of D&C of complex civil engineering is mainly aimed at the control of effectiveness and efficiency of the D&C process.

A multi-level meta-control model is proposed with corresponding decomposition methods, in order to execute the risk sharing principle as developed in chapter 3 for a satisfactory performance of the D&C process.

The lowest control level of this multi-level control model is substantive control of elements.
The first meta-control level is aimed at the control of relations between the elements (structure of system). The corresponding decomposition methods result in design clusters and construction clusters.
The second meta-control level refers to the goal control of the D&C Contractor. At this level the effectiveness (and subsequently efficiency) is controlled with a set of aspect-systems, originating from the clustering of requirements.
The third meta-control level is used by the Client, who becomes meta- controller of the D&C Contractor in case: (1) the actual normative performance of solution exceeds the contractual normative performance of solution and (2) the Client wants to adjust his goal concept (change of actual performance of solution).

A simple method is developed to quantify the changes of efforts corresponding with the changes of the performance of solution. Consequently, the Client is able to control the product of effectiveness and efficiency of the overall realization process, whereas the Contractor is able to control the product of effectiveness and efficiency of his D&C work.

The above control possibilities form the organizational basis of the specific D&C risk sharing principle. For the contractual part a FIPPER D&C contract is proposed standing for Fixed-Price-Performance-Reimbursement Design & Construct Contract. A Fixed-Price will be agreed for the Design & Construct of the conceptual solution as known at the start of the contractual period. During the work, each change of the performance of solution is reimbursable.

Notes

1. One of the recognized disadvantages for Owners (Clients) dealing with D&C projects is the reduction of control possibilities. In the proposed control system, the Owner should have full control of the overall realization process. Therefore, he is meta-controller of the problem solver (Contractor). This is, for instance, not the case with "turn key" projects. It will be clear that the "turn key" contractual form is certainly not recommended for the realization of large complex civil engineering systems.
2. Dubes, R. and Jain, A.K., Clustering methodologies in exploratory data analysis, Department of Computer Science, Michigan State University, Michigan, 1981.
3. Ibid.
4. Such aspect-systems can be derived for any specific type of realization process, which is shown by three examples:
   - Without a systematic decomposition (even without a system theoretical basis), the Dutch Department of Buildings (Rijksgebouwendienst, 1993) recognized three specific aspects, covering 80% of the performance of solution of public buildings: (1) climate inside the building, (2) energy consumption and (3) functionality of space;
   - Fokker Space & Systems developed Systems Engineering which is based on four aspect-systems: (1) reliability, (2) availability, (3) maintainability and (4) safety. Van Beek, F.A. and C.C. Kranenburg, "Risico's bij ontwerp en bouw beperken" in Land & Water, september 1993;
   - For the Storm Surge Barrier in the Eastern Scheldt, TNO distinguishes the following aspect-systems: (1) strength and (2) stability. TNO, Inleidende probabilistische berekeningen, Rapport nr.: B-78-30/62.3.2001. Rijswijk, 1978.
5. When reading the realization process as a real problem solving process, the utilization phases and even the elimination phase after utilization must be covered. However, these phases are not incorporated into the formation of phase-systems, being beyond the scope of study.
6. Note that the risk sharing principle makes it necessary to introduce the meta-control function of the Client. The Client as meta-controller is also mentioned by Peeters, W.A., The Appropriate use of Contract Types in Development Contracts, A system approach with emphasis on the European space sector, Noordwijk, 1987.

   However, Peeters did not define an active meta-control function for the Client (beyond the scope of his study). In this study, however, the meta-control function of the Client is probably the most essential part.
7. An example of a dynamically presented aspect-system is the strength of a structure expressed in the overturning moment as a function of incoming waves expressed in a combination of wave height, wave period and wave direction (see chapter 11) : $M = f(H_s, T, \alpha)$

   in which:

   H_s = significant wave height

   T = wave period

   α = wave direction
8. "Simple is best, best is beautiful" are titles of two subsequent chapters of an essay on design by: Loire, R., The Design way, Ghosh, Houston, TRAMCO, Paris, 1989.
9. This approach is totally different from the present approach observed by D&C Contractors. The present risk analysis prior to a D&C work is based on a traditional "effort" risk estimation with respect to the contract concept. Uncertainties, as, for instance, soil condition, are introduced as undesired events with an estimated and subjective conditional probability function. The influence of these events are calculated and incorporated as an additional sum in a fixed price. Pretending adequate quantification of real uncertainties.

The insertion of real uncertainties in risk analysis with subjective conditional probability functions is principally wrong. Uncertainties with conditional probability function and uncertainties without such functions are, by definition, totally different. The only agreement is that all imaginable events can be expected with a probability of occurance which lays between 0 an 1. It is better to perform for instance a min/max sensitivity analysis instead of putting all together and be uncertain about the uncertain input and uncertain output. Besides that, it will be clear that such an approach cannot cope with all relations of a complex system and all correlations between efforts. It certainly does not work in a competitive tendering.

10. Bijl, J. and Salet, W.J.H., Analytische meetkunde II, Delftse Uitgevers Maatschappij NV Delft, 1970.
11. Strang, G., Linear Algebra and Its Applications, Academic press, inc, New York, 1976.
12. The vectors $v_1, \ldots, v_n$ are linearly independent if all non-trivial combinations of the vectors are non-zero:
    $c_1 v_1 + \ldots + c_k v_k = 0$ unless $c_1 = c_2 = \ldots = c_k = 0$
    see: Strang, G., Linear Algebra and Its Applications, Academic press, inc, New York, 1976.
13. This statement is make by Quist, Fokker Aircraft Holland at the Conference on Complexity, held in Utrecht 1992.
14. Keuning, D., Verplatting van Organisaties, van Gorcum, Assen, 1993.

11. CASE STUDY : THE DYNAMIC CONTROL MODEL OF THE INSTALLATION OF THE EKOFISK PROTECTIVE BARRIER

11.1 General

This case study is meant to demonstrate the goal control model of a realization process by a number of relevant aspect systems. It concerns the installation and subsequent offshore completion of the Ekofisk Protective Barrier.

The chapters starts with the backgrounds and specific characteristics of the project. Then the contract and the project organization are highlighted, followed by a description of the main issues of the installation and offshore completion of the Protective Barrier. After that, the two dynamic control models are described as used for the coordination of all offshore works.

11.2 Background

The Ekofisk field is located at 400 km east of Edinburgh (see figure 11.2.1). It is a very important junction in the oil producing and transporting North Sea network.

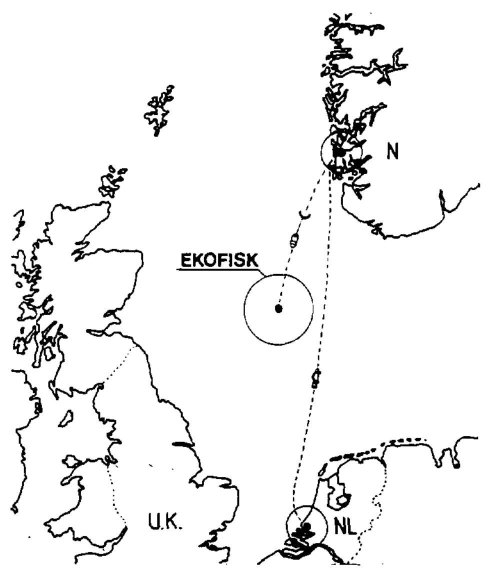
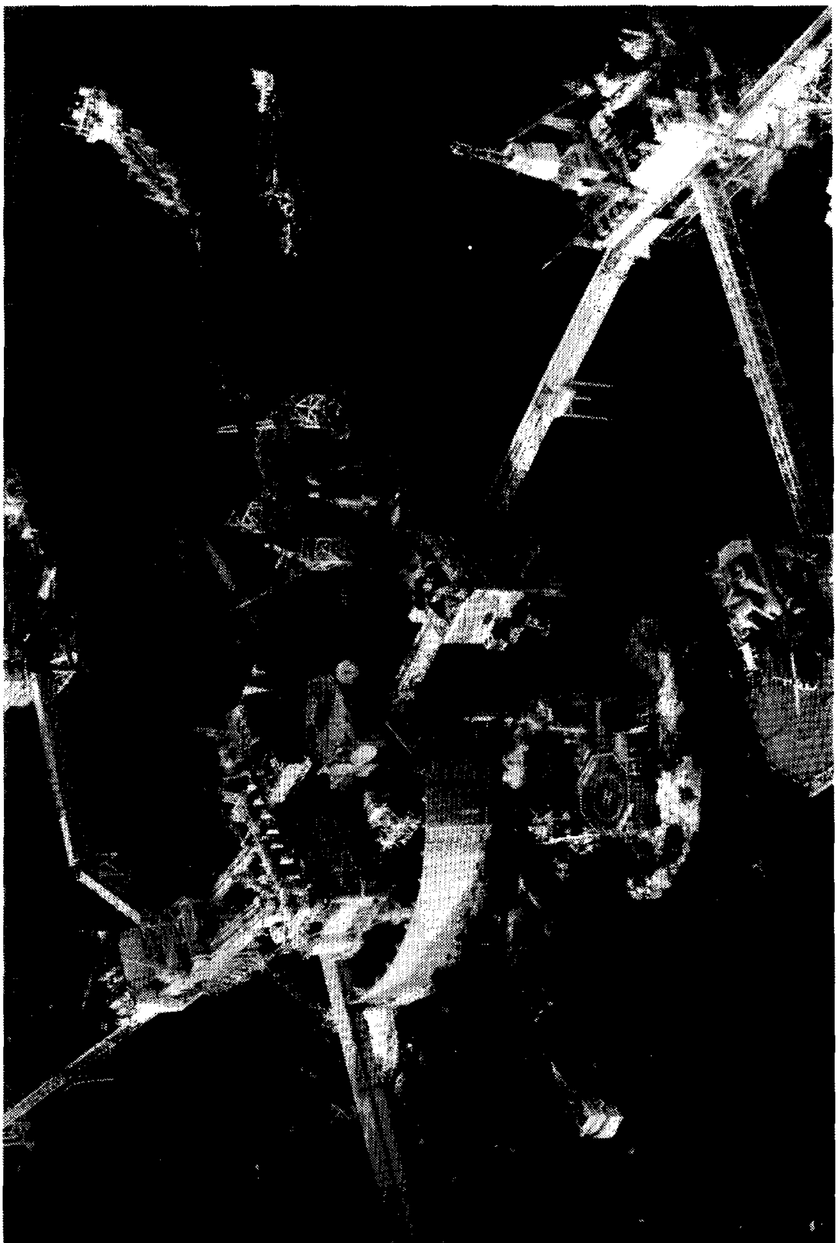


Fig. 11.2.1 The location of the Ekofisk Field in the North Sea



The Ekofisk Protective Barrier installed and being completed around the Ekofisk Central 2/4 Storage Tank

In 1987 it was necessary to elevate the decks supported by steel jackets at the Ekofisk Field due to significant seabed subsidence which resulted in an increased wave load. However, a different solution was required for the central concrete bottom founded tank, supporting the main field processing facilities. The solution adopted was a bottom founded concrete protective barrier surrounding the existing tank structure. This was to be installed in two separate half units, which were to be brought to the Ekofisk Field in floating condition. After installation, the two halves were to be structurally connected.

The Ekofisk Protective Barrier is rather unique. It is the first offshore concrete construction which was not installed as a monolith. Secondly, the shape of the construction is different from all structures realized in this construction discipline in the past. Thirdly, the wave load on the structure during both the constructional phase as well as the utilization phase is beyond the load on any other existing offshore structure. The safety of the tank required a very fast realization process of the Protective Barrier. Considering its size, the total available development time of 18 months, with just a rough concept as starting point, is probably the most significant characteristic of the project.

11.3 The contract

In February 1989, the D&C (Engineering, Procurement, Construction and Installation) contract for the realization of the Ekofisk Protective Barrier was awarded to the Joint Venture Peconor AF, consisting of two Dutch Contractors (Hollandsche Beton Groep (HBG) and Koninklijke Volker Stevin) and three Norwegian Contractors (H. Eeg-Henriksen AS, AS. Veidekke, Lau Eide AS).

The contract was divided into two parts: (1) A Fixed-Price with escalation contract for the construction of the Half Units including all coupling constructions (Dfl. 450 million) and (2) a reimbursable part for all offshore works (Dfl. 250 million at the end of the project).
For the construction work an Award Fee/penalty clause was incorporated in the contract, in order to ensure the planned tow out date (1-6-1989). This critical tow out date originated from the 3 month minimum period which was tentatively reserved for tow out, offshore installation and offshore completion given the rapidly worsening environmental conditions at the North Sea after August.

A very important part of the contract was the time schedule (see figure 11.3.1). The basic idea behind the time schedule was a straight forward engineering of the concept for a period of eight months, followed by a construction and installation phase.

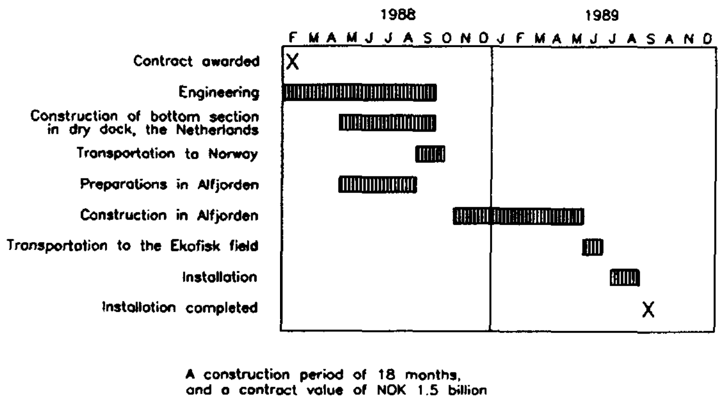


Fig. 11.3.1 The 18 months D&C time schedule

11.4 Project organization

The project team was organized according to the typically traditional contractor's organization. The main decomposition (clustering) method is (dis)similarity. In this case the dissimilarities refer to processes (the first bar below the project manager) and location (Verolme, Alfjorden and Ekofisk).

The structure of the design organization was mainly based on engineering disciplines, which were hierarchically placed in the organization. The disciplines were: (1) structural engineering, (2) marine engineering, (3) mechanical engineering. (4) electrical engineering and (5) geotechnical engineering.

The organizational structure of the project team is given in figure 11.4.1, while the design organization is given in figure 11.4.2.

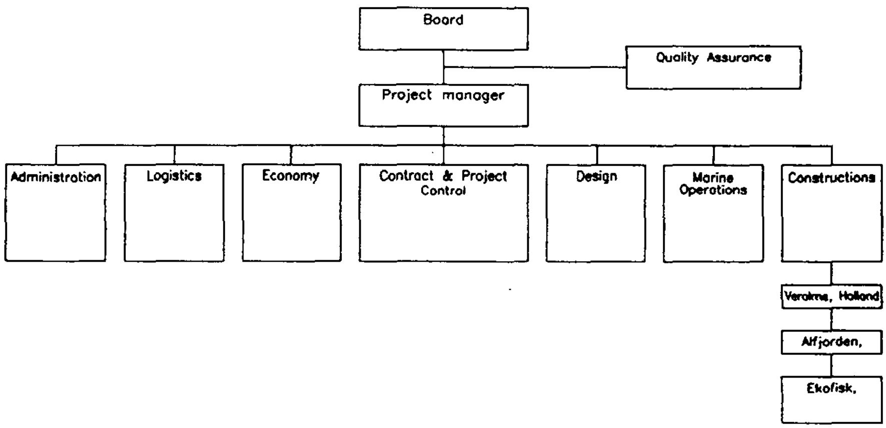


Fig. 11.4.1 *Organizational structure of Peconor Ekofisk AF clearly showing the typical organization clusters of contractors, characterized by a strict separation of different processes and locations.*

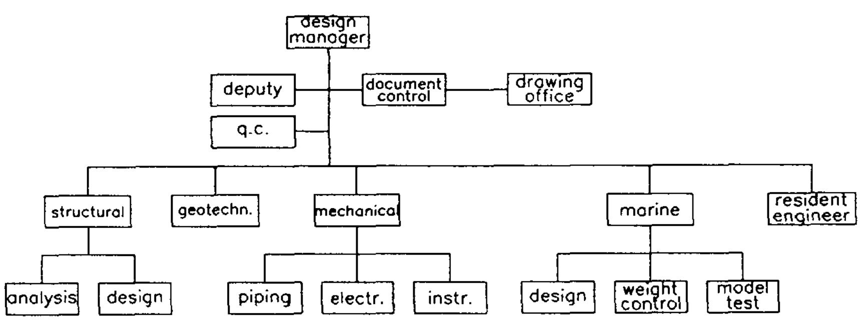


Fig. 11.4.2 *The design organization, decomposed according to (dis)similarity principles with reference to different design activities. Obviously the design organization is not decomposed with respect to coordination possibilities for the developing of complex systems.*

11.5 The overall concept and its environmental conditions at start of project

11.5.1 The problem

The problem was a reduced safety against wave action due to the subsidence of the seabed. Jacking up the installations at the top of the 2/4 Storage Tank was not feasible. The 2/4 Storage with surrounding platforms, connection bridges and the number of pipelines in the seabed formed a rather strict set of geometrical limitations (see figure 11.5.1).

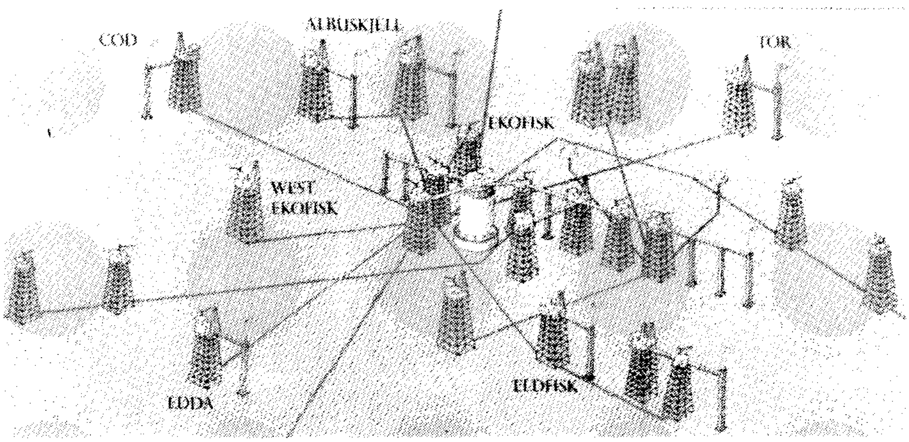


Fig. 11.5.1 The 2/4 Storage Tank with lay out of adjacent platforms and network of pipelines

The environment was further described with:

- 100 years wave condition for the in-service period, expressed in significant wave height and a wave period;
- 10 years summer wave condition for the temporary phase offshore with both half units uncoupled, expressed in a significant wave height and a wave period;
- type of soil, information relating to conditions at the locality, added to the angle of internal friction and cohesion;

11.5.2 The conceptual solution

The conceptual choice was a bottom founded large concrete structure. The concept was fixed by dimensions, construction material (concrete) and lay-out. A horizontal cross section of the Protective Barrier and a side view is given in figure 11.5.2.

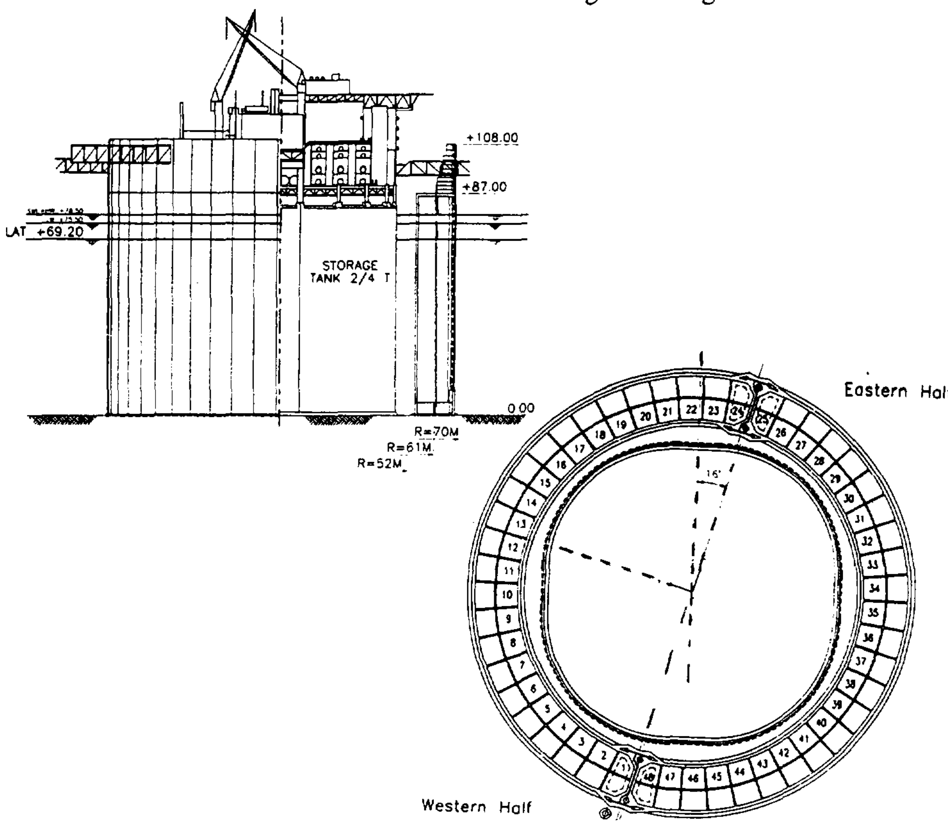


Fig. 11.5.2 Side view and horizontal cross-section of the Ekofisk Protective Barrier Dimensions: length outer wall 432 m, width 15.5 m, external diameter 140 m, height above seabed 106 m.

For the Barrier concept the following items were roughly investigated:

- global structural analysis;
- wave load on uncoupled half units;
- wave induced motions on floating half units.

Environment and conceptual design resulted in:

- dimensions, construction material and lay-out;
- principle of joint connection;
- guaranteed stability of uncoupled half units in summer storms during 10 years.

11.5.3 Requirements

1. Requirements concerning functionality

- dimensions (minima and maxima)
- seawater connection openings

2. Requirements concerning reliability

- Strength and stability of the Protective Barrier must be sufficient to withstand the storm condition with a return period of 100 years.

3. Requirements concerning durability

- Required lifetime is 30 years

4. Temporary construction phases

- Strength and stability of the Protective Barrier must in all temporary phases be enough to withstand the seasonal storm condition with a return period of 10 years.

11.6 General description and evolution of the joint connection

11.6.1 The joint connection concept

After installation, the two half units had to be coupled and had to provide enough strength and stability to withstand the design wave condition during joint connection works. The concept was based on a connection to be provided by key piles to be inserted in circular recesses in interlocking keys and in-situ concrete to be cast in the remaining holes. This concept is sketched in figure 11.6.1.

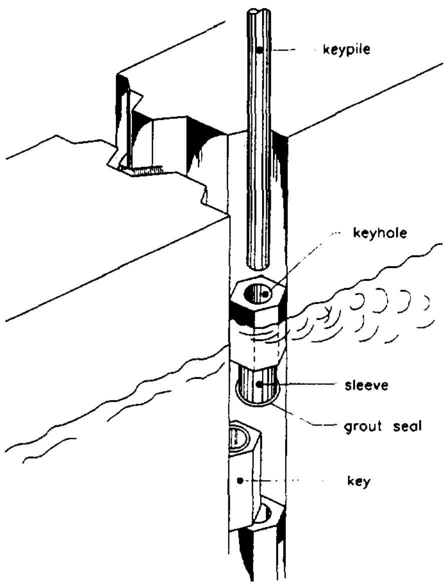


Fig. 11.6.1 *Contractual "key and key pile" concept for the connection between the half units*

A few months after the start of the project, it was concluded, that the magnitude of the forces to be transferred to the lower part of the joint, were substantially larger than assumed. Consequently, a connection of the bottom slab was also necessary. This, together with several related reasons concerning tolerances, strength, fatigue, construction problems, etc. enforced a change in the connection method from the "key and key pile" concept into a "steel plate and prepared box" concept. The enforced change took place approximately seven months after the start of detailed engineering. At that time the lowest keys were already constructed. The changed joint concept is sketched in figure 11.6.2.

11.6.2 Installation

After the inshore completion, the two caissons of the Barrier were towed to the Ekofisk field in floating position. The subsequent installation was as follows (figure 11.6.3):

- approach of the western half unit and positioning of the rotating point above the already installed docking pile (figure 11.6.3.a);

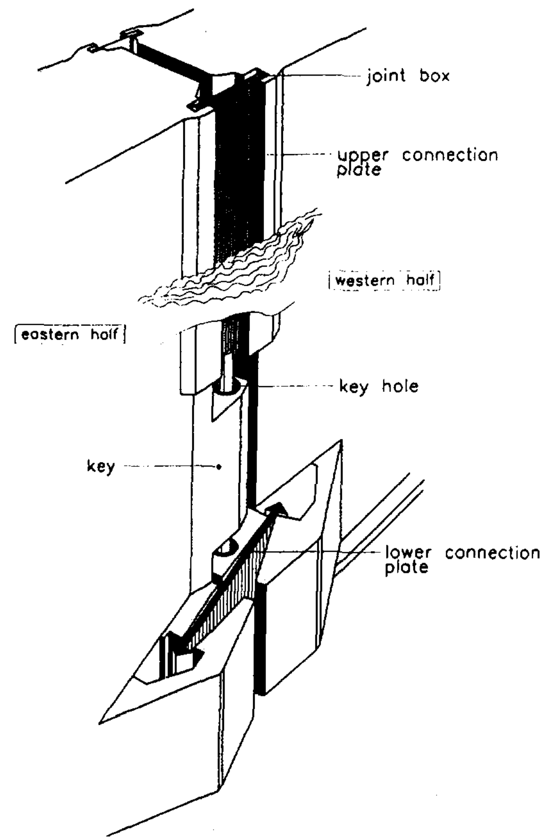


Fig. 11.6.2 *New connection "steel plate and prepared box" concept for the connection between the half units*

- rotation of the western half unit around the docking pile until the desired position was reached. Rotation impact taken by a bumper fender, attached to the inner side of the western half unit;

- lowering by water ballasting;

- underbase grouting after sufficient penetration, in order to provide enough stability;

- approach of the eastern half unit and positioning the topside at a distance of 1 meter from the western half unit with top fenders (figure 11.6.3.b);

- tilting of the eastern half unit with differential water ballasting until contact is made with the lower fenders (figure 11.6.3.c);

- lowering by water ballasting and, after penetration, underbase grouting.

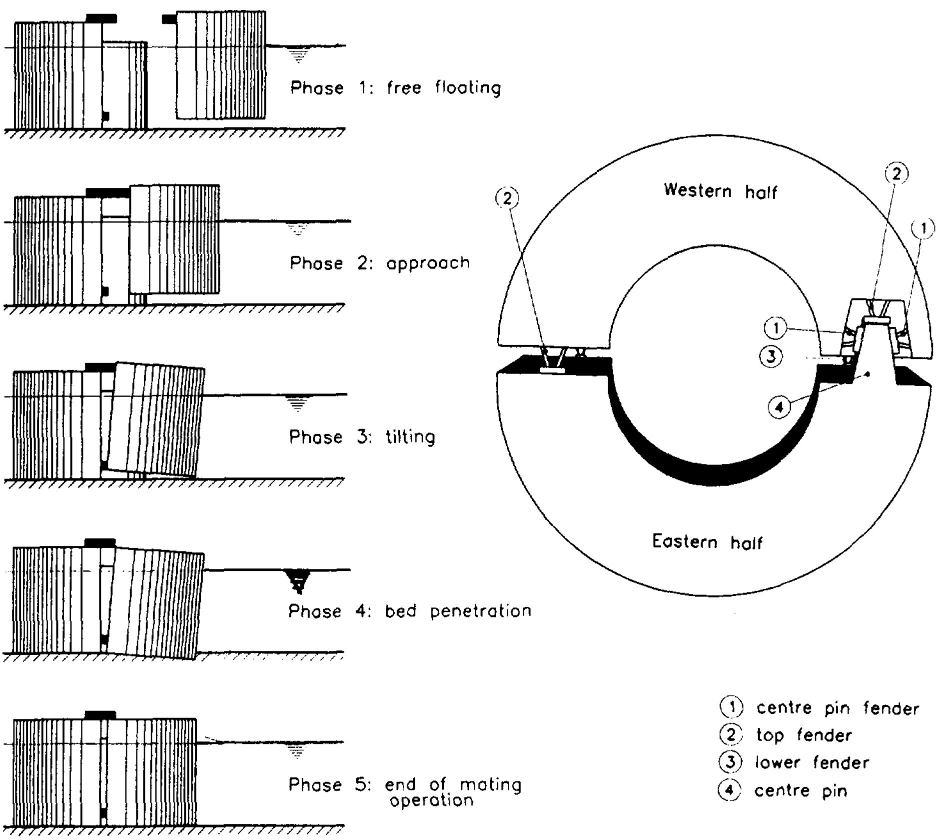


Fig. 11.6.3 The installation procedure of the Ekofisk Protective Barrier around the Ekofisk central Storage Tank and the various fendering systems needed for safe operations.

11.7 The problems with installation and offshore completion

A few months after the start of the engineering, wave load model tests revealed that the wave loads with the defined 10 years summer storm condition on the uncoupled half units were twice as much as assumed in the orientation phase prior to the D&C contract. Due to the larger wave loads and given the defined soil condition, the stability of the uncoupled half units was not ensured during the temporary offshore phase at Ekofisk.

Stability could be improved by increasing the amount of ballast. However, a larger amount of ballast would cause larger differential penetration and settlements due to non-uniform soil conditions. This would lead to horizontal fitting problems (figure 11.7.1).

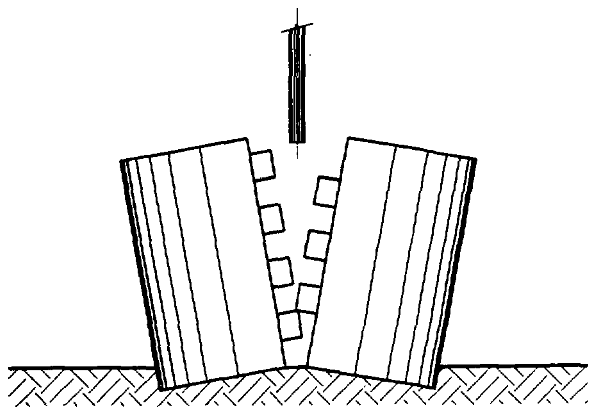


Fig. 11.7.1 Improving stability of the uncoupled half units by increasing the amount of ballast. The associated extra differential penetration causes fitting problems of the coupling construction

Due to the fitting problems it was advisable to limit the amount of ballast prior to joint connection works. Unfortunately, the initial phasing of a reduced ballast quantity would lead to larger built-in stresses due to deformations after the connection works when the balance of the ballast was added (figure 11.7.2).

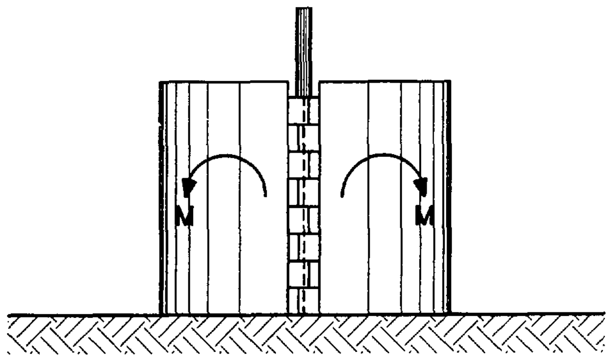


Fig. 11.7.2 *Improving stability by a fast coupling procedure with limited ballast quantities in the half units. Large built-in stresses for the joint connection are incurred by the extra ballast to be poured in after the coupling of the half units*

Confronted with this stability problem, the client decided to change the summer storm condition. Instead of a 10-year return period, a 3-year return period was decided upon for the governing wave condition. However, even this wave condition proved to be too heavy to ensure stability. Besides that, the tolerance problem remained.
Moreover, model tests on floating behaviour resulted in larger wave induced motions than assumed during the floating position prior to installation of the second half unit, enlarging the risk of clashes during the critical joining operation.
In order to avoid clashes, two further measures were investigated. Firstly, the gap between the two installed halves had to be enlarged. As a result, the amount of concrete to be cast into the gap became larger and, consequently, the necessary offshore concreting time increased(1). Secondly, the vertical space between the keys had to be changed to allow for vertical motions.
The larger gap and the required hardening time together required a minimum concreting period of one week. During this week, motions were not allowed in order to guarantee adequate strength development of the concrete. This requirement made it necessary to find a week in which the wave action had to be negligible.

11.8 The design approach

11.8.1 Analysis

The principal design task of accommodating the three critical aspects during installation and offshore completion (tolerances, stability and temporary strength) culminated in a conclusion that contradictory requirements on the coupling philosophy existed in relation to the ballasting strategy which contains two other critical aspects (weight and ballasting capacity):

- the tolerance problem would be less critical if the amount of ballast prior to the connection is at the minimum requirement;

- the stability of the uncoupled halves and the strength of the joint would be less critical if the maximum amount of ballast is achieved as soon as possible.

An examination of the design task showed that a large number of variables influenced the critical aspect systems. A logical interrelation scheme is given in figure 11.8.1.

Without doubt, the temporary phase offshore could be considered as a complex system. The development of that system was additionally complicated due to four factors:

- major boundary conditions e.g. actual soil condition and actual wave climate were not provided;

- behaviour of the total temporary system was influenced by changing stochastical boundary conditions (see section 11.10.1)

- the solution of these design problems was urgently required, as the construction works of the lower Barrier walls had already started.

- the timing of the offshore installation works had to be advanced tentatively in an attempt to find a more favourable wave climate, which caused even more time pressure on the engineering schedule.

Due to these facts the total development process changed from a phased engineering and construction into a simultaneous engineering and construction development process. Consequently, the planned eight months engineering period lasted over the full construction period.

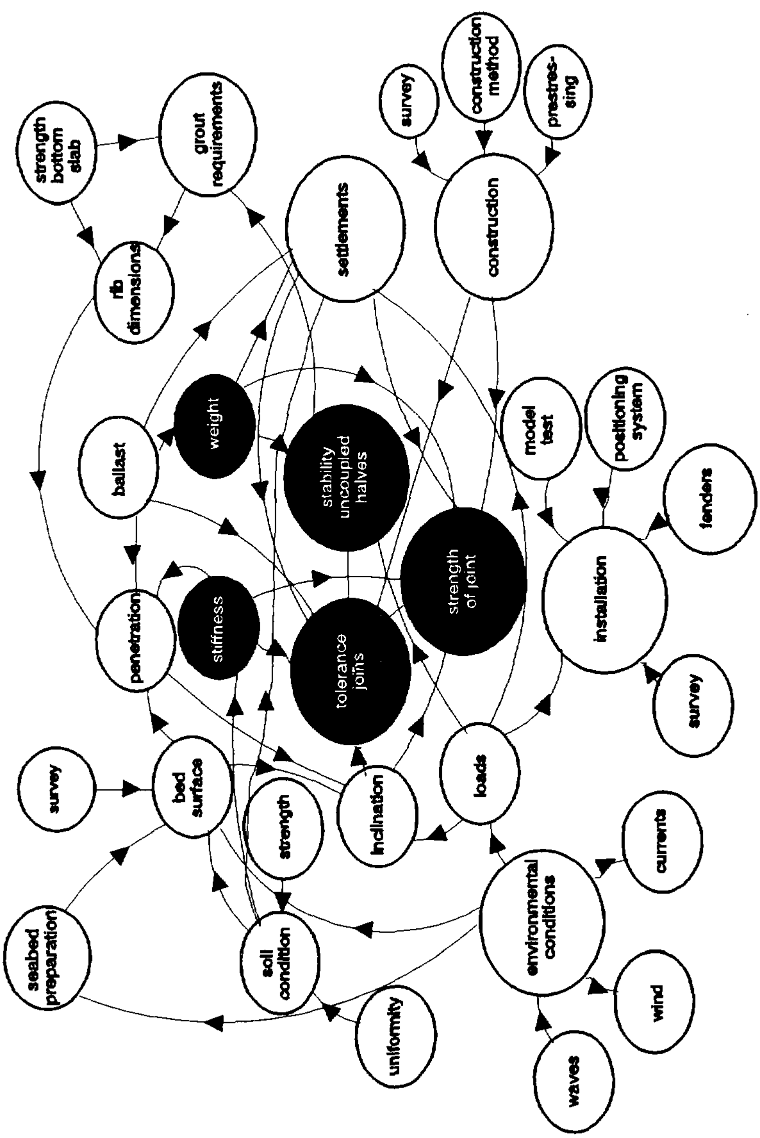


Fig. 11.8.1 *The logical interrelation scheme of the installation and subsequent offshore completion of the Ekofisk Protective Barrier showing the relation between the main aspect-systems, the boundary conditions and the starting points*

11.8.2 Development strategy

The optimum way to solve the design dilemma without iterations was to describe the total behaviour of the installation and subsequent offshore completion with respect to the critical aspect-systems in a mathematical model. This model could be used as an overall controller of the system for the temporary phase-system offshore (see figure 11.8.1).

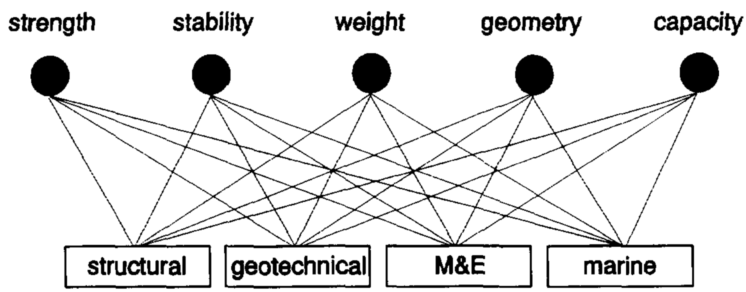


Fig. 11.8.2 *Schematic representation of the control function of the dynamic control models built up by five specific aspect-systems of equal scope and significance. Four sub-systems were dynamically controlled.*

Therefore, it was necessary to have insight in both strength and uniformity of the soil as well as the wave climate during the summer months.

Both boundary conditions played too important a role to suffice with a sensitivity analysis of the uncertainty of the soil and with schematized unfavourable wave data valid for the defined four months installation period. Therefore, soil and wave climate investigations were started. Since the behaviour of the total system was dominated by transient stochastic parameters, the model to be developed had to be a simulation model. Given the urgency and the main purpose (coordination), the following modelling philosophy was adopted:

- keep the models as simple as possible;
- split-up the models where possible (modules).
- develop the models from rough to fine; the visualization of the overall performance of solution is more important than the overall validity.

A schematic diagram of the model of the offshore installation and subsequent offshore completion is given in figure 11.8.3.

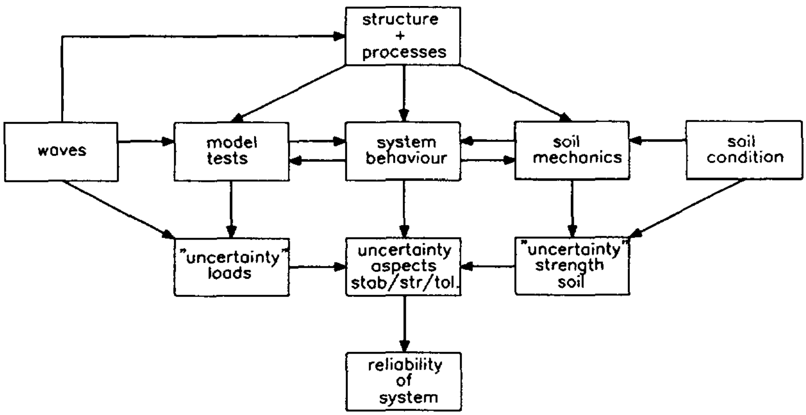


Fig. 11.8.3 Schematic diagram of the model used for the offshore installation and offshore completion of the Ekofisk Protective Barrier

11.9 The dynamic model of aspect-system geometry

11.9.1 General

A detailed analysis of the fitting of the joint constructions which had to cope with deformations, deviations and displacements, concluded that a deterministic approach to the influencing processes would lead to unrealistic joint dimensions. Due to the two dimensional problem as a function of the height, and the stochastically independent processes, a Monte Carlo simulation model was developed, with three main components: (1) the concept and the design variables, (2) the environmental boundary conditions and (3) the processes[2].

The geometric model was developed for the temporary phase after installation of both half units. Consequently, clashing possibilities during the mating operation (western half unit installed and eastern half unit floating) had to be dealt with by the design of the installation system.

11.9.2 Geometrical model and design variables

The fitting problem concentrated on two typical cross sections e.g. above and below El +12m (figure 11.9.1) and concerned the fitting of the connection plates and keys into the associated recesses. The direct design variables were:

- diameters lowest key holes and key piles
- dimensions of the boxes
- length of the plates
- dimensions of the wing wall recesses

The coordination of geometry eventually resulted in an optimal choice of the above variables. The resulting composite chart of clearances in final design, showing the available tolerance space, is given in figure 11.9.2.
The geometric considerations were necessary to deal with deformations, deviations and displacements of the two installed half units with respect to each other. These processes had to be determined and combined into a geometrical model. This model was built up in three dimensions with translations and rotations. Hence, the position of any arbitrary point on the two half units was given in coordinates.

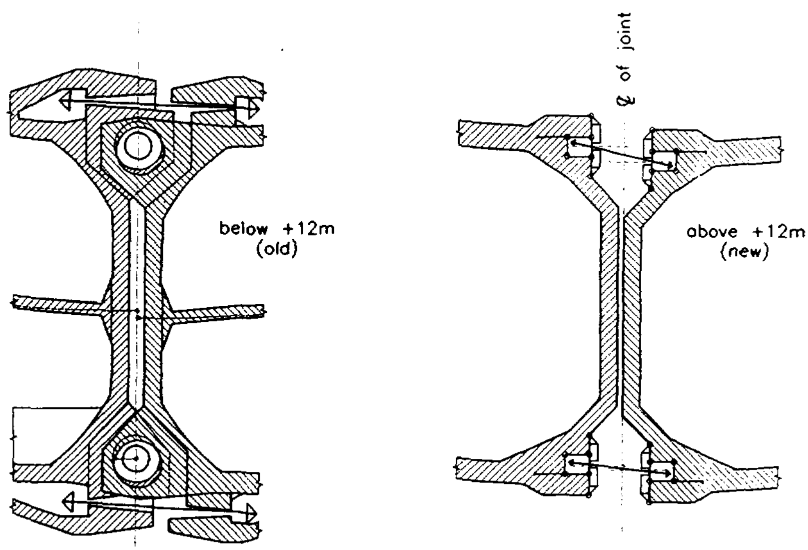


Fig. 11.9.1 Two typical horizontal cross-sections of the joint connection construction. The first is the lowest part which is the result of the two connection concepts (key + key pile and steel plates + box). The second is the upper part with the "steel plates + box concept" only.

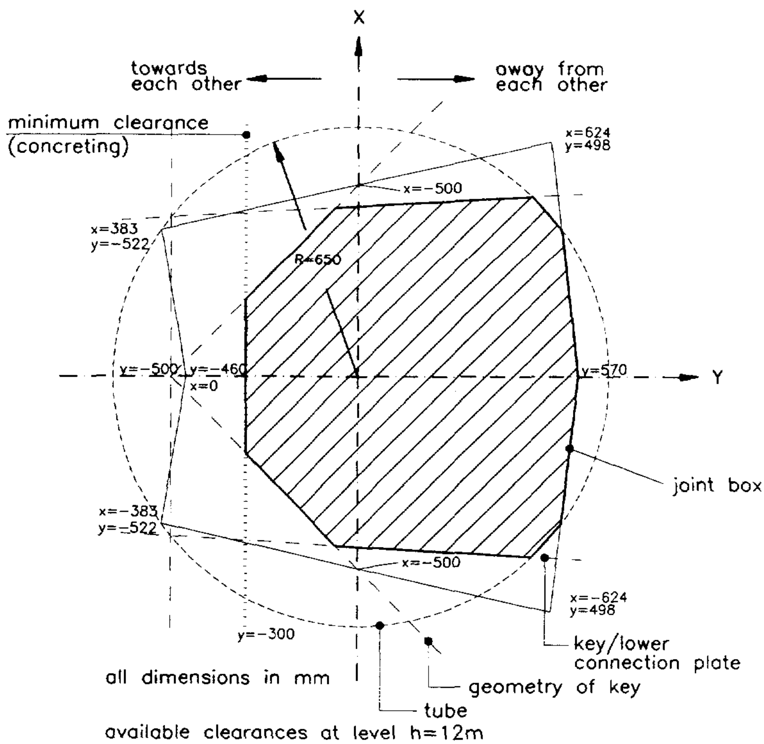


Fig. 11.9.2 *An illustration of the fitting problem expressed in available clearances at elevation +12 m. The hatched area represents the available clearances as a result of the various geometrical constraints.*

11.9.3 Environmental boundary conditions

Soil condition

The initial soil information provided, concerned the bed material (sand) and a given average value of the angle of internal friction provided with a range. However, it was essential to have insight into the uniformity (see section 11.9.4).

Wave climate

An overall insight into the summer wave climate was necessary for two reasons:

- The close distance between the two half units allowed relatively small wave induced motions during the installation. The question was whether a very favourable wave condition could be predicted for the installation.

- The deformations of the two half units after installation but prior to the connection were partially a function of wave induced forces.

11.9.4 Processes during the temporary phase

The processes during the temporary phase with respect to tolerances were divided into three categories. Firstly intrinsic processes, which inevitably had to be passed through. Secondly strategic processes, influencing the installation processes. Thirdly tactical processes, which were used for the control of the total operation. Given the Monte Carlo simulation model, the processes had to be described in probability distribution functions. Therefore it was necessary to convert the deterministic calculation results of the contributing disciplines into Gaussian distributed parameters. The main assumption was that "maximum values" equal two times the standard deviation.

Intrinsic processes

- Wave induced motions of the eastern half unit during installation. These motions were the governing boundary conditions for the design of the fendering system, whereas the fenders were main parameter for the final positioning accuracy. For the defined installation condition (Hs= 1.5 m with Tp= 8 sec), the maximum horizontal amplitudes at the top of the half unit were about 0.60 meter.

- Penetration and differential penetration into the seabed. This process was influenced by the on bottom weight of the half unit, the geometry of the ribs underneath the bottom slab and the soil condition. The penetration had to exceed a minimum in order to avoid leakage during the underbase grouting. The mean value differential penetration was determined by the uniformity of the soil. The spreading of the distribution functions was built up by spreading of the soil condition and by the models used.

- Settlement and differential settlement, which also determined the relative positions. The spreading was mainly determined by the soil condition.

Strategic processes

- Preparation of the seabed. With help of transfer functions of inclination of the half unit on bed ribbles and a fourier analysis of ribbles, it was possible to establish the relation between bed unevenness and inclination of the half units.

- Principle of installation.

- High construction accuracy inshore, which provides more clearances offshore.

- Speed of inshore construction, which would lead to earlier tow out date and consequently to limited deformations due to milder wave climate offshore.

Tactical processes

- Underbase grouting. This process, which was necessary for the uncoupled stability, stopped penetration. Hence, it was a tactical process for the fitting problem. Since the bottom slab was divided into compartments by ribs, underbase grouting could be applied selectively to counteract too large differential penetration.

- Water ballasting. This process influenced the short term immersed weight. Due to the compartmentation of the half units also differential water ballasting was possible to counteract too large penetration.

- Solid ballasting. This process influenced the long term immersed weight and thus settlements.

11.9.5 Results

The Gaussian distributed processes made it possible to define a two dimensional failure criterion. The calculated criterion (2.7%) was based on a practical failure criterion for a one dimensional failure function concerning temporary construction works (1%). - Failure was defined as non fitting of at least one of the construction parts.

The simulation model was able to determine the relative contribution of the various processes to the total failure. Hence, it was simple to detect the most critical processes, which made the geometrical model a sophisticated control system.

A result of a fitting simulation is given in figure 11.9.3, showing the composite tolerance chart and the 10000 simulations.

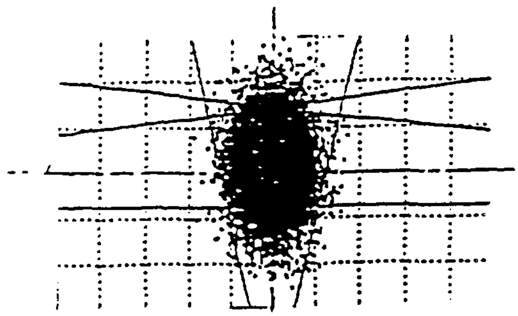


Fig. 11.9.3 *10000 simulations of the fitting problem. Each dot in the composite tolerance chart is a simulated offshore process focused on the fitting problem and including all boundary conditions and all variables*

The eventual result of the geometrical model given in probability of failure as a function of on-bottom weight of the half units is given in figure 11.9.4. It is noted that the corrective measures are not included in this figure. The outcome of the control model of geometry together with the corrective measures, provided enough reserve to solve the problems with the stability and strength problems of the uncoupled half units.

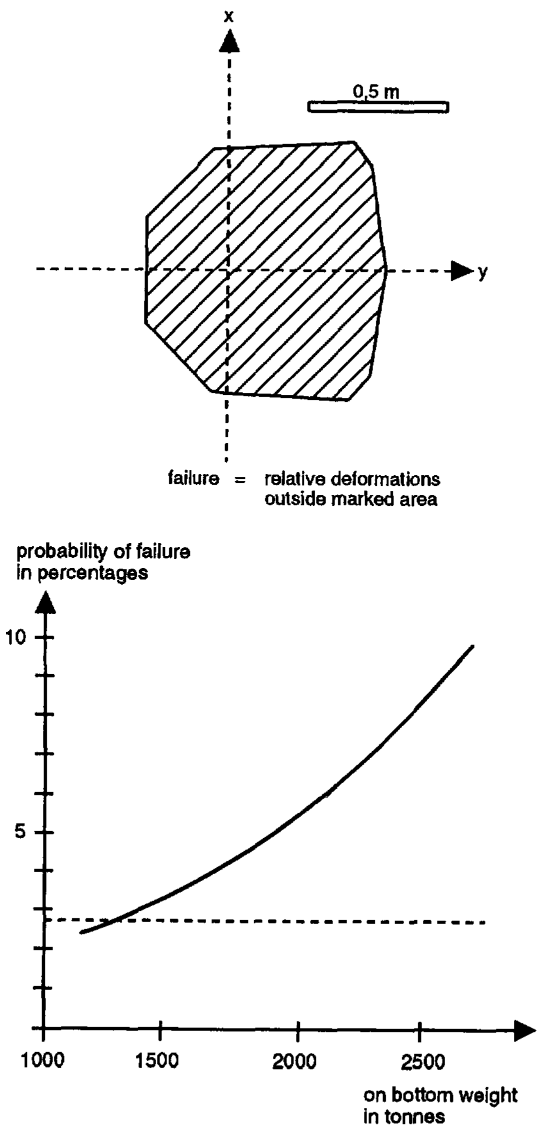


Fig. 11.9.4 *The outcome of the dynamic geometrical model which is given in a probability of failure of the joint connection system as a function of on bottom weight of the half units. It is noted that the outcome is extremely simple and easy to interpret.*

11.10 The dynamic model of the offshore completion

11.10.1 General

The dynamic model was built with three critical aspect-system e.g. stability, strength and on-bottom weight. Due to the transient stochastical character the aspect-systems were described as a function of time. At the highest abstraction level the dynamic model consisted of the integrated failure functions for stability and strength:

- $F_i(t) = R_i(W,Q)/L_i(Hs,Tp,Alpha)$

i	=	1: Stability Western Half
i	=	2: Stability Eastern half
i	=	3: Strength Joint construction

with:

F_i	=	Failure function
R_i	=	Resistance Moment (MNm)
L_i	=	Load Moment (MNm)
Hs	=	f(T,Alpha) = Significant wave height (m)
T	=	Time (week number)
Tp	=	f(Hs) = Peak period of wave spectrum (s)
Alpha	=	Wave direction (deg.to North)
W	=	f(bp) = on bottom weight (KN); i=1,2
bp	=	ballasting process = f(t,Hs,Tp)(Kn)
t	=	time (days after start connection works)
Q	=	f(t) = strength temporary connection (KNm); i=3

For the total temporary phase, failure was defined as $Pr\{F_i<1\}>1\%$ for i=1 to 3. The purpose of the coordination model was to:

- visualize the critical items;
- *establish the optimal sequence;*
- establish the latest possible start date;
- determine the various process parameters.

11.10.2 Wave loads

Wave climate

The wave climate with reference to wave height was investigated in detail by the client for the summer months June, July, August and September, using ten years of observations. For interpretation purposes the results were extrapolated for October and November (figure 11.10.1).

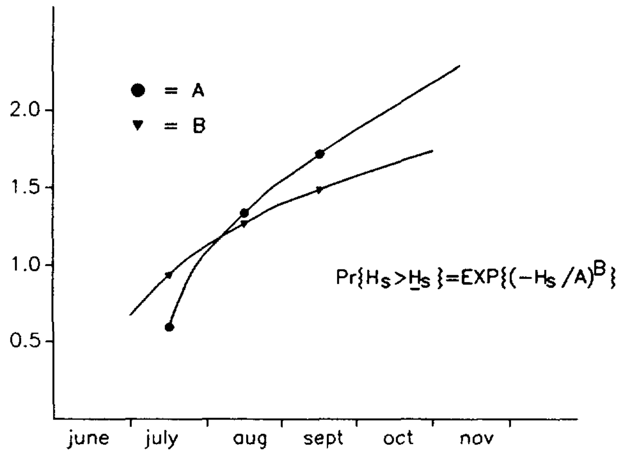


Fig. 11.10.1 Extrapolation of wave climate for the months October and November using the available wave data of June, July, August and September

The relation between Hs and Tp was established using the existing scatter diagrams and expressed as an average relation with standard deviations. In that way, the representation of available scatter diagram is most simple and with the highest possible accuracy. This was very important due to the strong relation between wave load and wave period.

The relation between Hs and wave direction Alpha was also established using available scatter diagrams and was fitted into a Gaussian distribution function around an average relationship. In order to generate a representative wave climate for the simulation model an auto-correlation function was established using Ekofisk time series of waves over a period of ten years.

With the above wave information the wave climate could be generated and compared to the available time series. The validation was based on 10.000 runs. The comparison with the wave climate was found satisfactory.

Wave loads

For the input of the simulation model it was necessary to establish the wave loads as a function of wave height, wave period and wave direction. As a consequence of Client's decision to change the summer storm condition (3 years return period) additional wave load tests on the uncoupled half units were performed in model tests at SSPA Goteborg (3 years return period). These additional tests together with the initial tests (10 years return period) made it possible to derive the general relationship between loads and wave parameters and express them into a general relation with standard deviation.

The wave load is given in the most critical direction (180 degree in fig. 11.10.4). The governing backward overturning moment and the backward force are given in fig. 11.10.2 and fig. 11.10.3 respectively.

The wave load on the half units as a function of incident wave direction was determined using a diffraction model. Although the reliability of such a model is questionable for the Barrier Halves close to the 2/4 Tank, the dependency of the wave load as a function of incident waves could well be established (fig. 11.10.4).

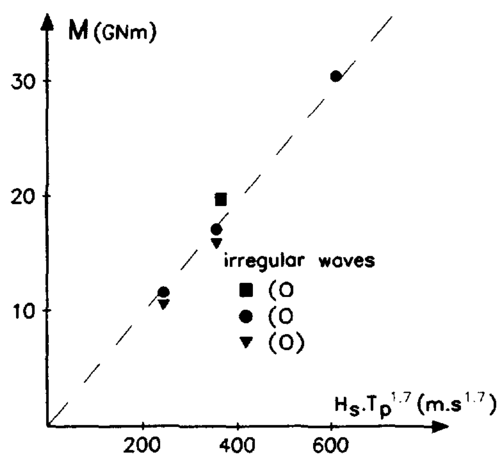


Fig. 11.10.2 Backward overturning moment on Barrier half as function of Hs and Tp

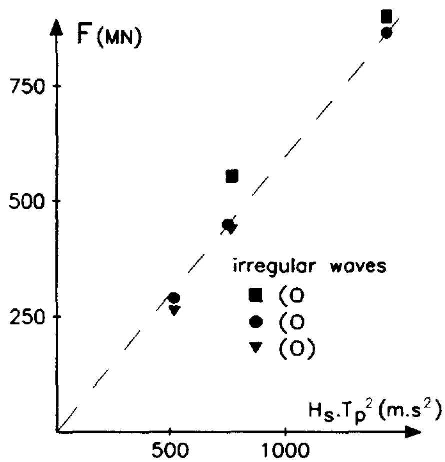


Fig. 11.10.3 Backward force on Barrier half as a function of Hs and Tp

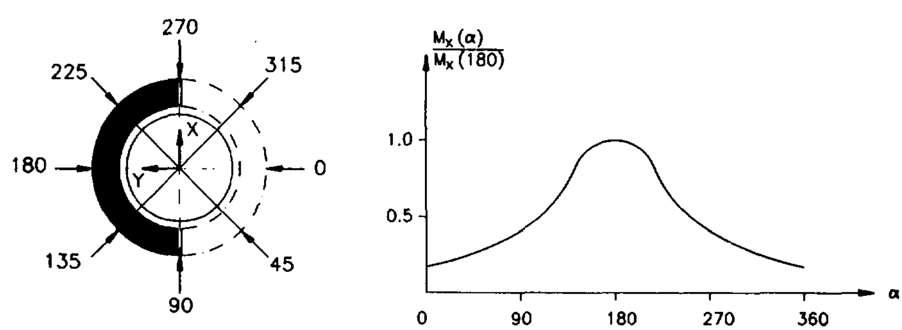


Fig. 11.10.4 Wave load on Barrier half as a function of direction of incoming waves

Given the orientation of the two half units with respect to north, the wave load could easily be described with reference to the Ekofisk wave climate.

11.10.3 Resistance of uncoupled half units

The resistance of the uncoupled half units against wave loads was a function of on-bottom weight and soil properties. Due to the "horse foot" shaped bottom slab, the backward wave induced moments were the governing wave loads. The results of the soil investigation (see section 11.8.2) showed that the soil properties east of the tank were substantially worse than the soil properties west of the tank. The backward allowable overturning moments were expressed in parameters of a Gaussian distribution as a function of on-bottom weight. The spreading in the moments originate from the spreading in the properties of the soil samples and the models used to transform the ensemble of half unit and soil properties into a resistance moment (fig. 11.10.5):

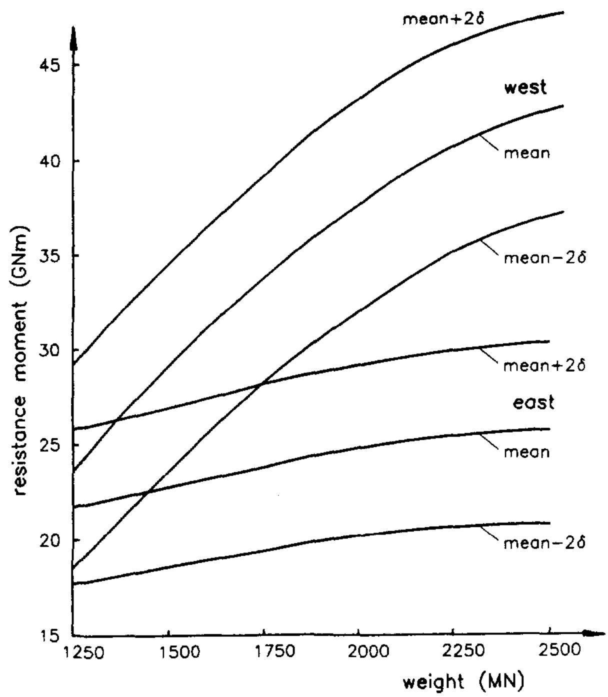


Fig. 11.10.5 The resistance moments of the half units as a function of on-bottom weight. The spreading of the moments originate from the spreading in the sampled soil properties and the model used.

11.10.4 Time schedule offshore completion

The time schedule of the offshore completion formed the heart of the model. After establishing a basic sequence, the main design requirements were brought in:

- ballasting and coupling strategy following the outcome of the tolerance model;
- hardening of concrete and strength development in relation with allowable motions.

The last requirement resulted in a temporary connection on top of the half units. The allowable moment of this temporary connection was substantially lower than the allowable moments on the free standing half units. This dip in the resistance moment is illustrated in fig. 11.10.9.

For the time schedule the following operational aspects were brought in:

- number of cranes for mounting all equipment;
- number and capacity of hoppers for solid ballast;
- capacity of concrete plant.

In addition, the required sea states for each wave dependant activity was established. Finally the durations of all activities were determined. The evaluated time schedule is given in fig. 11.10.6.

ACTIVITY ID	ACTIVITY DESCRIPTION	ORIG DUR	EARLY START	EARLY FINISH
6-T440X00	INSTALLATION BARRIER HALVES	3	21JUN89	23JUN89
7-C010X00	UNDERBASEGROUTING	3	24JUN89	26JUN89
7-C020X00	JOINT (STEELPLATES) + REMOVAL OF JOINTCRANES	11	25JUN89	5JUL89
7-C020320	INSTALL JACKS	5	24JUN89	28JUN89
7-C020350	PREPARATIONS FOR UNDERWATERCONCRETING	10	4JUL89	13JUL89
7-C0204X0	UNDERWATERCONCRETING JOINT + REMOVAL FRAME	6	14JUL89	19JUL89
7-C022X00	UPPEROUTSIDESHUTTERING BOTTOM	4	11JUL89	18JUL89
7-C022Y00	UPPEROUTSIDESHUTTERINGTOP	5	24JUL89	28JUL89
7-C024X00	INNERCONNECTIONWALL	12	20JUL89	31JUL89
7-C026X00	ROOFSLABCONNECTION INNERSIDE	18	4JUL89	31JUL89
7-C026Y00	ROOFSLABCONNECTION OUTERSIDE	18	4JUL89	31JUL89
7-C055X00	START SCREENWALL IN SITU	0	1AUG89	1AUG89
7-T010400	SOLID BALLASTING OFFSHORE PHASE 1	18	26JUN89	13JUL89
7-T010800	SOLID BALLASTING OFFSHORE PHASE 2	24	19JUL89	11AUG89

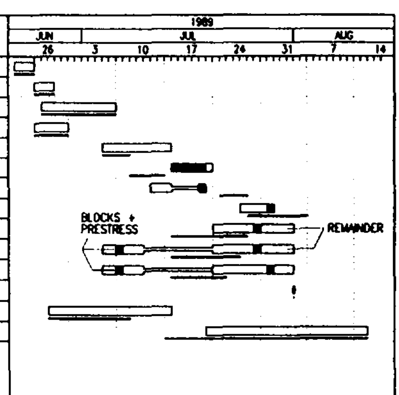


Fig. 11.10.6 Evaluated time schedule offshore installation and offshore completion

11.10.5 Contingency plans and Emergency measures

The main contingency was the possible increase of the backward resistance moment by differential solid ballasting (figure 11.10.7). However, as the forward resistance moment decreased, the capacity of this contingency was limited (approx. 15 % of the total allowable backward moment).

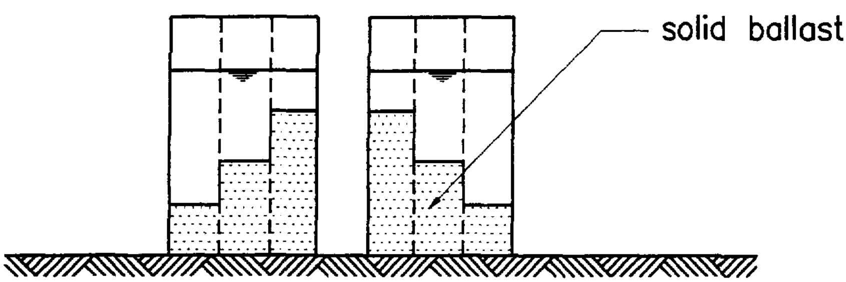


Fig. 11.10.7 Enlargement of backward resistance moment by differential solid ballasting

The allowable moment of the temporary connection needed for the hardening process of the in-situ cast concrete was substantially smaller when compared to the allowable moment during the fully uncoupled situation. Therefore, an emergency system was developed to protect the already cast part of the joint against damage during sea states exceeding the limits. Provisions were developed for lowering the water level in the annulus between Barrier and Tank in combination with concrete blocks (fig. 11.10.8).

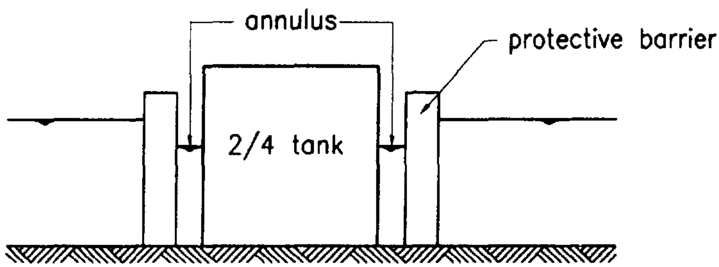


Fig. 11.10.8 Emergency system to withstand extreme sea states. By lowering the water level in the annulus, the two Barrier half units were pressed together.

The combined resistance function of the half units and the joint construction is given in fig. 11.10.9 as function of on-bottom weight and time after start concreting.

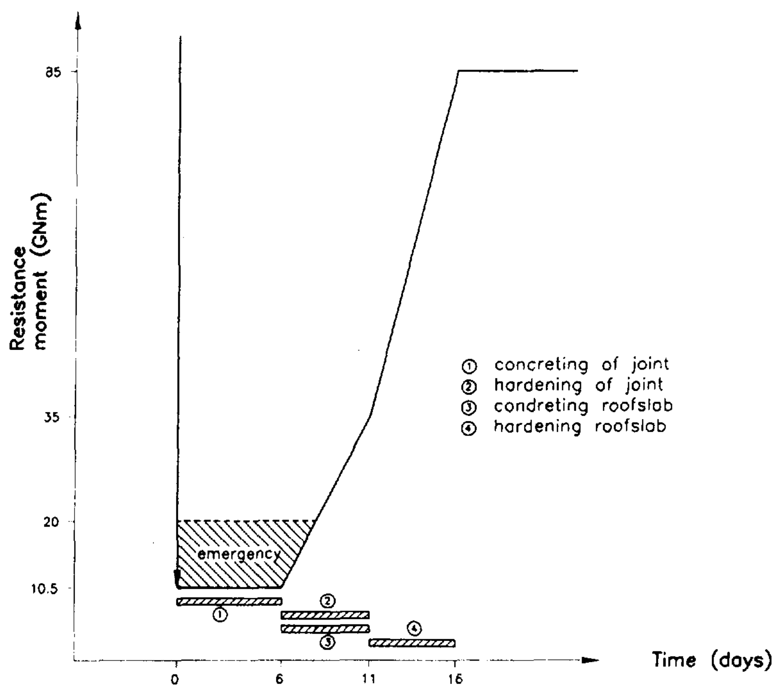


Fig. 11.10.9 Resistance moments of western half unit, eastern half unit and joint connection respectively, as a function of time

11.10.6 Results

A Monte Carlo model was used to simulate 1000 offshore completion works per run. Per simulation first the wave climate was established. Then the activities with associated weather windows were put in. After that, failure functions could be established per time step. For the three components every failure was counted to determine the total probability of failure. Several cases were investigated by the model. Sensitivity analyses were carried out for ballast strategies and delays. A lot of interesting data could be established as workability, total duration, as a function of start date and expressed in probability of exceedance. Two main outcomes are given. In fig. 11.10.10 the probability of failure of main components is given as a function of an uncertainty factor on soil condition for the planned tow-out date. In fig. 11.10.11 the probability of failure of the main components is presented as a function of tow-out date.

It became evident that for the defined 1% criterion which was accepted for the failure of the offshore operation the ultimate tow-out date was approximately June 11th, 1989. With help of many accelerators the construction was finished in time and tow-out started on June 10th, 1989.

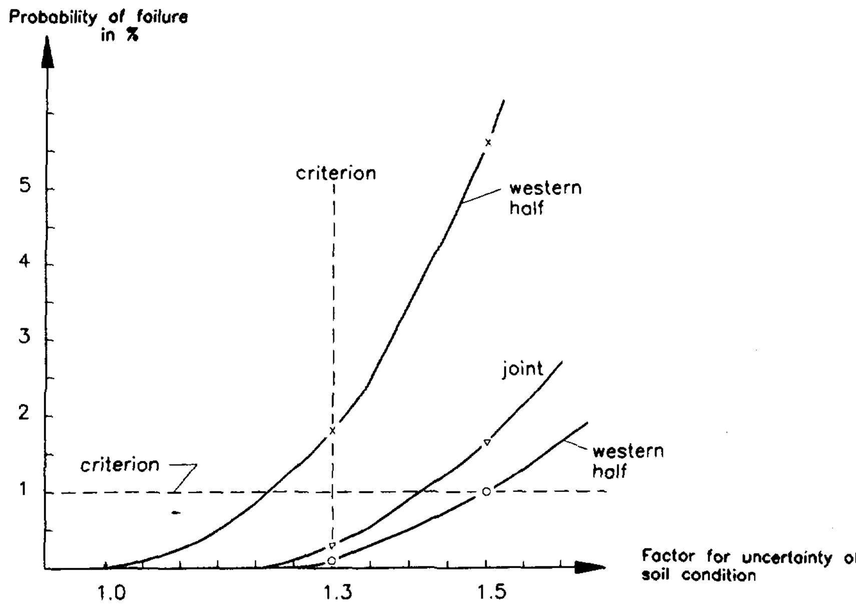


Fig. 11.10.10 Probability of failure of main components as a function of an uncertainty factor on soil condition for the planned tow-out date

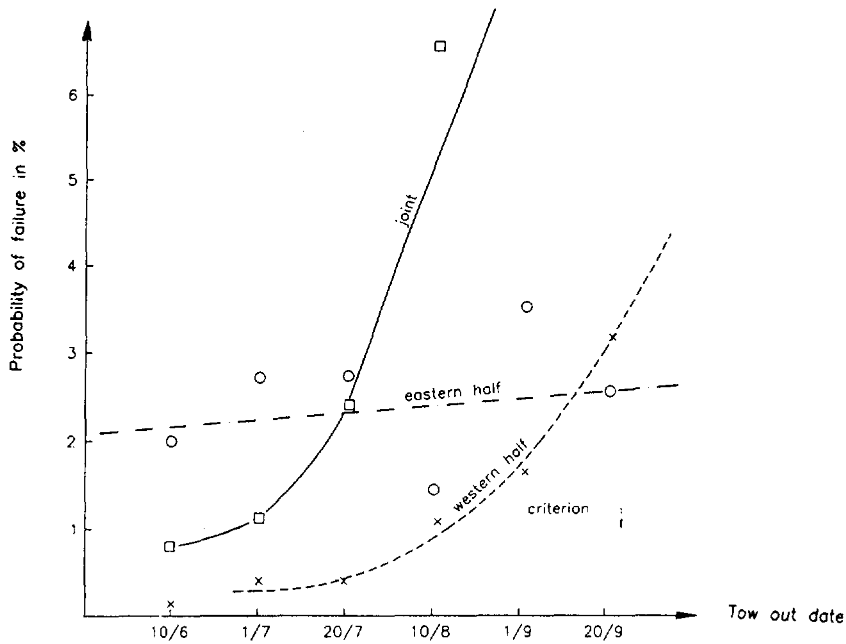


Fig. 11.10.11 Probability of failure of main components as a function of tow-out date

11.11 Conclusion

The realization of the Ekofisk Protective Barrier was a very complex realization process to be performed under extreme time pressure.

The offshore installation and subsequent completion in the North Sea, with its hostile wave climate, was the most critical operation. The design of this operation was governed by a large number of conflicting requirements.

For the description of the behaviour of the total system during the offshore operations two dynamic models were developed, covering the six relevant aspect-systems (stability, strength, stiffness, weight, geometry and capacity).

Due to the transient stochastic environmental loads, the two models were developed as Monte Carlo simulation models, providing a sophisticated and adequate goal control system, taking into account all relations between requirements, elements and loads. With these models the whole operation was visualized, optimized and thus fully controlled.

Notes

1. The concrete formed the pressure part of the joint connection construction. The tension part consisted of the steel plates and the boxes.
2. The processes played a significant and dominant role in the offshore operations. Mainly due to the relation with the hostile environmental condition.

12. CASE STUDY: DYNAMIC CONTROL MODEL OF GEOMETRY OF THE STORM SURGE BARRIER IN THE EASTERN SCHELDT

12.1 Purpose of the case study

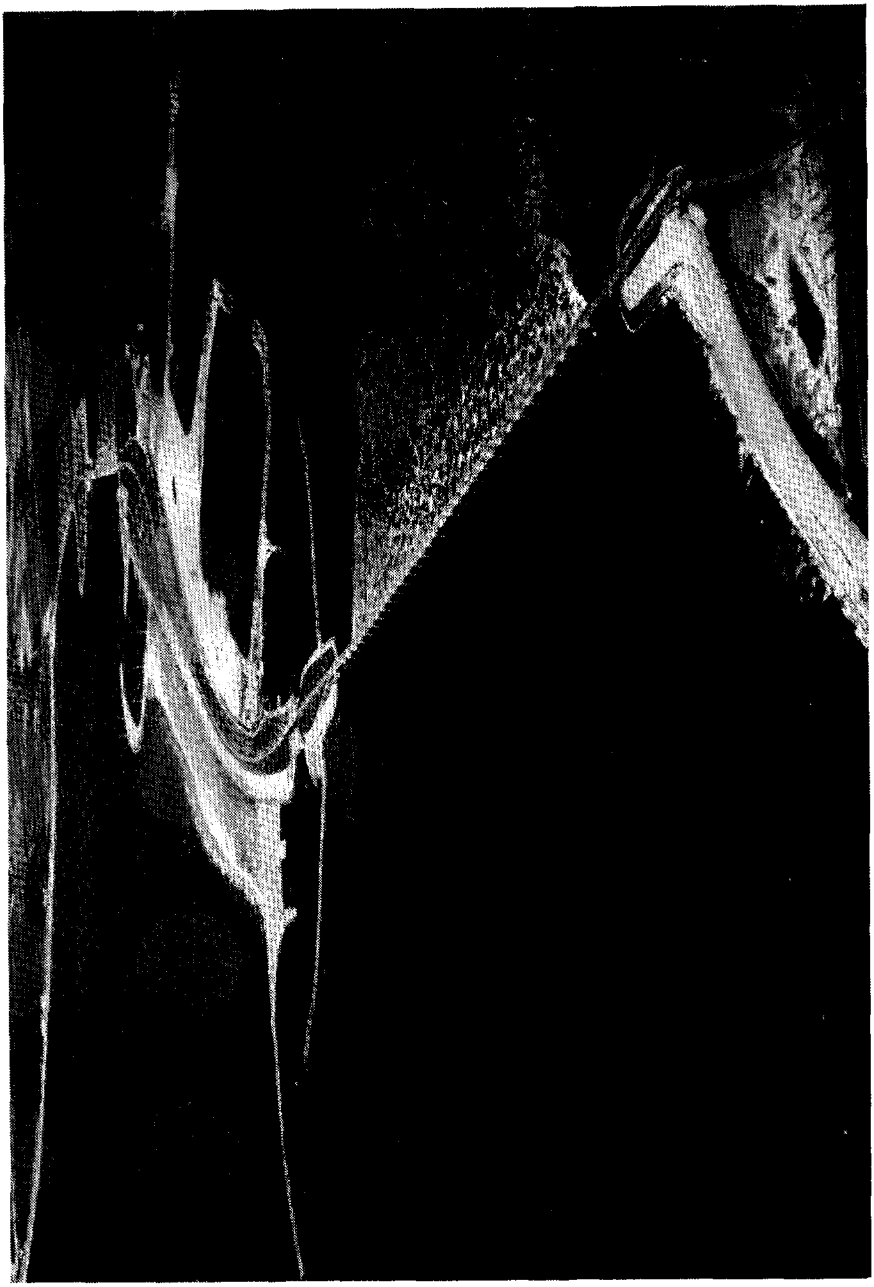
This case study illustrates the meta-control model as proposed for goal-control of the realization of a large complex civil engineering system. The geometrical control model of the prefab sub-systems of the Storm Surge Barrier can be considered as a one-aspect dynamic meta-control model for goal coordination. This dynamic meta-control model was applied during both the design as well as the construction phases and comprised not only the geometrical deviations and tolerances, but also contingency and emergency measures to cope with non-satisfactory results during construction.

12.2 Backgrounds[1]

The final part of the delta project was to be a dam closing off the Eastern Scheldt (see figure 12.2.1). This was considered to be the most complicated part of the whole Delta Project, but became feasible due to the experience gained during the earlier operations conducted in the framework of the Delta Project.

It was not long however, before voices were raised in favour of keeping the Eastern Scheldt open and maintaining the tidal flow to preserve the original natural environment of the area. As public disquiet grew, the Dutch government ordered a new study to investigate whether it was technically feasible to keep the Eastern Scheldt open while not only ensuring the safety of the population at all times, but also maintaining the original natural environment as much as possible. The study proved positive and the decision was taken to build the Storm Surge Barrier with steel gates. The alternative, to keep the estuary open and to raise approximately 150 kilometres of dykes along the islands to the required height, was rejected. Complete closure, for which contracts had already been awarded, ceased to be a possibility. The Eastern Scheldt was to be kept open under normal circumstances, but would be closed when storm surges were expected.

The decision to build a storm surge barrier also necessitated the construction of two auxiliary dams, the Philips Dam and the Oester Dam. These dams have two functions. Firstly, they reduce the area of the tidal basin behind the Storm Surge Barrier, thus maintaining a greater tidal range at Yerseke (3.00 m) than would otherwise have been possible. Secondly, they create a tide-free shipping route between Antwerp and the Rhine.



The Storm Surge Barrier in the Eastern Scheldt

The decision to build a storm surge barrier in the largest estuary of the Dutch coast had considerable consequences. In order not to interfere with the channel configuration in the Eastern Scheldt, the Storm Surge Barrier had to be built in the three tidal channels, the deepest part of the estuary. Experience gained from previous projects now proved to be insufficient. The development of even more new techniques, never before tested, was called for. It was decided to prefabricate as many components as possible in advance, as construction operations in-situ would not only affect the tidal currents in the channel and cause environmental problems, but could also prove hazardous to those working on them. These components would then only have to be installed or assembled on the spot.

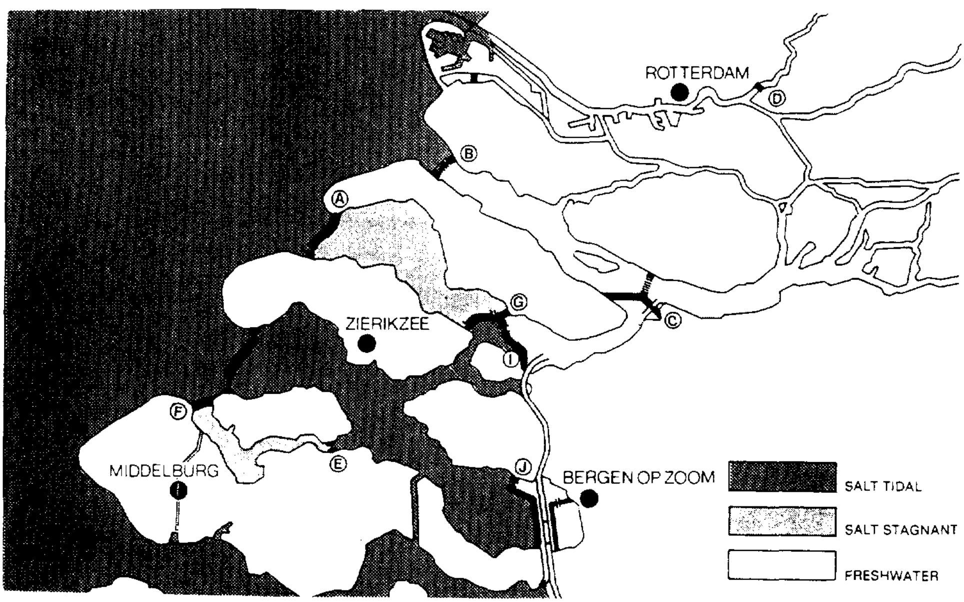


Fig. 12.2.1 Situation sketch of the Delta area in the South-Western part of The Netherlands indicating the delta project.

As the new Storm Surge Barrier in the Eastern Scheldt (from now on abbreviated as SSBES) had to be operational by 1985, the design process and the study of construction methods were started simultaneously. From the outset, the public works department (Rijkswaterstaat) which commissioned the Work and the Joint Venture of Contractors (Dosbouw), worked in close co-operation, assisted by advisors and consultants from a wide range of specialized areas.

Various alternative plans were studied and developed and within a few years a basic design was produced accompanied by suggestions as to construction methods and the equipment to be used. Although the details of design, techniques and materials had still to be worked out, the broad outline of the project was agreed.

12.3 The concept

12.3.1 General

The SSBES, in all 3.000 m long, was to be built in the three tidal channels, Hammen, Schaar van Roggenplaat and Roompot (see figure 12.3.1).

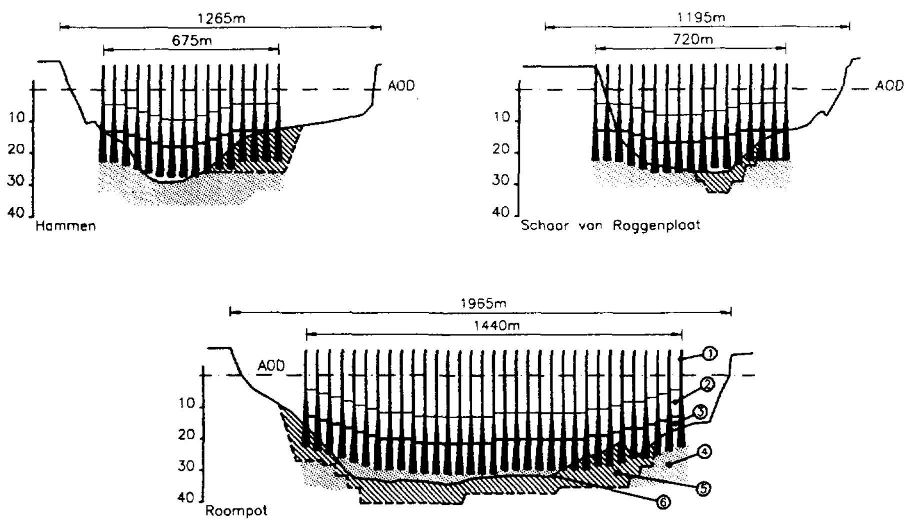


Fig. 12.3.1 Cross-sections of the three tidal channels with the SSBES: (1) piers, (2) sill beam, (3) underwater sill, (4) depth compaction, (5) seabed improvement, (6) original bed profile.

The SSBES was to consist of 65 prefabricated concrete piers, between which 62 sliding steel gates were to be installed (figure 12.3.2). With the gates in a raised position, the difference between the high and low tide behind the barrier would be maintained at least three-quarters of its original range, sufficient to preserve the natural environment of the Eastern Scheldt basin.

When storms and dangerously high water levels are forecast the gates can be closed, thus safeguarding the population of the islands from the ravages of the North Sea.

In connection with the initial plans to build a dam across the Eastern Scheldt, some islands (Roggenplaat and Geul) had already been constructed at shallow points in the estuary. The construction islands, Neeltje Jans and Noordland, are connected by Geul, which is, in fact, a section of dam. These raised parts will form the dam sections of the SSBES. In view of its convenient situation and the facilities which had already been constructed there, Neeltje Jans was turned into a construction island from where operations were conducted. The greater part of the prefabricated components were also built here: the piers, the beams and the foundation mattresses. The stone to be dumped to form the underwater sill around the piers was also stockpiled here.

The construction of the SSBES is, for many of its aspects, a unique project[2]:

- size of the structure: total length about 3 km;
- design/construction methods: prefabricated huge element, put in place in open water subjected to currents and waves;
- poor soil conditions at site: low bearing capacity and liquefaction liability;
- small tolerances admitted and attained during the execution of the works.

12.3.2 Foundation (bed and piers)

The piers are the backbone of the SSBES, supporting the superstructure which consists of steel gates, a roadway and the beams. When storms occur and the gates are closed, the barrier will be subjected to enormous forces which the piers must transfer to the foundation bed. This bed must be constructed in such a way that it does not cause movement of the pier, which might result in jamming of the gates. It is, therefore, as in any construction, of vital importance.

The piers of the Eastern Scheldt Storm Surge Barrier are positioned on the seabed without pile foundations. First, a cunette was excavated and, where necessary, unsuitable sand replaced by better quality sand. The deepest parts of the tidal channels were raised and covered with gravel to prevent erosion. To improve the bearing capacity of the seabed further and to prevent settlement of the piers, it was compacted over a distance of 80 m around the piers.

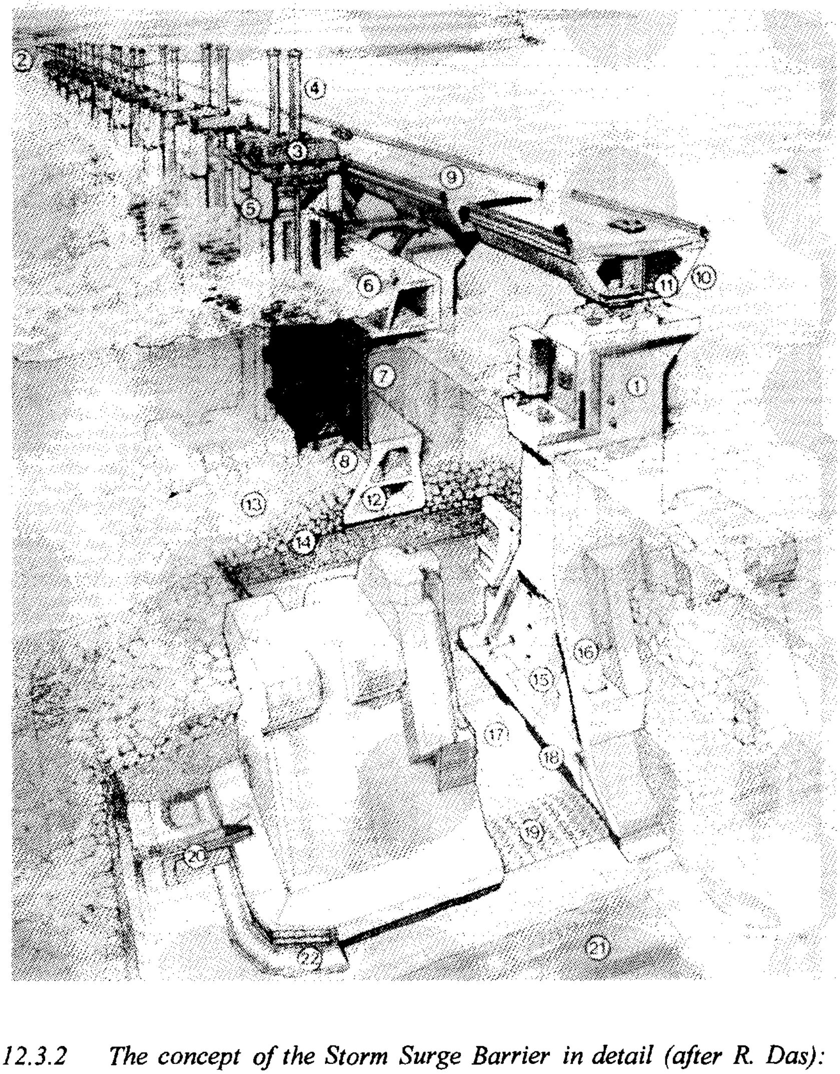


Fig. 12.3.2 The concept of the Storm Surge Barrier in detail (after R. Das):

(1) pier
(2) quarry stone dam for land abutment construction
(3) beam supporting operating equipment
(4) hydraulic cylinders
(5) capping unit
(6) upper beam
(7) gate
(8) sill beam
(9) road
(10) road box girder and machinery for gate operation
(11) power supply duct
(12) sand filling of sill beam
(13) top layer of sill
(14) core of sill
(15) sand filling of pier base slab
(16) sill beam stops/bearings
(17) upper mattress
(18) grout filling
(19) block mattress
(20) bottom mattress
(21) compacted sand under the bed of the Eastern Scheldt
(22) gravel bag

After compaction and inspection and before installation of the piers, the seabed had to be dredged and levelled off to the correct depth and covered with a prefabricated foundation mattress, measuring 200 x 42 m x 36 cm laid under each pier. The simultaneous dredging of the seabed and positioning of the foundation mattresses were carried out by the Cardium (cockle), a special purpose-built rig (figure 12.3.3).

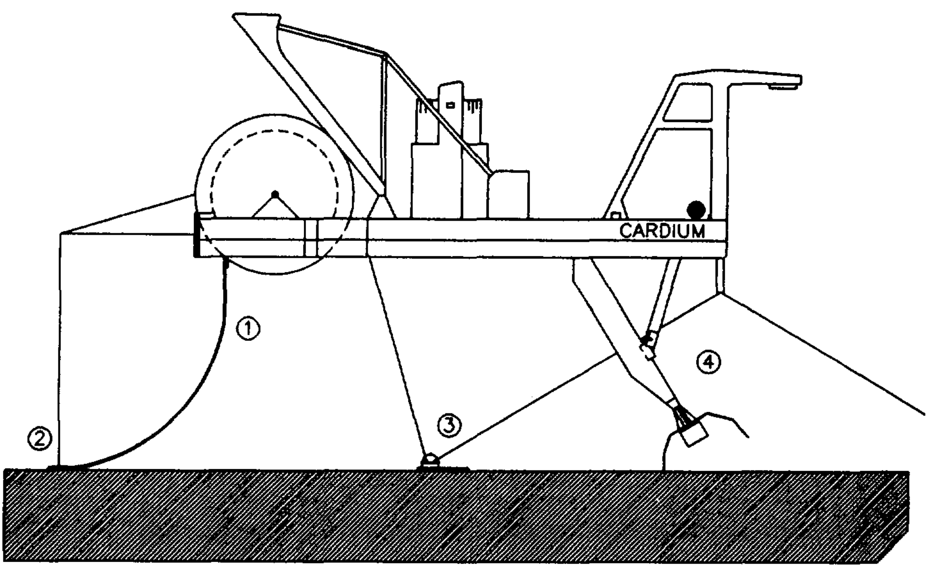


Fig. 12.3.3 *The Cardium, a rig specially built for this purpose, simultaneously dredged the seabed. and positioned the foundation mattresses at the seabed. (1) mattress being unrolled, (2) beam at end of roll, (3) compacting unit, (4) adjustable dredger/dustpan.*

The piers and the mattresses are positioned at a centre-to-centre distance of 45 m, leaving a gap of about 3 m between the 42 m mattresses. This gap between the mattresses was filled with loose sea gravel topped by two layers of heavier stone. This particular operation was carried out by a specially developed stone dumping vessel. To reinforce the foundation structure, which does after all have to bear the weight of the pier, a second smaller mattress, measuring 60 x 29 m and again 36 cm thick, was placed by the Cardium on top of the first one. The foundation bed, therefore, consists of a lower and an upper mattress.

The placing of the lower mattress was the most crucial operation, because this is what ultimately determines the levelness of the foundation on which the piers were to be installed.

Both upper and lower mattresses were manufactured in the filter mattress plant, specially built for this purpose on the construction island, Neeltje Jans. They were called filter mattresses they were constructed in three layers of graded material (sand, fine gravel, coarse gravel) to absorb the changing water pressure in the subsoil, avoiding weakening and ensuring that the fine sand on the seabed would not be washed away. The filter mattresses are an essential part of the whole foundation structure, designed to prevent settlement of the piers.

The levelling, which could be achieved by the Cardium, could vary by some 30 cm however, whereas the ribs under the piers require an even more level surface. If surveys of the upper mattress would have indicated that the foundations are not level enough, a block mattress could be positioned immediately under the pier. These block mattresses consist of concrete blocks varying in thickness from 15 to 60 cm in order to smooth out any unevenness. The block mattresses were manufactured in a plant at Sophia and wounded onto a floating cylinder, towed to a pontoon, which positioned the mattress on the seabed.

There was a danger that the layer of quarry stone covering the joints between the mattresses might be damaged by unexpected high currents or turbulence around the piers, and the joints were therefore protected by a 200 m long and 13,5 m wide gravel-ballast mattress consisting of a flexible steel woven mat to which rolls of quarry stone (ballast), packed in a wire mesh, were attached diagonally. The number and weight of the rolls were chosen so as to ensure that the mattress would be able to withstand the current in any circumstances. These mattresses were made on a special site with loading facilities at Sophia-haven, rolled up and transported to a pontoon with winding equipment in order to be able to unroll the ballast-mattresses over the joints.

The construction of the foundation bed is sketched in figure 12.3.4. After the completion of the foundation, all 65 piers could be installed with the lifting vessel "Ostrea", specially built for this purpose (figure 12.3.5).

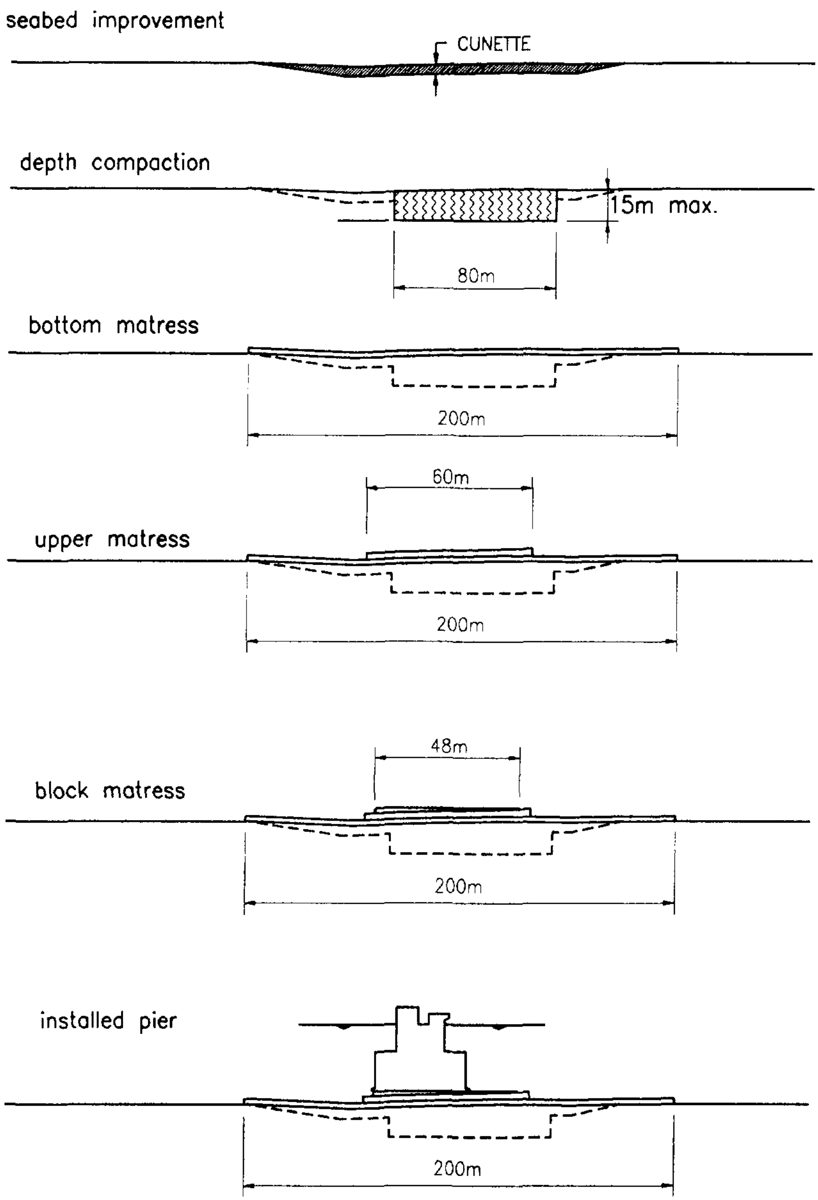


Fig. 12.3.4 Construction of the foundation

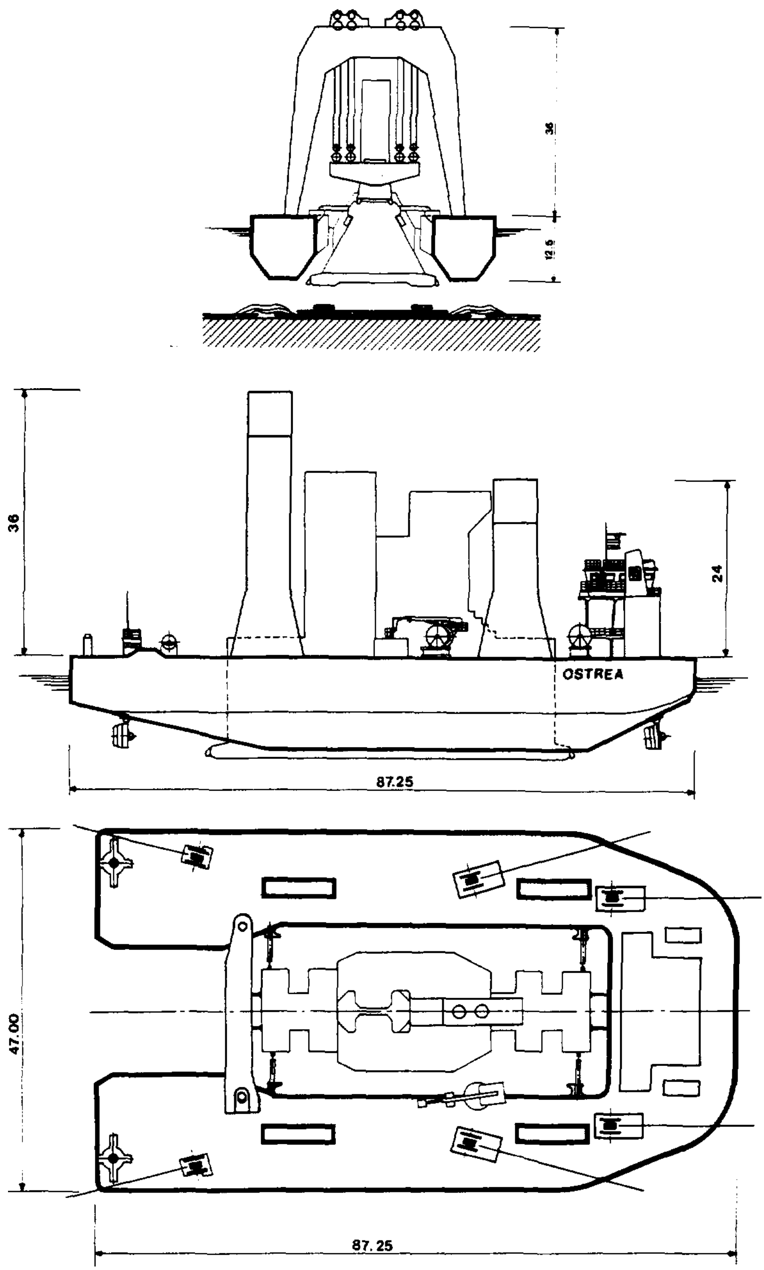


Fig. 12.3.5 *The lifting vessel "Ostrea" used for transport and installation of the piers.*

12.3.3 Superstructure

Once the underwater sill had been completed, the superstructure could be installed. In order of assembly, the superstructure consists of: (1) road bridge box girders, (2) pier capping units, (3) gates, sill beams and upper beams. Each component has a specific function and presents its own problems of manufacture, and they are therefore all briefly described here.

The road bridge box girders, 45 m long, made of prestressed concrete and each weighing 1.200 tonnes at the time of assembly, were placed on the piers. The space within them houses the gate operating machinery and the road is constructed on top of them. Apart from the 62 box girders resting on the piers, there are six additional girders, all extra long (80 m) and links the first pier in each section of the barrier with the land or island adjacent to it. These are made of light weight concrete.

The capping units were prefabricated and also made of prestressed concrete. They increase the height of the piers so as to accommodate the gate structure. Each pier has two connected capping units, together weighing between 250 to 460 tonnes.

The sill beams, 39 m long, 8 m wide and 8 m high, are hollow beams, each weighing 2,500 tonnes, installed between the piers on top of the underwater sill. Once the sill beams have been positioned, stone is placed against them on both sides to improve the flow profile of the barrier. They are made of prestressed concrete and were finished to their exact length only when the exact position of the piers, which may deviate from that planned, was known. After final construction, they were filled with sand.

The upper beams form the upper edge of the openings in the barrier which can be closed by the gates. They are hollow rectangular beams measuring 5 x 4 m and are made of prestressed concrete; the weight of each is about 1.100 tonnes.

The 62 steel gates were installed between the piers. When the gates are raised, the Eastern Scheldt will be open, i.e., the barrier will have an opening of 14.000 m^2, allowing sufficient water to pass through in order to maintain three-quarters of the original tidal range. The gates, made of steel, have a span of about 42 m. The exact dimensions could be determined only after the precise distance between the piers concerned was known. The height of the gates varies from 5.90 to 11.90 m as the flow profile of the barrier roughly follows the bottom profile of the tidal channels, which is deeper in the centre and shallower at the sides. The gates in the middle of the tidal channels are therefore much higher than those at the sides. Their weight varies from 300 to 500 tonnes.

The gates can be closed and opened under even the most adverse conditions. A hydraulic system has been chosen to operate the gates. Each gate is opened and closed with the aid of two hydraulic cylinders. All 124 cylinders are operated from the central control building.

12.3.4 Decomposition of the concept

With the decomposition into two main components e.g. foundation/piers and superstructure, it was possible to decompose the complex system of the SSBES simply into a number of complex sub-systems. This decomposition is based on the maximization of relations inside the sub-system and the minimization of the relations outside the sub-system. This resulted in a number of working clusters (A to D) corresponding with sub-systems. Together with the working clusters "large equipment" and "survey" the clusters A to D formed the framework of the organization. These more or less autonomous clusters remained unchanged during the various phases in the realization process. This is, in fact, the way an integrated design and construction work should be decomposed (see chapter 10).

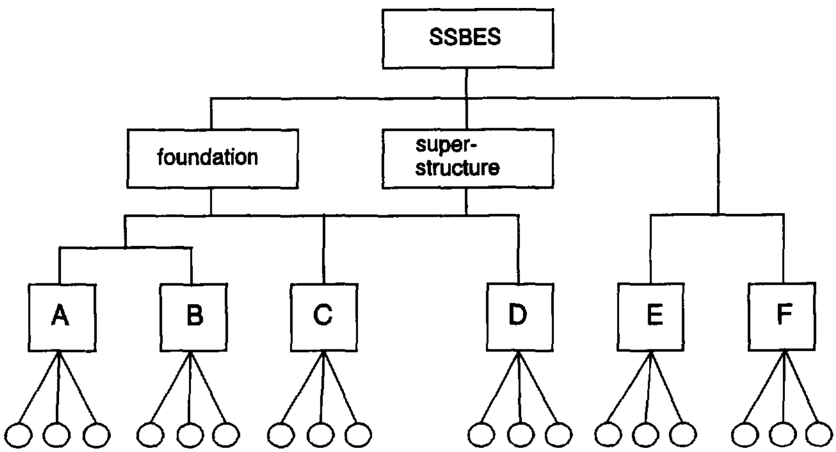


Fig. 12.3.6 Decomposition of the SSBES into a number of working clusters corresponding with sub-systems. A = bedprotection, B = mattresses, C = concrete works, D = steel works, E = equipment and F = survey.

Intermezzo 12.1

As far as the meta-control of the sub-systems is concerned, the goal control was limited to one aspect only: geometry (see paragraph 12.5). This is caused by the fact that the basic concept of the SSBES is prefabrication of elements to be installed offshore. All other aspects were dealt with in the sub-system clusters, which needed two meta-control systems for additional coordination purposes: (1) centralized distribution of design loadcases and (2) centralized research and development.

12.4 The concept and the associated geometrical problems[3]

The SSBES was to be built under offshore conditions. Therefore, the concept showed a degree of prefabrication especially for the technical reasons pertaining to construction. The SSBES comprises 66 openings. Each opening is surrounded by a concrete frame (piers, sill beam and upper beam,) and can be closed by a steel gate (see figure 12.4.1).

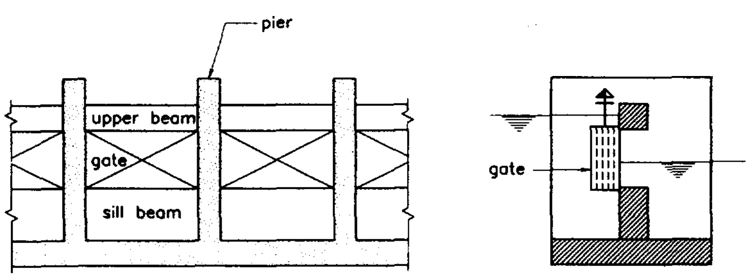


Fig. 12.4.1 Schematization of the Barrier

Roughly two methods of dividing the barrier into pre-fabricated elements can be distinguished. The first method is to fabricate all 66 concrete frames as monolithic units to be subsequently placed in position in the channel. The second method divides each frame into smaller fabricated components (viz. piers, sill beam and upper beam), all to be assembled in the channel (figure 12.4.2).

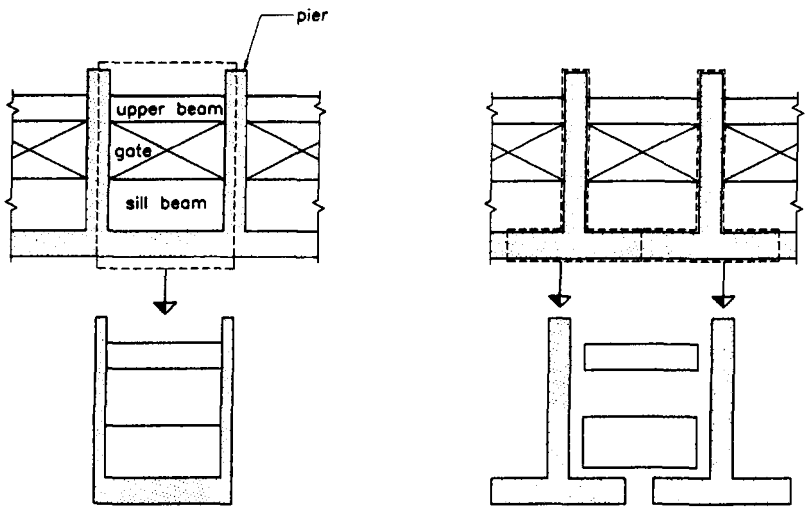


Fig. 12.4.2 *Prefab method 1 (left), characterized by a joint a the pier and prefab method 2 (right), characterized by a joint between piers, upper beams and sill beam.*

Method 1 is attractive, because geometrical deviations when placing the frame, and/or an unevenness of the foundation bed will not have any influence on the tolerances between pier and gate. As a result the eventual functioning of the gates is unaffected (figure 12.4.3). This is in contrast to method 2, where geometrical deviations when placing the piers, and/or an unevenness of the foundation bed will influence the shape and the dimensions of the frame. If this is not controlled, difficulties may arise in the functioning of the gates (figure 12.4.4). Self-evidently in the pre-design stage method 1 was one of the alternatives. This method, however, calls for large units. The corresponding foundation problems and costs were the most important reasons why this alternative was rejected. The choice of method 2 implied however, that the composition and the function of the barrier strongly depends on geometrical deviations.

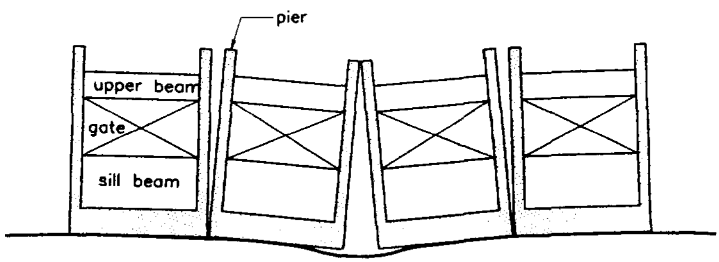


Fig. 12.4.3 Method 1: Influence of the unevenness of the bed surface and placing the piers on geometry.

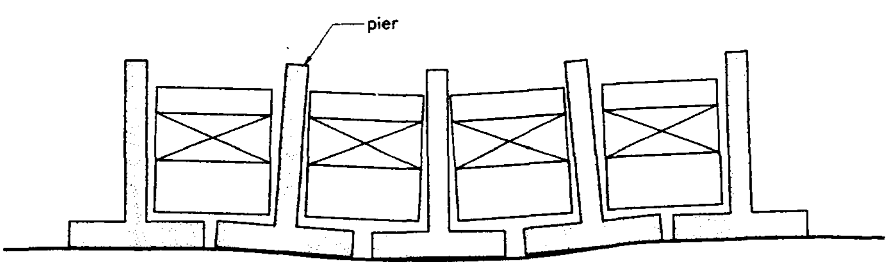


Fig. 12.4.4 Method 2: Influence of the unevenness of the bottom surface and placing the piers on geometry.

An analysis of the inherent problems could be divided into the following points, which will be explained in the next paragraph.

- tracing of causes influencing the good fitting of the parts;
- determination of the assumptions required for the assembly and for assessing of any deviations;

- determination of the tolerances and deformations;
- examining the influence of the measuring procedures and of the sequence of implementation;
- determination of the inspection procedures during construction;
- stock-taking of the measurements that are available in the case of unfavourable results.

12.5 The dynamic meta-control model for goal-control using the aspect-system geometry

12.5.1 Causes of geometrical deviations

As mentioned in the previous paragraph, the prefabricated parts of the construction were: (1) foundation mattresses, (2) piers, (3) sill beams, (4) upper beams, (5) the box girder bridge, (6) the capping units, and (7) the movable gates (figure 12.5.1).

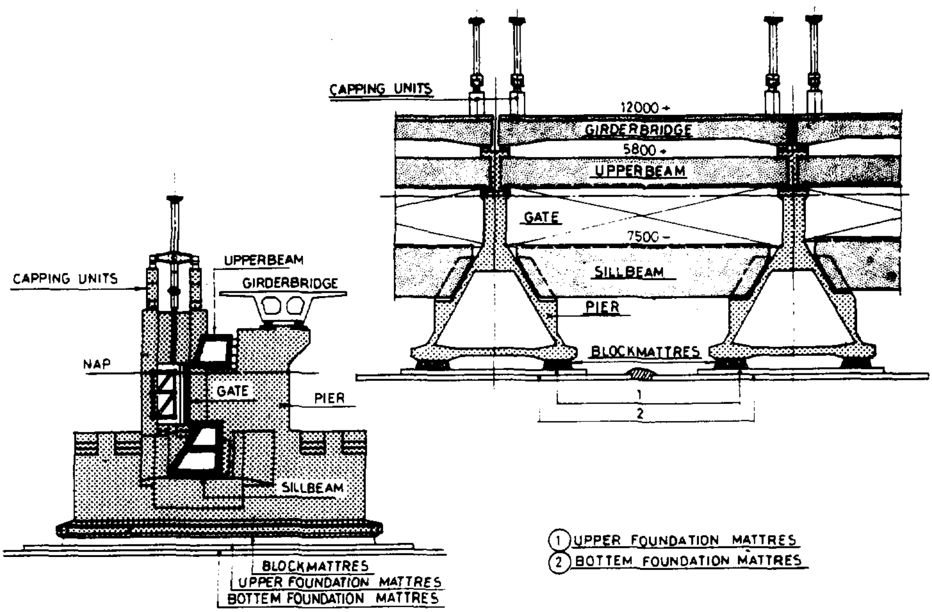


Fig. 12.5.1 The prefabricated parts of the SSBES

When composing these parts in order to realize the whole system, the following connections were critical:

- the position of the foundation mattresses with respect to the piers;
- the connection of the sill, upper beams and the traffic deck with the pier;
- the guideways for the gates let into the pier.

Because the gates had to fit in both closed and lifted position, it became apparent that the guideways for the gates on the piers were the most critical geometrical factor. The fitting was affected by the geometrical deviations of the pier and the gate with respect to their theoretical positions. The most important geometrical deviations are observed in the y-z plane and were caused by (figure 12.5.2):

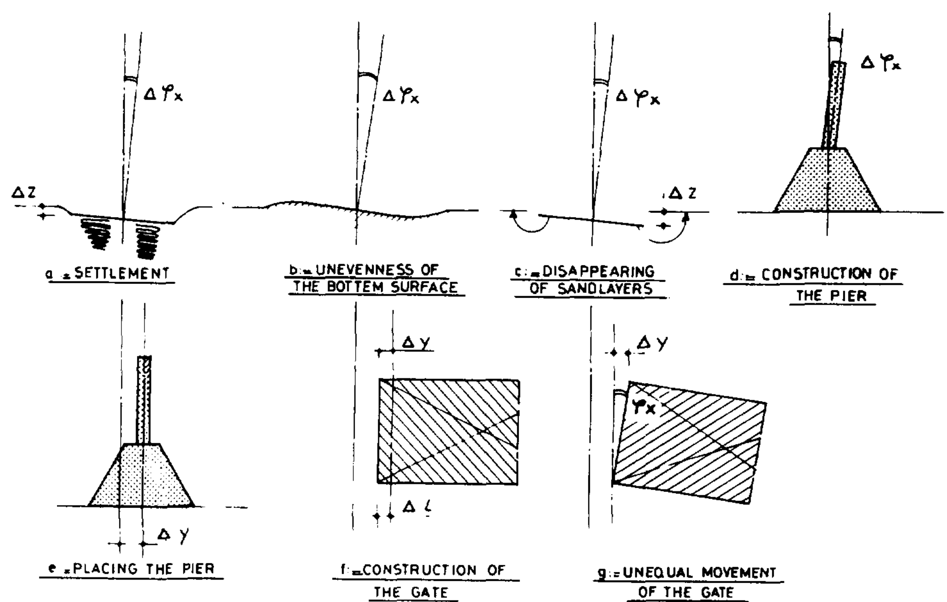


Fig. 12.5.2 Most important causes of variation of dimension in z-y plane.

A. *Deformations of the subsoil.* This depends on the decomposition of the soil and the rate of compaction.

B. *The unevenness of the foundation.* For constructive and safety reasons, two filter mattresses are needed. It could not be expected that the surface of the mattresses in all cases show enough evenness to meet the tolerance criteria. Therefore, two block-mattresses, made as a reverse moulding, were fitted on the spot of the bearing plates. The remaining unevenness was mainly caused by the geometrical accuracy in the determination of the reverse moulding.

C. *Washing out enclosed sand layers.* Despite the construction method it was not entirely excluded that sand will remain between, and on the filter mattresses. These sand layers could be washed out at a later stage and would have caused settlement and/or rotation of the piers.

D. *Manufacturing errors in the piers.* The shaft with the guideways had to be perpendicular to the mean plane through the underside of the bearing plates of the pier. In the determination of this plane, inaccuracies could have been observed, caused by the usual construction errors (swelling up, adjustment and deformation of the formwork) during construction of the pier, and settlement of the subsoil.

E. *Installing the piers in the channel.* The accuracy of placing was determined by any geometrical errors in fixing the pier, by any adjustment error of the anchorage system and by the motions of the piers induced by current and/or waves.

F. *Unequal movement of the gates.* The gates are suspended on both sides and driven independently. Because of the chosen hydraulic cylinder drive, it is not possible to move the suspension points synchronically.

12.5.2 Assumptions for the dynamic geometrical meta-control model

When designing constructions that are sensitive to geometric deviations, it is necessary to determine a number of design assumptions. The following assumptions were determined:

- the occurring geometrical deviations can be described with a normal distribution, with the characteristic parameters μ and σ;

- combination and assessment of the geometrical deviations takes place within 95 % reliability boundaries that is to say $\mu + 2\sigma$-values. These boundaries will be used as tolerance boundaries;

- combination of geometrical deviations is effected according probability theory;

- the total tolerance for the gate bearing is divided into two parts. The first part is reserved for geometrical deviations that may occur in the construction and installation phases. The second part is reserved for geometrical deviations that may occur in the operational phase, after commissioning of the barrier. This subdivision is necessary because at the moment of commissioning every gate of the Barrier should be able to move with a certain degree of reliability. This can be seen as a performance requirement at the time when the completed barrier is handed over;

- in the elaboration of the design, endeavours are made to render the tolerances in the gate bearing as large as possible, in order to restrict the tolerances as little as possible for the processes still executing offshore. However, enlarging the tolerances in the gate bearing is limited for two reasons: (1) the technical limits set to the manufacturing of these high quality bearings with respect to the very high demands of evenness and (2) the limited dimensions of the pier due to the admissible lifting weight of the pier and because of the minimum size of the cross-sectional area of the channels.

12.5.3 The dynamic geometrical meta-control model

The tolerance boundaries for the processes causing geometrical deviations were determined by: (1) the design assumptions, (2) the measuring procedures and (3) the adaptation to the implementation. To this end, the tolerance boundaries were optimally adjusted according to discipline, commensurate with what can be achieved from both the technical and the economic point of view. In consequence big differences in absolute sense between the tolerance boundaries of the different processes were observed. For the most important processes, the tolerance boundaries are given in table 12.5.1. The boundaries given in this table are expressed with respect to an orthogonal framework will origin in the bottom of the pier in the heart of the base slab. Not only the tolerance boundaries influencing the fit of the gate are given, but also boundaries influencing other less critical fits, like the concrete elements between the piers, and the connection between the foundation mattresses, which is situated between the piers. From this table it can be seen that the contribution of the offshore processes dominated the other processes (for example laying mattresses and placing the piers).

	Δ_x	Δ_y	Δ_z	$\Delta\phi_x$	$\Delta\phi_y$	$\Delta\phi_z$
implementation phase	± 25	± 25	± 25	± .6	± .3	--
construction of piers	--	± 20	± 20	± .4	--	--
construction of gates	±1000	±1000	± 95	± 9.3	± 3.7	± 20
placing upper mattresses	±1000	± 650	± 200	± 5.2	± 2.6	± 14
placing block mattresses	± 300	± 300	--	--	--	± 4.2
placing piers						
operational phase						
soil deformations	0	± 45	± 58	± 1.2	± 2.9	± .3
washing out of sand layers	--	--	± 50	± 2.8	± 1.4	--
unequal movement of a gate	--	--	--	± 3.7	--	--

Table 12.5.1 Tolerance boundaries for most important partial processes (mm and mm/m).

To give an impression of what the tolerance boundaries of the individual partial processes meant to the fit of the gates, these tolerances are transposed to a point of reference on the pier. For this point of reference the heart of the gate guideways is taken at the MSL-level for a pier with a construction depth of 30 m below mean sea level (figure 12.5.3).

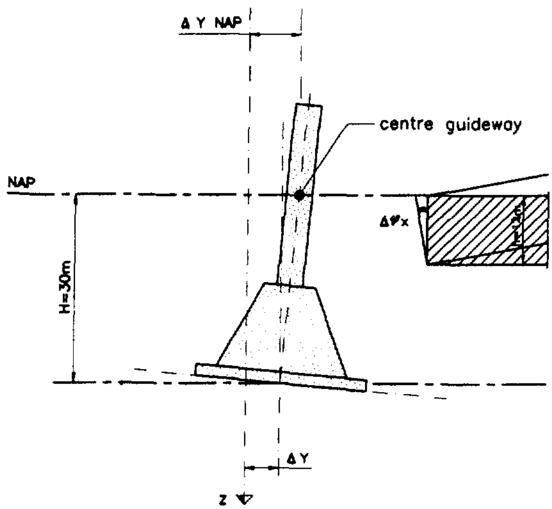


Fig. 12.5.3 Geometrical variations at the centre of guideway

Only the most important tolerance boundaries in the y-z plane are considered.

- *Construction stage*

  * in consequence of the unevenness of the foundation bed:
    $\Delta y_{MSL} = \mu.\Delta y = 30 \;.\; 5.2 = 156$ mm

  * in consequence of piers:
    $\Delta y_{MSL} = 300$ mm

- *Final stage*

  * in consequence of deformations:
    $\Delta y_{MSL} = H \;.\; \Delta\phi_x = 30 \;.\; 1.2 = 36$ mm

  * in consequence of the washing out of the sand layers:
    $\Delta y_{MSL} = 30 \;.\; 84$ mm

  * in consequence of uneven walk movement of the gates:
    $\Delta y_{MSL} = 12 \;.\; 3.7 = 44$ mm

The contributions to both the construction and the final stage may be collected and are assumed to be uncorrelated, except for the contribution to the uneven movement of the gates.

Hence, in the construction stage a total displacement of:

$$\Delta y_{OD} = \sqrt{300^2 + 156^2} = \pm 338mm$$

and in the final stage of:

$$\Delta y_{OD} = \sqrt{36^2 + 84^2} + 44 = \pm 135mm$$

must be taken into account.

Only for the tolerances mentioned above there has to be a width of the gate guideways of 2 x (338 + 135) = 946 mm. This width has yet to be enlarged by the required constructive bearing width due to the influences of neglected tolerances in consequence of the transposition of the problem to one point in the x-z plane.

Determination of the required width in this way gave an unrealistic result. It was therefore necessary to adapt the construction and dimensioning procedures to reduce the width of the guideways.

12.5.4 Construction procedures aimed at reducing tolerances

Since the implementation was based on the assembling of prefabricated parts in a limited time available for this purpose, the measuring had to be done with respect to an absolute frame of reference. This implied that in the prefabrication of the elements the tolerances of these elements had to include deviations resulting from the placing of the piers. In the previous section it is already demonstrated that this would have led to an unacceptable width of the gate guideways, particularly as a result of the unevenness of the foundation bed and also because of the deviation due to the placing of the pier.

However, the time required for the assembling of all parts of one location of the pier was relatively long. The numerous manoeuvres in the channel with vessels required long anchoring distances between them. For this reason, i.a. the total construction time after the placing of the pier up to the finished work took a number of years. This offered the opportunity of carrying out measuring procedures, so that major part of the geometrical deviations in the length of the gates and the concrete elements could be corrected.

In a construction sequence such as placing the piers, measuring their position, building and placing the gates, the production process of the gates is in direct dependence on the process of placing the piers. Because of the production time required for erecting the gates, it was impossible to start building them from scratch after only the dimensioning had been carried out. Hence, a way of execution was chosen in which every gate was constructed from one middle section of constant length and two variable end sections. The determination of the eventual length was materialized after the placing of the piers and as briefly as possible before assembly. For constructive reasons, adaptations of the length were limited. The maximum variation had to be determined beforehand. The tolerance boundaries, which had been chosen in this case, originated from the expected geometrical deviations up to the measuring of the pier positions. In real practice the correction in the gates had a maximum of ± 850 mm.

For the same reason that applied to the gates, it was necessary to determine the required length of the concrete elements after placing the piers. Just like the gates, the sill beams were prefabricated in sections.

A middle section with constant length and prismatic cross-section was made independently of the placing of the piers. After the piers were placed and secured the head sections were constructed. In all cases endeavours were made to carry out measuring as late as possible in order to eliminate the occurring deviations as much as possible. The remaining tolerances have been taken into account in the further details of the bearings and recesses in the way described above. In real practice this implied that measuring the sill beams and the bridge girder had taken place immediately after placement of the piers and the upper beams and simultaneously with the gates.

12.5.5 Inspection procedures during construction

In the design stage some assumptions on the fitting of the different parts were defined. The most important assumption referred to what was implemented, namely the assumption that occurring geometrical deviations satisfy the normal distribution with the assumed and accepted mean values and standard deviations. During the implementations it was important to determine the distribution functions of the observed deviations and to compare these with the "a priori" expected function. In view of the low number of realization, this was done with the aid of the theory of minor random inspections. A difference between the "a postiori" stated standard deviation, and the "a priori" expected value may give rise to correction. From a statistical point of view, a check of real value parameters to the mean values and the standard deviations is enough. If all values determined "a postiori" are equal to or less than the values expected in advance, their tolerance boundaries will be exceeded only in 5 % of the piers. However, there were a few reasons why it was desirable to have rejection limits fixed per action and per partial process.

- For given distributions of the partial processes, the probability of the gates and the concrete elements that do not fit is reduced.

- If the realized values satisfy a distribution with a much larger standard deviation, this would not be established in time with statistical methods. In this case fixed rejection limits prevent such deviation from influencing the definite results (the fit) too strongly.

- Fixed rejection limits keep up the discipline.

Because every partial process could not be inspected separately (e.g. measuring processes) it was necessary to have an inspection in which a number of partial processes were checked together.

Eventually the fitting of the gate, including the expected geometrical deviations in the operational stage was a test for all foregoing execution processes.

12.5.6 Measurements in case tolerance boundaries were exceeded

Regarding the presented design assumptions and testing procedures it could be expected that the realization of partial processes would exceed the fixed rejection limits. In case these limits were exceeded, the implementation was rejected and the process repeated. However, during implementation it was also possible to test whether the design assumptions were satisfactory. Deviations with respects to these assumptions could induce special measures for correction. These measures were divided into measures taken during the implementation and during the operational stage.

Measurements taken during the implementation

If the actual distribution of the realized values deviated from the previously estimated values, the following measures were foreseen:

1. adjustment of the examined process;
2. adjustment of the following processes;
3. adaption of the rejection limits of the examined process;
4. adaption of the rejection limits of the following partial processes;
5. acceptance of the loss of quality during the implementation stage and taking measurements in the operational stage after commencing.

An adjustment of the partial processes implied other working conditions or work procedures. In case adaption of the special rejection limits is chosen, the probability of rejection increases for equal working conditions. Then the number of repetitions increases. Both adaption of the working conditions and the additional repetition of the partial process have their consequences in planning and cost. The optimum measurement was to be determined by a risk analysis.

Measurement taken during the operational stage

The actual influence of some partial processes such as compaction of the foundation and washing out of the sand layers could only be observed in the operational stage after the first storms lead to a closing operation.

In case of unfavourable results, the following measures were considered. These measures referred to the fitting problems of the gates:

- enlarging the tolerance field of the gate guideways width by permitting the gate bearing gliding over the bolt holes (figure 12.5.4), meaning extra maintenance and a quicker replacing of the bearings;

- if disassembly was still possible, adjusting the gate to the right length and/or adjusting the bearings to the slope of the piers;

- if disassembly was not possible (the piers inclined too much toward each other) then the gates have to be burned off, and replaced by new ones.

For the concrete elements constituting upper beam and bridge girder, the following measures were envisaged:

- jacking up the beams which allows the rubber bearings to relax;
- replacing or exchanging the elements.

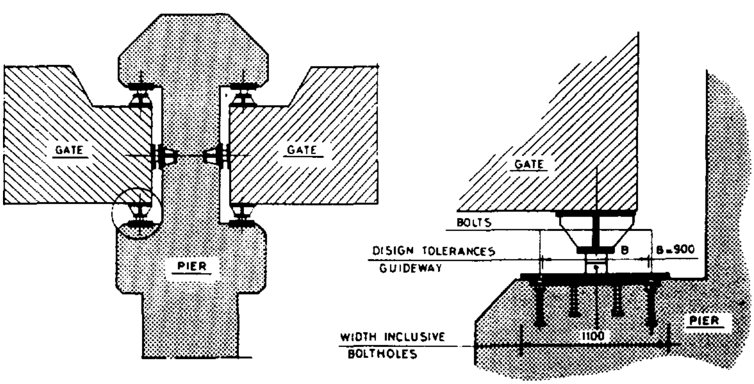


Fig. 12.5.4 Bearing of the gate and guideway on the piers

12.5.7 Evaluation

The dynamic meta-control model for the geometrical control of the prefab sub-systems of the Storm Surge Barrier in the Eastern Scheldt, provided a continuous insight in the performance of the Storm Surge Barrier with respect to geometrical problems during all design and construct phases. The meta-control on one aspect, e.g. geometry only was sufficient, because the concept of the Storm Surge Barrier was a prefabricated construction, which could easily be decomposed into sub-systems. Therefore, other relevant aspect-systems such as stability, strength, etc. could be (and have been) coordinated at sub-system level. These sub-systems were: mattresses, piers, beams, girders, etc.The goal-control is schematically sketched in figure 12.5.5.

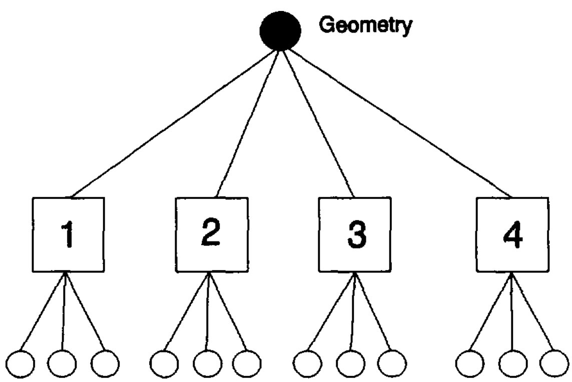


Fig. 12.5.5 The schematic goal control of the SSBES. 1 = mattresses, 2 = piers, 3 = beams, 4 = gates.

Intermezzo 12.2

With reference to the proposed control system for D&C of complex civil engineering systems, the goal-control with aspect-systems of the Storm Surge Barrier could have been conducted at two levels: (1) geometrical control of all prefab elements at meta-meta-control level and (2) meta-control level aimed at goal-control of the main sub-systems (foundation, piers, beams, sill, etc).
For two of these sub-systems (foundation and piers), two phase-systems could be distinguished: (1) temporary phase-system and (2) utilization phase-system. In consequence, the behaviour of the pier-foundation system could easily be described with four relation matrices of aspect-systems. For illustration purposes the set of aspect-systems are given for the utilization phase of the two sub-systems:

Piers

- Strength (overturning moment and forces)
- Stability (moment and forces);
- Stiffness (deformation);
- Weight (capacity lifting vessel);
- Maintenance (200 years lifetime);
- Geometry (foundation depth, center to center distance between two subsequent piers)

Foundation

- Strength (bearing capacity);
- Stability (gradients in filter);
- Stiffness (deformations);
- Maintenance (200 years lifetime)

Although the various types of measurements were developed in order to cope with geometrical deviations, it became apparent that in real practice, the processes were more accurate than was assumed. For instance, the block mattresses meant for correction of unevenness of the foundation mattress were hardly used (only a few times).

In all, the model was a sophisticated meta-control model and very helpful for the determination of the dimensions of all elements which were placed in between the piers.

12.6 Conclusion

The realization of the Storm Surge Barrier in the Eastern Scheldt was the largest and most difficult part of the Dutch Delta Works. The realization process was conducted in close cooperation between Client and Contractor, however, not arranged in a Design & Construct contract.

Although very complex, the whole system could easily be decomposed into complex sub-systems. In that way, the Barrier concept was divided into large complex prefab sub-systems (piers, foundation, gates, beams, etc), all to be installed at the mouth of the Eastern Scheldt estuary.

The working clusters corresponding with the above sub-systems were more or less autonomous clusters and remained unchanged during the various phases of the realization process which is, in fact, a confirmation of the decomposition of complex systems as proposed in chapter 10 when dealing with a Design & Construct task.

For the fitting of the prefab elements, referring to the only overall aspect-system at meta-level, a dynamic model was developed. This model was a very sophisticated and adequate coordination model, used during the whole realization process from pre-design phase until completion.

Notes

1. The general description is based on a joint publication of the contracting Joint Venture Dosbouw and the Ministry of Public Works., The Storm Surge Barrier in the Easter Scheldt, Dosbouw v.o.f., 1983.
2. Delft Hydraulics, "The Storm Surge Barrier in the Eastern scheldt" in Hydro Delft, no 77, 1989.
3. The description of the meta-control model is mainly based on a contribution to the Proceedings of the Delta Barrier Symposium, Rotterdam, 13-15 October 1982, by: Graaf, F.F.M. de, Surveying, Dimensional deviations and tolerances in the assembling of the construction elements.

13. CASE STUDIES: THREE DEMONSTRATIONS OF THE PROPOSED CONTROL-SYSTEM

13.1 General

The case studies to be presented in this chapter comprise three separate show cases in order to demonstrate the working principle of the proposed control-system. The show cases refer to the control of the consequences of a wrong problem perception at the start of a D&C task, resulting in a differential normative performance of solution. In all three show cases, the Contractor reached the actual normative performance of solution. However, due to the Fixed-Price D&C contracts, the D&C processes were certainly not efficient (see also chapter 8 for a general description of the present D&C situation). The extra efforts needed, were claimed from the Client. The purpose of these showcases can be obtained by comparing the procedures followed in the actual situation with the procedures which would have been followed with the proposed control-system.

The first showcase refers to the unexpected instability of the gates during the floating situation (vertical positioning) of the SSBNW (see also paragraph 9.6). A comparison is made between the way the problems are actually solved and how it could have been done with the proposed control-system.

The second showcase refers to the increase of loads on the gates of the SSBNW due to a better modelling of the system. It is shown how easily a financial compensation can be established with the proposed control-system.

The third showcase refers to the difficulties of the installation and subsequent offshore completion of the Ekofisk Protective Barrier (see also chapter 11). A comparison is made between the way the actual claim has been composed and how the proposed control-system could have been used for the claim.

13.2 Showcase 1: the instability of the floating gates of the SSBNW(1)

13.2.1 Description of floating stability problems

As mentioned in chapter 9, a few weeks prior to contract award, the auxiliary gates in the main gates of the Storm Surge Barrier were removed in order to reduce costs (approximately Dfl. 15 million including all effects(2)).

In the orientation phase, the floating situation with the auxiliary gates was extensively checked on stability in the Delft Hydraulic Laboratory. The situation without auxiliary gates was not checked on stability. The removal of the auxiliary gates from the concept was considered acceptable since the anticipated problems were perceived to be solvable with geometrical adjustments.

This perception was based on a simple two-dimensional translation wave model (see figure 13.2.1). As can be seen in this figure, an infinitesimal downwards displacement leads to a reduction of the gap (G) between sill and underside of the gate. This initially leads to a reduction of discharge through gap G, inducing two translation waves with height dh at both sides of the gate (+dh at the seaside and -dh at the riverside). These translation waves increase the existing head difference over the gate with 2 x dh, leading to larger current velocities through gap G. This means that the under-pressure at the underside of the gate will be larger and that the gate will immerse further. Consequently, the initial displacement is amplified. Such a situation is defined as being instable. The amplification is counteracted by width B of the gate at the water surface. The larger B is, the larger the counter action will be. B should not be too large as this would imply the de-ballasting capacity being too large during the lifting of the gates for the opening procedure. Extra de-ballasting capacity would have been expensive. In all, the stability phenomenon was perceived to be a simple optimization problem.

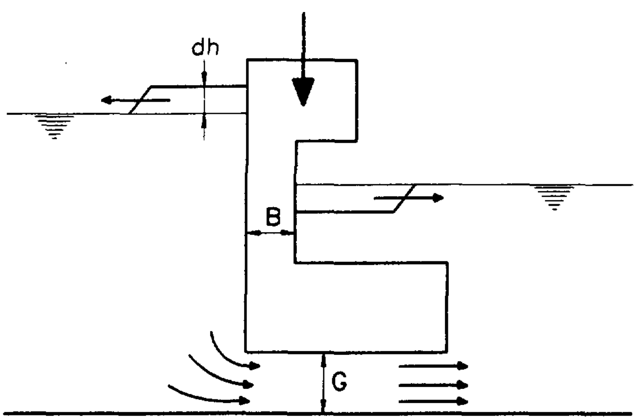


Fig. 13.2.1 *Two-dimensional instability problem. A downward displacement reduces the gap between gate and sill, inducing translation waves which, in turn, increase the head difference over the gates and result in larger flow velocities under the gates. This causes extra under-pressure, amplifying the initial downward displacement. The amplification is counteracted by width B.*

However, the actual situation was totally different from the perceived situation. In fact, the dynamic behaviour had a three-dimensional character. A translation wave across the Nieuwe Waterweg was induced by small displacements of the gates, being a short cut of wave energy generated by the moving gates (see figure 13.2.2).

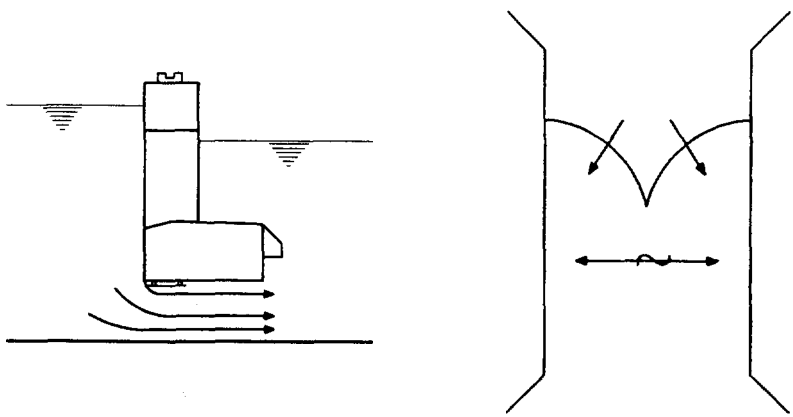


Fig. 13.2.2 *Three-dimensional stability problem. The waves, induced by initial instability of the gates will be short-circuited by a sanding wave across the Nieuwe Waterweg. Together, the abutments and gates formed a more or less closed dynamic system driven by the head difference over the gates.*

The working area of the gates in which instability was not allowed is a set of combinations of head difference and gap G. Each isoline has a certain probability of occurrence. The reserved probability of occurrence was 10E-6 (according to the fault-tree philosophy as described in chapter 9) and the corresponding isoline of head difference/gap combinations is indicated in figure 13.2.3.

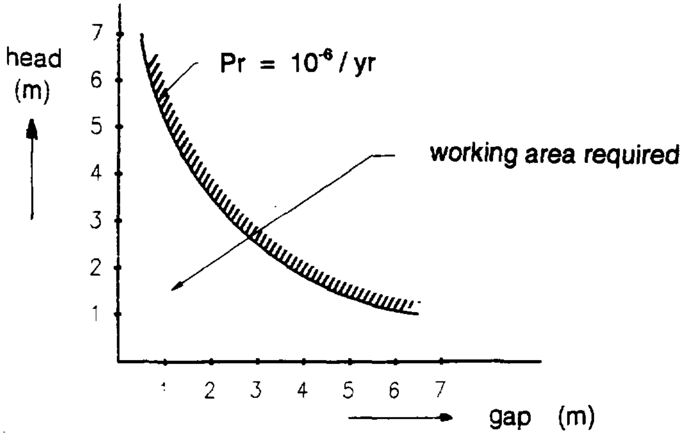


Fig. 13.2.3 *The reserved working area for the gates, being the area above the 10^{-6} isoline of combination of head differences and gap between the underside of gates and topside of the sill.*

However, the model tests showed that the isoline of head-gap combinations which yielded instable behaviour of the gates, were inside the working area (figure 13.2.4).

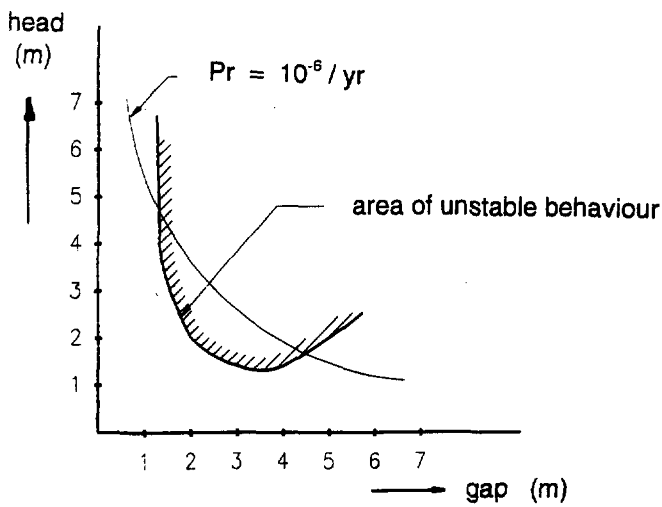


Fig. 13.2.4 *Isolines of unstable behaviour showing that the unstable behaviour at one point occurred with a loadcase being only 50 % of the required loadcase.*

13.2.2 The solution for floating stability problem and claim for additional cost

Model tests showed that extra buoyancy at the sea side of the gates solved the problem adequately, but since such a solution would induce extra costs for dock and associated sub-systems, it was decided to find solutions within the geometrical concept(3). In other words, the outer dimensions of the gates were fixed. The long way to the solution is roughly sketched in figure 13.2.5. The total time involved with research and development was approximately 3.5 years. However, the time schedule for the project was extended with only one year, causing overlaps of design phases and construction phases.

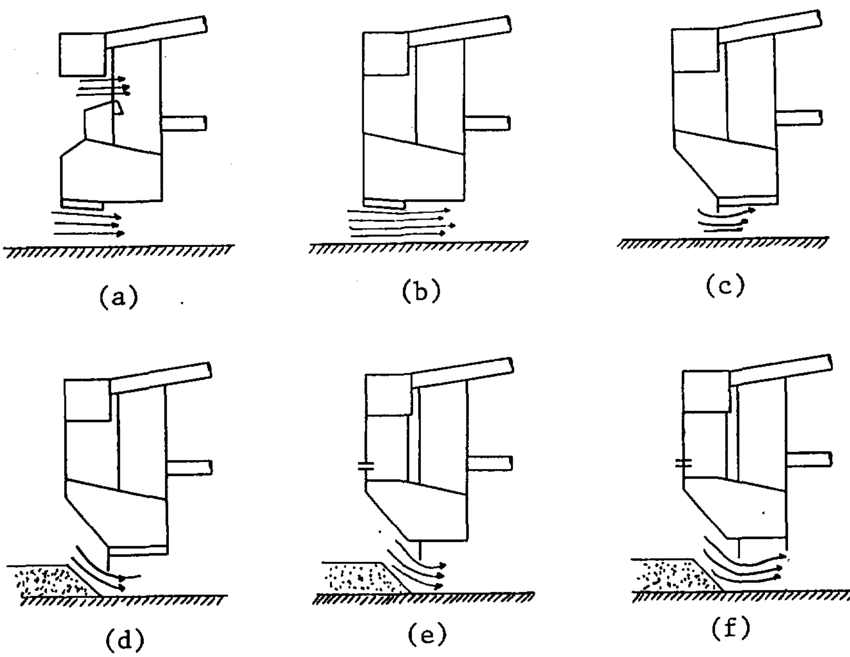


Fig. 13.2.5 *The problem solving process of the instability of the gates. (a) old concept, (b) pre-contractual change of concept, (c) adjustment of bottom profile and introduction of skirt, (d) higher skirt and introduction of perforated wall (improvement short-term dynamic behaviour without influencing ballast capacity), (e) change of skirt/skirt position and (f) introduction of second skirt.*

In 1993, three years after the start of the project, the Contractor claimed a large amount of money from the Client for compensation of the additional work needed to solve the stability problems. The precise sum cannot be given here (see note 2). However, the claimed sum was in any case more than twice as much as the costs of the gates. The reason that the extra money, needed to solve the stability problems, is at least twice as much as the costs of the auxiliary gates is caused by the choice for small adjustments of one particular sub-system of a complex system without an adequate control model (see chapter 9). This inevitably leads to large cost overruns.

Anyway, for the demonstration purpose of this example, it is assumed that the claim was exactly twice the cost of the gates, that is Dfl. 30 million. The rate at which the Client accepted the claim cannot be given (see note 2). However, the Client did accept the claimed sum to a large extent. In this example it is assumed that the Client compensated Dfl. 20 million.

13.2.3 How the proposed control-system would have performed(4)

In contrast to the limited possibilities available to participants in the Fixed-Price contractual situation, the proposed control-system probably would have given room for better solutions. At the time instability began to show, the Client would have become meta-controller of the realization process. For goal control, both parties would have used the relation matrix of aspect-systems for the phase system "vertical positioning" in order to transform the individual values of aspect-systems in an overall performance (see annex 10 for the composition of the relation matrix as given in table 13.2.1):

	Str.	Sta	Sta	Geo.	Cap.
Strength	1	0	0	1	0
Floating Stability	0	1	0	1	0
Stability Riverbed	0	0	1	0	0
Geometry Gate	1	1	0	1	1
Capacity Deballasting	0	0	0	1	1

Table 13.2.1 Relation matrix of aspect-system of the phase-system vertical positioning

The contractual normative performance of solution for the phase-system "vertical positioning" is obtained by multiplying the unit vector (just "ones") with the relation matrix of aspect-systems:

$$\begin{pmatrix} 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 \end{pmatrix} \times \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 2 \\ 2 \\ 1 \\ 4 \\ 2 \end{pmatrix}$$

The length of the vector representing the contractual normative performance is:

$$|P_0| = \sqrt{2^2 + 2^2 + 1^2 + 4^2 + 2^2} = 5.38 \qquad (13.2.1)$$

In the real situation, the instability occurred already with 50% of the isoline of loads belonging to the working area (see figure 13.2.4). Consequently, the value of the aspect-system "floating stability" in the aspect-system matrix becomes 2 instead of 1 (the changed aspect-system value is indicated in the marked area).

$$\begin{pmatrix} 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 \end{pmatrix} \times \begin{pmatrix} 1 \\ \boxed{2} \\ 1 \\ 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 2 \\ 3 \\ 1 \\ 5 \\ 2 \end{pmatrix}$$

The length of the actual normative performance of solution vector is:

$$|P_a| = \sqrt{2^2 + 2^2 + 1^2 + 4^2 + 2^2} = 6.56 \qquad (13.2.2)$$

Hence, the relative differential normative performance of solution is:

$$\left(\frac{6.56}{5.38} - 1\right) * 100 = 22\% \qquad (13.2.3)$$

The total cost of the vertical positioning phase system is approximately 50 million guilders (see annex 10). In the proposed control-system with the Fixed-Price-Performance-Reimbursable Contract, the "perception risk" can now be quantified and presented to the Client for meta-control:

$$(P_{DC} - dP_{DC}) * E = Eo * \frac{P}{P_o} * \left(1 + \frac{dP_o}{P_o}\right) \qquad (13.2.4)$$

The Client would then have the following control possibilities (actions) available:

A. Reduction of the performance of solution

1. enlargement of width B (see figure 13.2.1), leading to a longer opening procedure which can be accepted under certain conditions;

2. relaxation of the defined working area, which is possible since the loadcase is rather strict with negligible probability of exceedance (10E-6/year, see paragraph 9.7).

B. Put more efforts into the realization process

1. re-introduction of the auxiliary gates, being an attractive control action since the effect on stability is exactly known;

2. enlargement of width B and installation of more de-ballasting capacity;

3. small adjustments associated with a lot of research.

C. Some combinations of A and B

1. A2 combined with B2

2. A2 combined with B3

For simplicity, the combinations of A and B will not be explored further in this example.

In case the Client is willing to adjust the goal, the total sum to be provided by the Client can be limited when compared to the money to be spent in order to solve the stability problems without goal adjustment.

It is assumed that the Client is not willing to adjust the normative performance of solution. Then, with $P/P_o = 1$, the Client's control variety (given in equation 13.2.1) is changed in:

$$(P_{DC} - dP_{DC}) * E = E_o \left(1 + \frac{dP_o}{P_o}\right) \qquad (13.2.5)$$

The assumption that the Client does not change the goal implies that the actual normative performance should be reached. In that case, the Contractor would have received additional efforts for solving this particular problem:

$$E_o \cdot \frac{dP_o}{P_o} = 0{,}22\ E_o \qquad (13.2.6)$$

In chapter 10, it is recommended to express the additional efforts in money only. The costs needed for the realization process of the vertical positioning system is approximately Dfl. 50 million (C_0). Hence, the Client should additionally provide:

$$0.22E_o = 0.22C_o = Dfl.\ 11\ million \qquad (13.2.7)$$

After providing this additional sum, the Client would have withdrawn as meta-controller and would have delegated the control of the realization process once more to the Contractor. The Contractor would, at that moment, have available to him a control variety with the following three actions:

1. re-introduction of the auxiliary gates, solving the stability problems immediately without uncertainties, delays and additional investigation.

2. enlargement of width B and the installation of extra de-ballasting capacity, being a fundamental solution, however, containing uncertainties and giving additional investigation;

3. small adjustments, not being a fundamental solution, containing a number of uncertainties and associated with substantial R&D efforts.

As explained already, the third action which was actually chosen and which is, in fact, a logical consequence of the present D&C situation, did cost the Client Dfl. 20 million (accepted claim) and the Contractor Dfl. 10 million (real costs minus accepted claim). Moreover, the project duration was extended with one year. For this comparison, it is assumed that the costs of extra de-ballasting is approximately Dfl. 10 million. The other two actions are compared with this third (actual) action. The results are expressed in costs only and are given in table 13.2.2.

Action	Client	Contractor
1.	-11	+11 -15
2.	-11	+11 -10
3.	-20	-10

Table 13.2.2 Cost comparison of the three decisive actions in mln Dfl.

An evaluation of the first two actions with respect to the third action (which was actually carried out), is given in table 13.2.3.

Action	Client	Contractor
1.	saving Dfl. 9 million no delay	saving Dfl. 6 million no uncertainties
2.	saving Dfl. 9 million no delay	saving Dfl. 11 million extra R&D required

Table 13.2.3 Consequences of goal control with the proposed control system with respect to the actually followed scenario.

13.3 Showcase 2: increase of loads SSBNW

13.3.1 General description

During the early design phase of the SSBNW it became apparent that the design load case during the phase-system "functioning", was increased with 10 % regarding the design load case on the contractually agreed concept. The consequences of this increase were outlined by a claim team during 2 years by summing up all extra efforts needed to cope with these consequences. This resulted in a claim for additional money.

13.3.2 Establishment of financial compensation with the proposed control-system

With the proposed control-system, the composition of a claim is very simple. Four aspect-systems are distinguished for the phase-system functioning : (1) strength of sub-systems (gates, frameworks, ball & sockets, foundation blocks), (2) stiffness of sub-systems, (3) stability of sill (including bedprotection) and (4) geometry (related to the leakage requirement).

The interactions between the aspect-systems can be established by investigating the physical implications of a change. A positive interaction between aspect-system A and aspect-system B means that in case aspect-system A is changed in a positive direction, then aspect-system B is changed automatically in a positive direction. The interactions are as follows:

- strength interacts positively with stiffness (the stronger, the stiffer);
- stiffness interacts negatively with geometry (the stiffer, the less problems with leakage);
- stability does not interact with the other aspects;

Having established the interactions, the relation matrix of aspect-systems can be made:

	Str.	Str.	Sta	Geo.
Strength	1	1	0	0
Stiffness	1	1	0	-1
Stability Sill	0	0	1	0
Geometry	0	-1	0	1

The contractual normative performance of solution vector for this phase-system is obtained by multiplying the relation matrix by the unit aspect-system vector:

$$\begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 1 & -1 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 2 \\ 1 \\ 1 \\ 0 \end{pmatrix}$$

The length of the normative performance of solution vector is:
The 10% increase of the dominant load case requires an additional strength of 10%.

$$|P_0| = \sqrt{2^2 + 1^2 + 1^2 + 1^2} = 2.45 \tag{13.3.1}$$

The real normative performance of solution vector is established as follows:

$$\begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 1 & -1 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \boxed{1} \\ 1 \\ 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 2.1 \\ 1.1 \\ 1 \\ 0 \end{pmatrix}$$

The actual normative performance of solution vector is :

$$|P_a| = \sqrt{2.1^2 + 1.1^2 + 1^2} = 2.573 \tag{13.3.2}$$

It is assumed that the Client is not willing to relax the rather strict loadcases as a consequence of the full probabilistic design approach (see chapter 9). Hence $P/P_0=1$. Consequently, the relative differential normative performance is:

$$\left(\frac{2.573}{2.45} - 1\right) * 100 = 5\% \tag{13.3.3}$$

The total cost of this phase-system is approximately Dfl. 400 million. Consequently, the claim due to the increase of loads is 5 % of 400 million, that is Dfl. 20 million.

13.4 Showcase 3: the Claim situation of the Ekofisk Protective Barrier[5]

13.4.1 General

The design and realization process of the Ekofisk Protective Barrier was extremely complicated due to the complexity of the system to be developed and the very short time available. Like almost all projects of this type[6], in this case also, the Contractor claimed a substantial percentage (more than 30 %) of the lump-sum part of the contractual sum after finishing the project.
Amongst other items, the basis of the claim was:

- a change in the governing wave load case, which was caused by the wave trough of the design wave (once every 100 years). This load case, resulting in a split mechanism, was initially not recognized to be a governing load case but resulted in 10 % extra required strength.

- a change in the wave load on the Barrier Halves during the temporary phases offshore, revealed (twice as much as was indicated in the contract documents revealed with model lengths) and a soil condition on site (worse than indicated in the contract documents). Both items resulted in a reduced stability of the Barrier Halves in the temporary phase offshore, leading to substantial additional efforts (see chapter 11).

The Ekofisk claim was built up using a: (1) detailed, (2) technical, (3) event-consequence, and (4) down-top oriented approach, resulting in a difficult technical report, however, without correctly coping with all relations. The main objection against such a method for a D&C claim is that the two main risk components of a D&C task (perception risk and construction process risk) are mixed up. In that particular case, it is quite easy for the Client to show that claim is not correct. This also happened with the Ekofisk claim, leading to a disappointing settlement after arbitrage.

13.4.2 The offshore installation and completion

The most relevant facts of the offshore installation and completion are described in chapter 11. For the determination of the relation matrix of aspect-systems it is necessary to: (1) define the aspect-systems and (2) to establish the interactions.

The definitions of the relevant aspect-systems for the offshore installation and completion are given in table 13.4.1. A definition sketch of the aspect-systems is given in figure 13.4.1.

aspect-system	definition	item
strength	more strength = positive	joint construction
stability	more stability = positive	uncoupled halves
stiffness	stiffer = positive	foundation(7)
weight	more weight = positive	uncoupled halves
capacity	more capacity = positive	solid ballasting
geometry	more clearances = positive	connection structures

Table 13.4.1 Definition of aspect-systems

The interactions between the aspect-systems can be established by investigating the physical implications of a change. A positive interaction between aspect-system A and aspect-system B means that in case aspect-system A is changed in a positive direction, then aspect-system B is automatically changed in a positive direction.

- strength interacts negatively with on-bottom weight (more weight implies less efforts on strength);
- strength interacts positively with geometry (more clearances implies more efforts on strength);
- strength interacts negatively with stiffness (stiffer foundation implies less efforts on strength);
- stability interacts negatively with weight (more weight implies less efforts on stability);
- stability interacts negatively with stiffness (stiffer foundation implies less efforts on stability);
- weight interacts positively with capacity (more weight implies more efforts on capacity);
- geometry interacts negatively with weight (more weight implies more deformations, which implies more efforts on clearances);
- geometry interacts negatively with stiffness (stiffer implies less deformations, which implies more clearances);

This results in the following relation matrix of aspect systems (table 13.4.2).

	Str.	Sta	Wei	Geo	Cap	Sti
Strength	1	0	-1	1	0	-1
Stability	0	1	-1	0	0	-1
Weight	-1	-1	1	1	1	0
Geometry	1	0	1	1	0	-1
Capacity	0	0	1	0	1	0
Stiffness	-1	-1	0	-1	0	1

Table 13.4.2 Relation matrix of aspect-systems for the offshore installation and completion of the Ekofisk Protective Barrier

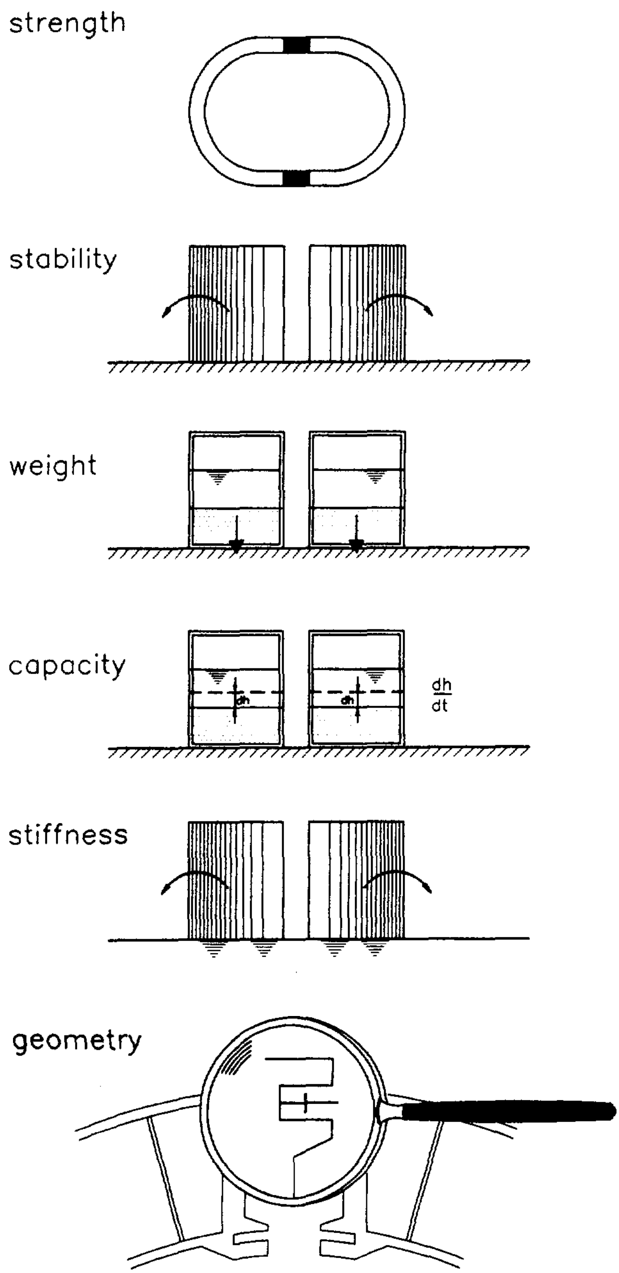


Fig. 13.4.1 Definition sketch of aspect-systems

The normative performance of solution vector is established by multiplying the relation matrix of aspect-systems by the vector of aspect-systems with unit values:

$$\begin{pmatrix} 1 & 0 & -1 & 1 & 0 & -1 \\ 0 & 1 & -1 & 0 & 0 & -1 \\ -1 & -1 & 1 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & -1 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ -1 & -1 & 0 & -1 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 0 \\ -1 \\ 1 \\ 2 \\ 2 \\ -2 \end{pmatrix}$$

Hence, the length of the normative performance of solution vector is:

$$|P_0| = \sqrt{1^2 + 1^2 + 2^2 + 2^2 + 2^2} = 3.74 \qquad (13.4.1)$$

The changes are:

- wave loads on uncoupled Barrier Halves twice as much, leading to stability problems in the temporary phases offshore.

- stiffness of soil under Eastern Barrier Half 10 % less than was assumed, leading to larger deformations than was assumed.

The actual normative aspect-system matrix becomes: (changes are indicated in the marked areas)

$$A = \begin{pmatrix} 1 \\ \boxed{2} \\ 1 \\ 1 \\ 1 \\ \boxed{1.1} \end{pmatrix}$$

The actual normative performance of solution is calculated as follows:

$$\begin{pmatrix} 1 & 0 & -1 & 1 & 0 & -1 \\ 0 & 1 & -1 & 0 & 0 & -1 \\ -1 & -1 & 1 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & -1 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ -1 & -1 & 0 & -1 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 \\ \boxed{2} \\ 1 \\ 1 \\ 1 \\ \boxed{1.1} \end{pmatrix} = \begin{pmatrix} -0.1 \\ -0.1 \\ 0 \\ 1.9 \\ 2 \\ -3 \end{pmatrix}$$

The actual normative performance of solution vector is:

$$|P_a| = \sqrt{0.1^2 + 0.1^2 + 1.9^2 + 3^2 + 2^2} = 4.08 \qquad (13.4.2)$$

The relative differential normative performance of solution is:

$$\left(\frac{4.08}{3.74} - 1\right) 100\% = 9\% \qquad (13.4.3)$$

Goal adjustment by accepting a smaller performance of solution than the normative performance of solution was not possible. None of the aspect-systems could be used for goal adjustment. Hence $P/P_0 = 1$.

With respect to the efforts, the estimated normative cost (C_0) of the provisions for the temporary phases offshore are 20 % of the total Fixed-Price of the contract:

C_0 temporary phase offshore is Dfl. 90 million (0.20 x 450).

The compensation to be claimed then is: 0.09 x 90 mln = Dfl. 8.1 million

With this compensation, the Contractor could have easily paid the measures to guarantee the extra strength, stability and geometrical clearances (see intermezzo 13.1).

Intermezzo 13.1

The compensation as described above is calculated with the proposed control-system with all associated conditions. One of these conditions is that the design period must be 1.5 year at least. Given the extremely short design period for the Protective Barrier, the rather substantial changes can not be considered normal design work. The compensation should therefore be more than the calculated compensation.

Another complicating factor was that the Client did not want to change the contractual "Key-concept" (see chapter 11). Given the changed context, such a curious meta-control of the Client has prevented the finding of an adequate solution and has caused disproportional cost overruns.

13.4.3 The changed loadcase

For the phase-system "utilization" of the Ekofisk Protective Barrier, the following relation matrix of aspect-systems can be distinguished, all referring to the completed Barrier: (1) strength, (2) stability, (3) stiffness, (4) weight (on bottom), (5) geometry (inner and outer diameter) and (6) maintenance.

The interactions between the aspect-systems are as follows:

- strength interacts positively with stiffness (the stronger, the stiffer);
- strength interacts positively with geometry (the larger the diameter, the more strength required);
- strength interacts negatively with maintenance (the stronger the concrete prestressing, the less the maintenance);
- weight interacts positively with stability (the more on-bottom weight, the more stability);
- geometry interacts positively with stiffness (the larger the diameter, the stiffer the barrier);

With the interactions, the relation matrix of aspect-systems can be composed (table 13.4.3):

	Str	Stab	Sti	Wei	Geo	Main
Strength	1	0	-1	0	1	-1
Stability	0	1	0	1	0	0
Stiffness	1	0	1	0	1	0
Weight	0	1	0	1	0	0
Geometry	1	0	1	0	1	0
Maintenance	-1	0	0	0	0	1

Table 13.4.3 Relation matrix of aspect-systems utilization phase

The normative performance of solution vector is calculated as follows:

$$\begin{pmatrix} 1 & 0 & 1 & 0 & 1 & -1 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 1 \\ -1 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 2 \\ 2 \\ 3 \\ 2 \\ 3 \\ 0 \end{pmatrix}$$

The length of the normative performance of solution vector is:

$$|P_0| = \sqrt{2^2 + 2^2 + 3^2 + 2^2 + 3^2} = 5.477 \qquad (13.4.4)$$

The real normative performance of solution vector is calculated as follows: (changed aspect-system is indicated with the marked area):

$$\begin{pmatrix} 1 & 0 & 1 & 0 & 1 & -1 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 & 1 \\ -1 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \boxed{1.1} \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 2.1 \\ 2 \\ 3.1 \\ 2 \\ 3.1 \\ -0.1 \end{pmatrix}$$

The length of the actual normative performance vector is:

$$|Pr| = \sqrt{2.1^2 + 2^2 + 3.1^2 + 2^2 + 3.1^2 + (-0.1)^2} = 5.625 \qquad (13.4.5)$$

The relative differential performance is:

$$\left(\frac{5.625}{5.477} - 1\right)100\% = 2.7\% \qquad (13.4.6)$$

The estimated normative realization costs for the phase system "utilization" of the Protective Barrier is 80% of the total lump-sum part of the contract. This is: 80% of Dfl. 450 million = Dfl. 360 million.

The compensation for the Contractor is: ($P/P_0 = 1$):

$$C_{additional} = E_0 \frac{dP_0}{P_0} = C_0 * \frac{dP_0}{P_0} \qquad (13.4.7)$$

$= 0.027 \times 0.8 \times 450$ mln = Dfl. 9.35 million.

The total "perception" claim of the realization process of the Ekofisk Protective Barrier as calculated with the proposed control-system would be:

Claim = Dfl. 8.1 million + Dfl. 9.35 million = Dfl. 17.45 million

13.5 Conclusions

Showcase 1 Floating stability of the gates of the Storm Surge Barrier in the Nieuwe Waterweg Rotterdam

Prior to contract awarding, the concept of the Storm Surge Barrier was changed in order to reduce costs (removal of auxiliary gates). Immediately after the start of the project, model tests revealed instable floating behaviour of the changed concept.

Due to the Fixed-Price contract, however, the Contractor was reluctant to investigate costly, fundamental solutions. Instead small adjustments were tested, eventually resulting in an extensive research program corresponding with disproportional extra costs, which were claimed from and accepted by the Client.

With this showcase it is shown that with the proposed control-system:

- a better solution would probably have been found;
- the Client would have saved a lot of money;
- the Contractor would have saved a lot of money
- the project would not have been delayed

Showcase 2 Changed loadcase of the Storm Surge Barrier in the Nieuwe Waterweg, Rotterdam

During the design period, detailed mathematical models revealed that the design loads on the Storm Surge Barrier exceeded the originally estimated loads on the contractual concept by 10%.

Two years were spent determining efforts needed to adjust the concept in order to withstand the changed loadcase. Using the proposed control-system, however, it is possible to determine those efforts correctly in a very short period of time.

Showcase 3 Offshore installation and completion of the Ekofisk Protective Barrier

Shortly after the start of the project, it became apparent that the wave loads on the Barrier, for both the temporary as well as the utilization phase, exceeded the initially estimated wave loads. Moreover, the bearing capacity of the soil was overestimated. Due to the Fixed-Price contract, Client and Contractor were at first not able to develop fundamental solutions. Nevertheless, these solutions were needed, leading to disproportional extra costs which were claimed from the Client.

With the proposed control-system the efforts needed for solving the perception problems mentioned above, are reimbursable. It is shown that these efforts can easily be calculated. It is also shown that a substantial amount of money would have been saved as fundamental solutions would have been searched for immediately.

Notes

1. This show case should be read in conjunction with chapter 9, giving a general description of the Storm Surge Barrier project in the Nieuwe Waterweg.
2. Precise cost figures can for several reasons (a.o. due to fact that it concerns an on-going work) not be given. The assumed figures however are not far beyond the true figures.
3. This is in accordance with the described present D&C situation (see also annex 6), in which the Contractor tries to stay as close to the contractual concept.
4. In this case study the working principle of the proposed control-system is demonstrated and therefore compared as good as possible with the way the control was done in the actual situation. It is noted that the decisions made in the actual situation must be seen in the actual context (organization and contract) of the project. With that respect the assumed freedom of decision making is certainly not present. For instance the re-introduction of the auxiliary gates is not only a technical and economical, but also a political decision.
5. This show case should be read in conjunction with chapter 11, giving a more general description of the Ekofisk Protective Barrier project.
6. Claims have been submitted for all five D&C projects in which the two largest Dutch civil engineering Contractors (HBG and KVS) participated (Dunlin A, Lac Nord de Tunis, Ekofisk Protective Barrier, NAM F3 Platform, Storm Surge Barrier in the Nieuwe Waterweg). The average contractual Fixed Price is Dfl. 350 million, whereas the average claim expressed in average percentage of the Fixed-Price is approximately 40%.
7. The stiffness of the foundation is determined by: (1) stiffness of soil, (2) rib penetration and (3) underbase grouting. The stiffness of the foundation therefore is considered a variable.

14. SYNOPSIS, CONCLUSIONS AND RECOMMENDATIONS

14.1 Synopsis

Control system for D&C

A simple and powerful control system for the realization of complex civil engineering systems with a D&C contract between Client and Contractor has been developed in this study.

Goal of D&C

The goal of D&C is the search for and the subsequent implementation of a solution for a problem. In fact, the goal of D&C is to take away the difference between problem and solution. The characterization of this friction is, however, neither complete, nor explicit and factually not correct. The reason is that in general the problem perception is subjective, relative and partial, whereas the solution is at best known in a rough conceptual form. The incorrect goal definition leads to an underestimation of the efforts needed for the D&C process.

Goal control concept of D&C

D&C must meet two criteria: (1) the solution should be effective and (2) the solution should be implemented efficiently. The rate in which these criteria are met is a measure of the quality of the D&C process.

Risk sharing principle

Given the goal concept and the incorrect goal definition, D&C induces risks for both Client as well as Contractor. For an optimal D&C process, the risk should be carried by the party best able to either control the risk or estimate the risk. In that way, "perception risks" are carried by the Client who controls the risks with goal adjustment. The "process risks" are carried by the Contractor who controls the risks with the productivity of his D&C process. The importance of the proposed control system is the possibility of goal adjustment.

Conditions for risk sharing principle

For the proposed risk sharing principle the following conditions must be fulfilled: (1) the goal at the start of the contract period is quantified (initially required performance of solution), (2) the actual required performance of the actual solution can be measured with respect to the initially required performance, (3) the actual performance can be adjusted and (4) the extra efforts needed for actual performance exceeding the initially required performance can be determined and made reimbursable.

Components of control system

The main components of the proposed control system are: (1) a simplification method of a complex system giving a compressed and correct insight into the overall performance and behaviour of the system, (2) a multi-level control model to be used for both goal coordination (effectiveness x efficiency) as well as structural coordination (relations between elements), (3) an organizational structure corresponding with the multi-level control system and coping with the changed (more interactive) roles of D&C participants and (4) a new type of contract.

Simplification of complex systems

A complex system is characterized by: (1) a large number of requirements, (2) a large number of non-simple relations between the elements, (3) non-correspondence between requirements and elements and (4) unpredictable behaviour when not simplified.
With the proposed simplification method a complex system is decomposed in four types of part-systems: (1) a decomposition aimed at the clustering of requirements resulting in a set of aspect-systems, (2) a decomposition aimed at the clustering of elements during design in order to handle relations between elements, resulting in design clusters (sub-systems), (3) a decomposition aimed at clustering of elements for construction, resulting in construction clusters and (4) a decomposition aimed at clustering of time, resulting in phase-systems. With these four part-systems, the system behaviour can be correctly described, being the main condition for goal control.

Goal control

Goal control is aimed at obtaining a satisfactory value for the product of effectiveness and efficiency. For a complex system the effectiveness can only be measured with respect to the total system. For each phase-system (for instance temporary or utilization phase), the set of aspect-systems represents the overall system behaviour on a long term basis which can be used for goal control. Aspect-systems must be: (1) as specific as possible, (2) as independent as possible and (3) as equal as possible with respect to scope and significance. For Civil Engineering systems, seven such aspect-systems are distinguished: capacity, stiffness, stability, strength, maintenance, weight and geometry. By taking into account the relations between these aspect-systems it is possible to measure any change in the performance of the total system, providing a tool for goal adjustment. Having available the overall performance, the efficiency part can be arranged according to the common cost-control and time-control methods.

Structural control

Structural control is aimed at maintaining the structure of the system, that is, the total set of relations between the elements of the system during the development work. For the clustering of elements, e.g. formation of design clusters, the number of relations inside the cluster are maximized whereas the relations outside the cluster are minimized. In that way, the elements inside the cluster can be changed freely on a short term basis, without influencing the overall long term behaviour/performance of the total system. The formation of construction clusters is based on similarity principles (location, material, etc.).

Organizational structure

The structure of a D&C organization is based on the meta-control principle. Meta-control takes over control in case the controller is incompetent or inadequate.
Starting at the lowest level, the design and construction engineers are controllers of elements. The structure of the system, given by the relation between elements, is controlled at a higher level (meta-control). Goal control of the Contractor is meta-meta-control. Finally the goal control by the client is considered to be meta-meta-meta-control and takes over control: (1) in case the contractual conceptual system does not provide an effective solution for Client's problem or (2) in case the Client wishes to change the initial goal.

In the corresponding organizational structure each level adds a particular control variety and corresponding authority. This reduces the *information transmission flow*, avoids bureaucracy and makes the control system work.

Contract type for D&C enabling the risk sharing principle

With respect to the contractual side of the control system a new type is introduced: the Fixed-Price-Performance-Reimbursement D&C contract (FIPPER D&C). Without taking into account non-quantifiable uncertainties, a fixed price is agreed for the D&C contract using the conceptual solution as a frame of reference. With a proportionality principle between performance and efforts, a change in the required performance of with respect to the initially required performance is made reimbursable.

The initially required performance of solution

The basis of the proposed D&C control system is the initially required performance of solution, which can be established with the set of quantified aspect-systems and the relations between the aspect-systems for each distinguished phase-system. In this respect the type of relations between the aspect-systems should be established: (1) totally independent, (2) conflicting and (3) concurring (physical implications). For each phase-system (for civil engineering systems at least two: temporary construction phase and utilization phase), the contractual normative performance of solution can be established by a linear vector transformation of the unit vector of aspect-system values (only "ones"). The transformation matrix is the relation matrix of aspect-systems.

Contractual efforts

Based on the contractual concept the efforts can be determined in the traditional way by estimating efforts for concrete, steel, labour, etc. These efforts consist of normative necessary cost (budget) and necessary time (time schedule). It is assumed that efforts in the proximity of the contractual efforts are proportional to the performance of solution. This assumption is rather essential for the proposed D&C control system. An important advantage of the proposed control system is that Contractors can give their prices for the concept only, thus without various allowances for uncertainties about the concept. This simplifies Client's evaluation of the proposals.

The control system in practice

When confronted with "performance problems" for a certain phase-system, the procedure is as follows:

- determine the relative increase of the actual values of the aspect-systems with respect to the contractual values of aspect-systems;
- multiply the newly established aspect-system vector by the relation matrix of aspect-systems, yielding the actual required performance of solution;
- multiply the relative increase of required performance of solution by the contractual efforts in order to establish the extra efforts, expressed in costs only and needed with unchanged goal,
  or:
  select an aspect-system suited for adjustment in order to keep as close to the budget as possible. In this case, the adjusted aspect-system vector is multiplied by the relation matrix of aspect-systems, yielding the reduced extra efforts, expressed in costs only.

The crucial role of the relation matrix of aspect-systems

The relation matrix of aspect-systems plays a crucial role in the proposed control system. Therefore, much attention should be paid to the determination of this matrix. Contractual consensus must be achieved about this matrix between Client and Contractor.

Nevertheless it is possible that this contractual matrix is not correct. This does not have any influence on the proposed control system. Even with an incorrect matrix it is quite well possible for the Client to choose his preferable direction for the realization process. As far as the financial compensation is concerned, it is possible to redescribe the contractual concept can be described by an adjusted matrix of aspect-systems at any time during the project, even at the end. Hence, it is always possible to arrange financial compensation in a correct way.

14.2 Conclusions

Present D&C situation

It must be realized that "a present D&C" situation does not really exist, because each realization process of a complex civil engineering system with a D&C contract is different from another. Therefore, the present situation is sketched with a hypothesis and illustrated with a case study.

The hypothesis is that Clients and Contractors experience D&C as a construction work with some preceding minor design work on details only. Both parties mistakenly take the line that the problem statement is correct and consequently the efforts can be precisely estimated. This is the reason that, at present, the D&C task is organized as a construction task and arranged with a Fixed-Price contract. With such a contract (all fixed) and the underestimation of the efforts needed, the traditionally operating Clients and Contractors can hardly control the D&C process. Both parties run risks in this situation. Not only the effectiveness of the solution is influenced negatively by a Contractor working with an incorrect problem statement, but also an overrun of costs is inevitable, because there is no contractual room to adjust the goal between times. Since the cost overruns will be claimed, the Client will be confronted with shortcomings on effectiveness as well as efficiency.

The hypothesis above, is illustrated with and confirmed by a case study: The D&C of the Storm Surge Barrier in the Nieuwe Waterweg. The typical "construction" approach follows from the following organizational and contractual issues, all being in conflict with the proposed control system for D&C:

- A Fixed-Price contract was agreed between Client and Contractor.

- The D&C task of the complex system was simply decomposed in sub-tasks expressed in three dimensions (Costs, Time and Resources), however not taking into account the relations between sub-systems of a system.

- The project organization was divided in operational islands, as a consequence of a strict functional and hierarchical structure. These islands hindered communication.

- The project neither used a dynamic goal control model nor a dynamic structural control model.

It is concluded that the present D&C situation does not lead to a satisfactory performance of the D&C process for neither the Client nor the Contractor.

The proposed control system

Although the proposed control system is not tested as a whole yet, some components of the control systems are tested in two different ways. The first way is the practical application of goal control with the set of aspect-systems, which was conducted in two projects, showing the applicability. The second way is a check on how the control system would have been performed in a few actual control situations, showing the beneficiality. The suitability for overall control is shown by two case studies.

The first project which used one aspect-system (geometry: fitting of the prefabricated parts) for the overall goal control was the realization of the Eastern Scheldt Storm Surge Barrier. All sub-systems (piers, sills, gates, foundation, etc) were coordinated and optimized with this meta-control concept.

Another project which used aspect-systems for goal control was the realization of the Ekofisk Protective Barrier. The control of the offshore installation and offshore completion of the Barrier Halves was based on a set of five aspect-system which were brought together in two dynamic control models. With these models it became possible to optimize the full offshore operation, where initially the conflicting aspects could not be coped with by the typical construction oriented, functional organization.

Based on these two case studies it is concluded that the proposed control system is able to control the D&C of complex civil engineering systems, with respect to effectiveness and efficiency.

Benefits for both parties are gained in case the risk sharing principle will be correctly applied. Therefore the control system must be able to separate "perception risks" from "process risks".

Two showcases are used to demonstrate the ability of the proposed control system to separate the two types of risks. The first showcase refers to the initially underestimated loadcase of the Storm Surge Barrier in the Nieuwe Waterweg, which could simply be quantified. The second showcase refers to the underestimated waveloads and overestimated soil condition which influenced the offshore works of the Ekofisk Protective Barrier.

The benefit for the two parties of D&C when using the proposed control system is illustrated by the way the stability problems of the floating gates of the Storm Surge Barrier in the Nieuwe Waterweg would have been solved in comparison with the way it has actually been solved. Both parties would have saved a lot of money, the project would not have been delayed and the eventual solution would probably have been better.

It is concluded that the proposed control system is beneficial to both parties operating with a D&C contract.

14.3 Recommendations

Preparation of Clients and Contractors

Promotion

Due to the significant advantages of the proposed D&C control system for all involved parties, it is worthwhile to promote this system amongst the various potential parties in the civil engineering construction sector (nationally as well as internationally), possibly leading to a new contracting D&C convention.

The proposed control system is developed for the realization of large complex civil engineering systems by two parties (Client and Contractor). This means that the control system is able to control the development of unique, complex systems where effectiveness and efficiency is concerned. In other words, the control system is able to cope with: (1) a large number of independent, conflicting and concurrent requirements, (2) limited efforts available and (3) two involved parties (Problem Owner and Problem Solver). This makes the control system suitable for all sorts of complex problem solving processes. In its essence, the proposed system is not only a blueprint for the control of realization processes of complex systems, but also for control of a wider spectrum of complex problems. Therefore, it is recommended to distribute this study also in the periphery of, or even outside, the civil engineering society.

Testing

Given the potential control power of the proposed system it is recommended to find a pilot environment to test the system. This can only be done with a competent coordination team, in Client's as well in Contractor's organization (see next paragraph).

Selection and education of D&C coordinators

Not only for D&C of complex civil engineering systems, but also due to the increasing complexity of our society and the associated complex solutions for problems, it is strongly recommended to: (1) start selection procedures for D&C coordinators, integrators with the thinking profile as presented in annex 5 and (2) develop appropriate education programs at universities, governments and large contracting companies for D&C coordinators providing a minimum competency level to coordinate D&C of complex systems.

Project approach

D&C management

This study on various aspects of the D&C situation resulted in a conceptual framework for a control system, consisting of two parts: (1) organizational and (2) type of contract. Personnel aspects (for instance the question what kind of people should be selected for D&C management) falls definitely out of the scope. However, given the proposed fundamental change of the organizational structure an indication must be given on the right type of personnel. It is recommended that D&C should be controlled by D&C coordinators on Client's side as well as on Contractor's side. This means a fundamental change of the traditional civil engineering situation which, nevertheless, is a condition for satisfactory D&C projects.

Joint Ventures for D&C projects

Most D&C work is conducted by a Joint Venture of Contractor's in order to spread the risks. Since D&C is principally aimed at the development of a yet non-existing overall solution to a problem, a Joint Venture as Problem Solver is only possible in case all members of the Joint Venture are responsible for the product of effectiveness and efficiency of the realization process of the whole system.

Minimum design period for complex civil engineering systems

With respect to the currently observed trend in D&C to minimize the design phase (0.5 year), it is recommended to reserve a minimum design period prior to construction of 1.5 year. With the proposed control system and an adequate project management each complex system can be designed in such a period.

Design of complex systems in general

The control system developed in this study for a combined D&C process, consists of an organizational part and a contractual part. The organizational part aimed at the control of the D&C task, whereas the contractual part is aimed at the control of risk. For seperate design work the risk aspect is less relevant. However, since design work itself cannot be done without taking into account the construction aspects, the organizational part of the control system is also very suitable for controlling only design of complex systems.

ANNEX 1 BRIEF INTRODUCTION TO SYSTEM THEORY[1]

System

A system is a set of elements to be distinguished from the universe as a function of the purpose of the system. These elements are interrelated and can also be related to elements belonging to the universe outside the system.

- ***Elements***

  Elements are the smallest parts of the system which are relevant to the purpose of the system.

- ***Content***

  The content is equal to the total set of elements.

- ***Attributes***

  Although the possibility that some elements do not have any attributes must not be excluded, generally most of the elements show typical attributes.

- ***Relations***

  The relations represent the coherence between the elements. Every element is per definition interrelated with all other elements. This means that the attributes of one element can change the value of the attributes of any other element.

- ***Structure***

  The structure of a system is the total set of relations.

- ***Environment***

  The environment of a system is composed by those elements of the universe, which influence the attributes (or the values thereof) of the elements belonging to the system, or reversely are influenced by the system. It will be clear that, given this definition, both an internal as well as an external structure can be distinguished.

In an open system the environmental elements have relations with the elements of the systems. In a closed system no relation exists between the content of the system and the environment.

- ***System boundary***

  The boundary of a system is subjectively chosen. The choice depends of the aim of the study and is generally a matter of experience. When too narrow, the system does not reflect the reality and when too wide, the system is too complex to solve.

- ***Coherence***

  A system is fully coherent in case every element is related to all other elements. In case the set of relations is empty, a system does not exist.

Sub-systems and aspect-systems

- ***Sub-system***

  A sub-system is a part of the elements of the system with conservation of all original relations between all elements. It will be clear that a part of the total system is the environment of a sub-system.

- ***Aspect-system***

  An aspect-system is a part of the relations of the system including all elements of the system.

State, process and behaviour

For the description of the relations between the elements and the associated changes of the attributes of the elements, the notions state, process and behaviour are very important.

- ***State***

The state of a system at a certain point in time is given by the value of the attributes within the system at that time. A change in the state of the system is called an *event*. In case an event leads to another event, then the system is subject to an *activity*. Not only elements can be changed, but also relations. In that case the system is recognized as a changing system. In addition, systems can be divided in *static* and *dynamic* systems. A static system does not need events to fulfil the required functions. Dynamic systems need both events as well as activities to fulfil the required functions.

- ***Process***

A process is a series of transformations during throughput, which changes the input of the element. This can be a change in attribute, position, function, shape, etc.[2].

- ***Behaviour***

The behaviour of a system is the way the system reacts on circumstances inside or outside the system. Two types of behaviour are distinguished:

- The *static system behaviour*. Here the output is dependant on the input at a certain time.

- The *dynamic system behaviour*. In this particular case the output is not only dependant on the input at a certain time but also on the history of the input.

A division can be made in a *deterministic* and a *stochastic* behaviour. In case the behaviour can be predicted, it is defined as deterministic. In case the input is of stochastical nature, the behaviour is stochastic.

A *steady state stochastic behaviour* is observed in case the probability of occurrence of the input does not change. A *transient stochastic behaviour* is observed in case the probability of occurrence of the input changes.

Purpose, function and task

- ***Purpose***

  The purpose of a system is that the necessary and required functions of the system, with respect to the environment, are fulfilled.

- ***Function***

  The function of a system is the required contribution of the system to a greater entity. A function must be fulfilled and can be considered as output.

- ***Task***

  The task is equal to the required contribution as defined above in order to fulfil the functions of the system. A task must be carried out. The design of technical systems can be based on tasks as well as functions. In case functions will be used to work out a system, some freedom remains for alternative ways to carry out the tasks. Such a system is called a function-system and the relations between the functions are mainly determined by the processes.

Notes

1. This brief introduction to the most relevant notions of systems theory is adopted from In't Veld, Analyse van organisatieproblemen, Stenfert Kroese B.V. Leiden/Antwerpen, 1988.
2. It is concluded that the content, structure and processes of a system cannot be separated for the prediction of the behaviour of the system.

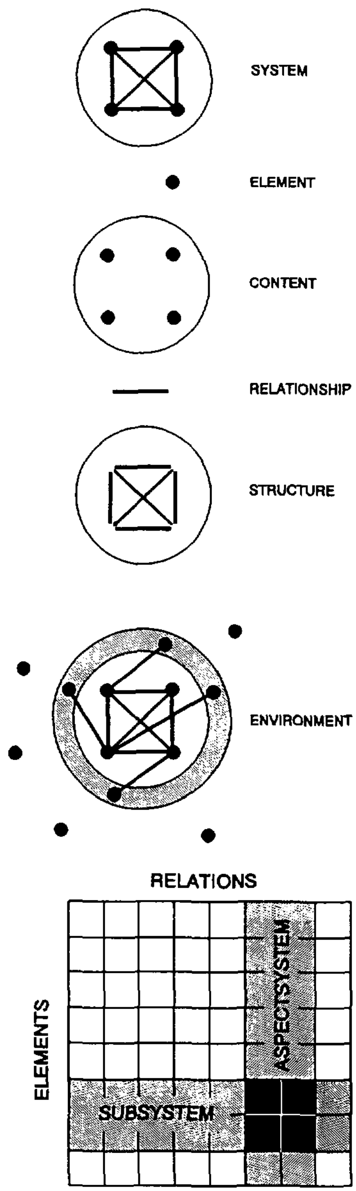


Fig. A.1.1 Definition sketch

ANNEX 2 COMPLEXITY

Interaction as additive contribution to complexity

The common strategy to approach a complex system is based on "divide and rule". In this case it means to find out whether the complex system is simply composed of complex sub-systems. In applying this strategy, the complexity of a total system is decomposed with every decomposition step in a number of sub-systems with reduced complexities. In fact, the total system is classified.

In order to derive a mathematical expression for complexity it is fruitful to investigate a particular decomposition of a system[(1)]. Consider a system as a whole and let sub-systems be the parts. The partition of the system S in sub-systems is denoted as S_1, S_2, S_3 ... etc.

The next partition level is denoted as follows:

S_1 in S_{12}, S_{13}.... and S_2 in S_{21}, S_{22}.... etc.

The lowest level of partition ends with the elementary objects (E_1, E_2, E_3....E_n). The partitioning is schematically sketched in figure A.2.1.

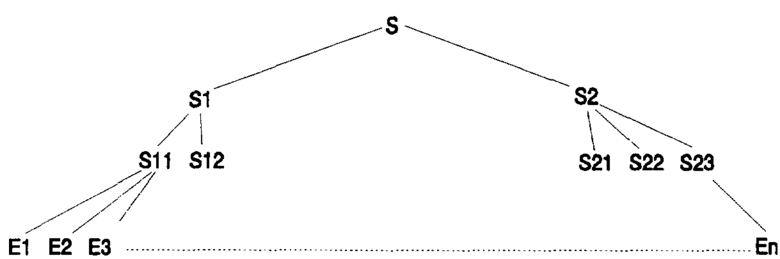


Fig. A.2.1 Partitioning of system S

Writing C for the complexity of a sub-system and R for the interaction between sub-systems, the complexity of a system can be expressed in the following formula:

$$C(S) = R(S_1, S_2) + C(S_1) + C(S_2)$$

$$= R(S_1, S_2) + R(S_{11}, S_{12}) + R(S_{21}, S_{22}, S_{23}) +$$

$$C(S_{11}) + C(S_{12}) + C(S_{21}) + C(S_{22}) + C(S_{23}) \qquad (A.2.1)$$

Subtracting the complexities of the elements of the total complexity results in the following equation:

$$C(S) - C(E_1) - ... - C(E_n) =$$

$$= R(S_1.S_2) + R(S_{11}, S_{12}) + R(S_{21}, S_{22}, S_{23}) + ... \qquad (A.2.2)$$

It is shown that the difference between the complexity of the whole system and the complexities at the elementary level of E's, equals the total amount of interactions.

An attempt at quantification

An interesting combination of influencing factors for complexity is given by Tolsma(2). Here, complexity is determined by a large number of components, diversity, coupling and interaction. Diversity can be combined with the large number of components in a functional sense(3). Hence, the large number of components is converted into a large number of functions. The factor coupling stands for static interaction, which is then, by definition, a subset of the set of interactions.

The other subset of interactions concerns the dynamic interactions. Hence, in this vision the rate of complexity is determined by the number of functions on one side and a measure for interactions on the other. Based on these considerations "iso-complexity-curves" were developed (figure A.2.2)(4). The higher the number of the curve, the more complex the system.

However, these curves cannot directly be used for a measure of complexity of systems to be developed or problems to be solved. The number of functions is determined by means of which decomposition is carried out. In fact, the level at which further decomposition is impossible or meaningless must be determined. Unfortunately, this is a subjective level.

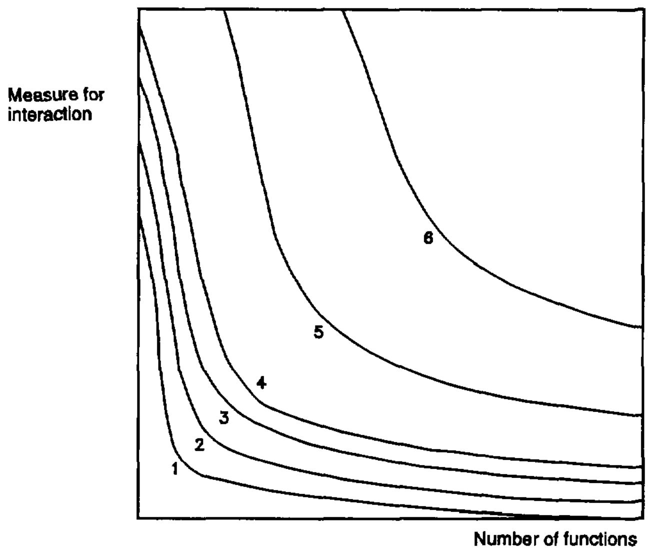


Fig. A.2.2 *Complexity of systems as a function of the number of functions and a measure for interaction*

Notes

1. Emden, M.H. van, An Analysis of Complexity, Mathematical Centre, Amsterdam, 1971
2. Tolsma, H., "Hoe blijven grote, complexe systemen toch beheersbaar: 12 op de schaal van Wintzen", in: Ingenieurskrant, nr. 15, 1991, (in Dutch).
3. Stassen, H.G., "Hoe complex is een industrieel proces voor een procesoperator?", in: Inspelen op complexiteit, mens techniek informatie en organisatie, Alphen aan den Rijn, 1992, (in Dutch).
4. Ibid.

ANNEX 3 DECOMPOSITION OF RELATIONS

Definitions

The decomposition of relations is based on graph theory. A graph is directly connected to the concept of relation. A graph is actually an abstract configuration of a set of elements and relations. The most necessary definitions and notions of graph theory with respect to decomposition and relations will be described first[1].

Graph G (V, A) contains a set (V) of elements and a set (A) of interrelations, where A contains non-directed, signed, one-dimensional elements called links, of which each joins exactly two elements of V. In case the joined pairs of elements are ordered, that is, the links joining the elements are directed, the graph is defined to be a digraph (directed graph). A digraph represents a binary relation R: each related pair (v_i,v_j) R can be represented by two elements and a directed link.

The adjacency matrix A(D) = $[a_{ij}]$ of a digraph D has an entry a_{ij} = 1 in case the directed link v_iv_j is in D and has an entry a_{ij} = 0 in case the directed link v_iv_j is not in D.

An element v_i is joined to an element v_j if and only if there is an undirected path (semi-path) joining v_i and v_j. A semi-path is a set of points v_1, v_2....v_n together with n-1 undirected links, where each link joins one pair of elements v_1v_2, v_2,v_3....v_{n-1}, v_n.

An element v_j is accessible from v_i if a path exists from v_i to v_j. A path is a set of directed links. The length of a path from v_i to v_j, that is, the number of directed links in the path, is defined as the distance between v_i and v_j.

A digraph D is strongly connected, or unilateral, or strong if, for any two elements belonging to D at least one is reachable (directed path). A digraph D is weakly connected, or weak, if every two elements are joined (undirected path). A sub-graph of maximum strength of a digraph D is defined as a strong component. A maximal weak sub-graph of a digraph D is defined as a weak component. A sub-graph is defined as maximal if it contains no other sub-graph.

Having all relevant definitions, it is now possible to use the graph theoretical concepts to decompose a digraph into sub-graphs or to decompose a system into sub-systems.

Decomposition of the system

The decomposition starts with the adjacency matrix A(D) of digraph D, which is in fact a relation matrix of elements. If the adjacency matrix can be partitioned into:

$$A = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}$$

so that a_{12} and a_{21} are filled with zero's then matrix A is decomposed. In case all off-diagonal blocks (A_{ij} with $i \neq j$) are zero, than A is called to be completely decomposed. In this particular case the system represented by the digraph can be decomposed into completely autonomous sub-systems.

The square matrix A is defined to be hierarchically decomposed in case all blocks above the diagonal are zero. This is called the block-triangular form. In this case inter-relations between the blocks remain. A is maximally decomposed if m is maximal.

$$A = \begin{pmatrix} a_{11} & 0 & . & 0 \\ a_{21} & a_{22} & . & 0 \\ . & . & . & . \\ a_{m1} & a_{m2} & . & a_{mm} \end{pmatrix}$$

The decomposition rule (an example)

According to Simon's "nearly decomposability" rule, the system must be decomposed in sub-systems in such a way that the number of relations inside the sub-system is maximized and the number of relations between these sub-systems are minimized.

This criterion is rather clear and would tentatively lead to an unambiguous optimum. In order to investigate the rule, an example is given of a simple system consisting of 7 elements[(2)]. The digraph of this simple system is given in figure A.3.1.

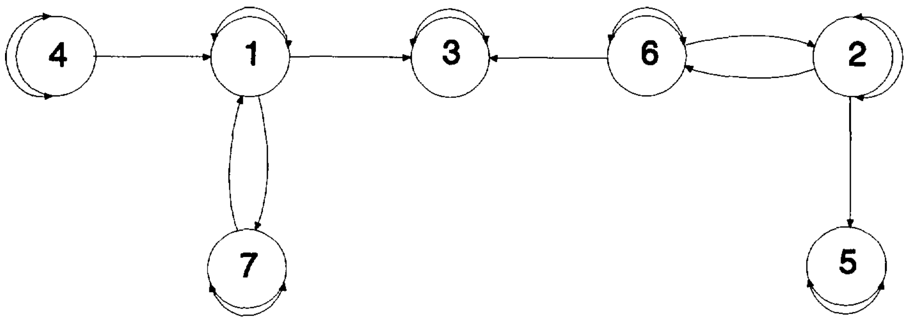


Fig. A.3.1 *A digraph of a simple system consisting of seven elements. The circles represent the elements and the lines are relations.*

The above digraph can be represented by its adjacency matrix (A):

$$A = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \end{array} \begin{array}{c} \begin{array}{ccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 \end{array} \\ \begin{pmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \end{array}$$

The decomposition rule requires a transformation of matrix A into a form

$$A = \begin{pmatrix} a_{11} & a_{12} & . & a_{1n} \\ a_{21} & a_{22} & . & a_{2n} \\ . & . & . & . \\ a_{n1} & a_{n2} & . & a_{nn} \end{pmatrix}$$

such that matrix A have as many "ones" (1) as possible inside the diagonal blocks a_{ii} and as few "ones" (1) as possible in the off-diagonal blocks a_{ij} (with $i \neq j$). This must be done by a series of row-and-column permutations. For a hierarchical decomposition, it is necessary to obtain a block triangular form of matrix A. This results in the following transformed matrix:

$$
A = \begin{array}{c} \\ 1 \\ 3 \\ 7 \\ 5 \\ 4 \\ 2 \\ 6 \end{array}
\begin{array}{c}
\begin{array}{ccccccc} 1 & 3 & 7 & 5 & 4 & 2 & 6 \end{array} \\
\left(\begin{array}{ccc|c|c|cc}
1 & 1 & 1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 1 & 0 & 0 & 0 & 0 \\
\hline
0 & 0 & 0 & 1 & 0 & 0 & 0 \\
\hline
1 & 0 & 0 & 0 & 1 & 0 & 0 \\
\hline
0 & 0 & 0 & 1 & 0 & 1 & 1 \\
0 & 1 & 0 & 0 & 0 & 1 & 1
\end{array}\right)
\end{array}
$$

The above matrix has a block triangular form:

$$
A = \begin{pmatrix}
a_{11} & 0 & 0 & 0 \\
0 & a_{22} & 0 & 0 \\
a_{31} & 0 & a_{33} & 0 \\
a_{41} & a_{42} & 0 & a_{44}
\end{pmatrix}
$$

The decomposition of the system into sub-systems is given in figure A.3.2.

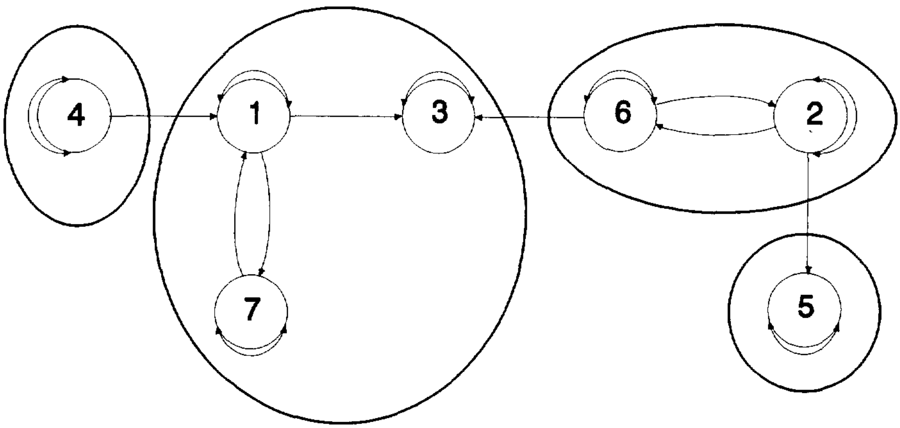


Fig. A.3.2 *Hierarchical decomposition of a system into four sub-systems. The relations inside the sub-systems are maximized and the relations outside the sub-systems are minimized.*

From the above partition it can be seen that the number of inter-relations is 3, corresponding with the off-diagonal "ones" and the number of intra-relations is 12, corresponding with the diagonal "ones". Hence, it is clear that the partition has a hierarchical character.

However, another decomposition is possible as well. Obviously, the "nearly decomposability" rule does not automatically lead to an unambiguous optimum of sub-systems. It is concluded that additional requirements are needed for a general decomposition rule.

The following additional requirements are suggested[3]:

- specification of the desired number of elements in a sub-system;
- specification of the desired number of sub-systems;
- specification of the maximum number of steps between the elements of a sub-system (distance = length of a path, also see annex 3).

The most important additional requirement would be the introduction of the strength of the relations. However, the use of graph theory, based on binary Boolean relations, implies that the strength of the relations cannot be incorporated in the decomposition directly.

Polak[4] introduced an analogue method to incorporate the strength of the relations. He developed a program for the operation of a graphical relation matrix. It is graphical because the strength of the relations is proportional to the graphical symbols. In that way it is possible to minimize the off-diagonally weighted density of graphical symbols.

Notes

1. The most relevant issues on graph theory in relation to decomposition and relations between elements of a system were presented by: Kickert, W.J.M., Organisation of decision making, North holland press Cy, New York, 1979. A more fundamental treatment of the graph theory is given by: Harary, F. and Z. Norman, Graph Theory as a Mathematical Model in Social Science, Ann Arbor, 1955 and Even, S., Graph Algorithms, Computer Science Press Inc., Rockville, Maryland, 1979.
2. This example was in exactly the same form given by: Kickert, W.J.M., Organisation of decision making, North holland press Cy, New York, 1979. It is also given here as it is a clear example of a rather essential decomposition rule for the development of complex systems.
3. Ibid.
4. Polak, B.M. and Beheshti, M.R., Systematisch Ontwerpen, Delft University, Civil Engineering, Delft, 1991.

ANNEX 4 DECOMPOSITION OF (DIS)SIMILARITY

General definition of the cluster problem on dissimilarity

The basic problem is to decompose a system into sub-systems in such a way that the elements inside the sub-systems are as similar and the elements of different sub-systems are as dissimilar as possible. This problem can be solved mathematically by Cluster Analysis.

There are a large number of publications on cluster analysis. A unified exposition of cluster analysis is given by Duran(1) which is the theoretical background of the content of this annex. Here, only the most relevant, most necessary and main principles of cluster analysis are dealt with.

A clustering problem is defined as follows:

Let the set $I = \{ I_1, I_2, ...I_n \}$ denote n elements from a conceptual population pI. It is assumed that a set of characteristics $C = \{C_1, C_2,.....C_p\}$ exists, which is observable and possessed by each element of I. For simplicity it is assumed that the observable characteristics can be measured. Although certainly not a condition for cluster analysis, the discussion is confined to quantitative data. These quantitative data are called measurements.

The value of the measurement on the $_{ith}$ characteristic of element I_j is denoted as x_{ij}. $X_j = [x_{ij}]$ denotes the p x 1 vector of measurements per element. Hence, the set of elements I is described by a corresponding set of p x 1 measurements vectors $X = \{X_1, X_2,...X_n\}$.

If m is an integer, which is less than n, the cluster problem is to determine m clusters (sub-sets) of elements in I $(p_{i1}, p_{i2},....p_{im})$, such that I_i belongs to one and only one subset and those elements which are assigned to the same cluster are similar, whereas those assigned to different clusters are different (not similar).

In general, the solution of the cluster problem must result in a partitioning (decomposition) which satisfies some optimalization criterion. Such an optimalization criterion can be given in an objective function representing the desired level of partitioning.

In order to solve the cluster problem it is desirable to define the terms "similarity" and "difference" (non-similarity or dissimilarity) in a quantitative fashion. In fact, the meaning of the difference between two elements must be explained, as discussed in the next two sections.

Distance functions as a measure for dissimilarity

A possible solution to the cluster problem could be obtained by assigning the i-th and j-th elements to: (1) the same cluster if the distance between the vectors X_i and X_j is small enough and (2) different clusters if the distance between X_i and X_j is large enough. The measurements for the distance between X_i and X_j can be given by a distance function $d(X_i, X_j)$, which must fulfil the following conditions:

- *non-negative*: $d(X_i, X_j) \geq 0$ *for all* X_i *and* X_j; (A.4.1)

- *anti-reflexive*: $d(X_i, X_j) = 0$ *if and only if* $X_i = X_j$; (A.4.2)

- *symmetric* : $d(X_i, X_j) = d(X_j, X_i)$; (A.4.3)

- *transitive* : $d(Xi, Xj) \leq d(Xi, Xk) + d(Xk, Xj)$ (A.4.4)

The distance function is a measure for dissimilarity. There are many types of distance functions, which are not discussed here.

Measures of similarity

The n measurements $X_1, X_2, \ldots X_n$ can be described by the p x n matrix:

$$X = \begin{pmatrix} x_{11} & x_{12} & . & . & x_{1n} \\ x_{21} & x_{22} & . & . & x_{2n} \\ x_{p1} & x_{p2} & . & . & x_{pn} \end{pmatrix} = (X_1, X_2, \ldots X_n)$$

In the same way, the paired distances $d(X_i,X_j)$ can be described by the symmetric n x n distance matrix:

$$D = \begin{pmatrix} 0 & d_{12} & . & d_{1n} \\ d_{12} & 0 & . & d_{2n} \\ . & . & . & . \\ d_{n1} & d_{n2} & . & 0 \end{pmatrix}$$

Complementary to the notion of distances between X_i and X_j, the notion of similarity between two elements I_i and I_j can be developed.

The similarity function $s(X_i,X_j) = s_{ij}$ must fulfil the following conditions:

- *non-negative*: $0 \le s(X_i, X_j) < 1$ *for* $X_i \neq X_j$; *(A.4.5)*

- *reflexive* : $s(X_i, X_i) = 1$; *(A.4.6)*

- *symmetric* : $s(X_i, X_j) = s(X_j, X_i)$; *(A.4.7)*

The paired similarities can be arranged in the similarity matrix

$$S = \begin{pmatrix} 1 & s_{12} & . & s_{1n} \\ s_{12} & 1 & . & s_{2n} \\ . & . & . & . \\ s_{n1} & s_{n2} & . & 1 \end{pmatrix}$$

s_{ij} is defined as a similarity coefficient. There are a number of possibilities to arrange similarity coefficients[(2)], which will not be discussed here. It will be clear that distance functions can be composed based on similarity functions and vice-versa.

Notes

1. Duran, B.S. and P.L. Odell, Cluster Analysis, A Survey, Springer-Verlag, New York, 1974.
2. Sokal, R.R. and P.H.A. Sneath, Principles of Numerical Taxonomy, San Francisco, W.H. Freeman and Company, 1963.

ANNEX 5 MODELS

Model-system typology

As far as the description of systems is concerned, three categories can be distinguished[1]:
- concrete systems, defined as a whole of concrete or empirical entities with mutual relations;
- conceptual systems, defined as a whole of notions with which the empirical real situation is classified;
- formal models, defined as a form of language using symbols expressing the above notions.

It is useful, therefore, to distinguish three kinds of entities: (1) concrete entities, corresponding with "things", (2) conceptual entities, corresponding with notions and (3) formal entities, corresponding with abstract names (symbols).

Because a model can be considered a system, with a certain isomorphism with another system, also three types of models can be distinguished: (1) concrete or empirical models, (2) conceptual models and (3) formal models. Consequently, nine combinations of model-system pairs are possible, which will shortly be discussed by means of an example in table A.5.1.

Model	Example
empirical model of concrete system	the behaviour of steel under tension
empirical model of conceptual system	the pyramid of Cheops as an application of the stereometrical figure "pyramid"
empirical model of formal system	the temperature scale as application of the formal theory of numbers
conceptual model of concrete system	a relation diagram as a model of all interactions between elements of a system
conceptual model of conceptual system	the algebraic representation of a circle
conceptual model of formal system	a language system of formal logic
formal model of concrete system	a mathematical model of an economic process
formal model of conceptual system	the Euclidian space
formal model of formal system	the translation from one formal system to another

Table A.5.1 Model/system typology

The conceptual models can be sub-divided into theoretical models and realization models. The distinction is illustrated by the relation between them: a theoretical model becomes a realization model in case a partition of the empirical science is formalized. Following this distinction, the theoretical models are relevant to the empirical sciences and the realization models are relevant to the formal sciences.

Function of models

As far as the function of models is concerned, the following classification can be made[(2)]:

- *Thought models*

  Thought models are used to control the perception of facts and experimental research. The function of these models can be divided into three sub-functions: (1) exploration and heuristic function, (2) description and reduction and (3) explanation.

- *Operational models*

  Operational models are auxiliary tools for the execution of operations (for instance quantification). The function of operational models are: (1) handling of material and facts (scale models and analogy models) and (2) formalizing and automizing of research (mathematical models and structural models).

- *Bridging model*

  Bridging models are used for the application of abstract theories. These models bridge the gap between theory and the empirical world and are used to simulate the behaviour of systems.

Working principles of models

The main types of models with respect to working principles are[(3)]:

- *Scale models*

  The main principle is that the mutual relations remain constant. Scale models represent concrete systems or conceptual systems.

- *Analogy models*

Two types can be distinguished: (1) theoretical or transplantational analogy models and (2) empirical analogy models. The main principle is that the medium is changed, whereas the structure remains unchanged. The analogy guarantees isomorphy. A particular family of analogy models is the set of cybernetic models. These analogy models are based on an information processing medium. Operations are isomorph, the behaviour is analogue and the dynamic relationship is simulation. Another family is the set of bionic models, which uses the knowledge of living organisms for the analysis and realization of mechanical systems(4).

- *Ideal models*

Two types can be distinguished: (1) theoretically ideal models, mostly referring to experiments of minds, reconstructions, hypotheses and (2) empirically ideal models which are mostly simplified prototypes. The main principle is an idealized limitation. A particularly ideal model is the "Black Box", standing in between open and closed systems (see annex 1). The "open" system is modelled by a "closed" system with simplified relations with the environment (input and output only).

- *Structural models*

These models give a qualitative structure of reality (for instance construction schemes and road maps). An important family of structural models is the set of flow diagrams, which can be considered as a hierarchic scheme of black box models.

- *Mathematical models*

Given the two distinguished types of conceptual models (theoretical and realization models), it will be clear that the mathematical models can be subdivided in that sense: (1) theoretical mathematical models and (2) mathematical realization models.

- *Abstract models*

These models are only relevant as realization models of formal systems.

The basic principles of the use of models

The basis of any use of models is the abstraction principle as, for instance, given by Rosenblueth[5]:

> *"Abstraction consists of replacing the part of the universe under consideration by a model of similar but simpler structure".*

When reasoning in terms of generalization and abstraction, the direction of isomorph modelling is from concrete system via conceptual system towards formal system. However, the reverse sequence is rather relevant to the purpose of this study which is aimed at: (1) specification instead of generalisation, (2) realisation instead of abstraction and (3) application of unruly data.

The use and therefore the function of different type of models and the associated working principals are given in table A.5.2 (after Bertels[6]). Given the context of this study, the table does not include the formal sciences and is therefore limited to empirical sciences only.

With respect to application of models in relation with realization processes, Schultheiss[7] gives a practical overview of the relation between models and phases of the first part of the realization process.

Scale models, structural models and mathematical models are used for all realization phases from problem definition to detailed engineering. In addition, ideal models and analogy models are also used for the conceptual design phase.

CONCRETE SYSTEMS			CONCEPTUAL SYSTEMS		
EMPIRICAL MODELS			THEORETICAL MODELS		
Working principle	Type	Application	Working principle	Type	Applica-tion
Number, space, time	Scale model	Research Statistics			
Transplantation Other medium Information processing	Analogy model	Verification Making operational Simulation	Transplantation	Analogy model	Explana-tion Initiation Reduction
Applied black box Information processing Analogy, digital	Cybernetic model	Simulation Neuristics	Program Flow diagram Black box	Cybernetic model	Automat-ization
Applied black box Applied standard Simplification	Ideal model	Reconstruc-tion Regularity Typology	Black box Blue print Working hypothesis Measuring model	Ideal model	Recon-struction Experiment Extrapola-tion Regulation
	Applications of structural model		Pattern Map Diagram Graph	Structural model	Creative Suggestive Visual (of head-lines)
	Realization of mathematical model		Algebraic numerical Metric Probabilistic Topologic Graphic	Mathematical model (quantitative)	Automat-ization Measuring Generaliz-ation Description

Table A.5.2 Use, function and working principles of models (after Bertels and Nauta, 1969).

Notes

1. Most remarks on models made in this section are drawn form the theoretical works of Bertels, C.P. and Nauta D., Inleiding tot het modelbegrip, De Haan, Bussum, 1969.
2. Ibid.
3. Ibid.
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   Gerardin, L., Bionica, Schakel tussen bioloog en ingenieur, De Haan, Bussum, 1968.
5. Rosenblueth, A. and Wiener, N., "The role of models in science" in: Philosophy of Science, 12, 1945.
6. Bertels, C.P. and Nauta D., Inleiding tot het modelbegrip, De Haan, Bussum, 1969.
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ANNEX 6 THINKING PROFILE OF DESIGN COORDINATOR

The individual perception of a complex environment and the individual response on a complex environment plays an important role in the design process. The individual human being has abilities, yet also restrictions in dealing with complexity. In a way it is possible to consider the individual human being in the interaction with the direct environment as an information processing system[1]. A reference is made to Rasmussen[2] with respect to the way information is processed:

- based on routine : actions are unselfconscious;
- based on rules : actions are more or less self-conscious, but restricted by rules;
- based on knowledge : actions are induced after information processing and associated strategy development.

It will be clear that dealing with complex problems, from Rasmussen's point of view, must be based on knowledge. However, on knowledge level the information processing capacity of human beings is determined by the short term memory of which the capacity is rather low. Hence, the design process must be done in small steps[3]. Specialists with skill, experience and selective attention, however, show larger capacities of the short term working memory[4]. This is due to the fact that knowledge based actions are shifted to rules or routine based actions, which is induced by learning effects[5]. This learning process is a process of learning by doing. In this sense, the learning result is an acquisition of intuition and know-how. Dreyfus[6] distinguishes five stages of individual skill acquisition:(1) Novice, (2) Advanced beginner, (3) Competence, (4) Proficiency, (5) Expertise.

As described in chapter 2, the design process is a search process aimed at finding a solution to a problem. In order to solve a complex problem it is necessary to split up the problem into sub-problems. These sub-problems can be solved by specialists. However, due to complexity, the individually solved sub-problems do not provide an overall solution to the whole problem. It is necessary to coordinate the large number of sub-problem solving processes. This is, in fact, the main difficulty of the complex problem solving process.

The design coordinator has to create an overall solution. At the start of the problem solving process the solution does not exist. Hence, the sum of all partial search processes must give an overall solution which does not exist yet. This requires creativity. The question then is, what makes someone creative.

Van Gunsteren[7] quotes McKinnon with an interesting list of characteristics of creativity: (1) openness: shows feelings and emotions, (2) sensitive intellect, (3) self-awareness, (4) wide ranging interests, (5) uninterested in details, (6) cognitive flexibility, (7) verbally skilful, (8) intellectually curious.

A search process can also be aimed at finding an unknown, yet existing solution. This requires inventivity. Creativity and inventivity must be considered as two different characteristics. In this respect Bertels[8] connects inventivity to rapidity and suppleness with problem solving and creativity with finding the right problem definition. As shown clearly in chapter 2, the design process is a continuous process of defining problems. Therefore, design work preferably should be delegated to creative people. Together, inventivity and creativity are characterized by:

- taking new points of view;
- recognizing new operational relations between goal and means;
- re-ordering data (permutations);
- selecting data in a unique way.

Here, the discussion is started about the ideal profile for complex problem solvers:

- the increasing complexity of discipline bounded developments gives reason to select specialists to solve sub-problems. As it is possible to split up the system in such small parts that the problem solving processes of those parts can be based on existing standard solutions, the specialists can be selected on analytical skills and inventivity.

- however, for complex problems in particular, substantial coordination and synthesis efforts is required, which apply to creativity. Traditionally, generalists play an important role in coordination.

In view of the limited orientation of the first type, the lacking technical skill of the second type and the communication problems between the two types, the ideal profile should be an "integrator", having the characteristics of both specialist and generalist[9]. Consequently, the integrator's "thinking profile" consists of three main characteristics: (1) creativity, (2) inventivity and (3) analytical skills. When considering these three skills only, the integrator's position can be considered as being in the middle of the scientist and artist[10] (see figure A.6.1). For illustrative purposes, the positions of the specialist and the designer/architect are also indicated.

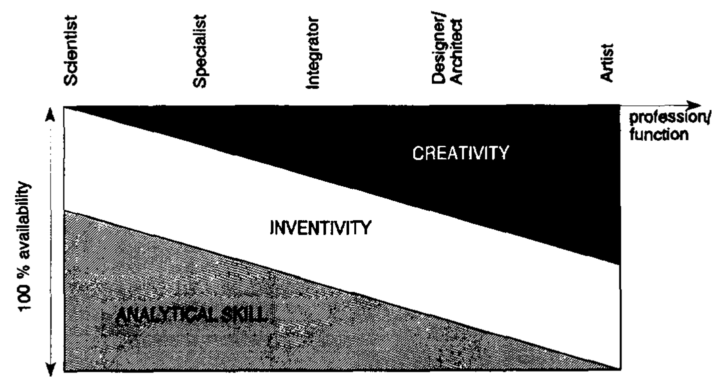

Fig. A.6.1 *Characteristic thinking profile as a function of profession/function. Pure science is aimed at description which does not require creativity. Pure art is aimed at synthesis of form which hardly requires analytical skill. It is noted that human action at a certain level is hardly possible without inventivity. That is the reason that an inventivity "contribution" is indicated for all distinguished professions/functions. The thinking profile of the integrator as coordinator of complex solving processes contains a contribution of all three thinking profile characteristics.*

It is clear that in the visions as given above, the integrator takes care of all complexity, whereas specialists can work on their sub-problems, which have reduced complexity but can still be very difficult.

With the three skills as given above, the integrator profile meets at least the expert profile (stage 5) in all cases as defined by Dreyfus[(11)]:

> *"From stage three to stage five a gradual shift from analytical understanding and decision making towards intuitive understanding and decision making can be observed. However, it is stated that these two ways of understanding and decision making are certainly not mutually conflicting and can be applied simultaneously."*

Cooley[(12)] defined the expert level as follows:

> *"At expert level, not only situations but also associated decisions are intuitively understood. Using his intuitive skills, the expert may also cope with uncertainties and unforeseen or critical situations".*

Notes

1. Alkemade, M.J.A., "Complexiteit, mens en technisch systeem", in: Inspelen op complexiteit; Mens, Techniek, Informatie en Organisatie, SST, Samson, Alphen aan de Rijn (1992).
2. Rasmussen, J., Information processing and human-machine interaction, North Holland, New York, 1986.
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6. Dreyfus & Dreyfus, Mind over Machine, Glasgow, 1986.
7. Van Gunsteren, L.A. van, Management of Industrial R&D, a View Point from Practice, Eburon, Delft, 1992.
8. Bertels, C.P. and Nauta, D., Inleiding tot het modelbegrip, De Haan, Bussem, 1969
   This separation between creativity, inventivity and analystical skill is also found by Harskamp, J.T., De scheppende mens, Essays over creativiteit en cultuur, 1984. He mentions two sources: (1) Fuseli, H., lectures on painting, London, 1801, and (2) Laharpe, J.F., Lycee ou cours de la litterature ancienne et moderne, Paris, 1799-1805.
9. Trum, H.M.G.J and M.F.Th. Bax, "Complexiteit en technologisch ontwerpen: domeinentheorie als ontwerpgereedschap", in: Inspelen op Complexiteit; Mens, Techniek, Informatie en Organisatie, SST, Samson, Alphen aan de Rijn, 1992.
10. This is a purely personal vision on the relation between required skills and profession c.q. functions.
11. Dreyfus & Dreyfus, Mind over Machine, Glasgow, 1986.
12. Cooley, M., Architect or bee?; the human price of technology, Hogarth Press, London, 1987.

ANNEX 7 PHASES OF THE REALIZATION PROCESS OF COMPLEX CIVIL ENGINEERING SYSTEMS

Based on the consulted literature, a general phasing of the realization process of civil engineering systems can be defined[1]. This phasing, together with possible D&C tasks, is sketched in table A.7.1.

Milestone	*Phase*					
Nothing						
	Orientation					
Problem						
	Project identification					
Problem statement						
	Project planning and feasibility					
Overall realization plan						
	Conceptual design					
Concept						
	Preliminary design					
Solution						E
	Detailed engineering				D	
Specifications				C		
	Preparation and procurement		B			
Constr. & Install. plan		A				
	Construction and installation					
Structure						

Table A.7.1. General phasing of the realization process of civil engineering systems and an overview of D&C possibilities. The phasing is based on the following starting points: (1) every phase is equal in terms of importance, (2) every phase ends with an essential choice for the project and (3) the total number of phases must be surveyable.

Apart from task E, all indicated D&C tasks have been conducted in the D&C projects mentioned in this book:

- D: Storm Surge Barrier in the Nieuwe Waterweg (chapter 9)
- C: Lac Nord de Tunis (preface)
- B: Ekofisk Protective Barrier (chapter 11), Dunlin-A (preface)
- A: NAM F3 platform (preface)

Obviously, the task definition of D&C. It can be shown that the tasks are mutually different. The difference between the D&C task can be visualized by considering the relevant aspects of each phase of table A.7.1.

Phase 1: Orientation

The *orientation phase resulting in a* problem (context) defined as the difference between perceived desired situation and perceived present situation, has been discussed in a theoretical context already.

Phase 2: Project identification

The project identification is an extremely important phase. In this phase the project team must produce a problem statement based on the subjective, partial and relative problem. During this phase the project objectives and the organization must be covered[2] which, as clearly shown in the study, are the most essential issues of a project (see intermezzo).

Intermezzo

Project objectives

In the conventional view, the project objectives is to finish the project: (1) within the time schedule, (2) within budget and (3) in accordance with quality/performance specifications. This approach is too simplistic:

Firstly, objectives vary depending on the type of project. An illustration can be given by a simple classification with respect to objective in the public sector projects versus commercial projects[3]. As shown before, the objective (goal) is important to the direction of the problem solving process.
An interesting project classification with respect to objectives is given in table 4.3.1[4].

Motive	*Project*	*Objective*	*Primary discipline*
Necessity	Storm Surge Barrier	It should work	Engineering
Opportunity	Nuclear power plant	It should pay	Economics
Prestige	Eiffel Tower Sydney Opera House	It should exit	Politics
Research	CERN project	Reaching a solution	Science

Table A.7.2 Types of projects and associated motives, objectives and primary disciplines. It is shown that objectives are dependant on the type of project.

Secondly, the relevant project life cycle phases must be recognized. The emphasis on what is important in a project changes from one phase to the next, which can be seen as a control variety in the performance of the problem solving process(5).

Thirdly, throughout the project life cycle, different levels must be considered in the management hierarchy associated with project objectives. The concept of hierarchy of objectives is useful to visualize the relation between organizational objectives and project objectives. Every objective requires a strategy by which it will be attained(6):

Fourthly, specific objectives of stakeholders involved must be defined(7). Project managers should be aware of stakeholders and their objectives. Examples are, for instance, government, local politicians, environmental groups, etc.

Organization

In this phase, organization refers to Client's project organization:
- listing of participants
- constraints
- funding
- options for development
- data of environment
- estimation of project benefits.

Phase 3: Project planning and feasibility

The project planning and feasibility phase must produce an assessment of viability, an assessment of risks and a broad plan for project realization.

Phase 4: Conceptual design

The conceptual design phase produces the concept and a project plan for realization. In this phase the realization process is started, giving the first direction to the solution. The initial information is obtained from the relation between project objectives, environment, participants and constraints. Once the outcome of this phase is given, the Client does not have opportunities to change the concept or scope of work without incurring substantial delays and extra costs[8].

Phase 5: Preliminary Design

The preliminary design phase yields the solution for the problem of the Client. The basic principles of the systems and sub-systems are fixed. Materials are known and method statements for execution are available with an indication of the type of equipment to be used.

Phase 6: Detailed design

The main purpose of the detailed design phase is the dimensioning of the system to be realized and the capacity of equipment to manipulate the system (if necessary). The output of this phase consists of three main documentation files, namely, design reports, specifications, drawings and sometimes a bill of quantities.

Phase 7: Preparation and procurement

Based on the specifications and drawings the preparation and procurement phase starts by making method statements and detailed working plans. Then the strategy, finance and organization of the procurement will be established. Requisitions will be sent to potential suppliers and the phase ends with sub-contracts for supply.

Phase 8: Construction and installation

The construction phase roughly covers the following topics: (1) planning for construction, (2) changing order procedure, (3) organizing construction and (4) controlling of construction.

Notes

1. TNO, Toegepaste Wetenschap, oktober, nr. 9, 1990.
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   Wijnen, G., Renes, W. and Storm, P., Projektmatig Werken, Het Spectrum B.V., 1984.
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   Corrie, R.K., Project evaluation, Thomas Telford Ltd, London, 1991.
2. Corrie, R.K., Project evaluation, Thomas Telford Ltd, London, 1991.Ibid.
3. Sykes, A., "Reducing neglected risks on giant projects" in: Kelly, AS.J.(Ed.), New dimensions of Project Management, Lexington Books, DC Heath and Company, USA, 1982.
4. Fraser, D., An approach to major projects, Major Projects Association, Oxford, 1984.
5. In confirmation of the control variety of the problem solving process (effectivity and efficiency), the varying controlling interests are described by Avots, I., "Why does project management fail?" in: California Management Review, Vol 12 No1, 1969:

   "During the early phase of the project, schedule is of primary importance, while cost takes second place and quality third. Later in the project, cost becomes the controlling interest, with schedule taking a secondary role. After the project has been completed, schedule and cost problems are easily forgotten and quality becomes the key".
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7. De Wit, A. "Measurement of project success" in: International Journal of Project Management, Vol 6, nr. 3, 1988.
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ANNEX 8 LINEAR VECTOR TRANSFORMATIONS[1]

Suppose R_n and R_m are two linear vector spaces. Then, a transformation of R_n into Rm must be found, which is defined as the situation in which every vector $\underline{x}$ ε R_n just one vector x' ε R_m is connected. In that case:

$$A\ \underline{x} = \underline{x}' \qquad (A.8.1)$$

A vector transformation A of a vector space R_n into a vector space R_m is called a linear vectortransformations, if for every two vectors $\underline{x}^1$ and $\underline{x}_2$ in R_n and for every λ:

$$A(\underline{x}_1 + x_2) = A\underline{x}_1 + A\underline{x}_2 \qquad (A.8.2)$$

$$A(\lambda\ \underline{x}_1) = \lambda\ A(\underline{x}_1) \qquad (A.8.3)$$

Consider a linear transformation A from R_n to R_m. Both in R_n as well as in R_m, linear independent bases are chosen, which are:

$$p_1, p_2, p_3, \dots, p_n \text{ for } R_n \qquad (A.8.4)$$

and

$$q_1, q_2, q_3, \dots, q_m \text{ for } R_m \qquad (A.8.5)$$

The vector spaces are spanned by the linear independent bases.

Suppose for k = 1, 2, 3, .., n:

$$A \cdot \underline{p_k} = \underline{a_k} \in R_m \qquad (A.8.6)$$

with:

$$\underline{a_k} = (a_{1k}, a_{2k}, \dots a_{mk}) = a_{1kq1} + a_{2kq2} \dots a_{mkqm} \qquad (A.8.7)$$

Every vector $\underline{x}$ ε R_n is mapped at a vector $\underline{x}$' ε R_m by the linear transformation A.

Let:

$$\underline{x} = (x_1, x_2, x_3, \ldots\ldots x_n) = x_1\underline{p}_1 + x_2\underline{p}_2 + \ldots\ldots x_n.\underline{p}_n \qquad (A.8.8)$$

and:

$$\underline{x}' = (x_1', x_2', x_3' \ldots\ldots, x^m) = x_1' \underline{q}_1 + x_2' \underline{q}_2 + \ldots\ldots x_m \underline{q}_m \qquad (A.8.9)$$

It is known that:

$$\underline{x}' = A.\underline{x}$$

$$= x_1 A \underline{p}_1 + x_2 A \underline{p}_2 + \ldots\ldots x_n A \underline{p}_n$$

$$= x_1 \underline{a}_1 + x_2 a_2 + \ldots\ldots x_n \underline{a}_n \qquad (A.8.10)$$

Thus:

$$\begin{pmatrix} x_2' \\ \cdot \\ \cdot \\ \cdot \\ x_{m'} \end{pmatrix} = x_1 \begin{pmatrix} a_{21} \\ \cdot \\ \cdot \\ \cdot \\ a_{m1} \end{pmatrix} + x_2 \begin{pmatrix} a_{22} \\ \cdot \\ \cdot \\ \cdot \\ a_{m2} \end{pmatrix} + \ldots x_n \begin{pmatrix} a_{2n} \\ \cdot \\ \cdot \\ \cdot \\ a_{mn} \end{pmatrix}$$

This expression can also be written as a set of m not homogeneous equations with n variables.

$$\begin{array}{lllllll} x_1 & = & a_{11}\, x_1 & + & a_{12}\, x_2 & + & \ldots a_{1n}\, x_n \\ x_2 & = & a_{21}\, x_1 & + & a_{22}\, x_2 & + & \ldots a_{2n}\, x_n \\ \cdot & \cdot & \cdot & & & \cdot & \\ \cdot & \cdot & \cdot & & & \cdot & \\ x_m & = & a_{m1}\, x_1 & + & a_{m2}\, x_2 & + & \ldots a_{mn}\, x_n \end{array}$$

The above equations are defined as transformations equations.

The associated matrix is:

$$A = \begin{pmatrix} a_{11} & a_{12} & . & . & . & a_{1n} \\ a_{21} & a_{22} & . & . & . & a_{2n} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ a_{m1} & a_{m1} & . & . & . & a_{mn} \end{pmatrix}$$

The matrix is determined by the linear transformation. The matrix itself is called the transformation matrix of the linear transformation of R_n into R_m with respect to the chosen bases.

It is concluded that in case of a linear transformation A of R_n into R_m and for both R_n as well as R_m a linear and independent basis is chosen, the k-th column vector of the transformation matrix A is the transformed vector in Rm of the k-th basis vector of R_n. Such a matrix is a matrix with m rows and n columns and is called a m x n-matrix.

If in R_n and in R_m a linear independent basis is chosen then every m x n-matrix A can be considered as a transformation matrix of a linear transformation A of R_n into R_m with respect to the above bases. This linear transformation $\underline{x}^1 = A.\underline{x}$ can also be written as:

$$\begin{pmatrix} x_1' \\ x_2' \\ . \\ . \\ . \\ x_m' \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & . & . & a_{1n} \\ a_{21} & a_{22} & . & . & a_{2n} \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ a_{m1} & a_{m2} & . & . & a_{mn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ . \\ . \\ . \\ x_n \end{pmatrix}$$

ANNEX 9 THE CONTRACT FOR THE REALIZATION OF THE STORM SURGE BARRIER IN THE EASTERN SCHELDT[1]

General

The contract between Client and Contractor was a unique contract dealing with integration of design and construction with the two parties. The most striking point of the contract was that the risk sharing principle, as proposed for an ideal D&C contract, was fully arranged in the contract for this project. The only difference between this contract and a normal D&C contract is that: (1) the design process was conducted and controlled by the Client assisted by the Contractor for constructability reasons and (2) the construction was conducted by the contractor while fully and traditionally controlled by the client. Hence, the D&C task was not delegated to the Contractor. Consequently, the Client was responsible for the performance of any part of the realization process. Although is was not a D&C contract, it was nevertheless very interesting.

Contractors

The construction of the civil part was assigned to the Joint Venture, with whom RWS (Rijkswaterstaat, Department of Public Works) had entered into an assistance contract. This Joint Venture consisted of six Dutch Contractors and was called Dosbouw. The contract had a ten year validity term, anticipating commissioning of the Barrier in October 1985 with October 1st, 1987 as the final date. A second agreement was concluded with a combination of construction firms called Ostem for the sealing materials, the steel gates with their movement installation and electromechanic powering. RWS designed these gates. The agreement was concluded in February 1980. Purchase of building materials, such as quarry stone and steel was done by RWS via internationally competitive bidding. Cement, reinforcing steel and building machinery were bought by Dosbouw in name of RWS. The values of the agreements, expressed in percentages of the entire project, excluding public servants costs, amounted to:

- Dosbouw	55%
- Ostem	12%
- Rubble and steel	16%
- Plant	10%
- Studies and services	7%

Risk sharing principle

As the construction of a sealable barrier across a broad inlet on the lee shore of the North Sea was an adventure with which nobody had any experience, a contract was agreed concerning this pioneer work, in which no more risk was allocated to the Contractor than he could initially carry. The entire inflation risk was taken on by the Government.

The Contractor's agreement provided rules for the determination of the contract sums for parts of the work once these had been properly detailed. The contract sum for each of these parts was negotiated after both the Client and the Contractor had, each independently, made an estimate. The Contractor had no fixed contract sum for the entire works, at the most an idea of the probable building costs and the total construction time.

Should negotiations about a sub-contract not result in agreement, a third party could be appointed for the execution of that part of the work. There was also a possibility to build under reimbursable cost conditions. Neither of these alternatives has been used in practice. As unforeseen circumstances could be transformed into adaptations of design, these adaptations could lead to the formulation of new subsidiary contracts. Thus, the overall idea of the contract was a reimbursable cost contract, except for the fact that to every subdivision it looked like common contract work.

Insurance

No CAR insurance was taken out for the work. The Government holds the point of view that its capital is large enough to carry the construction risks. This implied that the evaluation of the accounting of construction faults on the site had to be done by the supervising management. Within the concluded subcontracts, this did not cause any trouble because RWS has sufficient expert knowledge to execute this evaluation.

However, for the steel construction contract with Ostem, a CAR insurance was taken out. In contrast to the Dosbouw contract, there was a fixed total amount and the steel business in The Netherlands is used to transferring part of the risks to an insurance company. The same was done concerning the construction of special plant, all of them floating equipment, of which the construction sum had been insured.

Overruns

Early 1981 it became evident that the date for taking the SSBO into use could not be met. It was postponed from October 1985 to October 1986.

It also became clear that the budget which had initially been fixed in 1976, would be exceeded by 10 to 40%, depending on optimistic or pessimistic scenarios.

This correction of the earlier expectations was not caused by building accidents or industrial disputes, but by an initial underestimation of the difficulty of fixating the unstable sand floor of the Oosterschelde during the construction process.

During construction, the mouth of the Oosterschelde would tighten with every newly placed element, so that the flow rates would triple those of the zero phase, while the eventual protective quarry stone floor covering would not yet be there. The measures that had to be taken in order to get a flat and yet stable floor on which the piers could be placed, are the cause of the estimate increase.

Reallocation of risk

The risk allocation for each part was determined. Especially the activities in the barrier's axis, therefore in the tidal currents in the inlet, were so risky that a contract sum for those sub-activities could not be fixed. The compaction of the foundation by means of vibration was the first non-conventional closing operation. This work was paid by time unit. The repair costs of the vibration unit were settled on cost+basis. The same method of payment was used for the placement of the matrasses, the most critical activity.

A premium was offered as an incentive for conclusion before 1 June 1984. This premium could indeed be paid. The placement of the mattresses was followed by the following activities in such a way that no separate premium for progress was necessary. This was because, mid-1984, the idea had ripened that once all piers had been placed, there would be a sufficient reduction of uncertainty for the rest of the work to be executed as contract work. The risk of progress and costs could thus be transferred to the Contractors.

Towards completion

The change to a different risk allocation in the final stages of the work took place under the following circumstances:

- growing unrest among the Government supervisors about the increase of the estimate;

- the year of maximum turnover in the project had been reached, reduction of the organization was near;

- the construction teams on both the Contractor's side and the Client's side, thought that the combined estimate of problems would lead to the cheapest possible procedure that could be paid on time basis;

- a probabilistic prediction of final date and final sum had shown that there was a 50% chance of completion within the set time and budget.

The reason why the Client agreed to a transfer of risk, was the prospect of obtaining certainty about the final sum of the project, even if that implied a risk compensation sum. The reason why the Contractor agreed to the transfer, was the chance of realizing better margins than was possible at cost+ratio. He realized it was impossible to deny the Client's wish to fix a price. The project management's reason for accomplishing the transfer was to give the 50% chance of success a self-fulfilling incentive.

The contract changing process lasted more than a year. The difficulty lay within the exact definition of the transition of the hundreds of sub-specifications into the final specifications and within the exact allocation of the risks. In the first attempt to reach an agreement, so many progress risks had been allocated to the Contractor that an unacceptable price was asked in return. After months of negotiations, a balanced division was finally established, as well as a fitting contract sum of 10% of the overall value of the Dosbouw contract. The final date of the original contract could be maintained. Part of the construction risk was transferred to an insurance company in a wrap-up policy.

Finalization of the work took two more years after conclusion of the last sub-agreement. The gradual dismissal of personnel and materials took place without problems, the date of introduction, which had been announced two years before, was achieved, as well as the finalization date of the contract.

Evaluation

Contractual form

The chosen form of cooperation with Dosbouw has been quite satisfactory. In view of the unfamiliarity of the task, the choice was:

- cooperation with one consortium of Contractors during both the design and construction phase, with an open-end contract with a fixed profit compensation.

- compensation for the loss of possibility to induce competition by:
  * good cost price expertise of the Client;
  * sub-contracts for well detailed parts;
  * flexible division of risk for every kind of operation, depending on the extent of experience with the work in hand;
  * relatively extensive final agreement (ca. 10% of the contract value of the civil Contractor);
  * an expert construction team of the Client, capable of counselling the activities of the Contractors and of evaluating them in the construction phase.

Performance of the realization process

The estimate of the project was exceeded by 32% because of alterations in the draft perceptions and by 68% on account of inflation.

The final amount in guilders of 1987 is about twice as high as the 1979 estimate in guilders of that time.

The commissioning took place one year later than was expected in 1976. The contract did not have to be changed because it had a flexible risk allocation and because the remaining activities could be finished within the given time.

The quality of the barrier is perfect. All technical specifications have been met. The environmental minimal tidal flow demand was even considerably exceeded.

Client and Contractor did not have any industrial disputes.

Notes

1. The most relevant contractual matters are taken from Visser, T., Completion, Oosterschelde Storm Surge Barrier, Ministry of Public Works, The Netherlands 1988.

ANNEX 10 EXAMPLE OF THE PROPOSED DESIGN & CONSTRUCT CONTRACT

General

The most suitable type of contract for a D&C task is a Fixed-Price-Performance-Reimbursement contract, ("FIPPER-D&C" contract). This new type of contract with its main contractual content is illustrated in this annex. For convenience, it would be preferable to take one of the case studies as a demonstration example for the type of contract. The case study of chapter 9, The Storm Surge Barrier in the Nieuwe Waterweg, is selected for this showcase. It is noted that contractual arrangements are presented as showcase together with comments. It is certainly not the intention to give a Contract model.

Delimitation

In line with the delimitation of the total study, only the typical technical and typical administrative aspects of contracts will be highlighted which are necessary to show the principle of the new type of contract. Consequently, all contractual clauses on quality, standards, terms of payment, organization, responsibilities, etc. are not included.

The relevant contractual issues

For the D&C part of a realization process, the following issues should be incorporated in the contract:

- boundary conditions;
- concept;
- set of requirements;
- contractual normative performance of solution;
- contractual normative efforts;
- risk sharing principle and method.

These contractual issues will be generally presented.

Boundary conditions

The short list of boundary conditions as given below, represents the present contract of the SSBNW in a qualitative sense. The quantitative content is not relevant with respect to the purpose of this annex, but can be found in Contract BD001 of the Dutch Ministry of Public Works, Construction Department[1]. The following environmental boundary conditions are defined:

- tidal information
- probability distribution function of storm set up;
- probability distribution function of storm duration;
- probability distribution function of seiches;
- probability distribution function of Rhine discharge
- isolines of equal water levels in the lower part of the Rhine Delta
- salt information, density currents
- sediment transport;
- shipping: frequencies as a function of tonnes, dimensions and types;
- shipping: ship collision statistics
- soil information
- river geometry and depth contours

Concept

The concept of the Storm Surge Barrier, e.g. the set of starting points, is described in the first part of chapter 9.

Requirements

The requirements are outlined in chapter 9. The distinguished classes of requirements are:

- functional requirements
- structural requirements
- temporary construction phases
- exploitation and use
- others

However, it is recommended to use the classes as given in chapter 10:

- requirements concerning functionality
- requirements concerning reliability
- requirements concerning durability
- requirements concerning availability
- requirements concerning constructability

The contractual normative performance of solution

General

As shown in chapter 9, the performance of solution of a system is given by the set of valued aspect-systems for each relevant phase. Therefore, at first the relation matrix of aspect-systems and phase-systems should be established. After that, the relation matrix of aspect-systems should be determined for the determination of the normative performance of solution vector. This vector is obtained by multiplying the relation matrix of aspect-systems with the unit aspect-system vector. This procedure is given below.

Relation matrix aspect-systems/phase-systems

In the present contract BD001, only three phases were recognized:

- closing;
- functioning;
- opening.

It is preferred however, to distinguish the following phase-systems:

- installation;
- rest;
- horizontal positioning; float out/float in (horizontally);
- vertical positioning (sink down and lifting up);
- functioning.

It is noted that the phase-system "installation" covers only the temporary phases in the Nieuwe Waterweg. The other phases-systems refer to the utilization phase.

As derived from chapter 9, the performance of solution of civil engineering systems can be given in a set of relevant aspect-systems for each recognized phase-system. The relation matrix aspect-systems/phase-systems is given in table A.10.1.

Phase-systems / Aspect-systems	Constr./Inst.	Rest	Hor. pos.	Vert. pos.	Funct.
Strength	x	x	x	x	x
Stiffness	x	x	x		x
Stability	x			x	x
Weight		x	x		x
Geometry	x		x	x	
Capacity			x	x	
Durability		x			

Table A.10.1 Relation between aspect-systems and phase-systems

Because this annex is only meant for illustration of the type of contract, the explanation of the aspect-systems is only given for the vertical positioning system (see also chapter 9).

The vertical positioning system is a floating condition. During this condition a head difference between the seaside and the riverside is built up, causing large current velocities through the gap between sill and underside of the gates. For this phase system the following aspect-systems are relevant:

- strength, referring to the connection of the gates with the locomobile;
- stability, referring to (1) the floating stability and (2) the stability of the sill;
- geometry, referring to the width of the gates B;
- capacity, referring to deballasting capacity.

Relation matrices aspect-systems/aspect-systems

Having defined the relation matrix aspect-systems/phase-systems, the relation matrices of aspect-systems/aspect-systems can be determined for each phase. This is done for the phase-system vertical positioning only.

- Strength of the connection of the gates with the locomobile interacts positively with geometry. Larger width of the gates causes larger motions of the gates, resulting in larger forces during the landing of the gates on the sill.

- Floating stability of the gates interacts positively with geometry. The larger the width, the larger the stability.

- Stability of the sill and stability of riverbed are independent.

- Geometry of the gates interacts positively with strength, floating stability of the gates and deballasting capacity. The larger the width of the gates the larger the deballasting capacity should be.

- Capacity (deballasting) interacts positively with geometry.

The relationships as mentioned above result in the following matrix:

	Str	Sta	Sta	Geo	Cap
Strength	1	0	0	1	0
Floating stability	0	1	0	1	0
Stability riverbed	0	0	1	0	0
Geometry gate	1	1	0	1	1
Capacity	0	0	0	1	1

It is noted that the geometry of the dock is also related to the geometry of the gates. However, this relation is concentrated on the floating conditions during horizontal positioning. This is the reason that this relation is not incorporated in this matrix.

<u>The set of vectors representing the contractual normative performance of solution</u>

Since the aspect-systems form a linear independent basis (unity vectors) for each phase-system, the contractual normative performance of solution of each of the distinguished phase-systems is given by the associated product of the respective unit aspect-system vectors and the respective relation matrix of aspect-systems.

Hence, the contractual normative performance of solution vectors are given for:

- construction and installation;
- rest;
- horizontal positioning system;
- vertical positioning system;
- functioning.

For the vertical positioning phase-system, the contractual normative performance vector is established as follows:

$$\begin{pmatrix} 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 \end{pmatrix} \times \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 2 \\ 2 \\ 1 \\ 4 \\ 2 \end{pmatrix}$$

The length of the vector representing the contractual normative performance of solution is:

$$P_0 = \sqrt{2^2 + 2^2 + 1^2 + 4^2 + 2^2} = 5.38$$

The contractual normative efforts

The total contractual sum is 100%. Escalation is compensated. The typical construction risks as prices, weather delays, etc, are included in this price. Provisions for uncertainties (soil) are not included in this fixed price.

For the risk sharing principle, it is necessary to make a breakdown of the normative efforts for each distinguished phase system.

The cost components are expressed in percentages of the total contract sum:

-	installation	:	6 %
-	rest	:	20 %
-	horizontal positioning	:	7 %
-	vertical positioning	:	7 %
-	functioning	:	60 %

The most relevant issue of the time schedule is the minimum design period of 18 months without any construction activity.

Risk sharing principle

The performance of the realization process is fixed by:

- the normative performance of solution as described in the previous sections of this annex (P_0).
- the normative time schedule T_0
- the normative cost C_0 (budget)

For the risk sharing principle only costs will be compensated.

The process risk (= risk of design work and risk of construction work) is to be taken by the Contractor:

Actual costs = $C_0 \times P/P_0 \times (1 + dE/E - dP/P)$

with C_0 = normative efforts;
P_0 = normative performance of solution;
E = actual efforts;
P = actual performance of solution;
dE = differential actual efforts;
dP = differential actual performance of solution;

In other words, the Contractor is responsible for cost overruns which are related to his efforts. It is noted that all values < 1 of the ratio P/P_0 can only be determined by the Client.

The "performance of solution" risk (= perception risk) is to be taken by the Client.

Real costs = C_0 x P/P_0 x $(1 + dP_0/P_0)$

with: dP_0 = differential normative performance of solution;

The risk sharing principle should be applied for the five different phase-systems.

Risk sharing method

The Contractor is obliged to quantify the normative performance of solution for each phase-system continuously during the full D&C period.

The determination of the values of the aspect-systems for each distinguished phase-system must be based on the defined loadcases with corresponding probability of occurrence and the governing standards.

The risk sharing principle will only be applied in case of positive differential normative performance of solution ($dP_0/P_0 \geq 1$).

Given a certain differential normative performance dP_{0i} for a phase-system i, the Client can freely choose between the following control possibilities:

- Contractor receives $C_i = E_{0i}$ x $(1 + dP_{0i}/P_{0i})$. In that case, the Client wants a 100% solution (no adjustment of goal);
- Client wants to adjust the goal ($P/P_0 < 1$). In this case the Contractor receives: $C_i = C_{0i}$ x P_i/P_{0i} x $(1 + dP_{0i}/P_{0i})$

  with: C_{0i}= normative cost (budget) for phase system i, only valid for compensation of perception.
  P_i = actual performance of solution of phase-system i

The automatic risk sharing principle is only valid in case the differential normative performance of the total solution is less than 20 % of the contractual normative performance of solution. For differential normative performance of the total solution larger than 20 %, being a fundamental change of the concept, new contractual arrangements must be made.

The compensation procedure is as follows:

1. In case a certain aspect-system for a certain phase-system exceeds the contractual normative value (moment, force, etc.), the relative exceedance is included in the actual performance matrix (n x 1 matrix with n = number of aspect-systems).

2. The differential performance of that phase-system is established by multiplying the relation matrix of aspect-systems (n x n matrix) by the actual performance matrix (n x 1 matrix).

3. The Contractor presents dP_0/P_0 for that particular phase-system to the Client within a period of one week after the exceedance of the aspect-systems became clear.

4. Within one week the Client decides whether the goal can be adjusted or not.

5. In case an aspect-system is selected for the saving of efforts, the new vector of aspect-systems is established and multiplied by the relation matrix of aspect-systems. The outcome is the actual performance of solution vector (P) of that particular phase-system.

6. After another week, the Contractor is compensated the calculated and agreed compensation, which from that time point is incorporated in the schedule of payment.

Notes

1. This is an internal document (1989) of the Ministry of Public Works, Department of Construction in Utrecht, Westraven.

CURRICULUM VITAE

Henri Arie Johan de Ridder was born on the 18th of April 1947, in Zuilen, the Netherlands. He attended the Thorbecke Lyceum in Utrecht (the Netherlands) and completed this secondary education in 1966 (HBS-B). He subsequently studied Civil Engineering at the Technical College in Utrecht and completed the education in 1970 (BSc). After the fulfilment of his military obligations he studied Civil Engineering at the Delft University of Technology, specializing in Hydraulic Engineering.

Upon completion of his studies he worked with the Hollandsche Beton- en Waterbouw bv, working company of the largest Dutch Civil Engineering Contractor, Hollandsche Beton Groep, and participated in the design and construction of a number of large complex civil engineering systems, such as The Storm Surge Barrier in the Eastern Scheldt, Lac Nord de Tunis, The Ekofisk Protective Barrier and the Storm Surge Barrier in the Nieuwe Waterweg, Rotterdam. Moreover, as consultant he has been involved with many projects abroad on coastal engineering.

At the moment he works as a Senior Consultant with Delta Marine Consultants bv (DMC), a working company of HBG.

Stellingen van H.A.J. de Ridder, behorend bij het proefschrift
"Design & Construct of complex civil engineering systems",
in het openbaar te verdedigen op 20 september 1994.

Stellingen

1. Een contract voor een geïntegreerde ontwerp- en uitvoeringstaak voor de realisatie van een complex systeem op basis van een vaste prijs leidt tot verspilling.

2. Met een foutenboom kunnen de relaties tussen de elementen van een systeem noch volledig, noch correct worden afgebeeld. Daardoor is de foutenboom ongeschikt als hulpmiddel voor het ontwerpen van complexe systemen.

3. De Tweede Kamer is als volksvertegenwoordiging het hoogste politieke orgaan van het land. De regering, aan te stellen en aan te sturen door de Tweede Kamer, is slechts een probleemoplosser met een contractduur van maximaal vier jaar. Het lijkt dat de heer Bolkestein dit principe als enige vooraanstaande politicus begrepen heeft door als politiek leider in de Tweede Kamer zitting te nemen.

4. Bij complexe systemen zoals bijvoorbeeld onze samenleving wordt het algemeen belang veelal, overigens ten onrechte, ervaren als strijdig met het individueel belang. Het is de taak van bestuurders niet alleen het systeembelang te laten prevaleren, maar ook duidelijk te maken dat de voornoemde strijdigheid slechts schijn is. Omdat de bestuurders van onze complexe samenleving voortkomen uit (en gevormd worden door) partijen die zich meer en meer ontwikkelen tot belangenbehartigers, wordt effectieve uitvoering van bovengeschetste taak belemmerd. Dit wordt meestal uitgelegd als een gebrek aan politiek draagvlak.

5. Het feit dat de regering in Nederland meestal wordt gevormd uit mensen van elkaar bestrijdende partijen en de ministers slechts verantwoordelijk zijn voor hun eigen departement en niet voor het geheel, heeft tot gevolg dat er nauwelijks problemen kunnen worden opgelost.

6. Het spreekwoord "Verbeter de wereld, begin bij jezelf" getuigt van weinig inzicht in de (bij)sturing van complexe systemen.

7. Het door Komrij (NRC, 19/8/1992) genoemde evenwicht tussen ambitie en luiheid als voorwaarde voor een aangenaam mens, is ook toepasbaar op mensen die leiding geven aan organisaties die met interne veranderingsprocessen moeten reageren op een veranderende omgeving. Immers van zowel ambitieuze ijverigen als niet-ambitieuze luiaards valt weinig veranderingszin te verwachten.

8. Het feit dat er nog geen, altijd van ieder mens winnend, schaakprogramma is ontwikkeld heeft slechts een commerciële achtergrond.

9. Het zonder enige gêne vertellen dat men beschikt over twee linkerhanden heeft meer te maken met intellectuele pretenties dan met intelligentie.

10. Gezien het verschil in leefkwaliteit tussen gevangenissen enerzijds en verpleeg- en verzorgingshuizen anderzijds is het niet onwaarschijnlijk dat de Calculerende Burger van nu de Criminele Bejaarde van morgen is.

11. Als alles meezit ontwikkelt Amsterdam zich tot het Volendam van Europa.

12. De vaak in proefschriften voorkomende opdracht aan echtgenote en/of kinderen is in veel gevallen misleidend. Het is aanbevelenswaardig de volgende standaardtekst in het promotiereglement op te nemen: "voor mijzelf".