The 'Delft design method' for hydraulic engineering

technical report

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Preface

This technical report has been developed as part of my research on the 'structural evaluation of multifunctional flood defences'. The research is part of the programme on 'integral and sustainable design of multifunctional flood defences'. It is supported by the Dutch Technology Foundation STW, which is part of the Netherlands Organisation for Scientific Research (NWO), and which is partly funded by the Ministry of Economic Affairs.

The new curriculum of the BSc education on Civil Engineering at Delft University of Technology has changed per September 2013 and since then the design skills of our students have reduced. MSc-students from abroad often entirely lack these design skills, so they could benefit a lot from a clearly described, well-structured design approach.

This report intends to stimulate the discussion about enhancing and tuning the application of the traditional method for engineering design projects for educational purposes at Delft University of Technology - and possibly for the engineering practice as well. It aims at creating awareness of putting the design activities in a logical order and in applying the main design phases more consciously. It also attempts to enhance an integrated approach. The proposed improvements are not fundamental in the sense that they change the main design process, but they rather streamline the application of the method. I intend to incorporate feedback in a next version of this text, which will be available to anyone who is interested.

The current project on structural evaluation is being carried out under supervision of promoter prof. drs.ir. Han Vrijling and with help from ir. Wilfred Molenaar, dr.ir. Jarit de Gijt and dr.ir. Klaas Jan Bakker, all working at Delft University of Technology. The research project is externally supported by Witteveen+Bos (especially ir. Paul Ravenstijn and ir. Gerben Spaargaren), Arcadis (dr.ir. Marco Veendorp and dr.ir. Hessel Voortman), Deltares (dr.ir. Meindert Van, ir. Han Knoeff and ir. Harrie Schelfhout) and STOWA (ir. Henk van Hemert). I also got much support from many (other) employees of Delft University of Technology, especially prof.dr.ir. Bas Jonkman, prof.dr.ir. Matthijs Kok, prof.dr.ir. Marcel Stive, ir. Henk Jan Verhagen, dr.ir. Paul Visser and drs.ing. Hans de Boer. All their support is highly appreciated! In particulary Hessel Voortman is acknowledged for critically reviewing this report, and Ad van der Toorn for his fruitful discussions.

Reading hint: Those who are familiar with the current design approach could skip the first chapters and focus on Chapters 4 and 5.

Mark Voorendt
Delft, December 11, 2015

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Introduction

Professor Mick Eekhout characterised design as *the tunnel through which the results of scientific research are brought to society* (van Genderen, 2007). This definition emphasizes the *application* of knowledge of natural, social or psychological processes for the benefit of society. More generally, design can be described as the process of creating a plan or convention for realising an object or a system that is needed to solve a present or foreseen problem. This definition seems more complete, because it includes the *goal* of the process: solving a problem.

Depending on the specific purpose, several kinds of design can be distinguished, like industrial design, urban design, engineering design and product design. These definitions partially overlap, but the process of creating a plan for the realisation of a solution is mainly the same for all of these types of design.

The general form of the systematic process for accomplishing a design is called a *design method*. It is emphasized here that a method should be considered as a tool rather than as an end. A method at least provides a way to organize and report the design activities in a logical order. Furthermore, a design process is not uni-vocal like in maths: in a design there can be more than one valid solution that remedies the problem. This report presents the design process as a systematic and chronological activity, but in reality it is less straightforward and less rational than suggested by the presented flow diagrams.

The complexity of design processes is usually dealt with by subdividing the entire project in parts, and by applying phasing. This enables the allocation of tasks and the coordination of the project, resulting in clarity and manageability. The design process can be regarded as a phased, decision-preparing think and work process, where information is gathered and processed. Designing is also a process of learning, because beforehand it is not possible to entirely define what every phase comprises and specify the exact results. Furthermore, designing is a creative and not-routinely activity that can only be prescribed to a limited extent. This also implies that feedback loops are needed, to improve earlier executed steps when concepts are better understood. During the design process, designers frequently move forward and backward between steps. As a result, the design objective becomes ever more clear.

There is ample literature on design and design methods and it looks like that there is a wide variety in these methods, but it is mainly a matter of terminology. Most methods are based upon the same, natural, cyclic way of problem-solving. Adriaan de Groot, a Dutch psychologist and founder of the Cito-assessment of pupils of primary schools, described this cycle as the *empirical cycle in reflection* and characterized it by five basic stages:

1. observe
2. presume
3. expect
4. verify
5. evaluate

Problem-solving starts with *observing* the situation and then, with available knowledge and skills, the problem-solver has *presumptions* about activities that could solve the problem, and *expectations* about the effects of these activities on the observed situation. Then it has to be verified whether the expected effects match the desired effects. Finally, the problem-solver evaluates the result of his thinking process by asking 'what did I learn from the process?' and 'how can I apply the gained experience (possibly for a next cycle)?'. This process is embedded in the logical way of thinking and psychological theories and protocol analyses show that this cycle is generic and unavoidable (de Groot, 1994). The methods described in the following chapters comply to this natural way of designing.

The classical design approach for civil engineering systems as taught at Delft University is described in Chapter 2. It is followed by a short description of the Dutch guideline for systems engineering (Chapter 5.2) and how the design process can be organised in practice, depending on the type of contract (Chapter 3). Suggestions for the improvement of the application of the design method are presented in Chapter 4.

2

THE 'DELFT DESIGN METHOD'

2.1 THE CLASSICAL DELFT APPROACH

The 'classical Delft design method' is a typical engineering approach. It does not deviate too much from other engineering design methods, so it is not typically a Delft method, but this section describes the way in which it has been taught to many generations of students of Delft University of Technology, who have applied this method later on in practice during their professional job as engineer. The method can also be recognised in the Dutch Guideline for systems engineering, which is briefly described in the Appendix to this report.

The method reasons from a need to solve a societal issue, starting with the exploration of the problem, followed by the formulation of the design goal that should somehow solve the problem. This goal is formulated in an abstract way, namely as the fulfilment of a function, the intended behaviour. It is transformed into actual, concrete shapes and materials during the design process.

Basic characteristics of the classical Delft design method are:

- Functions are transformed into specific shapes: functions are derived from the design goal and shapes originate in creative processes. This kind of reasoning is also denominated as *innovative abduction* (Roozenburg and Eekels, 1995);
- Various alternative solutions are developed, optimized, systematically evaluated and compared to each other;
- Iterations are needed to improve already carried out design steps, with more knowledge and insight. Also the system definition is an iterative process;
- Design sequences are repeated cyclically at levels with more detail[1].

A flow scheme of the entire process was presented in the 1980's as in Figure 2.1. It only shows one loop of the cycle.

[1]A distinction is made between an iterative and a cyclic process: *iterative* means that steps are repeated or re-done with more knowledge. *Cyclic* means that the same steps are done at a more detailed system level.

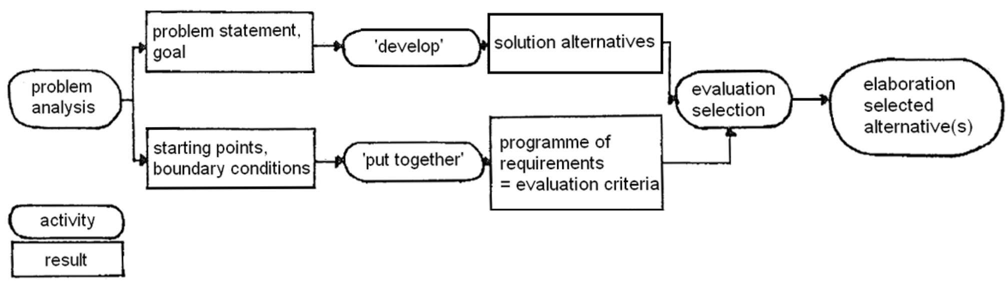

Figure 2.1: Flow scheme of problem solving, used for the education of civil engineers (Pols, 1982)

Later on, the process was gradually changed a bit, mainly by separating requirements from the evaluation criteria. The idea was to let all alternatives comply to the requirements before evaluating them with help of criteria. This leads to a flow scheme as presented in figure 2.2. This figure is used as a reference for the explanation of the method.

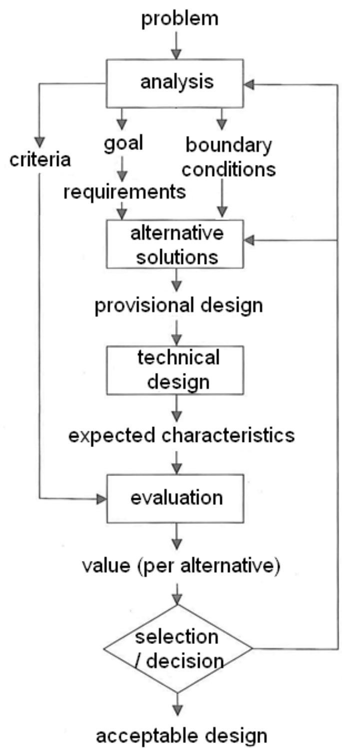

Figure 2.2: Flow scheme describing the design process for the education of civil engineers

So, the reasoning starts with analysing the problem, proceeds by specifying functions, formulated at an abstract level, and ends in actually shaped objects, structures or systems that fulfil the functional requirements and thus solve the problem.

This design method can be carried out on different levels of detail: it can be repeated in ever more detailed loops. The first loop starts at the level of a complete system (e.g., the upgrading of a harbour area including marina, breakwaters, storm surge barrier, congress centre, infrastructure and a bridge). It should then be repeated for the design of the subsystems (for instance the marina) and again for the sub-sub-systems (the jetties, boat house and canteen belonging to the marina) and the elements of the sub-subsystem (the walls, floor and roof of the canteen).

Different levels of detailing result in different products. A conceptual design (*schetsontwerp*) is the least detailed level, followed by a tentative design (*voorlopig ontwerp, VO*) and a final design (*definitief ontwerp, DO*)[2]. This implies that after the initial loop, many design processes can be carried out by different people at different design levels. This requires a good organisation of the entire design process (see Chapter 3).

A report including technical drawings and material specifications can be produced as the result of a design process, but this can also be a software model or a prototype model. The first designs are mostly quite rough, but they should be good enough to make a reliable cost estimate for the entire project, because these first overall designs are used to decide whether a tender proposal should be made. If it seems technically possible to realise the project for a reasonable price, a tender offer can be made. It requires much experience and knowledge to judge whether a tentative design suffices to make a good cost estimate.

The main design phases are explained below. For more information, reference is made to the TU Delft lecture notes on Integrated Design and Maintenance (Hertogh and Bosch-Rekveld, 2014) and to the Delft Design Guide (van Boeijen et al., 2013).

2.1.1 ANALYSIS

A problem is defined as the discrepancy between the desired (present or future) situation (or, in other words: the value preferences) and the factual reality. Problems are mostly signalled by managers, politicians, or those who are directly involved, but these people usually have a rather superficial and symptomatic observation. It is therefore essential that the problem is analysed thoroughly by the design team to find the actual cause and to make an inventory of the relevant interests and psychological, social, economic and cultural aspects. It is not necessary that the desired function is exactly defined at the start of the project, but there have to be some clues about it to give the designer an idea of the intention of the client.

Therefore, quite early in the design process, an inventory and analysis of the problem have to be made by means of given and found information (project file, informers, literature), to clarify the cause of the problem and to find out under what circumstances and by whom it is experienced as a problem.

The analysis phase includes several kinds of inventories and analyses. A inventory of many reports of BSc and MSc students has shown that the order of treating these aspects is rather arbitrary and not always all aspects were included. The analysis phase usually consisted of the following elements:

[2] In the HWBP, the Dutch high-water protection programme, two phases are described that precede the construction phase: Exploration (*Verkenning*) and Planning (*Planvorming*).

- general backgrounds and problem motivation (client-oriented)
- inventory of involved stakeholders;
- system functions (process analysis, function analysis and relation analysis)
- spatial aspects (a.o. sieve analysis and potential surface analysis)
- problem statement and design objective
- requirements
- boundary conditions and starting points
- reference projects;
- risks;
- possibilities to add values;
- rough project planning.

The process starts with describing *general backgrounds*: a first description of the motivation to bring up the problem and a sketch of involved processes, history, developments, etcetera.

A *stakeholder analysis* should include all relevant involved parties, next to the client. It is important to know what their interest is in what stage of the project and how much influence and power they have. It should be indicated how the stakeholders will be involved in the project. This can range from providing information in local newspapers to organising participation meetings and to adopting their interests as requirements (next to the clients' requirements). Usually, their interests are formulated as criteria (next to the clients' wishes that are not formulated as requirements) that are used later in the design process to value the design alternatives.

To determine the exact *system functions*, analyses of processes, functions and relations between the functions can be done. A process analysis can be helpful to make an inventory of activities needed for the system to be constructed and perform its function in its use phase. A function analysis can be carried out to precise the expected performance of the system. The main function is herewith subdivided into sub-functions and a relation analysis can be performed to estimate the intensity of the relations between individual sub-functions. This can be helpful when setting-up a spatial plan for the project area. (Sub)functions can be related to (sub)systems or objects that can be arranged in a systematic and clear way in an *object tree*. In a first inventory, it is important to describe these objects in a general way without too specific shapes, to stimulate out-of-the-box thinking. The object tree can later on be extended and used for the specification of requirements, resulting in a *requirement tree*.

A sieve analysis and a potential surface analysis can be carried out to find potential suitable project locations. In a sieve analysis, the unsuitable areas are indicated so that finally the not marked area is left over for realisation of the project. A potential surface analysis works the other way around and can be done succeeding a sieve analysis, or independently. In a potential surface analysis, a map of the area is provided with a grid and the degree of suitability for the realisation of the project is indicated for every cell with a score per rating criterion. The cell with the highest score is the most appropriate location.

After having analysed the problem and making inventories of relevant aspects, the actual *problem statement* can be formulated. This is not as straight-forward as it could seem at first sight, because it is not perceived by all stakeholders in the same way[3]. Moreover, the client sometimes already proposes a solution without having studied the actual problem properly. This could guide the process in the wrong direction, so the client should be convinced that a thorough problem analysis is needed.

The analysis results in a problem statement, which should not be too narrow, nor too wide, because that would result in more design loops than necessary, or in sub-optimal solutions. It is then a small step to formulate the *project goal* during the first loop and the sub(sub)system goals during further loops. The design objective namely aims at solving the stated problem. The objective is primarily formulated in an abstract way, for instance like 'providing a transport connection between two river sides' as part of a wider infrastructural plan, and not 'create a bridge' or 'create a tunnel'. It should be prevented that one too soon jumps to specific solutions (familiar structures), because this would spoil creativity and therefore possibly lead to suboptimal solutions.

Both the problem statement and the design goal are attuned to the considered detailing level in the cyclic design process. The first loop is often on a regional scale where strategical decisions are made.

After the project objective has been defined, *requirements* can be formulated to facilitate the verification phase. To obtain a clear overview of requirements, it can be helpful to group them by type[4]. The Guideline on Functional Specification of *Rijkswaterstaat* (van Netten, 2005) distinguishes five types of requirements, including *boundary conditions*. However, boundary conditions differ principally from requirements, because requirements indicate what is desired and boundary conditions restrict the possibilities by the environment. So, four types of requirements remain:

- functional requirements.
- aspect requirements
- external interface requirements
- internal interface requirements

These types of requirements are explained below.

Functional requirements qualitatively or quantitatively describe the desired behaviour, or performance, of the system or subsystem under defined conditions. They are directly derived from the design objective, which is formulated as a solution to the problem. An example of such a requirement is 'to provide sufficient underground space to solve the parking problem in the city of ...'. For the benefit of a technical verification, qualitatively described requirements are preferably translated into quantitative functional requirements, for example: 'provide underground parking space for

[3]The consequence is that it is very unlikely that a solution can be found that fully satisfies all stakeholders. This means that a compromise will have to be reached.

[4]Grouping of requirements could also be counter-productive when too much effort is made to define and distinguish types. The main issue is that all relevant requirements are listed in such a way that they can be used for verifying alternative solutions later in the design process

600 cars', or 'protect against storm surges with an average return frequency of once per 1250 years'. Functional requirements often determine the main effective dimensions of a system.

Aspect requirements describe specific characteristics of the system that support the primary functioning of the system. These requirements are related to the so-called RAMS system properties. RAMS is an acronym for Reliability, Availability, Maintainability, and Safety. Usually the following aspect requirements are distinguished:

- structural requirements
- availability and reliability (including the design life time of the system)
- maintenance
- constructibility
- safety (during construction and all other life stages; including an indication of the consequence class)
- demolition
- sustainability
- environmental health (dust, noise, vibrations, smell)
- aesthetics

Structural requirements do not follow directly from the design objective, but they are inherent to a well-functioning structure. Structural requirements can be derived from the main principles of structural integrity of providing sufficient strength, stability and stiffness. These requirements, and the methods to attain these, are often laid down in national or international standards like the Eurocodes. For hydraulic structures like quay walls, sheetpile walls and flood defences, guidelines and technical reports are provided.

Constructibility requirements ensure that the designed system or structure can be built. These requirements are also inherent in the sense that they do not originate in the design goal, but they are essential for a well-functioning solution: a structure or system that cannot be built, is no solution.

External interface requirements originate from the fact that the system often crosses or influences adjacent elements in its surroundings. External interface requirements can be found by identifying the elements in the surroundings that will be intersected by the new system and then identifying the functions and requirements connected to these objects. An example of these external interface requirements is the requirement that a new bridge is accessible for pickle trucks or maintenance equipment. An other example is the requirement that adjacent elements connect well in vertical and horizontal direction to ensure the functioning of system-crossing functions.

Internal interface requirements originate on the boundaries in between subsystems or elements within the system that is under design. It could, for example, be required that the interface in between objects provides a smooth and fluent connection.

Requirements restrict the possibilities to what is useful. *Boundary conditions* restrict the solutions to what is possible. Boundary conditions can comprise many aspects given by the environment where the solution has to be realised. They often further limit the possibilities and could pose a major challenge in the realisation of generated concepts.

Boundary conditions can, amongst others, be subdivided into:

- meteorological conditions (wind velocity and direction, temperature, humidity);
- hydraulic conditions (water levels, wave heights, structural erosion or accretion);
- nautical conditions (governing ship, shipping intensity, maximum wait for a lock, max. currents for navigability)[5];
- geo-technical conditions (soil properties, layers, groundwater, ground levels, land subsidence);
- geological conditions (presence of hills, mountains, rivers, lakes, sea, earthquake conditions);
- environmental conditions (possible presence of pylons, other land use);
- legal conditions (relevant laws and regulations, municipal plans);
- social and cultural aspects.

Starting points are design choices made in agreement with the client. For example, it could already be decided to design a bridge instead of a tunnel to connect two sides of a river, instead of optimizing it in the design. Another example is the decision to design a cable-stayed bridge instead of a steel truss bridge, or other alternatives.

Requirements, boundary conditions and starting points can be collected in separate lists. Wishes of the client and interests of the stakeholders can be summarized in a list of selection criteria, to be used later to evaluate alternative solutions.

Reference projects are useful to get an idea of possibilities, opportunities and drawbacks. If appropriate, a short description of the reference project should be incorporated in the report, followed by a short description of the relevancy for the design project in progress.

It is also good to have an idea of the *risks* that could threaten the realisation of the project. Several types of risk should be distinguished, like

- procedural risks;
- design risks;
- construction risks;
- maintenance and usage risks;
- societal risks;
- economical risks.

To manage risks, the RISMAN method is often used. This method consists of four main steps:

1. define the goal;
2. make an inventory of the risks;
3. determine to most influential risks;

[5]The client could also decide to specify these nautical characteristics as requirements.

4. determine the way how to deal with these risks;

A risk matrix can be used to visualise the probability of occurrence and the resulting damage per risk. It can then be decided to accept the risk (low probability of occurrence and low consequences), avoid the risk (high probability and much damage), or take additional measures (other combinations).

The consideration of *possibilities to add values* to the project is also sometimes included in the Analysis phase. These are opportunities to make alternatives more profitable by adding functionality.

A *rough project planning* in this stage gives an indication about the feasibility of the project regarding time.

2.1.2 ALTERNATIVE SOLUTIONS

The outcome of the problem and design statement is *what* function a solution should perform. The creative process deals with *how* this can be accomplished: The abstract design objective gets shape and material properties. The result of this phase only consists of provisional conceps, so other steps are needed to complete the design. In the educational practice of the Civil Engineering Faculty of Delft University of Technology, usually several alternative provisional concepts are generated in this stage, for instance by using brainstorming sessions, attribute listing, or by drawing morphological maps. If a provisional design appears to be not feasible in a previous design loop, possibilities of generating surplus value (extra income) should be considered in this design step.

Exploratory sketches are often made to trigger and enhance the thinking on solutions and stimulate creativity. These sketches are preferably made by hand without too much help of drawing aids like rulers. During the process of sketching, namely, ideas are generated and get shape. Drawing by hand is also a quick way to explore concepts. Exploratory sketching can therefore be considered as 'visual thinking', or 'externalised thinking'. It has been shown that the human mind works more creatively while making sketches by hand. While creating concepts, the sketches should not be too detailed and too precise, because that will be a hindrance for creativity, especially during initial design stages (Liu and Sorby, 2007).

Exploratory sketching should not be confused with representational sketching, because representational sketching is used to communicate ideas, not to develop them. Therefore, technical drawings, especially when made with help of computer programmes, are not suitable to stimulate creativity and can better be used in another stage of the design.

2.1.3 TECHNICAL DESIGN

Subsequently, the behaviour and characteristics of the designed alternatives are estimated, at long last aiming at possible actual construction and use. It is verified whether the concepts meet the requirements, formulated at the design level that is in progress, and thus it is checked whether the system as such fulfils its function adequately. A wide range of theories, formulas, tables and research methods from technical and behavioural science are at the disposal of the designer. *Simulations* can be used as a verification tool, for example to check a transport infrastructure system to detect bottlenecks. For structural designs, *calculations* are suitable to determine the dimensions of the system or structure.

To clearly recognize what should be done in this phase, *functional* verification is explained here separate from *structural* verification.

Functional verification The main dimensions needed for usage are usually roughly determined during the conceptual design of the system or structure under consideration. They follow from the functional specifications, so they will facilitate the main function of the system. For example, the main dimensions of a navigation lock are determined by the size of the governing vessel and maximum waiting times, and the number of cars to be parked simultaneously determine the main dimensions of a parking garage (together with some boundary conditions). Sometimes, main dimensions are also determined by the magnitude and characteristics of loading and material properties. This is obvious for dikes, where the presence of an outer berm is determined by colliding waves, or an inner berm if soil properties cannot prevent inner slope instability or piping. The main property however, the crest height of a dike, is determined by the main requirement of retaining water. The main dimensions are determined more precisely during the structural verification.

Main dimensions, however, are not sufficient to achieve the intended functionality. A structure should therefore also include some kind of technical system. For navigation locks, for instance, gates and a filling- and emptying system are needed. Parking garages need entrances and exits and a main parking lay-out. For dikes, the core material is important as well as the erosion protection layer. Different alternatives should be verified at the appropriate design level. For navigation locks, for instance, the feasibility of mitre gates, lift gates, roller gates and so on should be considered. This can be done at different design levels: first in a provisional way during the conceptual design loop and later during the structural design.

If functional requirements cannot, or only problematically, be made quantitative, the effect of alternatives can be simulated and the extend of meeting these requirements can be checked with help of interviews, questionnaires, focus groups or user observations. For example, emotional impact of concepts can be tested with use of product emotion measurement instruments (like PrEmos, developed by Desmet (2003)). A simulation can also be used to experience psychological or social aspects of design alternatives. In this way, qualitative requirements regarding human well-being or social comfort can be checked.

Structural verification The dimensions of structural members are mainly determined by requirements regarding structural integrity (structural safety). In ultimate limit state, requirements for strength and stability are set and in usability limit state, requirements for deformation, deflection or wave overtopping are relevant[6]. Techniques and safety margins are often prescribed in standards, or advised upon in guidelines or technical reports.

If, after the functional or structural verification, it would appear that a concept cannot meet the requirements, it can be attempted to improve it. If that appears to be impossible for affordable costs, a concept can be rejected. It is worthwhile to consider combining strong aspects of several concepts into one, if it would improve the efficiency or effectiveness while the consistency of the system as a whole is not affected.

A major aspect of the verification phase is the constructibility. This is an integrated part of the verification phase and in an efficiently organized project not something that is only checked afterwards. After all, when it appears that a system or structure cannot be constructed, the design is worthless. Another reason to involve construction in a design is that governing load situations often occur during the construction phase. The structure can collapse before it is finished if this is not taken into account.

Sometimes expert opinions give a clue about the feasibility of proposed alternatives. For the use of this technique, individual experts can be consulted, but to include a wider range of experience, groups of experts can be brought together. The result can be an approval, or a conditional approval. Expert opinions should be verified with help of advanced techniques, possibly during more detailed design loops.

The verification phase differs per discipline and per detailing level. Civil engineers and architects mostly deliver custom products, so they start with requirements as a guidance for the dimensioning work. Electro-technical and mechanical engineers have alternatives within their reach in catalogues. Their properties have just to be compared to the requirements. This also applies to civil engineers and architects when it comes to designing structural details: their properties can often be found as well in product catalogues.

2.1.4 Evaluation

When it has been ascertained that all alternatives meet the requirements, their value, or quality, can be determined with help of relevant qualitative criteria. These criteria are derived from the clients' wishes and stakeholders' interests. Weighing factors are assigned to these criteria, because not all criteria are equally important. The client should be involved in estimating the weighing factors. The designer could, for instance, present the table with unweighed criteria and discuss with the client what criterion should have more or less influence. The designer and client then immediately get a feeling of the sensitivity of assigning weights and scores.

Then the alternatives get scores per criterion and the product of score and weighing factor is calculated for every alternative. The sum of these products is the value per alternative. After determining the total value per individual alternative, it is easy to

[6] Wave overtopping is often also mentioned as a mechanism that could cause erosion of the inner slope and in that case it is an ULS requirement.

compare them to each other. This systematic method of comparing alternatives is nowadays better known as the 'Multi Criteria Evaluation' (MCE).

2.1.5 SELECTION

For the selection of the best alternative, not only the created values should be taken into account, but also the costs. This is usually done by dividing the values by the costs per alternative. The result is a value-cost ratio, which is kind of a 'value for money' ratio. Net present value calculations are used to represent future costs and revenues. The higher the value-cost ratio, the better the alternative. The alternative with the highest value-cost ratio can be enhanced by combining it with strong elements of other alternatives, and eventually by adding extra functionality (surplus value) that generates more income.

An alternative for calculating value-cost ratios is provided by value-cost quadrants. This method of evaluating alternatives has been proposed and applied by dr.ir. H.G. Voortman of Arcadis. The values and costs per alternative are visualised in a graph. The advantage is that the scores per variant are displayed in an absolute way, whereas a value-cost ratio is relative (for example, 10 000/20 has the same value as 6 000/12). For an example see Figure 2.3, where five alternatives have found their place in a graph. Alternatives 1, 2 and 4 have about the same value-cost ratio, so the value-cost ratio alone does not give a clue to decide what alternative is to be preferred. Alternative 4 could therefore be preferred over 1 and 2, if there the budget suffices. The quadrants should be drawn with their origin in a chosen reference alternative. Alternatives situated in quadrant I are always more interesting than the reference alternative, because they create more value for less money. Alternatives in quadrant III are always less preferable, because they create less value for more money. Alternatives in quadrants II and IV need more consideration and here the available budget could be a deciding factor. It could also be helpful to consider the value and costs of alternatives during longer periods, because that could shift their position in the graph. For instance if not only construction costs are considered, but also the costs of maintenance and demolishing or re-use, sustainable alternatives become more interesting.

The best alternatives can be proposed to the client and the consequences of choosing an alternative can be discussed. If the client is not satisfied with the thus found optimal alternative, two optimisation loops are possible: either by going back to the phase of finding alternative solutions, or even back to the analysis phase when it appears that more understanding of the real nature of the problem is needed. The design and the programme of requirements can be adjusted in a strongly interactive way in successive cycles.

If the client likes the 'winning' alternative, an new design loop can be started, where more detailed calculations and drawings are generated for the subsystems within the system that was designed in the previous loop. The objective and programme of requirements and all other steps are then aimed at the subsystem and they are more specific than in the previous design loop. A new loop could also be used to re-consider the programme of requirements, for instance when the costs of the best

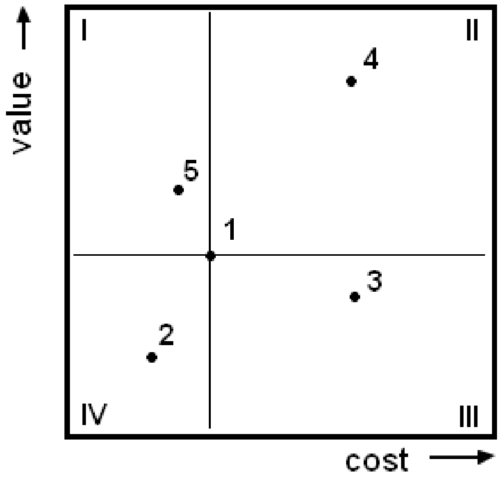

Figure 2.3: Value-cost quandrant for the evaluation of alternatives

alternatives appear to be unaffordable.

To complete the design project, the final results have to be communicated to others in a final report and/or a display board. Professional engineers usually document their solutions so that they can be constructed or manufactured.

2.2 THE METHOD OF ROOZENBURG AND EEKELS

Students of Architecture at Delft University of Technology also more or less follow the stages of the Delft design method as described in the previous chapter, but the steps are less explicitly executed and in the academic setting a real societal problem is not always present to justify a design. Industrial Design students are familiar with the method described by Norbert Roozenburg and Johannes Eekels. Their method does not differ fundamentally from the classic method, only the nomenclature is unfamiliar to civil engineers and the development of alternatives is not emphasized.

Roozenburg and Eekels, two former professors of the Industrial Design faculty of Delft University of Technology, described a design approach similar to the classical Delft method, but it is more specifically intended for product design (Roozenburg and Eekels, 1995). A design process according to this method consists of the following stages: Analysis, Synthesis, Simulation, Evaluation and Decision, which does not principally deviate from the steps described in the previous section. Only the names 'Synthesis' and 'Simulation' are unfamiliar to older generations of civil engineers, but the actual process is the same. The steps are depicted in Figure 2.4 according to the original publication of Roozenburg and Eekels, and alternatively presented according to the Delft Design Guide (van Boeijen et al., 2013).

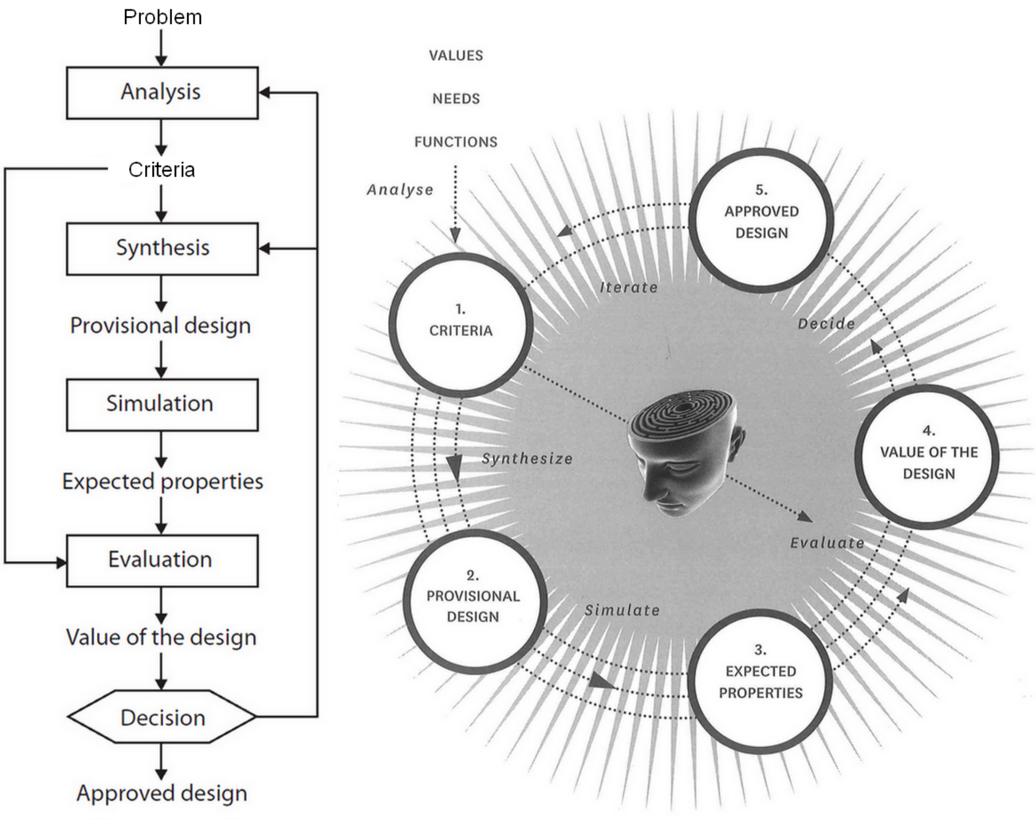

Figure 2.4: The basic design cycle of Roozenburg and Eekels as represented in Roozenburg and Eekels (1995) (left) and in van Boeijen et al. (2013) (right)

3

THE ORGANIZATION OF THE DESIGN PROCESS

The design scheme as presented in Figure 2.4 looks straight-forward, but one should realize that after the initial loop, many loops at subsystem and component level will take place simultaneously, involving various disciplines. This implies that many people have to work together and that coordination is needed to let the right people work together at the right moments. The budget and time have to be controlled and contacts with the client and stakeholders have to be streamlined. This requires a good organization of the entire process. This implies that the design team works well as a group, in good relation with the client and the stakeholders. The organization of the work also depends on the form of contracting. These two aspects are treated in the following sections.

3.1 TEAM WORK

Good teamwork is essential for the design process. British researcher and management theorist Meredith Belbin studied the effectiveness of team work, initially in management teams. He concluded that an effective team has members that cover nine key roles in managing the team and carrying out its work (Belbin, 1981). People can have more than one of these roles, but mostly one role is predominant. They can develop their 'weaker' roles when needed. These roles are:

- Plant: creatively generates ideas
- Resource Investigator: pursues contacts and opportunities
- Co-ordinator: distributes and tunes tasks
- Shaper: pursues objectives with vigour
- Monitor Evaluator: observes and judges what is going on in the team
- Teamworker: facilitates smooth inter-personal relations in the team
- Implementer: transforms suggestions and ideas into positive action
- Completer / Finisher: makes sure that the result has good quality
- Specialist: is a source of knowledge to the team members

Belbin's theory has been regularly used in educational settings and proved to be a useful tool in analysing the performance of student groups. Especially for not to well functioning groups, it is helpful to know what roles are missing, or overrepresented. Awareness of deviations of the ideal group composition helps reinforcing the weak spots.

American psychologist Timothy Leary developed a method to analyse behaviour of individuals and interactions between group members. He used an interaction circle, which is a graphical representation of different types of behaviour and their effects on others. This provides insight and can help team members in deciding how to interact. The interaction circle contains two axes. The vertical axis indicates the degree of dominance and the vertical axis the degree of collectivism. Dominance is complementary behaviour, because a dominant role provokes a docile role (and the other way around). Collectivism is symmetrical behaviour, because collective or solitary attitude of one person provokes the same attitude from other people. The behaviour per person is indicated in the circle. If two people are in the same quadrant, they maintain the same behaviour. If they are vertically opposed, a complementary reaction will be evoked, so behaviour that is complementary will reinforce the behaviour of the other person. If behaviour of two people is on the same horizontal line, it will have a constructive effect. This method too has been regularly used in education at Delft University of Technology.

Another approach to understand the functioning of teams is provided with the Organisational Cultural Model as developed by Geert Hofstede. He defined organisational culture as *the way in which members of an organisation relate to each other, their work and the outside world in comparison to other organisations.* Hofstede distinguishes eight dimensions or variables that enable alignment of organisational culture and strategy. These dimensions are:

- Means-oriented vs. goal-oriented
- Internally driven vs. externally driven
- Easygoing work discipline vs. strict work discipline
- Local vs. professional
- Open system vs. closed system
- Employee-oriented vs. work-oriented
- Degree of acceptance of leadership style
- Degree of identification with your organisation

Based on questionnaires under employees, the mean organisational behaviour can be determined. The dimensions hereby get scores from 0 to 100. The result could be helpful in explaining matches or mismatches with the kind or desired behaviour in a group.

3.2 CONTRACTING FORMS

It should be noticed that the result of a design process is a design, not a realised product or constructed system. After the design is finished, a process of manufacturing, assembling integration, etc. is required to finally create something, as shown in figure 3.1.

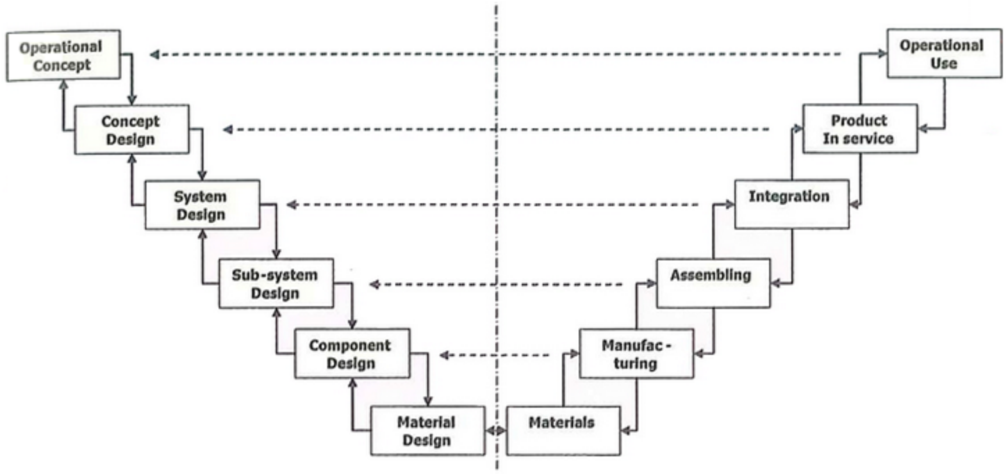

Figure 3.1: Generic model for the creation of systems (Hopman, 2007)

In the present construction practice, it is quite common to combine design and construction into one contract, sometimes also including financing and maintenance. The aim of making these combinations is to optimize the 'product' and the entire process to create and maintain that product. This also stimulates to consider all life stages of a product or system. The usual life stages are shown in figure 3.2. A design that takes al these stages into account is called a life-cycle design.

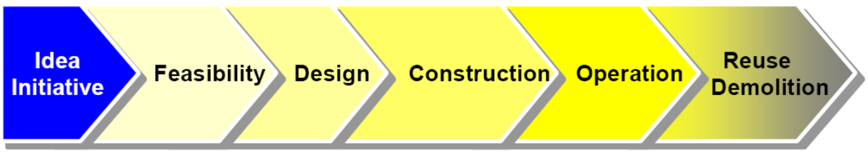

Figure 3.2: Life cycle stages

Today, there are many kinds of contracts with different division of activities for the involved parties. In the traditional contracting agreement, the client carries out the conceptual phase (the analysis including setting up the design goal and first client requirements) and the development phase (system specification and subsequent design, also carried out by a firm of consulting engineers). The realization phase is then carried out by the contractor and the maintenance is done by the client or a third party in commission of the client. In a *Design & Construct* contract, the contractor carries out the design and construction phases, which implies a partial shift of activities from the client to the contractor. In a *Design, Build and Maintenance* contract (DBM), also the maintenance is included in the contract. This can be further extended to arranging the finance for the project, which is called a *Design, Build, Finance and Maintenance* contract (DBFM). It was also endeavoured to let the contractor arrange all planning permissions, but for large projects this can easily lead to (near-)bankruptcy of the contractor. There are many more contract forms and it has to be determined per contract how activities, risks and responsibilities are divided.

4

Improving the design method

The author of this work has gained experience with the basic design method as supervisor of many students, working in groups or individually. Over-all, the method as described by Roozenburg and Eekels works quite well for civil engineering projects, although it has been developed for product design. Some improvements, that basically do not alter the natural way of problem-solving, could make the method more suitable. They mainly concern the application of the method than the over-all process that is quite natural and logic. The improvements are proposed in the following sections. A flow chart of the proposed adapted design method can be seen in Figure 4.1.

4.1 Nomenclature

The first phase is usually denominated *Analysis*, but that is a bit too narrow for the activities that take place. Next to analyses, namely, inventories are made, a design goal is formulated and a requirement program is drawn up as a specification of the intended system. Actually, all activities undertaken in this phase aim at drawing up the definition of the system, describing the intended performance, so *System definition*, or system specification, is proposed for this design step.

The names of the design steps *Synthesis* and *Simulation* are not common in civil engineering, so it is proposed to use other names. *Creation of alternatives* fairly describes what is done in the *Synthesis* phase. *Verification* can replace *Simulation*, because in this phase it is checked, or 'verified', whether the created alternatives meet the requirements.

The multi-criteria evaluation (MCE) is sometimes denominated as multi-criteria analysis (MCA). Actually, the systematic rating of alternatives with help of criteria and weighing factors is better described by the word *evaluation* than *analysis*. According to the Merriam-Webster dictionary, namely, evaluation means *to determine or fix the value of* something (an alternative solution in this case) and an analysis is the *separation of a whole into its component parts*. An analysis clearly does not cover all activities comprised in this stage.

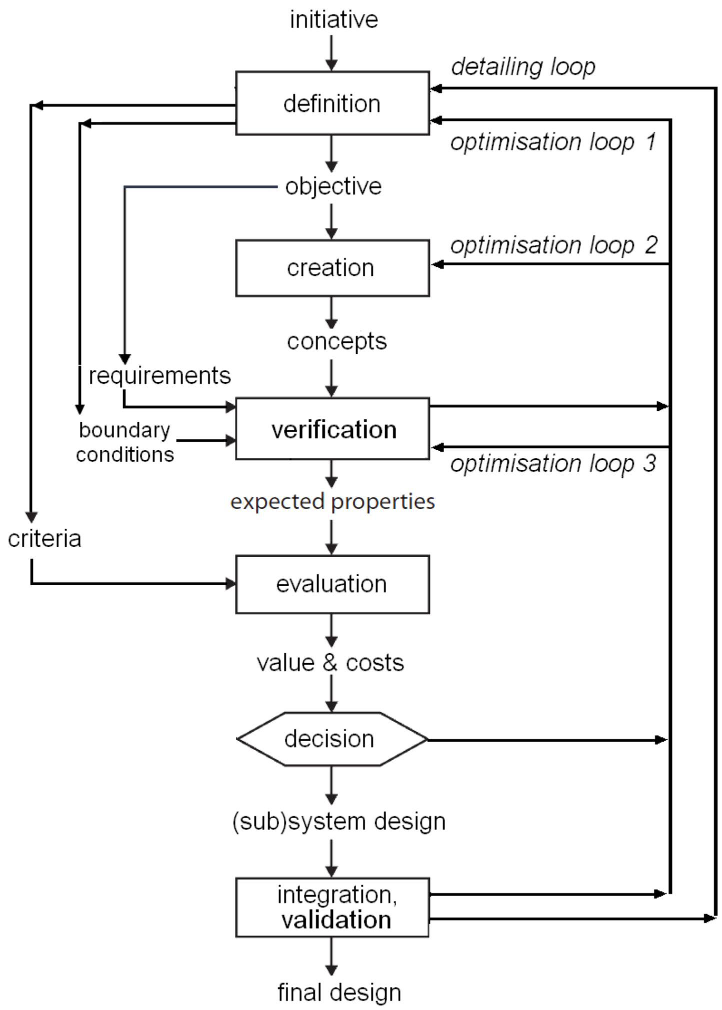

Figure 4.1: The adapted design cycle

4.2 THE DEFINITION PHASE

4.2.1 THE ORDER OF ACTIVITIES

There is no ideal order of activities in the definition phase that suits all situations. For example, if the problem is very clear from the start, the problem statement and objective can be formulated quite in the beginning. Otherwise, these activities could be better carried out after having done some inventories and analyses. In general, however, the following order seems to be quite logic and could be used, unless there are good reasons to deviate from it.

1. general backgrounds and problem motivation (client-oriented)
2. inventory of involved stakeholders;
3. system functions (process analysis, function analysis and relation analysis)

4. spatial aspects (a.o. sieve analysis and potential surface analysis)
5. inventory of risks
6. problem statement
7. design objective
8. list of requirements
9. list boundary conditions and starting points
10. rough project planning (not to be included in the design report).

It should be realised that these activities are not equally relevant for every detailing phase. For instance, it seems overdone to do a stakeholder analysis for the design of specific pier foundations, if that has already been done for the entire infrastructure project that contains the bridge that is supported by these piers.

It is proposed to move the analysis of reference projects and the generation of ideas to generate extra values to the Creation phase.

4.2.2 REQUIREMENTS VERSUS CRITERIA

A clear distinction should be made between *requirements* and *criteria*. All generated alternatives have to comply to the requirements formulated for the design phase under consideration before they can systematically be evaluated (in the multi-criteria evaluation). Therefore, requirements should not be used as criteria for the evaluation of alternatives. So, if alternatives don't meet all requirements, they have either to be optimized further, before they are evaluated. If this appears to be not possible, they have to be rejected as realistic alternatives.

It could be argued that some requirements could be met even better than strictly needed, for instance with a lower failure probability than required, which would after all be a reason to include a requirement as a criterion. The drawback of doing this is that the alternative that functions better than strictly required, will possibly be more expensive than needed. That would make that alternative less feasible.

Criteria can be derived from wishes of the client or from interests of stakeholders. It is sometimes endeavoured to formulate stakeholder interests as requirements, instead of criteria. In this way, stakeholder interests become major design considerations and social acceptance of the project by the concerned stakeholders is very likely. However, it is difficult to satisfy all stakeholders, because sometimes their interests are conflicting. Another disadvantage is that, if all major stakeholders interests are formulated as requirements, the selection of the best alternative can only be based on a comparison of costs. After all, there are no criteria left for rating, because the stakeholders' interests have already been formulated as requirements. This can feel unnatural or uncomfortable for those who are familiar with the basic design method, but that is the consequence of the choice.

A major drawback of formulating stakeholders' interest as requirements, is that stakeholders often do not consider the over-all consequences of formulating their interests as requirements. Firstly, they do not oversee the consequences of putting forward their interests as requirements for society as a whole. Secondly, they often have single-issue interests, so an overarching design and decision process is needed to balance all the stakeholders' interests (next to the client's requirements) and this can only be done if these interests are formulated as criteria. The advantage of the formulation of stakeholders' interests as criteria is that the rating and evaluation process is clear and transparent. In that way, everybody is able to know how interests are taken into account.

4.3 THE CREATION PHASE

It should be emphasized that the generation of alternatives is a *creative* process[1]. It is therefore important that the designers do not feel restricted by requirements. Therefore, for the first, not too detailed design loops, it is proposed to start developing alternatives right away after formulating the design goal, and to wait with defining requirements until the creation phase has led to first ideas about alternatives. A properly formulated design goal aims at fulfilling the intended main function, but also specifies the intended sub-functions. In that way, it should give sufficient direction to generate some concepts.

The design goal should be kept in mind during the creative process, and alternatives should be optimised later on, to meet the requirements connected to the detailing level in progress. While generating alternatives, it is the challenge to develop different *visions* on how one should experience residing in or using a certain (sub)system. Typical visions generated by BSc-students of TU Delft are a sustainable vision, a futuristic vision, a historical vision, a social vision and a transport-optimized vision.

A point of attention is the possible combination of functions. The design method subdivides functions into sub-functions and there is a tendency to look for separate solutions per sub-function. It could be very interesting to consider the combination of more than one sub-function into one structure or system, like combining a car park with a flood defence. Combining functions into one structure or system can lead to innovative solutions that could be more effective than separate solutions and are anyway good for public relations purposes.

In this stage, rather than in the Analysis phase, *reference projects* could be looked at. These projects could provide ideas additional to those already found by the project team. The consideration of reference projects is often more relevant for problem solving than for defining the system, what is done in the Analysis phase. Also the consideration of *additional value creation* is part of the phase of generating alternative solutions, mostly after a previous design loop where alternative solutions appeared to generate to little value.

For structural designs, the creation phase is often skipped in current practice, because of the availability of standard techniques. Experienced professionals have these techniques readily 'at reach', but for students it is advised to first make an inventory of main design considerations before verifying whether these are realistic. This is similar to collecting pieces of a puzzle, but putting them together is part of the following

[1]Which does not at all mean that creativity is not also needed for the other design steps.

phase, the structural verification phase.

The main design considerations vary per type of structure, but could include the following aspects:

- main construction methods: in situ, prefab or a combination of both
- possibilities to create dry workspace: sealing by a clay layer or underwater concrete, or apply dewatering
- vertical perimeter of the building site: natural slopes or walls (different types of walls!)
- support of the walls (strut framework or anchors)
- permanent use of temporary elements
- types of foundation: shallow or deep, also transfer of horizontal loads
- in case of buoyancy: tension piles or additional ballast

4.4 THE VERIFICATION PHASE

The purpose of the verification phase is to let all alternatives meet the requirements formulated at the level of the considered design phase. This is the basis of the evaluation and comparison of alternatives. The experience in education is that almost all generated alternatives meet all requirements quite early in the design process. The impression is that students are too much impeded in this creative process by already formulated quantitative requirements. It is therefore proposed to wait with setting-up specific (quantitative) requirements until alternatives are created at a conceptual level. The verification phase then starts with specifying the Programme of Requirements. It could also be considered to wait with making an inventory of boundary conditions until this phase.

Based on experience with supervising BSc and MSc students, it is proposed to follow next steps for the structural design of hydraulic structures in an educational setting. These steps are very alike the main design considerations that were inventoried in the previous step, but now choices are made with help of reasoning and calculations:

- figure out how the structure can be constructed: draw a construction sequence
- choose between in situ, prefab or a combination of both
- possibly create dry workspace: sealing by a clay layer or underwater concrete, or apply dewatering
- choose between natural slopes and vertical walls as a boundary for the building site
- consider making the construction pit part of the permanent structure
- provide sufficient strength and stability of temporary and permanent structures (equilibrium of forces and moments):
  - foundation: decide between shallow and deep
  - check buoyancy: tension piles or additional ballast needed?
  - for retaining walls: determine the embedded depth and the profile
  - possible support of the walls (strut framework or anchors)
  - for embankments: check piping possibility and slope stability

  - check piping, leakage, scour

The construction sequence consists of a series of construction and further life-cycle steps, depicted in a simple drawing (cross-section). In this way it becomes clear whether construction is feasible and possible bottlenecks can be detected. It is also helpful to find the governing load situation per design consideration or failure mechanism. It is recommended to make a drawing for every step, because skipping steps has regularly lead to overlooking some essential details or load situations.

It would be optimal if the mentioned steps could be carried out simultaneously, but that is impossible. There is no specific optimal design sequence, but starting with an idea of how a structure could be constructed is a reasonable start. At least, this is much better than ending the structural design with the consideration about how it should be constructed. Considering constructibility as the last design step will, namely, most surely result in re-doing all the previous work. It is therefore unavoidable that some assumptions have to be made to do the checks and probably some of them will prove to be wrong later on. This means that some steps will have to be redone until all the 'pieces of the puzzle' start fitting together. The number of iterations in this process decreases when the engineer (or student) becomes more experienced.

In a next design loop, dimensions of the structural *components* should be calculated. Also structural details should be elaborated; especially connections require attention. A popular saying is that 'the devil is in the details' and this is certainly true for hydraulic structures, so this step should be carried out with care (like all other steps).

4.5 THE EVALUATION PHASE

It must be ascertained that the design alternatives meet all requirements at the moment of evaluating them (this actually is the aim of the Verification phase). Otherwise the comparison between alternatives would be 'unfair', because 'good' alternatives would have to compete with 'unmatured' concepts. Even worse: it could lead to non-functional solutions.

Costs are sometimes used as a criterion in the multi-criteria evaluation, but this is principally not correct. Criteria, namely, represent values of the product or system, while costs represent the value of the money needed to create the product or system. In other words: value is a measure of the benefit that may be gained from goods or services, while costs represent the sacrifice that has to be made to realise a certain plan. Therefore it is more pure to separate values and costs. This implies separation of qualitative criteria for evaluating alternative solutions and quantitative cost (based on a net present value calculation).

To incorporate spatial design in the project, it is necessary to set-up spatial requirements, to ensure that these aspects will not be 'forgotten' during the process (especially by civil engineers). If these spatial aspects cannot be formulated in an exact or objective way, they can be included as criteria in the evaluation of alternative solutions. Suitable tools for spatial or urban design are needed.

4.6 INTEGRATION AND VALIDATION

Because this design method can be used for several design levels, solutions for the discriminate subsystems and components will have to be integrated into a complete 'working' system. This has to be checked, considering total costs, spatial aspects and planning. Technical drawings are made to indicate how the structure has to be constructed. Material quantities and needed equipment should be estimated, and a construction planning should be made. It is recommended to do a final check on the validity of the design: has the right system been designed?

4.7 USING THE DESIGN METHOD FOR PRINCIPLE SOLUTIONS

The general design method is sometimes used to evaluate the suitability of existing structures or products. For example, it could be studied what type of disembarking structure is most suitable for a specific berthing place. This differs from the design of tailor-made systems or structures, because existing alternatives are evaluated instead of specifically developed new systems or structures. This implies that the phase of developing possible alternatives (the *Creation* phase) consists of making an inventory of existing solutions, or 'principle solutions'. The possibilities of making these standard solutions fit to the requirements are often more limited than in case of tailor-made alternatives. Nonetheless, the same development cycle can be used as for tailor-made products. Often, making a design is making use of a combination of standard elements and tailor-made solutions.

The design method can also be used for developing a framework that supports making a choice between standard solutions for not very specifically defined circumstances. It could, for instance, be studied what kind of breakwaters would be most suitable for inland harbours in general. In that case the specific circumstances and boundary conditions are not clear, because the framework is location-independent as long as it concerns inland waterways, so it is not possible to include the judgement whether the various types meet the requirements in the framework. Moreover: the requirements can only be formulated in a qualitative way, if at all. For this purpose, the likelihood that solution types meet the requirements can be used as a criterion (with a high weighing factor) in the evaluation of solution types. It is advised to set up criteria for all individual main requirements and not only one criterion for meeting the requirements in general. So, in our example, the likelihood that a breakwater type will sufficiently provide calm water for shipping, the likelihood that it will be sufficiently stable, the likelihood that it will be reasonably constructible, etc, should be formulated as criteria.

5

On integrated and sustainable design

5.1 Integrated design

Integrated design is a collaborative method for designing systems or structures, which emphasizes a ’holistic’ approach. Holism is the concept of natural systems and their properties, considered as wholes, not as just a collection of parts[1]. Their functioning thus cannot be fully understood solely in terms of their component parts. A holistic (integrated) approach is believed to be more cost-effective and sustainable.

It is not sufficient to include experts of various disciplines in the design team. They tend to design only their own part or sub-system, resulting in a design that consists of separate mono-disciplinary solutions. So, a multifunctional design team is not a guarantee at all for an integrated design. An integrated design requires interdisciplinarity, which involves the combining of two or more disciplines into one design activity. It is about creating something new by crossing boundaries, and thinking across them. To achieve that, the multi-disciplinary team has to cooperate intensively during the phases of project definition, generation of alternatives and evaluation, at least during the first design-loops.

When it comes to a more detailed design, for instance the technical design of a reinforced concrete member, it is less problematic, and even desired if this is executed by a specialist. In this respect it is good to realise that there is a difference between using the proper tools and properly using the tools: it is the difference between doing calculations and making a design, which is illustrated in Figure 5.1. The design work is typically suited for an integrated group approach, whereas doing design calculations can be elaborated by individual specialists. The results of detailed calculations will have to be integrated again in the overall design activity.

Striving for an integrated approach also implies that all members of the design team

[1] Holism sometimes, in other fields of interest, includes super-natural systems, but that is not common in engineering.

Figure 5.1: The difference between only properly using tools (knowing how to bake bricks) and properly using the proper tools (constructing a navigation lock out of these bricks) (Zevenhuizer Verlaat, The Netherlands)

use the same design method and are aware of the goal in terms of functionality. In principle this should not be a big problem, because the way of problem solving is quite natural, but doing it in an explicit systematic way could arouse resistance by some type of people. However, it is unavoidable to work systematically when more people are involved in the process and the complexity increases.

To furthermore foster an integrated approach, the design objective should be formulated in such a way, that it contains all relevant (main) aspects. This is essential, because requirements are derived from the design objective. If the design objective is not complete, the programme of requirements will not be complete too and alternatives will not be checked for these aspects[2]. For example, the programme of requirements of a flood-retaining quay should contain requirements regarding spatial planning and aesthetics (next to requirements for flood protection), otherwise most probably a straight-forward hydraulic structure will be the result of the design process. Spatial requirements that could be included in an integrated design are described by Nillesen (2012), who used the three main components of spatial quality of Vitruvius (Pollio, 15BC):

- Utility
  - functioning as residential, commercial, recreational or public space
  - accessibility and routing
  - ecological functioning
  - maintainability
- Robustness
  - reversibility
  - development opportunities
  - multifunctional space utilisation
  - robustness
  - flexibility

[2]When, in educational practice, the final design appeared to be insufficiently integrated, it was mostly caused by a badly formulated design objective, next to al kinds of stupid things that can go wrong (like forgetting to formulate requirements at all).

  - durability
- Attractiveness
  - identity of the location / surroundings
  - recognition of structures
  - cultural recognition
  - spatial recognition
  - diversity / alteration
  - uniqueness
  - logic of spatial arrangement
  - image
  - safety experience
  - attractiveness
  - intervention scale versus location scale
  - relation to the water

These requirements are not quantifiable, so judging whether an alternative satisfies them requires approaches like expert meetings or questionnaires.

In a real project (so, not in an educational setting), workshops can be organized where stakeholders are brought together with multidisciplinary experts. Nillesen (2015) distinguishes interactive stakeholder sessions and expert sessions as *successful work formats to reach an integrated design*. The goal of interactive stakeholder sessions is to share knowledge, find facts together, identify relevant topics and assignments and create mutual understanding for different viewpoints. Expert sessions aim at collecting, sharing and creating knowledge. Both types of sessions can be used in various stages of the design. Nillesen reports that interactive stakeholder sessions were used for the system definition and development scenarios, then for the discussion of concepts prepared by experts based on the first session and finally for the discussion of design proposals that were developed after the second session by a multidisciplinary expert team.

Within Delft University of Technology a work-group was formed in response to a societal need for problem solving following an integrated approach by multidisciplinary teams. Delft University of Technology houses many disciplines and fields, but they are more science driven and they are specializing themselves more and more. Design, however, integrates knowledge and experience in order to solve complex issues within the domain of application. Collaboration is therefore seen as the key to reunite the disciplines of architecture and civil engineering. The minor on Integrated Design of Infrastructures, which started in September 2015, is the result of an effort of this work-group *to stimulate collaboration due to its engineering nature, architectural expression and its environmental context of cities and landscapes.*

This work-group produced a framework wherein *differing disciplines, 'lenses', types of infrastructure and all relevant related issues* can be positioned (de Boer et al., 2013), see figure 5.2.

Five 'lenses' were recognised during working sessions as themes that put focus on, or magnify, several relevant design aspects throughout the entire design process. Five

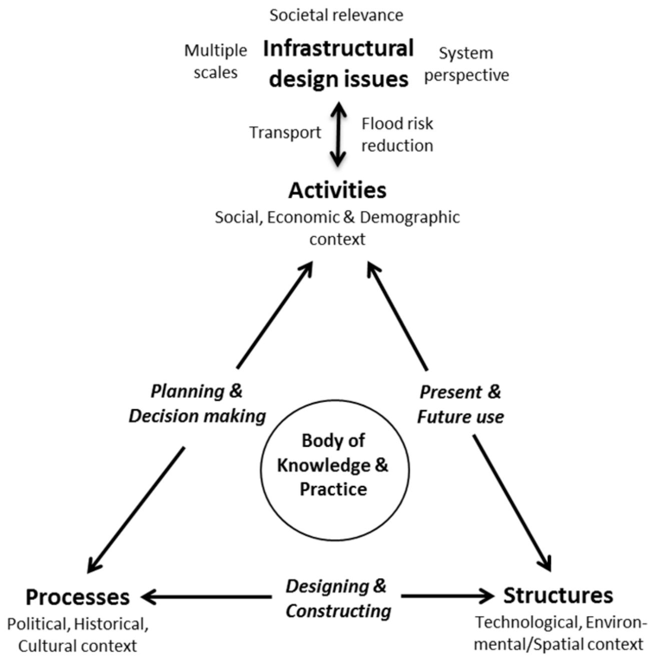

Figure 5.2: Framework for integrated infrastructure design, developed at Delft University of Technology (De Boer, 2015)

lenses were distinguished:

1. Complexity
2. Collaboration
3. Intervention scales
4. Permanence
5. Perception

These lenses provide cross-connections that reconnect the different disciplines[3].

5.2 SUSTAINABLE DESIGN

The term 'sustainability' was first used in the early 1980s and was popularized in the Brundtland Report of 1987[4]. The term has been open to different interpretations, but according to McLennan (2004), who is considered one of the most influential individuals in the green building movement today, sustainable design is *the philosophy of designing physical objects, the built environment, and services to comply with the principles of social, economic, and ecological sustainability*. This definition contains

[3]Nature is not subdivided into various disciplines - it is mankind that splits reality up into separate fields of knowledge and then concludes that these fields have to be integrated again. It is still a challenge to develop a direct, real holistic, approach wherein nature is not initially cut up into pieces.

[4]The report, titled 'Our common future', of the World Commission on Environment and Development (WCED), chaired by the prime minister of Norway, Gro Harlem Brundtland. The main finding of the report was that the main environmental problems are caused by poverty in one part of the world, and by non-sustainable consumption and production in another part of the world.

the three elements, or 'pillars' of sustainability that are commonly included: society, economy and environment.

Social sustainability could be defined as *a process for creating sustainable, successful places that promote well-being, by understanding what people need from the places they live and work. Social sustainability combines design of the physical realm with design of the social world – infrastructure to support social and cultural life, social amenities, systems for citizen engagement and space for people and places to evolve* (Woodcraft et al., 2011).

Economic sustainability is used *to identify various strategies that make it possible to use available resources to their best advantage. The idea is to promote the use of those resources in a way that is both efficient and responsible, and likely to provide long-term benefits. In the case of a business operation, it calls for using resources so that the business continues to function over a number of years, while consistently returning a profit. The goal is to establish profitability over the long term. A profitable business is much more likely to remain stable and continue to operate from one year to the next. From this perspective, this strategy can be seen as a tool to make sure the business does have a future and continues to contribute to the financial welfare of the owners, the employees, and to the community where it is located* (Collins World English Dictionary, 2015).

Ecological design is defined by Sim van der Ryn, leader in the field of sustainable architecture, as *any form of design that minimizes environmentally destructive impacts by integrating itself with living processes* (van der Ryn and Cowan, 2007). Ecological design takes into account the environment during the process of development of the system, structure or product, like an additional factor to those that traditionally are used for taking decisions: aesthetic design, cost, quality etc. It also aims to respond to declining energy resources as much as possible. Possible ways to achieve that goal are using energy conservation, efficient insulation, rainwater, solar radiation, and wind-power, and recycling. The concept of *Building with Nature* is quite similar to ecological design, but it not only comprises living nature, but also physical processes. Building with Nature could be described as the *integration of disciplines, knowledge, information and methods in the 'green-blue' development process related to wet infrastructure (decision-making, design, realisation, use, maintenance). The dynamism of the natural system is optimally taken into account, whereby cost and benefits are balanced for human and society against a background of a sustainable perspective. To achieve this goal, aspects like decision-making, design, biotic, a-biotic, socio-economical system knowledge, construction, monitoring and modelling should be integrated as leading research and application areas* (Stichting Ecoshape, 2008).

The three elements of sustainability can be made part of a design by incorporating them in the design goal and by setting up sustainability requirements. Furthermore, the right tools have to be at hand and the expertise to use them has to be present in the design team. Sustainable design is an attitude that also has to be embraced by the client and design team members. One also has to be aware of the changing awareness of the impact of technology on ecosystems. Ecological design manifested itself as an expression of a sustainable philosophy by the beginning of the twenty-first century. It attempted to achieve integration of human actions with a sustainable use of natural resources, limiting the negative impact on ecosystems within the bounds of viability. In that case, the integrity of both economy and ecology can be maintained (Çelik, 2013).

While technology usually aims at helping people or solving societal problems, it is now said, for example, that *with technological hegemony, our ecosystems have gained little and lost a lot* (Thayer jr., 1998). In this respect, the development of *appropriate technology* can be understood (Schumacher, 1973). It is a philosophy and movement initiated by Fritz Schumacher that aims at enhancing the self-reliance of people on local level by applying intermediate technology that is designed to be compatible with its local setting. Technology should be applied on an appropriate scale. Also the life-cycle approach, cradle-to-cradle and building-with-nature concepts can be seen as a response to the observed division between ecology and design.

APPENDIX: GUIDELINE FOR SYSTEMS ENGINEERING

The design of civil engineering systems is also described as part of the Dutch Guideline Systems Engineering (2013). Systems Engineering is *an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem: Operations - Performance - Test - Manufacturing - Cost & Schedule - Training & Support - Disposal. Systems Engineering integrates all the disciplines and speciality groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems Engineering considers both the business and technical needs of all stakeholders with the goal of providing a quality product that meet the users needs.* (International Council on Systems Engineering, 2015). So, it also covers the realisation, use/maintenance and demolition/re-use phases of the system, including the organisation of the entire process, but this section only considers the *design* of systems according to the Systems Engineering approach.

The design process according to Guideline Systems Engineering (2013) basically follows the steps as described in Chapter 2, but it uses different names for the activities. For instance, *development* is used instead of design, and *specifying* is mentioned as the process of determining the requirements and possibilities, obtained by interaction between analysing, structuring, allocating and designing.

In the Guideline Systems Engineering (2013) there is no clear distinction between the interests of the client and the interests of the stakeholders. All their interests are listed in a Customer Requirements Specification (*klant-eisenspecificatie* in Dutch) that contains a description of the intended functionality, the requirements per stakeholder, the available solution space, and a description of the system of interest of the client. This specification should be maintained and continuously updated during the development of the system. All steps within systems engineering aim at demonstrating that the system is optimally elaborated, based upon the defined Customer Requirements Specification.

The Guideline Systems Engineering (2013) explains that all activities needed to proof that the solution meets the requirements and suits the needs of the client, are covered by verification and validation. *Verification* shows that a solution objectively and explicitly meets the requirements formulated for the considered level of detail. *Validation* shows that a solution is suitable for the intended use. In other words: verification is checking whether the system can be properly constructed (efficiency) and validation is checking whether the right system can be constructed (effectiveness).

Both verification and validation should be carried out taking into account the appropriate level of detail for the design loop under consideration.

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