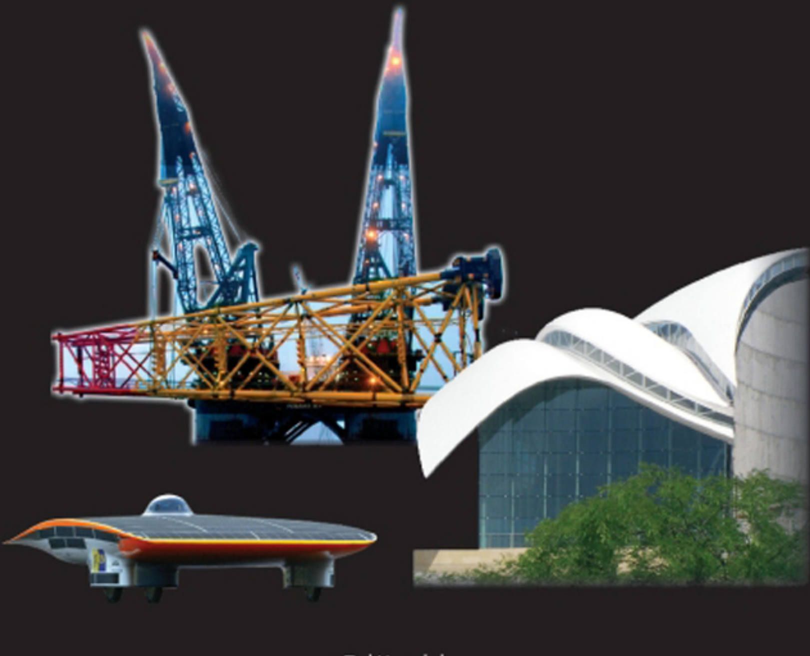
Research in Design Series, volume 3

# Delft Science in Design 2



Edited by
Mick Eekhout and Tetsuo Tomiyama

TU Delft
Delft University of Technology

# DELFT SCIENCE IN DESIGN

# 2

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# DELFT SCIENCE IN DESIGN 2

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# Preface
## Delft Science in Design 2

The Architecture Faculty is a highly appreciated, self-willed and essential part of TU Delft. With its design tradition the Architecture Faculty, together with Industrial Design Engineering, takes up a special place within our Delft University of Technology.

It is characteristic of both Faculties that they utilise the developments in both science and the art world. Not only do they improve everyday products - for instance a house or the heel of a women's shoe - but because of their creative designs they also add value to these products.

An issue is that the outside world tends to classify design studies as not being truly scientific. This often makes it more difficult to obtain extra funding for research, and the education is not always given its real merit by the evaluation committees of the Ministry.

I feel this is unjustified: to me, architecture and industrial design engineering are academic studies in the same way that applied physics or electrical engineering are academic studies. I do think, however, that the formulation of theories with regard to academic design needs to be further developed. For this reason this aspect has received increased attention within the Delft University in recent years.

## Academic design

At first glance an architect will design something differently from a chemical technologist, for instance. To be able to compare the academic level of both professional areas irrespective of these different angles, criteria have been formulated that an academic designer must comply with. To this effect Anthonie Meijers, Professor of Philosophy and Ethics of Technology at TU Eindhoven and TU Delft, interviewed representatives from different technical fields. Based on these interviews he concluded that the architect and the chemical technologist share a common design framework. For instance, he noted that all groups of academic designers will first redefine the problems before they start to look for a solution. They are all able to design at system level and with a high degree of complexity. It also became clear that matter-of-factness is an important characteristic that all engineers share. Both architects and chemical technologists are able to cope well with risks and changes to the definition of the problem in the course of the design process.

Based on these findings the three Universities of Technology in The Netherlands have formulated criteria with respect to the skills an academic designer must possess when he or she graduates from a University of Technology. For instance, engineers must have no difficulty with abstract thinking and with taking certain liberties in their designs. They must also be able to re-formulate poorly structured design problems in order to arrive at a better solution.

## Design Language

In addition to these criteria I also feel it is essential that designers are prepared to look at their own design process. In doing so it is important that they are able to distinguish between the context of discovery and the context of justification. In the context of discovery one describes how a certain design was created. However, I feel this alone is not enough. In the context of justification one reconstructs or analyses the decisions made during the design process, and then proceeds to justify these decisions. This approach makes it possible to come to a critical exchange of ideas about the academic level of a design.

At the same time this process can remove a lot of the perceived mystery that tends to surround the design process.

In order to facilitate a constructive debate about, for instance, the context of justification, it is important that the different parties involved speak the same language. I am therefore a proponent of the development of a 'design language'.

Louis Bucciarelli is a professor at the Massachusetts Institute of Technology (MIT) and was a guest lecturer at TU Delft some years ago. He too was an enthusiastic supporter of the idea of a design language. Bucciarelli concluded that, like science, the design process has also changed considerably in the last few decades. The design process has evolved from the application of fairly simple, traditional experiential knowledge to the use of advanced technology. According to Bucciarelli, design has now become a social process: it is a multi-disciplinary collaboration between different specialists. Increasing numbers of specialists collaborate on the design of a building or product. In order to develop a good product an exchange of knowledge, negotiation and an understanding of each other's wishes is essential - especially because, according to Bucciarelli, each party focuses on safeguarding the criteria of his own discipline within a design. In aircraft design strength is the focal point for a structural engineer, and speed comes second. An engineer who is responsible for propulsion, in contrast, will focus mainly on the engines and not so much on the structure. In a building process we can see a similar division. An architect wants to realise a high-profile design of the building as an object in the built environment; politicians seek to use the building as a means with which to impress the public; the structural engineer wants the design to be stable and structurally sound; the project developer wants the building mainly to be profitable for a long time. They all will mainly look at the same building from the perspective of their own interests.

A common design language could contribute to increasing the transparency of the discussion between these parties. Bucciarelli suggests that each discipline should compile a terminology list that is relevant to the professional field in question. In the list terms must be ranked in order of importance. Based on these terminology lists it would then be possible to devise a design language. It would, however, be essential to the development of this language that each party acknowledges the expertise of the other parties, and accepts their proposed terms. If this kind of acceptance is not realised consensus will never be achieved. And bearing in mind the strong-willed types of people usually involved in the design process, this will not be a simple task.

## Composer

I feel that the development of a design language is a challenge par excellence for engineers of Delft University of Technology. We are able to analyse problems matter-of-factly, but enjoy finding inventive and creative solutions. There may be architects who fear that a design language will restrict their creativity, but I don't think such fears are justified. Musical notation has never inhibited the creativity of composers. Quite the contrary: such notation allows composers to discuss their ideas with other composers and make it clear to musicians how the music must be played. I expect that a design language will fulfil a similar function, and that it will contribute to creative and academic designs that can be discussed in debates that push back frontiers and open up new horizons.

Prof. Jacob T. Fokkema
Rector Magnificus, Delft University of Technology

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## Design Processes

# Introduction

The series of congresses Delft Science in Design was initiated in 2005 by the so-called "Platform Design" of our university. The mission of this platform includes promoting and advancing the exchange of lessons-learned on design (as an activity of the scientific staff of the university) between members of staff of the university and between members of staff and industry. Also, the platform has been tasked to amplify the visibility of the results of academic effort in design at our university. The congresses serve these purposes.

The Platform Design is suggesting that many members of scientific staff design experiments, processes, "things", etc without recognizing them as design effort as such. Considering it this way, the majority of the TU Delft community is directly or indirectly involved in design activities, as are many of our graduates. The questions "what is design", "what is engineering", "what is science" can fiercely be debated. We understand that the difference cannot easily be measured: Between the extremes of artistic design and pure science the transitions are like in fluid: they are smooth and gradual. Maybe an approach focussing on how the university deals with knowledge provides a better entry to the debate. Many elements of knowledge can be readily transferred between peers (that is, between scientists / engineers at the same level of professionalism in the same field of science). In this case codified knowledge is a legitimate measure of output and performance. But frequently knowledge cannot be easily codified or is tacit. In such cases it is far more difficult to provide a yardstick to measure a group's or a person's performance. Objectification of performance by peer assessment might be the way out for the management of the university. The Platform Design is contributing, and will continue to contribute, to finding a fair solution.

Another very important consequence of the issue of appreciation of uncodified or tacit knowledge is that the mutual understanding between scientists from different disciplines may get lost. It is one of the two major objectives of the Delft Science in Design congress: offer a kaleidoscope of the activities of our various faculties to all university colleagues and students in order that staff and students can be made aware of activities in other laboratories and have the opportunity to be informed on details. Being informed is the first step to understanding. By doing so, another personal benefit can be served as well: more often than not, activities in other sciences, once properly understood, may stimulate new ideas, approaches and solutions in the own science.

The second objective of the congress is reflected in the metaphor proposed by the chairman of the congress, Mick Eekhout: "Design is the tunnel through which the results of scientific research are brought to society". The congress offers a variety of oral papers and poster-stands in interactive sessions. In particular the latter facilitate direct contacts between scientists and delegates during the congress. Many activities on conversion of scientific novelties into products or processes for commercial or governmental benefit start up from Small and Medium size Enterprises (SME's, in Dutch: MKB). Of course, large non-academic research institutes also have this ambition to create a roadmap for return on investment, but not at the level of direct transfer. For the purpose of supporting this "tunnel to society" the Chairman of MKB-Nederland, Mr. Loek Hermans, has delivered a keynote address in the congress. Entrepreneurs in SME's have been invited to join our congress and exchange views on opportunities with the authors of oral papers and interactive papers. Support on how to establish a joint project, how to deal with intellectual property etc. will be available in the interactive session area. We hope that the "tunnel to society" will not be one-way traffic, but that profitable contacts for both university and companies can be established.

Today's bouquet of lectures and posters is an arbitrary selection of TU Delft designers who have more or less worked in their design portfolio in multidisciplinary teams with remarkable results. The first series was quite material directed, this second issue of the Delft Science in Design Congress turned out to be more directed towards immaterial products and processes.

In totality this book contains 14 articles, organized in one block on Design of Products and one block on Design of Processes. In the congress however, the day was organised in 4 blocks. Each block of 3 or 4 lectures in the program was followed by a short discussion, supervised by a moderator whose function was to stimulate the discussion on methodology and results and the common and specific topics between the different presentations. The lectures were deliberately mixed as to their professional background in order to obtain an interdisciplinary view on TU Delft. The posters in the lunch area were presented with the aim of extensive discussion with the authors. The posters have been included in the first edition of the congress book, but were left out in this final peer-reviewed version of the final edition of Delft Science in Design 2.

We trust that the congress was inspiring and that it offered every participant shared benefits together with colleagues and entrepreneurs. We gladly solicit your feedback and active contribution to further advance the understanding and appreciation of design in our academic community.

Prof. Piet van Genderen
Chairman of the TU Delft 'Platform Design'

# DELFT SCIENCE IN DESIGN

# 2

## DESIGN PRODUCTS

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# Aircraft Fuselage Design in the Century Ahead
## A Multidisciplinary Approach

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**Abstract**

As the development of conventional aircraft has reached a point of saturation, novel configurations are required for coping with increased operational demands for airliners and stringent environmental requirements for the future. In the search for such configurations, old ideas like the Blended wing Body (BWB) seem to readily provide attractive solutions. However, for successful application of the BWB configuration, a major problem must be solved: the design of a rotationally non-symmetric fuselage with a reasonable weight. This paper outlines the search for the optimal fuselage. Beginning with a short historical overview and a presentation of future demands, the concept of multidisciplinary design, together with simple design rules, is enabled for crystallising the optimal anisotropic multi bubble fuselage arrangement.

Keywords: Blended Wing Body (BWB), Multidisciplinary design, Fuselage

## 1. Introduction

The relatively short history of aviation provides several examples where the success of a particular idea (usually reflecting on aircraft configurations), although technologically feasible, failed on technical and / or economical reasons [2, 4]. After a switch from wood and fabric to fully stressed aluminium shells, the appearance of conventional airliners has not changed sine the end of the 60's [10]. By considering the typical lifecycle curve of technological products and by taking the latest improvements in account (which did not lead to spectacular improvement of structural performance), the conclusion can be drawn that the assessment of alternative aircraft configurations is worth looking at [3, 5]. With the accelerating expansion of air travelling and the increasing economical and environmental requirements, failures of the past become nowadays interesting candidates. In particular, concepts like the flying wing and the blended wing body appear again as possible solutions. As compared to the past, the difference that can enable their success relies on a totally different economic / environmental framework and the advanced technologies that are available [16].

The a-priori selection of a suitable configuration for future aircraft is a dangerous task. Without a complete comparative investigation that provides a reliable picture of mainly structural and economic performance, it is difficult to select an aircraft set up with absolute confidentiality. However, with some design tools like the structural efficiency of basic geometry / load arrangements and performance data from the literature [10-13, 16], a particular direction can already be determined. Several studies performed by Boeing and NASA indicate the outstanding performance of Blended Wing Bodies. These configurations reflect on a mixture of conventional (tube – wing) aircraft and the flying wing, as invented around 70 years ago.

Despite its favourable performance, the Blended Wing Body imposes some significant structural problems, particularly in regard to the fuselage. The outer geometry does not permit for rotational symmetry; therefore the weight will definitely increase as compared to conventional aircraft fuselages [8, 11-13, 17]. However, with clever pressurised element arrangements and strategic use of the anisotropy provided by the utilised materials, feasible solutions can be found [4].

This paper outlines the search for the optimal fuselage. Beginning with a short overview of aviation history, several benchmark designs are identified. The classic airliner design is accordingly presented as a result of a long development trajectory and its suitability for future demands is tested against stringent environmental requirements. As the development of conventional airliners has already reached the consolidation phase, in section 3 the need for innovative configurations is motivated and the Blended Wing Body is presented as a feasible solution. In addition, the problem of designing a satisfactory BWB fuselage is outlined. In section 4 the principle of multidisciplinary design is explained in relation to the new fuselage. The main goal formulated here is the integration of various functions into a single design. With the aid of basic design rules and geometric simplifications we explain in section 5 why the multi-bubble option is the preferred solution. As a major condition, a membrane stress state for the fuselage panels is here introduced. The membrane stresses are further explained in section 6 where the principle of tailoring material anisotropy to the bubble geometry is outlined. After a short performance assessment, the paper ends with some concluding remarks, warnings and recommendations.

## 2. Framework

In this section we will try to place the central question of this paper (fuselages in the century ahead) in an historical and future perspective. On one hand we can learn from the past by identifying major breakthroughs, and on the other hand we can attempt to predict which aerostructure properties are the "hottest" given the economical climate of today and the environmental demands of tomorrow.

### 2.1 A brief history

After the first motorised flight, performed by Wilbur and Orville Wright in 1903, aviation has shown an exponential growth both in terms of technological sophistication and economic impact. To illustrate this, one must realise that the wingspan of a Boeing 747 is bigger than the first powered flight [4]. From a macroscopic point of view, this development looks rather smooth and continuous; however, particular breakthroughs are truly responsible for this success story.

While the first aircraft was mainly based on the combination of a wooden frame and fabric, the introduction of industrially produced all-aluminium stressed skin aircraft in 1932 (Boeing 247, DC2, DC3) initiated the scientific approach of evaluating aerostructures. The isotropic character of such materials paved the way for predicting and reliably dimensioning structural parts like wings and fuselage. As increased flight heights (coupled to increased velocity levels) proved more economical, designers had to face the challenge of providing a liveable passenger environment in terms of acceptable cabin pressure. One of the first pressurised cabin structures can be found in the Boeing 307 "Stratoliner" (1937). At the same time, the introduction of jet propulsion at the end of the Second World War finally broke the barrier of performing over seas flights within acceptable time. The pressurised cabin concept however, dramatically forced novel developments in the area of fuselage design. Until a series of dramatic accidents with the Comet of The Havilland, nobody was aware of phenomena like fatigue and crack forming. With Boeing and McDonnell Douglas being the first companies that successfully solved this problem with respectively the introduction of the 707 and DC8, a fascinating cycle of aircraft structures development is crystallised in the form of the typical passenger carrier as we know today: a cylindrical tube (optimal for internal pressurisation) with wings, a horizontal tail section and a rudder.

With the typical passenger carrier configuration entering our skies from the end of the sixties the only variation can be found in the number and position of engines and the number of decks. The 747 with a partially double deck is probably the biggest revolution in aviation history making overseas flights affordable for the "average" people. On the other hand, developments like the Concorde did not realise a breakthrough due to their disappointing economic performance (despite their extraordinary level of technology).

## 2.2 Future demands: economics

In a growing competitive environment, aviation economics are nowadays the decisive factor for the success of both manufacturers and operators. For an airliner, customer preference can be assured by either offering better services or lower prices. The first method, better services, would in first instance mean shorter travelling times followed by more comfort, better customer service etc.

Shortening the travelling time however, does not seem to be that important for potential customers [2, 4]. A flight from London to New York could last 4 hours instead of 7 but when considering the time for checking, boarding and arriving at the airport, such an improvement is only marginal. Passengers are not prepared to pay several times the average ticket price for saving a few hours. This is the reason for the unsuccessful story of the Concorde. We should mention here that reducing the flight time through supersonic velocities with a marginal increase in the ticket price is not feasible due to aerodynamic constraints [5]; the drag increase is disproportional. Hence, subsonic flights will be there for the next decades. To demonstrate the effect of travelling speed on the fuel efficiency we provide here in table 1 some typical results [5].The second method for attracting flying customers relies on the ticket price reduction. With the introduction of the so-called price fighters however, the margins for competition are narrowing. In figure 1, the trends in cost and revenue for passenger transport are given [5]. Although not completely up to date, the figure typically demonstrates the declining profit per passenger seat.


*Fig. 1. Trends in cost and revenue of passenger transport*

**Table 1. Transport systems and their fuel efficiency**

| Proven and Future Transport Systems | | | | |
|---|---|---|---|---|
| Velocity Domain (km/h) | Transport market / system | Fuel | **Dominant resistance/drag** | **Specific drag** (fraction of transported weight that is required for propulsion) |
| 50<V<100 | *Local:* **Smart busses** Smart cars Smart trains | **Gas and** electricity | Wheels (rubber/asphalt) (steel/steel) | $0.01<D_{spec}<0.02$ |
| 50<V<250 | *Local, regional and continental:* human controlled cars busses | Liquid fuels | Wheels, air friction (rubber/stone) | $0.01<D_{spec}<0.20$ |
| 125<V<300 | *Regional and continental:* high velocity trains | **Electricity** | Air friction (steel/steel) | $0.01<D_{spec}<0.05$ |
| 300<V<900 | ***Regional, continental and intercontinental:*** **subsonic aircraft** | Liquid fuel, hydrogen | Induced drag | $0.05<D_{spec}<0.08$ |
| V >1000 | *Intercontinental:* supersonic aircraft | Liquid fuels | Induced drag, wave drag | $0.10<D_{spec}<0.15$ |

The highlighted tendency can partially be assigned to the market mechanism. However, a decisive parameter for this development is the possibility for profit as determined by current technologies. To increase profit, aircraft should be more economical. A primary factor to improve economics is the reduction of fuel consumption by means of better engine performance, advanced aerodynamics or weight reduction. In particular the latter is highlighted by several researchers as an important candidate [6, 10-13, 16]. However, some of them share the opinion that a weight reduction of even 30% will result in an operating costs reduction of only 5%. Assuming more realistic values (like 10%) the operating costs gain is very small. On the other hand, we should not forget that structural weight reduction is the only thinkable short term improvement.

## 2.3 Environmental Goals in 2020

Having a rather ambitious character, the Strategic Research Agenda of ACARE (a European conglomeration of aerospace institutions, manufacturing companies, airports airliners etc) has formulated a set of requirements for a hypothetical medium sized airplane in the year 2020 [1, 9]. The main goal behind this set is the "greening" of aircraft. Points of special attention are:

1. $CO_2$ reduction by 50% per passenger kilometre. The breakdown of this reduction is: 20-25% fuel consumption reduction due to structural aircraft improvement, 15-20% by engine improvement and 5-10% by operations optimisation.
2. 50% noise reduction as compared to the current average levels. This is mainly to be achieved by improved engines that are placed more strategically, shorter take off trajectories, less required power and improved operations.
3. 80% reduction of $NO_x$ emissions, to globally be achieved by the techniques described above.
4. Minimisation of industrial impact during manufacture, maintenance, overhaul, repair and disposal. Although not quantified, the achievement of this goal will depend for a large portion on political issues.

According to Tenney and Pipes [16], such a rigorous reduction will probably imply a dramatic weight reduction. The question arising now focuses on the feasibility of current aircraft technology to meet this demand. To deploy a thorough judgement about the feasibility of these targets, we should keep in mind that aircraft structures as they exist now are the result of nearly 70 years development. During that time, little has changed when regarding airplane configurations at a very conceptual level. Current designs are still mainly based on fully stress aluminium skin concepts. Considering the technological life cycle of products in general, figure 2, one can distinguish four stages [3, 5].

The initial stage for airliners, the development, took place around the Second World War. From 1950 to 1975 an expansion can be observed, significantly aided by the development of jet engines. The technology reached the consolidation stage from roughly 1975 to 2000. From that point, little space for improvements can be found. The introduction of improved alloys in combination with the replacement of several secondary sub structures by composites (mainly applied in the empennage, control surfaces and high-lift devices) has only led to marginal improvements. In the 80's the Airbus A320 was the first to exceed 10% weight utilisation of composites [16]. Fibre metal laminates like Glare are introduced as well (Airbus A380). Boeing however, is already intending to create full composite aircraft by discarding the fibre-metal laminate option. Considering these two philosophies however, their common divisor is the assumption of the traditional tube-wing configuration.

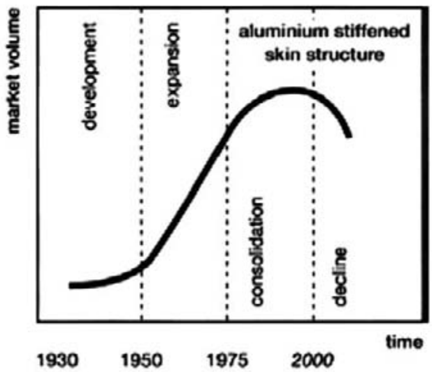



*Fig. 2. Technological product life cycle, projected on typical passenger aircraft*

## 3. Feasible solutions: the Blended Wing Body

In this section, by blending an overview of the "state of the art" technologies with the impact a particular configuration can have on the structural performance of aircraft, an assessment is presented regarding potential candidates, able to deal with the intensified economic and environmental requirements.

### 3.1 Configuration

From the previous section it becomes evident that meeting the "2020' goals in an economic environment where the profit margin per passenger seat is declining will be a difficult task. By extrapolating from the past where improvements on the classical wing-tube concept have resulted into rather marginal improvements (in terms of weight reduction) and by placing this event in the light of the technological product life cycle, one can conclude that the time has arrived for an entirely novel concept. With the latter we mean: a rigorously different aircraft configuration.

In regard to the (yet undefined) novel configuration, two questions arise immediately: is this desire for novelty really original and justified? And: why should this time be the right one for such an introduction? To answer the first question we mention here that aircraft designers have always been experimenting with novel configurations. In this sense the flying wing, the cylinder-wing or mixture of them (Blended Wing Body) have been conceptualised even before the Second World War. The first flying wing that flew is the Northrop YB 49 that entered the sky in 1948. Lack of advanced flight control techniques and absence of a sufficient technological or economical reason for their introduction has suppressed their development. The idea lost ground until 1988 with the introduction of the B2 spirit bomber (figure 3). Summarising, we must answer that the idea of introducing a "novel' configuration definitely lacks originality. However, the time is indeed right for doing something new: we are on the top of the product lifecycle curve (S-curve) for passenger carriers in an increasingly competitive environment. Hence a breakthrough is probably justified.

*Fig. 3. The B2 spirit bomber, a reintroduction of an old idea, but this time with feasible flight control characteristics.*

To most suitable configuration for enhancing significant weight reduction is the so-called flying wing. The main reason for this selection is that a flying wing does not incorporate a tail section, which is known for parasitic drag generation [3]. At the same time, the wing itself is both loaded by weight (payload, fuel, structural weight) and aerodynamic forces. In the optimal scenario, these loads do cancel each other on such a way that there is no bending. This will definitely lead to the lighter solution. However, from a flight control and passenger accommodation point of view, a less pronounced configuration is preferable: the blended wing body which is, in simple terms, the mixture of the classical passenger airplane and the flying wing, figure 4.

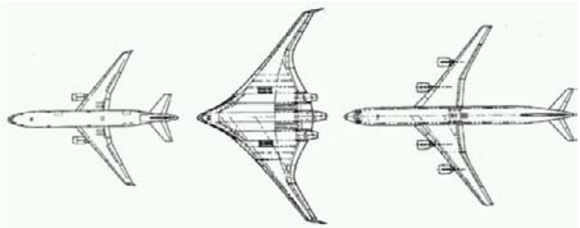


*Fig. 4. Blended Wing Body (middle) as compared to typical airliners*

According to [5] the change from a conventional 800 passenger carrier to a BWB will result in the following benefits:

- 27% lower fuel consumption
- 15% less take off weight
- 12% lower empty weight
- 27% lower required total thrust
- 20% higher lift to drag ratio

### 3.2 The potential of novel technologies

Independently of the aimed aircraft configuration, a study of Pipes and Tenney [16] provides some numbers regarding the individual weight reducing potential of modern technologies application. These numbers are given in table 2 for a typical 800 passenger carrier with subsonic cruise speed.

**Table 2. Possible aircraft weight reduction through application of cutting edge technology**

| Discipline | Specific areas | Weight reduction (%) | |
|---|---|---|---|
| | | Conventional | BWB |
| Aerodynamics | Laminar flow control<br>Design optimisation<br>Excrescence drag reduction | 4.6 | 11.8 |
| Structure | Composite wing & tails<br>Composite fuselage<br>Light weight landing gear<br>Advanced metals<br>Aeroelastic tailoring | 24.3 | 19.1 |
| Propulsion | Aero-mechanical design<br>Hot section<br>Materials<br>Secondary systems | 13.1 | 12.2 |
| Systems | Relaxed static stability<br>Fly by light /power by wire<br>Navigation<br>Intelligent flight systems | 9 | 2.6 |
| Total weight reduction (%) | | 51 | 45.7 |

The provided numbers set the BWB configuration in a more sceptical light. The performance gain through aerodynamics is bigger but the overall picture is counteracted by less favourable structural and control characteristics. For the propulsion, the numbers do hardly show any difference. The data presented here are extracted from a study performed in 1998. More recent studies show a more positive picture for the BWB [10-13]. As the general consensus clearly shows the BWB outperforming the conventional configuration, we will further focus on it.

### 3.2 Structural challenges: fuselage

As already indicated in table 2, the structure and control systems of a BWB are areas where the weight reduction potential is limited. Focussing on the structural aspects, an important distinction must be made for the wing section and the fuselage.

The wing section is expected to readily become lighter as the bending and twisting stresses will have a less profound character. The lift-induced forces are called to cancel weight over shorter distances as compared to conventional aircraft where in fact the fuselage is a cylinder that is carried by the wing section. With wingspans currently approaching 80 meters, these bending loads are impressive. At the same time, the BWB wing section will have significant height due to aerodynamic requirements and will provide space for a passenger cabin, figure 5. The increased height provides sufficient design space for creating proper moment of inertia to resist bending and twisting.

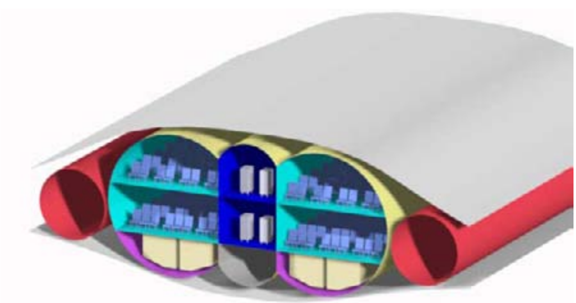


*Fig. 5. Artist impression of a BWB cabin space*

In regard to the fuselage section, there is a significant variety of load cases that have to be considered. However, the most critical for a rotationally non-symmetric configuration is the internal cabin pressurisation. Although in the order of 0.8 Bar the generated forces can be impressive. On an average access door this would mean a force in the order of 10.000 [Kg force].

It is known from mechanics of materials that the optimal pressurisable shape for isotropic materials is a sphere [8]. Although less optimal, the cylindrical tube, as nowadays applied in aircraft is a preferred solution: it provides usable cabin space and utilises at least 50% of the material strength, from a static point of view. However, we should mention here that the dimensioning a pressurised fuselage is mainly based on fatigue requirements. In figure 6, a simple comparison is presented regarding the performance of non-spherical pressure vessels [11-13].

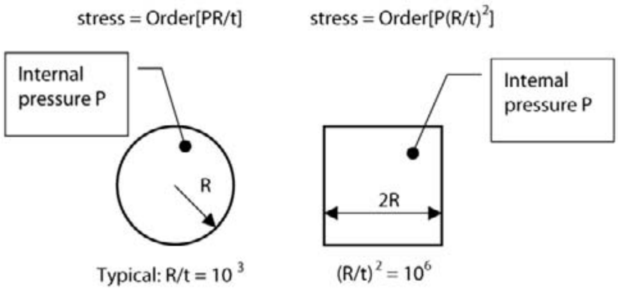



*Fig. 6. A non-cylindrical pressure vessel is subjected to high bending stresses*

Even from this simple comparison it becomes evident that the creation of non-cylindrical fuselages will introduce significant structural problems. Several studies are published with various concepts for alleviating this non-optimality [11-13]. However, the general indication is that the performance of the cylindrical fuselage is superior, but when considering the complete picture of the aircraft (including better load distribution, improved aerodynamics etc) there is a good reason for this introduction [6, 10].

Despite the less-favourable pressurisation characteristics, the abandonment of the cylindrical fuselage idea creates enough space for an entire reconsideration of the aircraft fuselage design where the principle of functional integration becomes viable.

## 4. Multidisciplinary design philosophy

In a generic consideration, a fuselage must in first instance provide a safe environment to travelling passengers. This demand implies structural integrity and proper internal atmospheric conditions. Secondary, the level of comfort must be acceptable in terms of noise, available space and accessibility. At the same time, the fuselage must be lightning strike resistant and suitable to withstand a broad range of atmospheric conditions. As an additional function, the fuselage provides space to various electronic, hydraulic and climate systems.

This extensive collection of functionality can be tackled by two principles: integration or segregation of functions [2, 4]. An example of segregation is the conventional fuselage where the loads are carried by the skin-stringer-frame combination and the insulation is provided by separate layers. Oppositely, integration would imply a load carrying insulator like a sandwich structure [17]. Without claiming that an integrated solution is always the lightest, several advantages can be found in this principle. To visualise this, in figure 7 we provide a schematic graph where the degree of integration is presented as a function of the number of fulfilled requirements [3, 5]. In other words, the horizontal axis tells us which requirements are fulfilled (the closed to the origin the more important) and the vertical axis represents the added value in terms of simultaneously fulfilling this number of requirements into one design (if you wish, a single subsystem).

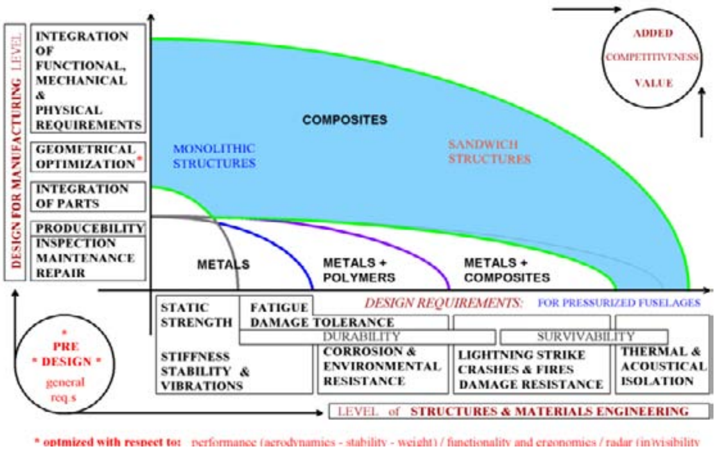



*Fig. 7. Degree of functions integration (vertical axis) as a function of the number of fulfilled requirements*

The figure clearly indicates that metals, while certainly satisfying mechanical requirements, and satisfactory dealing with corrosion problems, they are not able to immediately cover the problem of thermal and noise insulation. For this purpose, additional materials (thus weight) are needed. At the same time, composites on their own (with composites we mean the classical matrix-fibre combination) are not able to provide acceptable lightning strike resistance characteristics but certainly already include insulating properties. As indicated on the vertical axes, a single piece production of a sufficiently thick but light composite panel that contains metallic fibres would fulfil the complete requirements set.

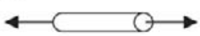
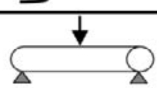
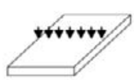
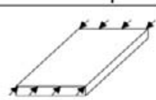
In regard to weight, we should mention here for metallic structures that this is mainly dependent on the frame pitch versus skin thickness. Under a certain pitch, the structure is governed by the allowed material stress levels and the weight remains more or less constant. Above the critical pitch, the structure is dominated by stability issues; hence the skin thickness must increase. Therefore, the weight reduction of a greater frame pitch is partially cancelled by the required elevated skin thickness. Since stability problems are dominated by geometry (stiffness and moments of inertia) a panel configuration providing increased effective thickness by low weight would in this case be preferable. Such a configuration is the so-called sandwich structure where the relatively stiff outer skins are separated by a thick layer of a light material (for example a honeycomb core or foam [3, 17]). While allowing for the increased frame pitch, the core can fulfil the function of thermal and acoustical insulator. An additional asset of composite-based sandwich panels relies on their tailorability: the fibre orientation can be adapted to the local load situation. Combination of this principle with a proper design of the panel curvatures will increase the possibilities for weight reduction.

## 5. Design toolboxes

After obtaining a general impression regarding the challenges and possible solution directions for non-cylindrical fuselage panels, it is time to gather some basic design selection mechanisms for motivating the introduction of the novel fuselage concept [2].

### 5.1 Materials selection

**Table 3. Material selection parameters for simple load situations**

| Load situation | Minimum weight for given strength | Minimum weight for given stiffness |
|---|---|---|
| Tension / thin cylinder under pressure  | $E/\rho$ | $\sigma/\rho$ |
| Torsion  | $G^{1/2}/\rho$ | $\sigma^{2/3}/\rho$ |
| Bending  | $E^{1/2}/\rho$ | $\sigma^{2/3}/\rho$ |
| Bending of a plate  | $E^{1/3}/\rho$ | $\sigma^{1/2}/\rho$ |
| Buckling of slender column  | $E^{1/2}/\rho$ | - |
| Buckling of thin plate  | $E^{1/3}/\rho$ | - |

To assess material performance we assume here simple load situations [2], as given in table 3. Steel has an elasticity modulus equal to 210.000 [MPa] which is three times the modulus of aluminium alloys. On the other hand, the density of steel alloys is app. 7.8 [g/cm$^3$] (aluminium: 2.8 [g/cm$^3$]). Composites show moduli that are between steel and aluminium but their density is usually lower. With these coarse indications it is easy to deduce why wing panels are made of aluminium and why steel is better for landing gears (titanium alloys are here omitted).

Returning to the role of the materials selection parameters for fuselage design, one can easily deduce that a preferable situation is the one where the internal pressure results in exclusively tensile loads (membrane approach). This is additionally motivated in section 3. In the case of having no other option, one should accept bending stresses. Considering the panel-like nature of fuselages, the challenge is now how to create maximised bending resistance with a minimised amount of material. Here the role of geometry becomes evident.

### 5.2 Geometric parameters for stiffened fuselage panels

One of the most critical loading conditions for a flat fuselage panel is the combination of internal pressure-induced bending and externally induced compression. For an initial geometry selection, the so-called 2-D beam column analysis has been developed [11-13]. Here an equivalent flat sandwich panel is compressed into a 2-D schematisation as given in figure 8.

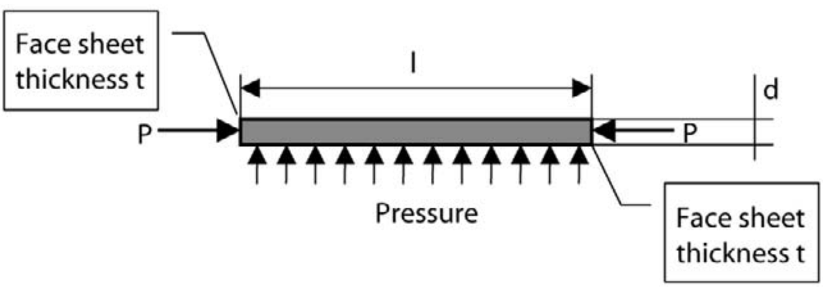



*Fig. 8. 2-Shematisation of a surface panel with bending inertia*

Without proceeding into the mathematical part of this concept, the idea is to locate the optimal distance of the two face sheets for simultaneously complying with stability and strength requirements. This is done by varying the (artificial) parameter d and the sheet thickness t. The parameter d is artificial because it can virtually represent any stiffened panel. The stringers are in the case "smeared" out onto an equivalent sandwich structure [6].

To exclusively create membrane stresses, one has to provide double curvatures to every panel. For dealing with the absence of rotational symmetry, the structure should accordingly be forced in the non-circular shape by supporting, fixing or clamping several, strategically chosen points of the structure. With a proper dimensioning and fixation, the stresses can then be transformed into tensile ones so stability will not be an issue anymore. In theory, stiffening of such a panel is not required, therefore it represents the lightest possible solution (d = 0, t is dominated by tensile strength).

## 6. From spheres through cylinders to bubbles

### 6.1 Geometry

A possible fuselage shape (regardless rotational symmetry) can be described in a particular curvature development in two directions, perpendicular to each other, figure 9 [8].

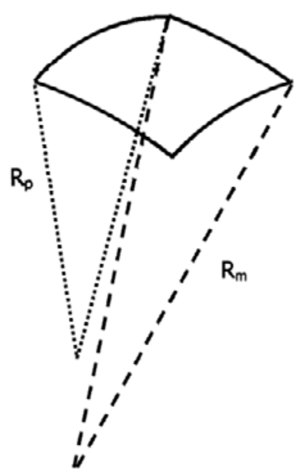



*Fig. 9. A doubly curved panel element with curvatures $R_m$ and $R_p$.*

By applying a uniform pressure on the inner side of the plate, the stress ratio in the two curvature directions is given by:

$$\frac{\sigma_p}{\sigma_m} = 2 - \frac{R_p}{R_m}$$

For simplicity we assume here that the main curvature directions are perpendicular to each other. From this simple equation it becomes evident why a sphere is optimal for isotropic materials; the strength in both directions is the same and so is the curvature. In the case of a cylinder, the radius of curvature in one direction (in this case $R_m$) is infinite since it represents a straight line. According to equation (1), the stress ratio will become equal to 2 which is the typical value found in an extensive collection of textbooks. However, when utilising isotropic materials, only 50% of the available strength is utilised. This is the case for conventional aircraft fuselages: 50% of the available material resources is a-priori not utilised. In the case of composites, one can align the fibres running over the panel with the so-called principal stress direction. In the case of a cylinder this would be 54.7°. When both curvatures show finite values, the fibre orientation can be adjusted accordingly. This principle will lead to a truly optimal material distribution where the occurring stresses show everywhere equal magnitude. Hence, the adjustment of the geometry to stresses can possibly provide the key for reducing fuselage weight.

To achieve the above mentioned optimality goal however, a major problem must be solved; pressure does not have a direction of preference and therefore is rotational symmetric. A BWB fuselage is not, hence the non-symmetry of the pressure carrying panels must be created on an artificial way by mechanical forcing strategic points and edges to obtain a certain position that ensures the desired curvature distribution. This inevitably calls for the incorporation of rods, bars and other members. An impression of such a solution (in one direction), is given in figure 10.

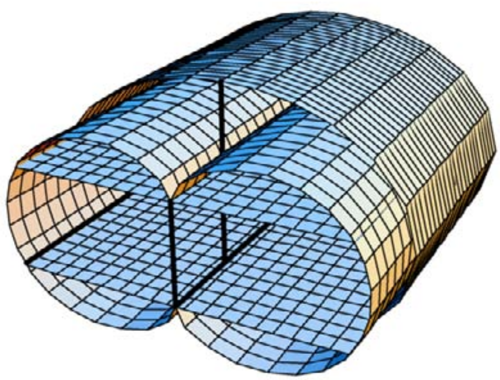


*Fig. 10. A pressure resisting membrane in an elliptical fuselage section*

The inner, pressure resisting membranes are forced into the two-lobe shapes by the tensional forces of the rods running from the floor to the ceiling. The membranes are exclusively loaded on tension and the fibre orientation of the utilised composite material is adapted to the curvature distribution. Disturbing the rotational symmetry in two directions leads to a conglomeration of "soap bells" usually referred to as "multi-bubble arrangement, figure 11 [4]:

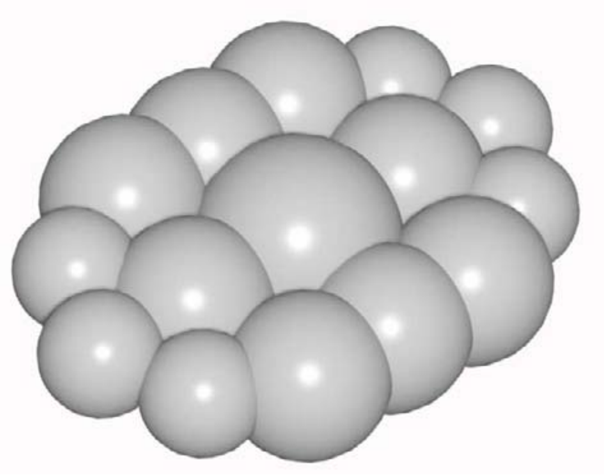


*Fig. 11. A multi bubble arrangement of pressurised elements*

The fixation in space of the bubbles is controlled by their intersection areas and the external forces (rods). The shape of the bubbles is additionally controlled by the material anisotropy: one can flatten out or sharpen a bubble by accordingly steering the fibre orientation.

## 6.2 Materials

The need for "bubbleness" steering and the desire not to waste any material (as in the case of a cylinder) sets composites in the place of ideal candidates. Maximum strength by a minimal use of material can be assured by adapting the fibre orientation to the curvature distribution. In addition, the supporting rods can be designed on such a way that they experience only tension. The latter will omit stability problems. Referring to figure 7, additional features like metallic fibres (lightning strike) and foam (insulation) will be needed. Furthermore, local reinforcements for structural attachments, rigid inclusions and openings will certainly be required as well.

With the information given in table 3, the ideal fibres candidate would be carbon [maximised elasticity modulus over material density]. The matrix selection is dominated by physical requirements (temperature range, flammability, UV resistance etc) since it only contributes to the overall strength in a very limited way. An outer protective shell is still needed for aerodynamic reasons. This is the only segregating step in this approach. While the shape (internal space), load carrying capabilities and other properties (insulation, conductivity etc) are fully integrated, the aerodynamic function is separated: bubbles and streamlined surfaces do not show any similarities.

### 6.3 Assessment

NASA Langley researchers [11-13] have performed an extensive study assessing feasible fuselage arrangements for BWB configurations. Next to ribbed and sandwich panels (flat and vaulted) and dedicated brace configurations, the multi-bubble concept is found superior. However, the performance of the cylindrical fuselage was still the best. We should mention however, that the option of tailored anisotropy is not considered in their work. On the other hand, buckling loads were included whereas in the present paper this topic has totally been omitted.

In conclusion, the multi bubble performance has been found to be approximately two times better than the rigid options. Extrapolation towards tailored anisotropic, doubly curved panels sets the ability for approaching or even improving the performance as compared to cylindrical fuselages.

## 7. Conclusions & recommendations

In this paper we have presented possible fuselage configurations for future aircraft. Beginning with a brief historical review where several benchmarks in the development of aerostructures have been identified, the future demands in terms of economic requirements and environmental constraints have been outlined. With the S-curve based theory (representing the lifecycle of technological products), the inability of conventional aircraft to cope with modern requirements has been demonstrated. From the alternatives for modern aircraft, the Blended Wing Body configuration has been chosen as a potential candidate. After a short assessment of the positive impact modern technologies can have on the weight reduction of aircraft, a major structural challenge for Blended Wing Bodies has been identified in the form of the fuselage geometry. With the principle of multidisciplinary design philosophy and with the aid of some basic design rules and tools, the multi bubble arrangement is finally selected as the most promising option. The proposed arrangement involves a simultaneous determination of the overall geometry in terms of curvature development and fixation points, and a local adaptation of the utilised anisotropic materials to ensure minimal weight.

With the Blended Wing Body, the absence of rotational symmetry for the fuselage induces some significant structural challenges. Resisting rotationally symmetric loads (like pressure) with a non-symmetric structure inevitably involves bending stresses. By application of sandwich plates or stiffened skin panels, this problem is partially solved. Moreover, in the case of sandwich panels, secondary functions like insulation (thermal and acoustic) are fulfilled as well, while other requirements like lightning strike protection do still require additional elements (e.g. metallic fibres). Nevertheless, the alleviation of bending stresses by adapted geometry is an issue of primary concern for controlling the weight. In this case, membrane elements like a 1-D or 2-D arrangement of bubbles proved to perform significantly better. In addition, tailoring of the involved panel anisotropy in combination with a strategic choice of fixation points and cell overlap has shown the ability for increasing the design space while still keeping the weight on acceptable levels. However, an outer protective (aerodynamic) shell is still found to be necessary. The space between the pressure resistor (membrane) and the outer shell can in this case be filled by lightweight foam or honeycomb materials for providing the desired insulating properties.

The intention of this paper is to only provide a general direction where possible solutions can be found. For a more reliable judgment of the proposed configurations, an extensive comparative analysis, based on various load cases, is required. Nevertheless, the authors believe that the multi-bubble arrangement in combination with tailored anisotropic properties shows great potential both in terms of structural performance as well as in terms of providing integrated design solutions.

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# Application of new technology as a starting point in Industrial Design.

## Challenging Graduation Projects

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**Abstract**

This paper gives a compact view on two graduation projects from the Faculty of Industrial Design Engineering. These projects have the challenging application of new technologies as a starting point. Among researchers in the faculty is a strong belief that human needs and possibilities are leading as a starting point for the development of really new products. Everyday reality shows however that technical innovations still are the main driving forces for new products or systems. Fuel cells or hybrid power trains are examples of technology, stimulating our students to develop highly interesting prototypes. The results of these projects act as serious stimulators for further development.

Keywords: DSiD2, industrial design, graduation projects, application of technology, fuel cells

## 1. Introduction

Industrial Design started in the 19-th century as the integration of technical possibilities and human aspects, such as: pleasing, beautiful and usable. The main starting points for new products sometimes are new technical solutions, and sometimes are aspects as style or fashion. Due to this situation there is an, ever present, interesting tension.

Until today this tension plays an important role in industrial design. Sometimes trends and fashion dominate, but not necessary leading to really new products. Sometimes aspects as safety dominate, for example in the development of cars. And very often new technologies lead towards new products. Nowadays products that are based on further developments in technology surround us. Among them are: computers, CD-players, mobile phones, digital cameras.

Because the Faculty of Industrial Design not only deals with technical implications but also with humanities, there is a strong believe among a group of young scientists that research in the field of human needs and possibilities should especially act as the starting point for new developments. Technical solutions should be based on these demands, or: these demands should not be influenced by the application of technology that was in a way ad-random developed.

However: the everyday reality shows that there are thousands of technical research patents, waiting for application. There are new technologies that are knocking on our doors for over decades.

One of these developments is the fuel cell. The fuel cell became world famous when Mercedes Benz intended to use it in its baby Benz. The whole structure of there A class, with a double bottom, was based on the use of that system. When they had to decide to use a traditional combustion engine, instead of a fuel cell, they forgot to compensate for the total balance of the vehicle, leading to severe problems in the so-called Elk test.

Some years ago the Faculty of Industrial Design Engineering started the Delft Design Institute (DDI), where researchers and students work together on challenging projects and products, sometimes acting as as showcases to the world.

Within the DDI there are three research themes:

- Energy and Intelligent Products
- Mobility
- Medisign.

Between the fields Energy and Mobility there were recently several students who were triggered by the possibilities of fuel cells or hybrid systems.

This paper tells the story of two of these graduation projects: the development of a fuel cell powered outboard motor and the design of a fuel cell powered scooter.

## 2. Graduation Projects in Industrial Design Engineering.

As in other Delft disciplines the graduation project is the climax in the educational structure. As a tradition some 85% of these projects take place within industry. There are of course also strong relations to private scientific organizations.

The last decade we have seen a shift in the content of graduation projects from solutions for real products, such as: a new coffee maker or a new vacuum cleaner towards the development of interesting concepts: from solving the problem of boarding in Schiphol to new concepts for fire fighting trucks. So: new graduation projects are less focusing on everyday problem solving. They are more related to exploring new solutions and opportunities. These days' students in graduation projects can follow two possible directions in their design process. There is a more traditional approach, based on a structure that takes steps as: orientation, analysis, ideas, concepts and prototype. And there is a structure that focuses on the design of the wanted interaction between user and product, before it comes to develop ideas or concepts, the Vision in Product design ( ViP) method. Because there was a wish for real functioning prototypes, and not just concepts, the students in the two projects used the more traditional method, with a strong focus on the realization of working models.

Within the existing research portfolio of the faculty one of the themes is a focus on sustainable energy systems. The two projects that will be described are positioned within this field.

As usual the students have searched for cooperation with industry. In the case of the outboard motor there was a thorough cooperation with the design agency Springtime and Yamaha Europe.

In the case of the scooter we tried to get cooperation with Piaggio, the manufacturer of the Vespa scooter in Italy. As that turned out to be impossible, again Yamaha was involved, but only on a low level.

## 3. The design of a fuel cell powered outboard motor.

Danish student Thomas Jensen, became, after his bachelor in engineering, interested in Industrial Design and due to the international reputation he choose Delft University and the master program Integrated Product Design ( IPD). When it came to investigate possibilities for his graduation project one of our PhD students, Hanna Hellman, came up with the idea to merge fuel cell technology and the marine environment, with an outboard motor as an example. It could be an opening in this rather traditional field and this project could, as an example of the application of this technology, be used as part of her PhD research.

### 3.1. Background.

Besides outboard motors with an internal combustion engine, there are, for surroundings where noise or pollution is less wanted, electric outboard propulsion systems. Under circumstances where a more powerful electric motor would be suitable there are many constraints due to volume, weight and charging.

Fuel cell technology gives the opportunity to use hydrogen to produce electrical power. Storing energy in hydrogen, compared to storing energy in batteries, gives the possibility to make the whole system smaller and lighter.

The basic principle of fuel technology is known for many years. Although this technology has already been used successful in some application fields, it is still too expensive and not reliable enough for mass production.

However, numerous prototypes were developed, challenging further development.

### 3.2. Focus.

After a thorough orientation and analysis phase the following decisions were made:

- The outboard motor should, on the basis of market research, be developed for a lower power range,
- The fuel cell system will be based on the Proton Exchange Membrane (PEM) architecture,
- The hydrogen will be stored in pressure vessels at ambient temperature.

### 3.3. Target groups.

Target groups were selected on basis of the possibilities that resulted from the analysis, among these were:

- Sailors, with a focus on boats shorter than 8 meter. These boats use an *outboard* motor, due to the fact that the price of installing an inboard motor is too high, compared to the total price of the boat.
- Fishermen, implementing a fuel cell system in a fishers boat suits better the conditions for environmental friendly behaviour.

### 3.4. The Pod.

During the idea-phase of the project series of interesting proposals were developed. But, by further discussing the target groups and their needs a whole new idea emerged. This idea was called " the Pod". The Pod could be: "a self-contained floating unit", which means that all components are included in one device. Once this concept was chosen, further research and development was necessary.

### 3.5. Designing The Pod.

The first question that came up was: in what circumstances will this product idea be used? In what way does this idea influence the products it is connected to? Could this idea also be used as an independent product?

A list was made of primary and secondary use.

Primary use focuses on the use with smaller boats, as for fishing, and the use as an outboard propulsion system for sailing boats. The secondary use deals with towing and pushing of boats under different circumstances; and the use in water sports, as a kind of water scooter, or for knee boarding.

The Pod could eventually also be used as a rescue device.

The concept phase of the design process started as a balance between working from the inside out and the other way around.

Working from the inside out, there was a thorough survey on useful components and their possible further development. Chosen components were configured to several proposals, following the scientific approach of Muller, described in his book.

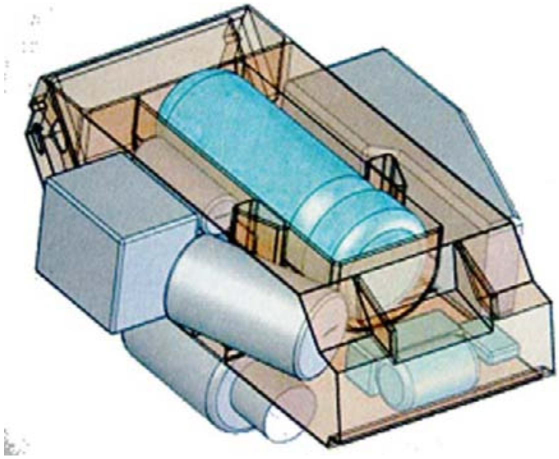

*Fig. 1. Structural layout of components*

At the same time a lot of time and energy was spend in designing a suitable form for this completely new product. Not only the wanted aesthetic form was determinative for the result, but also new possibilities of use influenced the final form and details.

*Fig. 2.Final proposal of the Pod.*

To investigate the different possible shapes several foam models on a scale of 1/3 were made. Discussions with professor Keuning from the Department of Maritime Technology lead to a product that also suits all formal marine requirements.

The result of this graduation project is a very interesting and certainly new product that challenges our imagination and that will act as a stimulator for further research and development.

## 4. The design of a fuel cell powered scooter.

### 4.1. Introduction.

Since traffic in towns becomes more and more problematic and public transport is overcrowded, people are looking for alternatives. Sometimes those situations lead to the rediscovering of almost extinct products as scooters.

Presented in 1946, the Vespa ( wasp in Italian) was a real innovation in transport in the crowded areas of Italy. The concept was a huge success, a success that remained through the fifties and sixties of the last century.

In spite of the fact that the role of the scooter in traffic seemed to be dominated by cars and motorcycles, the scooter had a very surprising come back in the nineties.

Since then there are two striking target groups for scooters. Youngsters in the age of 16 to 18 years old and elderly people who will or cannot afford a car. Recently these market domains are expanded with the use of the scooter by young professionals, due to the ever-increasing traffic situation in towns.

So: the design of a scooter is also an interesting subject to act as a demonstration project in the field of the use of fuel cells, batteries and electric drive train technology.

### 4.2. The project context.

Making a change to existing systems requires large investments. During the first phase of such a transition it can be of high interest that projects with tangible results are started to demonstrate possibilities. Such projects may help to evoke interest from industry, policy makers and consumers.

The goal of this project was defined as: design a fuel cell powered transportation device, suitable to transport at least one person. As a result of market research, it should be a hybrid propulsion system, consisting of a fuel cell system, energy storage and an electric motor to drive the product.

Key aspects of the project were:

- exploring the solution and design space for such a product
- investigating different shapes and designs
- investigating different product architectures
- creating possibilities to use the propulsion system as energy source for other purposes.

The research lead to following conclusions:

- the fuel cell PEM system (as also proposed in the outboard motor) should be used, although fuel storage would be complex,
- Li-ion batteries should be used for storage, at this moment they are best choice to be used in electrical drive trains,
- The use of a hub / wheel engine is the most promising way for traction.
- From an analysis of prospective users a scenario of use was made. "Urban commuting" seemed the most realistic scenario and target groups were defined.

### 4.3. Technical design process.

First the driving system should be developed. The required performance depended on a Taiwanese study on driving cycles in an urban environment, which resulted in the following:

- an average speed of 30 km/h should be possible
- the range before refueling should be 200 km.
- the acceleration should be at the same level as regular scooters ( > 3,6 m/s2 )
- a maximum weight of the product in total of 130 kg.

In addition there were requirements for special situations:

- a top speed of 45 km/h
- a speed of 10 km/h on a slope of 15 degrees.

These starting points defined the required performance.

In the end a 700 W fuel cell system was chosen, combined with high-power and high-density batteries, such as Li-ion. The hydrogen to be used could best be stored in a 700 bar compressed system.

### 4.4. The synthesis.

To get inspiration Crijn Bouman, our graduation student in this project, purchased a used Peugeot scooter. Based on analyzing and dismantling this scooter he came up with several structural variants, using Mullers method. In this scientific method the main components of a product are arranged in different positions to generate ideas for the basic structure.

The result of this exercise was a structure where most of the components are positioned in the front of the scooter. Also front wheel drive was chosen. Both Crijn as the mentor team were very curious whether this solution would lead to better handling.

The size and proportions of the chosen structure were explored by making full-size foam models.

After all the whole exercise lead to three concepts:

- a concept called: "Arrow Head", with a strong focus on a form that supports the front wheel drive,
- a concept called; "Briefcase", designed as small as possible, with components that are connected by a frame,
- a concept called: "Platform Transporter", the components are mainly horizontally oriented.

The third concept was chosen, a product idea with a clear link to existing scooters, but with numerous new solutions.

### 4.5. Materialization, detail design.

Because there was an emphatic wish to develop a full demonstration prototype, all choices in this part of the design process were made with the intention to create an attractive prototype with a high appeal factor.

The decision to make a working prototype turned out to be a real challenge.

Although some components of the Peugeot scooter were used, most of the parts for the new scooter had to be developed separately or had to be adapted to the new situation.

After month of work, with the cooperation of the workshop of Industrial Design and many, many others, the prototype was finished just before the graduation date.

Test drives showed that the product had the high appeal factor that was wanted.

Since the result could be seen on the Internet, the number of hits in Google have shown us how many interest there is, worldwide, in this kind of revealing products.

Crijn Bouman is now working in his own company, focusing on electric power solutions.

*Fig. 3. Working protoype of the scooter.*

## 5. Conclusion.

Still, the results of the application of technical research and development are very important stimulators in creating new products.

Many students are triggered by these developments when they also have a direct relation to solve upcoming problems. Nobody should be amazed that fuel cell technology, which already for more than decades is on the threshold to implementation, is one of the items that appeal to their imagination. In designing examples of applications in their graduation projects, the two students certainly have brought this kind of technology a step further to realization.

In the mean time new students have taken the baton to demonstrate the application of new technology.

One of these students also has developed a working prototype of a scooter, but now with focus on using LPG in a hybrid structure.

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# Blob-Shells: Composite Stressed Skin Roofs for Liquid Design Architecture

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**Abstract**

This article describes the design, development & research build process of a new generation of shell roof structures for architecture. The result marks a new era, the renaissance of the shell structures, once popular in architecture in the 1960's, but disappeared since. Liquid Design Architecture enhances a more free and complex geometry of buildings. The main attention in this contribution is given to the 'free form' roofs of the Rabin Center in Tel Aviv (architect Moshe Safdie). The principle idea was initated in discussions with colleagues from aeronautic and yacht design. The subsequent process of design & engineering, made use of state-of-the-art design and engineering computer programmes, but relied even more on the 'out of the box' abilities and imagination of the technical designers. The production stage was greatly assisted by the transfer of technology from yachting industry, although the architectural application, mainly in its size, but also in transport, shipment and assembly had to be developed further on the building industry's level of technology and pricing.

The development owes much to the interdisciplinary design vocabulary from the different designing faculties at the Delft University of Technology. Professors Adriaan Beukers and Michiel van Tooren became involved and gave a second opinion to the client on the developed sandwich composite technology. After four years of hard labour, great risks on many frontiers and engineering and production experimentation a new generation of shell structures is born, giving possibilities for other wild architectural ideas like the Mediateque in Pau, France, according to the design of architect Zaha Hadid of London.

Keywords: Collaborative Engineering, Blob Technology, One-off Industrialization, 3D Composite Components, Design & Build Approach, Product Development, Sandwich Constructions, Technological Innovation, Blob-shells, Free Form Design, Fluent Architecture.

## 1. Introduction

Technical design of roof and façade structures for architecture has accelerated in the last 3 decades from well-known traditional solutions into technically innovative solutions. After the development of stretched membrane structures in the 1970's, systemized metal space structures in the 1980's-, sophisticated tensegrity structures in the 1990's, glass envelope constructions and load bearing glass structures of the last decade it is now 'Liquid Design', 'Free Form' or 'Blob' architecture that caught the interest of young architects. The description of this type of architecture originates from a free form geometry, non describable with any regular mathematical formula. In a sense it is a direct consequence of technology driven interest of architects. Having learned the newest generations of 3D design and engineering computer programs, they are now capable to design (geometrically) complicated virtual 3D buildings that seem completely real on the screen without even being build. Yet the route to realisation is paved with numerous technical (and some social collaboration) experiments to produce the technical 3D components of these 'Blob' buildings. Often these components will be 3D-curved. Usually they are one-offs in their shape and non-repetitive. The extreme contradiction is the request for custom-made components versus the low budgets of the building industry on the one hand and researching and developing technological innovations in the speed of a real time building project process in order to acquire the new technology just-in-time on the other hand. The aid of other design professions like aeronautics, ship design and industrial design is very inspiring and necessary in order to develop a new 'Blob' technology with the 3D forms, yet fitting within the modest average $m^2$ budgets of the building industry. Extension of the building industry's traditional integration is necessary in order to develop suitable CAD/CAE, CAM/CAB procedures and special production and surveying technologies. In this case producing one-off GRP stressed skin sandwich components made it possible to make larger spans for the roofs , though in an arbitrary form in order to become true 3D-roofs.

Designing structural systems for use in architecture – including the necessary research & development, but always leading to actual realizations – is the core of the author's personal attitude towards designing. Many of the structural and constructional designs made as an architect, as a pioneer of space structures and as a structural designer, have followed an incremental approach of step-by-step with ever increasing know-how and elevated insight. This started for smaller projects in the Netherlands and led to applications of increasing scale both in the Netherlands and abroad. This approach is adapted to the (smaller) scale of projects in the building industry, their ever deviating character depending of the designing architects, their real time planning schedules and the desired degree of experimentation of the technical designer. The projects are performed as 'design and build' contracts in the Octatube company at Delft and sometimes in the architect's office. The position as the professor of product development at the TU Delft and the range of collaborating faculties within the Delft University of Technology itself offer excellent opportunities for contemplation and sharpen the mind amidst of scientific design colleagues from different disciplines. This particular second congress of Delft Science in Design enables us to continue the debate on the merits of Scientific Design at TU Delft. To discuss the merits of design, development and research and to discuss the valorisation side of designing, developing and researching as the major activities of the TU Delft. Design is able to tunnel results of scientific research to society. The relationship between research and design are mutually indispensable.

Some of the building systems, which were developed in the author's offices through time (see scientific site: www.mickeekhout.nl) have been boosted and accelerated by know-how from other professions, faculties and industries. Close traditional relationships are kept between architecture and (civil or) structural engineering.

## 2. Inventions, Innovations and a Competitive Market

Amongst the ever-recurrent obstacles in component design and product development in architectural projects are the low thresholds in the building industry, the lack of interest in entrepreneurial experimentations and the overall tendency for copying the results of the experimentation of others, minimizing the experimental expenditure by the lazy policy of 'wait-and-see' or the 'me-too' effect. This is counter-positioned by the experimenting designer, dragging an office and a company behind him that follows his whims, willing and able to undertake all technical adventures in the process. This has been a life-long attitude.

After the initial product design and developments of a new generation of structures has resulted in successful applications, professional publications are written. After publication new clients become interested but the competition has been awakened, too this flow of happenings haunts every new invention. It was this framework that made the Europeans invent the protection system of patents in the 19th century. But with many different systems at hand and even more differentiated applications, patents do not shield inventive development work in architecture. The number of repetitions is low and the variety asked in different projects is high. The eternal fate of the architectural and structural designer is to look for new horizons: either new markets for existing products or new products for existing markets. Luckily a number of 'me-too' competitors for example in Israel made a mess of their copied systems, but alas these projects were lost in the tender stage any way. For the Hashalom (Peace) project in Tel Aviv the client regretted his decision to subcontract an Italian glass company for frameless glazing, changed his mind, withdrew the contract from that consortium and contracted the original designer company, who re-designed, engineered, produced and installed the project in a miraculously short time. Because the building calendar has its own speed. In the last years prices of frameless glazing systems are dropping due to competent and incompetent rivalry. Although experimentation with a large distance between production and building site adds to the possibility of a negative outcome, the composite wings of Tel Aviv are an example of a well-defined experimental component design & development for one specific project. After successful completion this could lead to an entirely world-novel technique of engineering and producing roofs for liquid design buildings. In its turn, this hopefully leads to the establishment of a new Dutch consortium of small and medium-sized enterprises (SME). It is further to be expected that after duplication, multiplication and systematization of the developed technology the laws of economics interfere and that the enterprising structural engineer has to develop ever new products and systems.

## 3. Stage of Tender Documents

In November 2002 the client "Friends of Yitzhak Rabin' issued tender drawings and specifications of a design by architect Moshe Safdie from Boston USA as a part of the Yitzhak Rabin Center in Tel Aviv. The design of the building was an elaboration and extension of a former auxiliary electricity plant near a university campus of Tel Aviv in order to become a memorial building for the late prime minister Yitzhak Rabin who was murdered in November 1995. He was seen as a peace maker and was rewarded the Nobel price for Peace in 1994. His activities led to the so-called 'Oslo peace talks'. The entire building was tendered out in different lots. This particular tender provided for two building parts: the 'Great Hall' and the 'Library'. These two big rooms both have large glass façades facing south towards the Ayalon valley below. Both hall designs have remarkable and plastically designed roofs to resemble dove wings as a tribute to peace maker Rabin. Moshe Safdie is well known since he designed the dwelling complex 'Habitat' of Montreal as a part of the World Exhibition of 1967 when he was a 27 year old architect [Kohn, W. et al, 1996].

This was the author's second collaboration with architect Moshe Safdie: the first one being the conical glass wedding hall of the Samson Centre in Jerusalem, overlooking the valley adjacent to the old city of Jeruzalem near the Jaffa Gate. Safdie is an almost prophetic designer who designs beautiful spaces with dramatic interiors. In the last decades he redesigned the Jewish quarter in Jeruzalem. The Samson glass dome, overlooking the ancient city with its golden colour in the afternoon, is used for marriage feasts and other celebrations and is a great success. The hall is used for weddings twice a day. Safdie was very satisfied with the alternative design proposals for the cone and with the realized technical accuracy. For the new project the complicated liquid design roofs of the Rabin Center contained in the tender were analyzed by ARUP New York. They proposed a welded grid of steel beams in a rather arbitrary running of the open steel profiles with a layer of concrete on top. The specification left the roof cladding up to the contractors. On top of this the architect requested a seamless solution over the entire roof. Not a very appealing specification for a design & build company which had to transport all items over a distance of 5.000km. For two months the tender drawings and the thick specification were not given much notice. The 'seamless' requirement would make any prefabricated system very difficult and the success would depend entirely on local labour and supervision, which a producer of industrial and prefabricated systems does not like. However, the client and his building manager kept on reminding of the tender date and even postponed the tender.

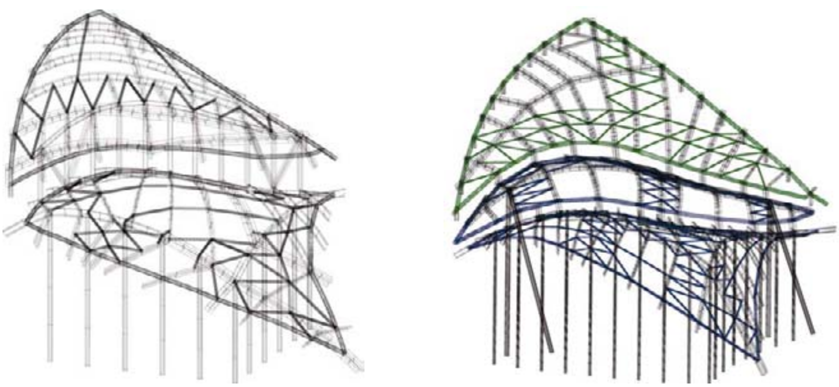


*Fig. 1-2. Tender drawings made by ARUP. Left, 'The Library' and right, the Great Hall.*

*Fig. 3. Architectural model of the Rabin Center, Tel Aviv (courtesy: Moshe Safdie & Associates).*

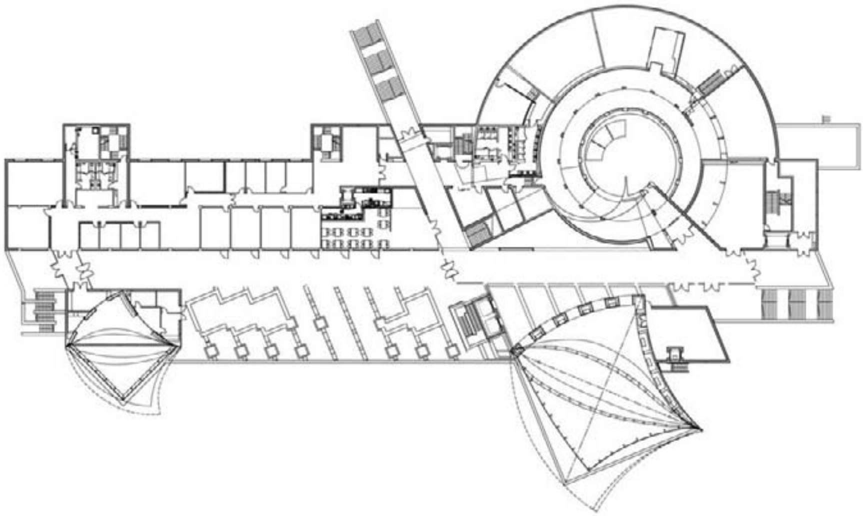


*Fig. 4. Plan of the Rabin Center, Tel Aviv (courtesy: Moshe Safdie & Associates).*

## 4. Development of Cladding Systems Through Projects

When struggling with an alternative technical design for the new cladding of the Atomium of Brussels (dating from 1958), TU Delft's professors Adriaan Beukers and Michel van Tooren (Faculty of Aeronautical Engineering) stated in their inaugural speeches that "aeroplanes always leak and condensate" [Beukers, 2003; van Tooren, 2003]. This one sentence inspired the quest for a recladding concept of the 9 spheres of the Atomium. The end result was that in the technical proposal each of the 18m diameter domes was to be clad with 2 x 8 spherical segments in the form of half an orange peal, size 14m long, 8 m wide and 3m curved. This resulted in a solution in which the total length of the seams was restricted to only 20% of the original joint length, which was 20.000m'. Even a low leakage percentage of 1% would result in 100m' of leaking upper seams. In the developed proposal the joints were detailed much like the old-fashioned 'Double Improved Dutch Roof Tiles' with double internal joints that never had to be replaced or maintained. Leakage problems would belong to the past with this solution. A patent was applied for. So in this case, an unexpected impulse from aeronautics helped to develop a new concept. Alas the politics around the tender were quite non-transparent and the contract for execution was awarded to a Belgian party. The design proposal keeps its value, however and is published here for its inspiration, returning to the alma mater of the original inspiration.

One year before the tender date of the Rabin Center, the design , engineering and building of the Municipal Floriade pavilion (now named Hydra Pier) of Asymptote Architects from New York was completed. One of the three experiments in that project were 3D-aluminum panels of 5mm thickness which were deformed through explosion on negative concrete moulds (based on machined positive polystyrene moulds). This production process originally seems to have been used in Russian submarines in the 1960's. The paths of technology transfer are sometimes strange. This process took place at the premises of the Exploform company in Delft. This complete production procedure from engineering drawings, via Styrofoam negative moulds and reinforced concrete moulds, the explosion process, the measuring and fitting on timber moulds up to the finished and installed watertight and coated panels proved to be a feasible, but also a laborious process to fabricate as 3D-curved panels. It was the first time in the world that 3d aluminium panels for architecture were produced along these complicated paths. Although the cladding was successfully realized in this Floriade project, the m² price of the 3D panels was too high for a next project in the building industry (which in the Netherlands was also at the edge of recession at that time).

*Fig. 5. Close-up of the Atomium, Brussels.*

*Fig. 6. Schematic drawing of the proposed division: 2 x 8 spherical segments in GRP.*

A cheaper system had to be developed for the next project. Haiko Dragstra, a very inventive mechanical/electrical engineer co-operated in this project from his company Complot, Delft  and came up with the idea to take thinner sheets of aluminium, laminate a foam panel with parallel transverse sleeves and an epoxy laminate as the inside skin in order to make a strong and stiff panel. So these panels were half aluminium, half composite sandwiches.

One step further was to make the complete panel out of two composite skins with a foam core and have the outside skin coated, if needed in an aluminium metallic colour. One does not see the difference from painted aluminium or steel panels and polycarbonate components in cars. However, at the time Asymptote Architects did not like the idea of mixing different materials, according to the contractor. It was this line of thinking that brought the development further. Haiko Dragstra was able to machine foam blocks into any desired form by the machines he built himself. Machining according to CAD data is possible both for the top and bottom layer of the foam. The total surface of the roof was subdivided in blocks and glued with the machined blocks of foam. Subsequently structural layers of glass-fibre reinforced polyester were applied to each side. These experiences came on the table when brainstorming on the new principles for the 3D wings of Tel Aviv.

*Fig. 7. Video captions of an 'Exploform explosion' in a water basin (from: exploform.nl)*

*Fig. 8-10. Left over polystyrene moulds used to make negative concrete moulds (left), exploformed aluminium panel (center) and fitting of a panel on a wooden fitting mould (right).*

*Fig. 11. 3D curved roof of the Hydra Pier, designed by Asymptote Architects*

## 5. Giant Stressed Skin Sandwich Constructions

So in a few brainstorms between designers and co-makers of different background , collaborating in a tender consortium, this was the basic idea: make the roofs as giant surfboards of foam with stressed GRP skins on both sides. The size of the roofs, subdivided into 5 different roof wings was maximum 30mx20m. The company Polyproducts of Werken-dam and her engineering office was invited to join the tender team of Octatube, as well as Haiko Dragstra. In a month time three successive brainstorms were organized on the product idea, the structural concept and the logistics & pricing. It was decided to work out and price the revolutionary stressed sandwich skin alternative as well as the original tender specification of the steel structure with a non-described, free covering as the variation. The steel deadweight of the steel structure was estimated by ARUP, so a price of the original design with the steel structure, supposed in curved CHS (circular tubes) with cladding variations in different foam layers, levelling and top layers was feasible from existing data and a little imagination. The cladding proposed for the original tender design was derived from the mega-sandwich idea, but now in a thinner scale version of 50 to 80 mm sandwich thickness, as it only needed to span the space between the steel structure elements (max. 3m).

The budget calculations came out on a level of 2.5 million Euro for the original design with a thin 80 mm thick GRP sandwich cladding instead of concrete. The alternative design with the full load bearing stressed skin sandwich would add up to more than 4 million Euro, largely due to the high estimates of the production of the polyester parts. The producer had never done a project of this magnitude but knew how to operate the production of sandwich panels using vacuum injection methods. It was argued in the final brainstorm that the maximum extra costs would not be acceptable to exceed the sum of one million Euro extra, resulting in a total alternative price of 3.5 million Euro. It was foreseen that any architect would fall in love with the alternative idea of the self-supporting stressed skin sandwich. This was the solution faxed to Israel, just in time before the tender closing date, accompanied by a letter explaining the two quoted systems: the original specification (with a variation on the tubular structure and the cladding) and the alternative for the composite sandwich panels.

## 6. Amazing Solution!

Only two days after the tender closed a telephone call was received from the local representative architect Zachi Halberstadt, speaking on behalf of Moshe Safdie. He gave the compliment that the architect saw the alternative proposal as "an amazing solution". Halberstadt invited for an immediate meeting in Tel Aviv the next day, so that the idea could be presented to the entire building commission. At this presentation the polystyrene models that Haiko Dragstra had machined in a demountable model scale 1 to 40 were shown. The models also proved that the corner details in the design had not yet been accurately designed and that the overall stability was not satisfactory. The design needed a considerable attention in the design perfection. But the enlarged scale model showed the seriousness of the tenderer.

The building commission was astonished after hearing the explanation of the construction and the consequential logistics of the alternative proposal. The five big wings would have to be constructed in one of the empty ship building halls in the Netherlands, like at Krimpen aan den Ijssel. This size of hall was necessary as the wings would have to be turned upside down after application of the stressed skin layer on top in order to apply the lower layer. The milling polystyrene machine had to be moved nearby this production hall and to be installed adjacent to the assembly area. After gluing the polystyrene blocks, the top skin could be applied. That is, if the polystyrene blocks would form a roof wing in horizontal position. After completion of the GRP top skin, the object had to be turned over and the bottom skin had to be applied. After the completion of the surfaces of the shells, they would be loaded on an open inland vessel and towed to the port of Rotterdam, where the cargo would be loaded on a specially chartered ship in which the 5 finished shells could be stacked vertically. This ship would sail to Tel Aviv and anchor at sea in front of the city. From this location a giant freight helicopter would lift the roof wings individually from the vessel on a route to the shore, 5km inland during the night, to position the roof wings on the flat open building site. A mobile crane would then swing the roofs on top of the columns. The whole shipment and air transport was pretty special and expensive. After explanation of the logistics of this alternative proposal, the representative Boaz Brown heard the architect Moshe Safdie mention to the chairman of the building team in Hebrew: *"you should try to get the one million extra"* or words of that meaning.

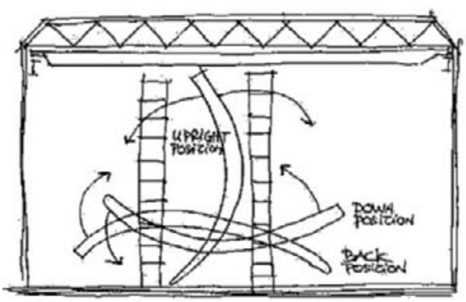



*Fig. 12. Schematic drawing of a shipyard building with roof-wing positions*

*Fig. 13. A 'wing' transported by helicopter (photomontage).*

## 7. Extremely Innovative, but Expensive

The client's building commission went into a separate meeting. After one hour of fierce discussions, the outcome was that the tender original with the thin GRP covering was practically on the average tender price level. On the other hand they noted that the alternative proposal with the composite sandwich constructions was indeed very attractive from viewpoint of its extremely innovative design and construction, but was priced one million Euro over budget. By the way, from a selling point of view and knowing the intellectual value of the alternative proposal, it would have been stupid to sell it at a lower price than the tender proposals. Usually technical alternatives are more efficient solutions for the contractors and tend to be lower in price than the original. A more expensive alternative is rare and hence extraordinary. Starting with the highest price and the best technology, may end with a contract at a compromised price. An 'avant-garde' designer also looses projects to competitors as they can copy the new technology after one completed project and execute this without the necessary research and without the higher Dutch labour costs of Octatube. But in the case of the wings, there was not a suitable technology yet in the world. The alternative idea was to become a technical world novelty and Moshe Safdie understood this.

*Fig. 14-15. Sydney Opera House, architect: Jørn Utzon*

The discussion at hand with Safdie was about the Sydney Opera House (built in the 1970's) and how lucky architect Jørn Utzon would have been if he could have used stiff GRP sandwich panels instead of the heavy concrete shells and ceramic tiles. Even though the realization of the Opera House meant a major step in the history of structural engineering. The Sydney Opera House, with its problematic realization, its time elongation, budget explosions, growth of Ove Arup Engineering and the architect's dismissal from the site, is now the most admired building of the continent of Australia. Through these discussions it was noticed that the marketing concept apparently had worked.

Safdie appraised his belief in stating that he thought that the idea was amazing and never done before to his knowledge. If someone could make it work in his opinion, it was to be Mick Eekhout cum suis. The response of the chairman of the building committee was to come up with different logistics for the GRP sandwich proposal in a manner that the price level could be lowered to 2,5 million Euro. He suggested that it might be possible to transfer the foam machining and the GRP production to Israel in order to reduce costs for shipment and labour at the same time. This was the message taken home on 29 April 2003.

## 8. Rethinking the Alternative

Back in Delft the consequences were discussed with the in-house engineers and the external consortium tender team members. The plan was born in the airplane from Israel to the Netherlands. If the GRP sandwich roofs could be realized, it would be a hit on the world market. It should be possible to transfer more labour to Israel in order to reduce costs and talk to new Israeli partners if the current partners would let the project down in order to realize this proposal. The first idea was to try to decompose the big wings into transportable components, which could be assembled on-site on a jig, smoothen the visual surfaces between the individual segments, to finish the outer GRP layers and give the shells a final top-layer or top-coat. Complot could machine the polystyrene blocks locally and Polyproducts could set up an Israeli GRP plant in Tel Aviv on the building site. The most likely position to assemble a wing would be in a vertical position. This way both outer skins on the polystyrene core foam could be treated simultaneously and the shrinking of the foam could be controlled. Subsequently, the roof wing could be easily lifted by a mobile crane from between two 20m high scaffolds.

However, after a few more meetings it appeared that machining the polystyrene blocks in Israel seemed very expensive. The subcontractor was not experienced in estimating larger productions than mock-ups. He had never exported his products and felt not comfortable in unknown areas. The bottom price of co-maker Polyproducts in Israel did not give much hope either. So the co-maker would think the world of the high number of innovations in this project and kept his price high. At the same time the usual squeezing of tender prices was set in, which forced the sales department to land on another price level altogether. For sake of financial negotiations, another point of view had to be taken in. It was decided to put all first emphasis on the original design with the internal steel structure and sandwich coverings. To take an internal and hidden steel space frame with a locally made sandwich panel system on top and bottom, forgetting for a moment the attraction of the possible world novelty of the stressed skin sandwich constructions, just to stay in the race. Based on this price and on the technical abilities Moshe Safdie was still convinced that Octatube could do the best job. Therefore Safdie pressed the client to take a wise decision: to issue an (experimental) pre-engineering contract to execute the design development and make material prototypes. A separate pre-engineering contract (or prototype development contract) was drafted for redesigning some steps on refinement of the roof models, and investigation in prototypes for different composition, to convince the makers themselves of the attainable quality and subsequently the architect and the client. After this decision the process went into redesign development and developing prototypes of segments of the construction of the Great Hall with the most complex wings, assuming that the details of the Library would follow those of the Great Hall.

## 9. Redesigning, Pre-Engineering and Prototyping

In the course of the design development of this first prototype development contract the redesign had to follow the rough contours given in the tender stage by the Safdie office. The official data of the three wings of the Great Hall were handed over by the architect's office as a Rhino scan from a material 3D model. The data within this model needed serious converting, since they proved to be inadequate and inaccurate for further engineering. Through analysis of different cross sections of the model and connecting these in fluent lines, a new and usable 3D model was developed. This ensemble was redesigned in another modelling program: Maya (3D CAD software). This software turned out to be an excellent medium for designing the different components. Also, the same software enabled constituent parts to be defined and combined into the total composition of the project: five sandwich roof wings, the steel columns, the three skylights and glass panels in the 4 glass facades. It became unavoidable in this stage that the final contract had to include also the reinforced concrete walls as well as the support plates of the concrete tops for anchoring of the columns, as the particular geometry of the roof wings would determine the concrete work below, although this concrete work was part of the main contractor's lot.

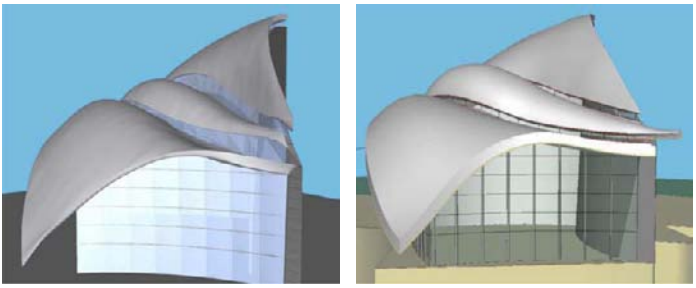


*Fig. 16-17. The Rhino model of Moshe Safdie & Associates and the first redesign in Maya by Octatube.*

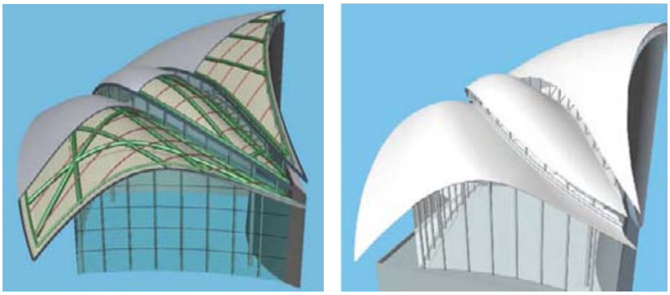


*Fig. 18-19. Two construction types: a steel structure of CHS circular sections (left) and the structural sandwich structure (right).*

At the same time a global structural analysis was made of the structural behaviour of the GRP wings and the steelwork. During this time the two quoted construction types were both worked on: the original version of a tubular steel structure of systemised CHS circular sections, covered with a thin GRP sandwich as the roof covering and the alternative designer's option of the structural sandwich composite structure.

Sales negotiations with the client had resulted in an unavoidable change on the purchase side of the co-maker for the polyester work. The price of Polyproducts was remained stiff on a too high level and they were terminated as a co-maker in the process. Holland Composites Industrials (based in Lelystad, NL) was invited as the polyester co-maker in their place. They had previously made hulls of motor yachts and sailing yachts in glass fibre reinforced polyester (GRP) up to 30m length with the vacuum injection method. This was an excellent starting point for the development of the structural sandwich panels. They employed the firm Solico Engineering (based in Oosterhout, NL) who started to globally analyse the GRP roofs. The two structural analysis of  Octatube and Solico were compared and matched.

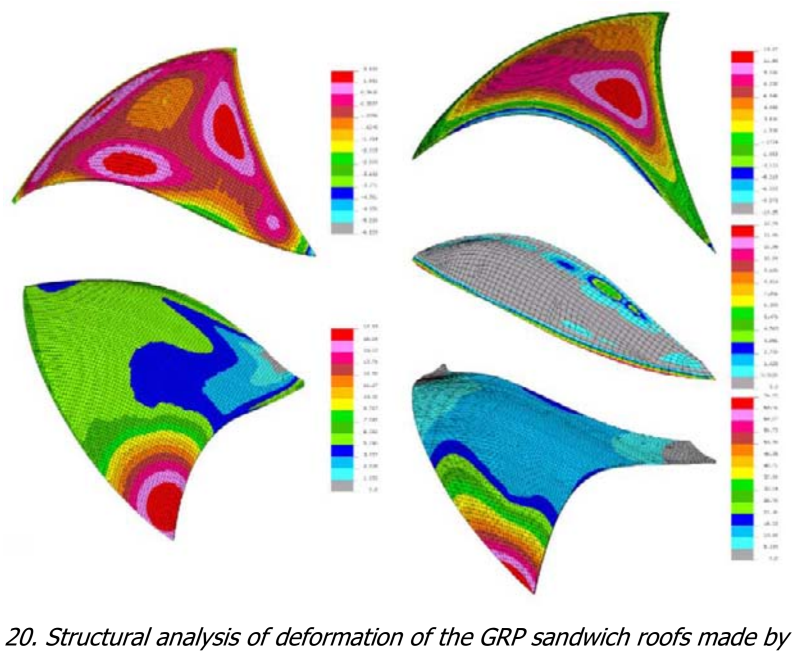


*Fig. 20. Structural analysis of deformation of the GRP sandwich roofs made by Solico. Left, the upper and lower wing of 'The Library'. Right, the upper wing, the central body (made of steel with a GRP covering) and the lower wing of 'The Great Hall'.*

At the same time, prototypes were made of both construction types: the tubular steel structure with a light composite sandwich polyester covering and the alternative designer's solution of the integral composite sandwich. Both prototypes were shown to architect Moshe Safdie, together with the first results of the Maya computer redesign work in July 2003. In the mean time this pre-engineering work had indeed resulted in a dramatic reduction of the cost price as the engineering team became more and more familiar with the experimental aspects and how to resolve these. The original quotation was reduced to around the original average price level, thanks to the results of this pre-engineering contract. So the pre-engineering contract, as it was seen by all involved in the process including the client, was a wise decision. Such pre-engineering prototype contracts are often proposed for experimental projects in the Netherlands, but hardly ever rewarded. The effect is that both sides are getting accustomed to the characteristics of the experiments at had and that the makers loose uncertainty, which would result in adding high contingencies in the global price. Clients mostly refuse these pre-engineering contracts out of fear for monopolisation of the involved contractor. In that case the client could also have the architect undertake such a prototype development contract with restricted legal conditions. And indeed, monopolies are almost a natural consequence of specialization.

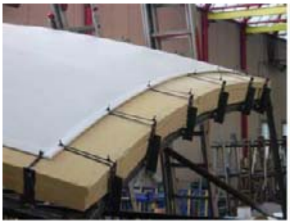


*Fig. 21. First prototype with a stressed membrane.*

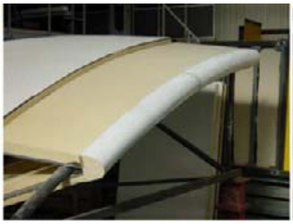


*Fig. 22. Third prototype to be locally produced.*

*Fig. 23. Fourth prototype, a prefab sandwich construction.*

## 10. Results of the Prototype Development

The course from redesign, pre-engineering and prototype development to final design took one year involving 5 to 6 engineers. The architect visited the development laboratory in Delft twice in that time to check the progress on the design and the new prototypes that were made on his specific instructions. It was agreed that, in contrast with previous projects involving Blob structures at the engineering department, there would only be one party involved with computer work. In this case the engineering department would be in the lead and the architect would only supervise and give instructions behind the monitor. It would also put the legal responsibility on the same table as the technical development responsibility. The impulses from the development of the prototypes, the production methods involving moulds and injection production plus the future assembly of the structural seams and the structural behaviour of the total wings, all had a deep impact on the final design and had to be fixed by the responsible 'design and build' contractor. The described innovative developments followed the three axioms of the contractor: *"Design and build in one hand", "Integration of architectonic, structural and industrial design"* and *"Development of new and experimental products".* Respecting the wishes of the architect an intensive design and engineering course was followed mastered in the engineering department, co-ordinating Holland Composites and Solico Engineering as indispensable co-makers. The urge for new product innovation, courage, spirit of enterprise and a certain naivety (not to know on forehand what hindrances would come in the future years of development of the project) prepared the embedment of an engineering course with multiple degrees of innovation. During the entire process the design methodology as development for special components, consisting of 3 mains phases:

- Design Concept,
- Prototype Development
- Production Preparation,

as published by Eekhout [2007] were followed quite literally.

## 11. Technical Engineering and Prototype Testing

After the first one year of experimental work and prototyping, the final 'design & build' contract was agreed on the basis of the adapted quotation and the approval of architect Safdie on the quality of the prototypes. The final engineering started on the basis of AutoCAD and Mechanical Desk Top. The final analysis incorporated:

- Final production methods of the GRP wings,
- Testing of the connections of the sandwich panels on delamination,
- Assembly connections loading deformations,
- Fire resistance
- Logistics in the Netherlands,
- Transport of the sandwich segments in special open containers,
- Assembly of the segments on special moulds on the building site,
- Jointing and finishing the wings,
- Hoisting of the completed wings into position.

After the prototype development phase of the first one year the final engineering inclusive prototype construction testing in the laboratory also took one full year.

At the Israeli side approvals became very complex, however. Due to political change in government from the Labour party of Rabin to the Likud party of Sharon, all proposals were reviewed by the local government bodies with extreme attention, so that many unforeseen and sometimes unnecessary problems were detected by the governmental bodies and had to be neutralized by the engineering parties. Many people in Israel apparently did like to see the project uncompleted or stopped half way. This also led to the involvement of the two experts in the field of glass fibre reinforced polyester: two professors of the TU Delft, faculty of Aeronautics, prof. Adriaan Beukers and prof.dr. Michel van Tooren, who played an inspiring  role in the Atomium recladding project, as mentioned in chapter 4. They were invited by the client (The Friends of the Rabin Center) directly to draft a second opinion on the supplied engineering and played their role in this project honourably.

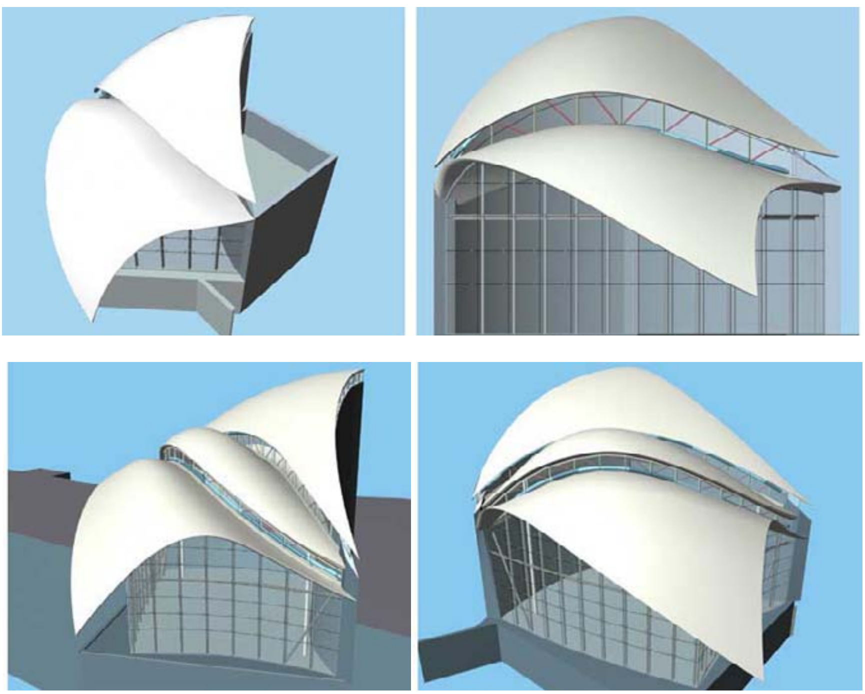


*Fig. 24-27. Birdseye and frontal views of 'The Library' and 'The Great Hall'*

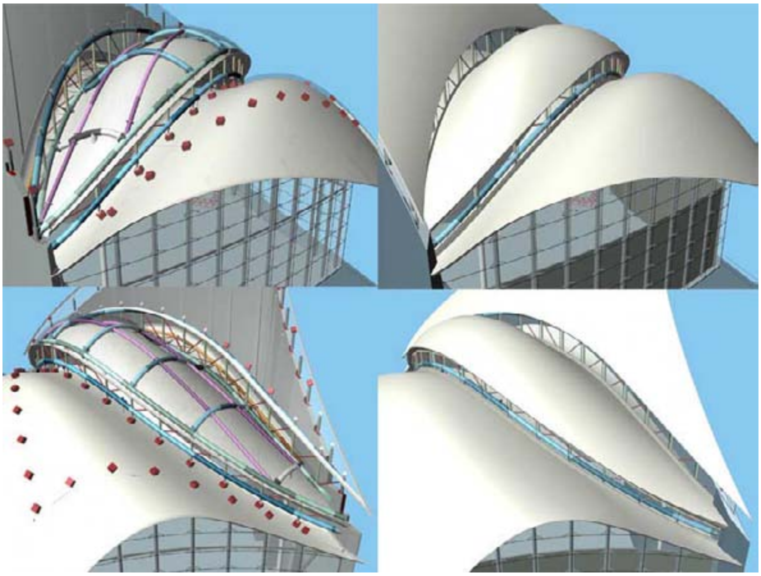


*Fig. 28. Close-up of 'The Great Hall' wings with insert points for connectors to connect the wings to the columns and structure of the 'central body'.*

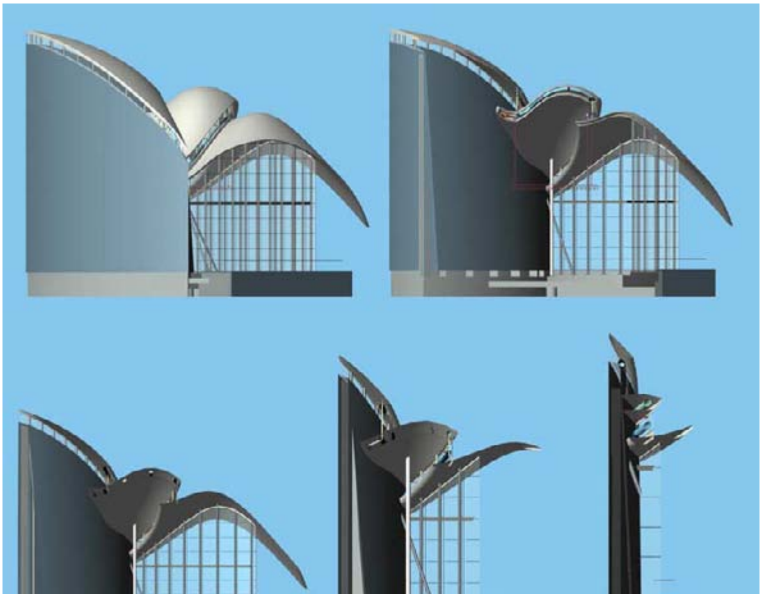


*Fig.29.Five sections of 'The Great Hall'*

## 12. Prototyping, Production and Installation

After two years, in January 2005 the go-ahead was given for production. From that time onwards the production of the composite segments went into operation. Hence the third project year of production and assembly started with the experimental production of the components on the negative moulds. It was decided that production would start with the smaller roof of the Library, although the client had in the back of his mind only eventually to build the Great Hall, just in case the costs of the sandwich construction operation would be too high. So seen from the learning curve in the production development, the very production of the two smaller roof wings of the Library was taken up first.

The production technique used in this case has been taken from standard production techniques of producing sailing ship hulls as Holland Composites had produced its integral mono-hull ship hulls. The base of the vacuum injected production was a good point of departure. In case of the sandwich wings the second dimension in the largest wings of 30x20m (compared to the 30x5m boat hulls) and the impossibility to sail the completed wings independently to the site like a sailing ship, proved to be a major experimental level for the GRP production. It was decided that the entire wings would have to be produced in more or less rectangular segments, to ship them out stacked in containers and to assemble them in the form of the completed wings on site and hoist them in as wings finally. This had as a consequence that the segments had to be produced individually in their deconstructed shape of one-off forms. Each segment form was different. All segments had a different form and some had long asymmetrical points. The shrinking of these segments after curing of production proved to be an unforeseen adventure. Shrinking of each segment appeared asymmetrical, always in another direction and during production one could wonder how all of these twisted panels could lead to a smooth form.

Unusually for the co-maker the production proved to be necessarily very engineering intensive. The foam blocks of polystyrene had been milled accurately by Marin bv, specialised in moulding ship models for hydraulic testing, to negative moulds from CAD/CAM files. After the milled moulds arrived at Holland Composites, the surface was first topped with an epoxy skin to work on, and then covered with a plastic foil. In the vacuum-injection procedure glass fibre is impregnated with polyester resin by sucking the plastic envelope around the fibre weaves and foam core blocks vacuum and by feeding polyester from the other side to enter into the cavities of the construction: in the fibre weaves and between the foam blocks. Since the resulting layer of GRP at the mould side describes the desired form of the roof in the best possible way, this side had to become the upper layer of the roof. From the prototypes it was concluded that the segments had to be produced top down: the upper surface needing the most accurate form in the opinion of the architect as the sun would shine over the upper surface and always would result in tangential rays over the surface. Hence all regularities would ruthlessly be visible. Less so on the lower side with its indirect day-lighting. So the upper surface had to be made on the mould side and the lower side would have to be made as the top layer and hence a little less accurate and flush. The fire proofing tests resulted in an extra internal layer of gypsum rich finish, which would heighten the fire proofing characteristics of the inner face of the wings to the required level. This implicated that the inner face had to be smoothened after assembly any way. So production with the upper surface at the mould side was the consequential procedure.

It was also decided to pre-cure the top layer as a single layer of fibre weaves with polyester resin before vacuum injection of the complete package of the segment construction. After the top layer of resin soaked fibre was cured, the core of fire-resistant polyurethane blocks was sawn and arranged to the roof layer. Between these foam blocks long glass fibre strips were placed in vertical position to act as stringers between the upper and lower skins. These stringers are the structural ribs in the sandwich as a replacement of the original steel structure or as a stiffening of the sandwich composition, which appeared to have too much flexibility for the roof structure. Tests and analysis had resulted in the introduction of these stringers to lead away the shear forces in the construction package. Due to results of the performed accelerated long time tests delamination could occur at the most critical points: at the supports of the columns, between the internal spans and the cantilevers. A similar problem and loading occurs ate the attachment of an airplane wing to the fuselage. The core foam blocks were subsequently covered with the lower set of glass fibre weaves to form the bottom skin of the segments and an enveloping foil for the next vacuum-injection. The polyester resin that was consequently injected between the blocks, forming the GRP glass fibre strips stringers, thus creating a structural connection between the upper and the lower skins.

In doing so the function of the core blocks had dramatically changes. From the original shear layer, they were now only functioning as 'lost internal moulds' for the lower surface of the wings. Its function was also foreseen as a stiffener of the upper surface to ensure that a solid backing is available behind the upper skin if an unfavourable local load was to occur on the outside of the upper roof skin. Local buckling of the GRP sandwich is prevented in this set-up.

After production of the first three roof segments of the Library, a mock-up was installed at the premises of Holland Composites. The segments were placed on a temporary supporting jig structure in order to fit all the segments, to connect them structurally and to smoothen the final layers in order to prove to the manufacturing team, the engineers , the architect and the client respectively that the wing-shape would have the desired fluent shape without any irregularities. This mock-up was built in March 2005. After a site visit of the architect, and with his approval, the full go-ahead for the production was issued. The remaining segments of the Library wings were produced in the above described production sequence.

In May 2005, around the time of the first congress of Delft Science in Design, the two wings of the 'Library' were shipped to Israel in specially designed super-crates, sized 3,5m x 3,5m x 15m in volume to contain as many segments possible in stacked position in a specifically designed order. Transport was foreseen in 5 lots of the 5 different wings via regular freight ships to the harbour of Ash Dod and from there on to the site by inland trucking transport.

Parallel to the production of GRP segments in Lelystad, the production of the steel columns and the rotating column heads had commenced in Delft. Next to the load bearing function towards the roof these columns also bear the deadweight and wind load of the frameless glass façade. Production of the columns appeared to be a routine job, the only difficulty being the connection between the columns and the roof. All columns had different 3D angles and the sandwich construction was quite weak on the positions of the supporting columns so that a danger of punching the column supports through the sandwich was analysed. Hence during the production of the GRP segments at Holland Composites steel plate inserts parallel to the lower surface of the wings were placed within the sandwich to be able to connect the steel upper plates of the ball joint column tops to the sandwich construction without perforating the wing. Specially developed ball-and socket-connections on top of the columns were designed to accommodate the very different corners of the supporting points under the lower skins of the wings. The ball joints had to be bolted to the inserts.

A large challenge for the steelmakers proved to be the central body: the central part of the 'Great Hall'. Due to the large forces from the upper and the lower roof wings amongst others, this part of the roof has to cope with, unfortunately a tubular steel space frame was the only solution to make this span under this loading possible. The result was a complex space frame structure of tubular steel, later to be fitted with thin GRP panels at the top (roof surface) and bottom (ceiling surface). Because accurate 3D rolling of tubular elements is a rather complex procedure, the entire composition was made in 2D rolled tubular segments, which possessed a greater accuracy. The 3D tubes, mainly situated in the length of the central body, at best approaching the desired shape, therefore had to be connected to the accurately shaped 2D tubes. At the premises of Holland Composites the entire central body was assembled in order to fit the panels. The structure appeared to be as high as 8m, which was very labour-intensive for the erectors. So after the trial assembly in Lelystad, it was decided to build up the final assembly on site in Tel Aviv in two halves, which would result in a building height of only 3 m. After the panels were trial fitted on the particularly engineered and positioned stool supports, the structure was disassembled en transported.

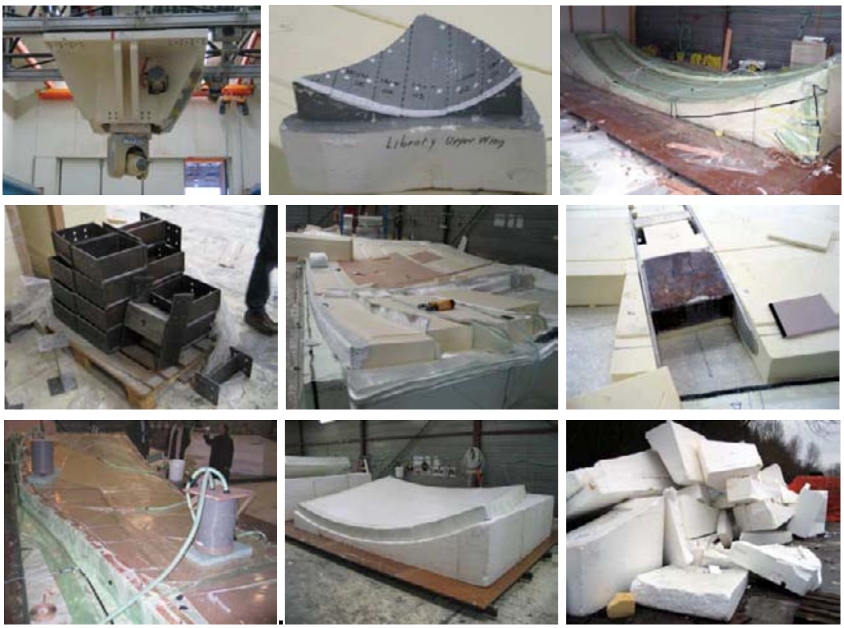


*Fig. 30-38. Milling machine at Marin (30), scale model of upper wing of 'The Library' (31) and production of the roof segments at Holland Composites (29-36). Vacuum injection of the top layer on foam block milled by Marin (32). Insert to be placed in the GRP sandwich roofs in order to make a connection between the roofs and the columns (33 & 35). Placement of foam blocks and glass fiber mats, which will become stringers (34). Vacuum injection of the bottom layer (36). Final result, in this case an early prototype (37). Discarded foam moulds (38).*

After the production of the roof segments of the lower wing of the Library, discrepancies between the theoretical drawings and the practical distortions and tolerances from shrinking of the polyester resin in the enveloping vacuum bags were measured. Tolerances because of warping of the negative moulds resulted in unforeseen deformations of the produced

GRP components. These components together had to form the ruthless smooth surface of the complete wing in the end. All aspects were approached in an engineering manner: measuring, analysing problems and deducting solutions. Analytical engineering in the best traditions of the TU Delft made the initial amazing, improbable design solution finally a reality. The resulting design is a combination of structural design with a strong architectural flavour, incorporating the technologies from aeronautics, ship building, industrial design and geodetic surveying. It poses an example of multiple innovation of technology.


*Fig. 39-40. The central body of the Great Hall (spanning ca. 30m)*


*Fig. 41-42. Roof segment (left) and fitting of all the roof segments of the lower wing of 'The Library' at Holland Composites in March 2005.*

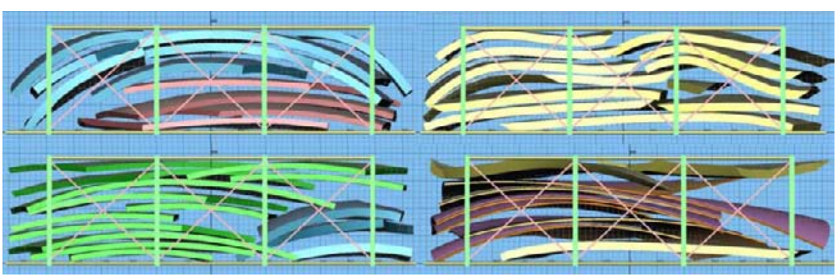


*Fig. 43. 3D drawings of the roof segements in 4 special transport containers*

*Fig. 44-45. Building site in Tel Aviv zoomed in on 'The Library' with the truss and columns already installed (left). Open container at Holland Composites with the roof segments ready for shipment in April 2005Holland Composites in March 2005.*

## 13. Assembly, Tolerances and the Neutralization Regime

Due to the experimental character of the production process and the initial unfamiliarity with the consequences of vacuum deformation, it was decided to perform a test-assembly or pre-assemblage on the premises of Holland Composites in Lelystad of all the wing segments. The fitting took place on a positive steel frame, the shell would therefore be curved upward. One of the conclusions was that we would assemble the wings inversely, so the downward curve would face upward. When a technician would fall, he would fall in the shell, instead of falling off the shell. Subsequently the shell was turned over with a mobile crane, by means of three temporary hoisting fixtures in the shell. From the pre-assembly conclusions could be drawn regarding the theoretical versus the practical measurements of the individual segments. All segments were produced on individual foam moulds and they all had their own shrinkage and shrink-direction. Yet together, these segments were required to form the unforgiving smooth surface desired by the client and architect.

It was noted that the total fitting of the individual deformed segments would still form a smooth surface when the entire shell was assembled. In order to acquire this smooth surface a solid frame was needed with clamps in order to force the segments in the desired position. In general the segments proved to be somewhat smaller than intended. They had shrunk because of the vacuum injection, causing the seams to be 20-25mm, instead of the anticipated 12-15mm. When filling up the seams during assembly a bigger seam meant more fibre and more resin (due to the required ratio between fibre and resin) and thus causing a larger weight of the shell.

The connections between the individual segments can be divided in connections in the length and connections in the width of the segments. Both have a structural function. On the side of the segments a rabbet has been made of 220mm with and 15mm depth. In this rabbet a prefabricated reinforcement strip of 200mm width and 10mm depth (of high density glass fibre weave layers that had been vacuum injected with resin) was placed. This reinforcement is glued and clamped by screws for curing purposes only. After the segments of the two wings in Lelystad were fitted on the steel frame, controlled and approved, the segments were dismantled and shipped in the special containers. The assembly on site had to take place on the south side of a tall wall on ground level.  The segments were assembled inversely, measured, connected by the prefabricated reinforced strips, measured again, touched-up and finished with the structural reinforcement meshes and filler. The lower side with a fire retarding layer, the upper side with a infrared light resistant layer. Next, the shells were turned over and identically finished on the other side. After the hoisting onto the Library, the first shell wing was positioned on a steel flat truss sub-structure, which in its turn rested on a concrete wall with a much larger tolerance difference.

Positioning directly from the crane onto the column heads, or wing-connectors with its adjustable shaft and connection plates, could only take place accurately by following the theoretical drawings. Until the end of the assembly and erection theoretical drawings remained the decisive factor. In all phases of engineering, production, assemblage up until the hoisting and positioning theoretical drawings were always present and compared, as this was the only assurance that at the end the wings would fit into position. Neutralizing different components is a adventure in itself. Building parts were simultaneously produced in locations all over the world. In this project the steel was manufactured in Delft, the glass in Luxembourg and Belgium, the polyester segments in Lelystad and the concrete works in Tel Aviv. The concrete had the biggest tolerances, up to 100mm. The seams of the roof segments measured theoretically 12mm, in reality 25 to 30 mm and the seams between the glass panels a more accurate 8 to 12, average 10mm. And all these different tolerances have to be neutralized in their principle detail design (allowing neutralizing at all). Tolerances in the different stages from design, through engineering to prototyping, production and building on site govern the success of each prototypical Free Form project. The geodetic supervision during the process of production and installation has grown in its importance since Blob structures for Free Form architecture had to be realized.

Having arrived at this point, one has to remember that the success of Henry Ford in the automotive industry was not the running belt. *"Ford's 1908 Model T was his 20$^{th}$ design over a five year period that began with the production the original model A in 1903. With his model T he finally achieved two objectives. He had a car that was designed for manufacture, as we would say today, and also was, in today's terms, user-friendly. Almost anyone could drive and repair the car without a chauffeur or a mechanic. These two achievements laid the groundwork for the revolutionary change in direction for the entire motor-vehicle industry. The key to mass production was not – as many people then and now believe – the moving or continuous assembly line. Rather it was the complete and consistent interchangeability of parts and the simplicity of attaching them to each other. These were the manufacturing innovations that made the assembly line possible"* [From Womack et al, *The Machine that Changed the World:5].* In similar projects where buildings with Free Form design had to be realized (for example: Town Hall, Alphen aan den Rijn, see www.mickeekhout.nl), the total costs involving geometrical surveying from prototyping and productions up to assembly and installation the costs were as much as 3% of the contractual turnover: a serious amount of man hours. The building industry has finally arrived at the international industrial level of 3D design of components, boosted by the inevitability of the technical compositions of Free Form architecture. From now on the different ingredients or components of free form architecture that are made in lots by different co-makers / subcontractors, sometimes in many countries all over the world for just one project, put the building industry in line with the automotive industry, only 100 years later. This is helped by the change-over from the concrete and bricks technology where joints always can be adapted locally, to the more industrial (factory manufacturing) metal and mid/high-technology where all components have to be fitted specifically in an industrial mode, so with outspoken and very accurate tolerances only. Once Henry Ford could force his components suppliers to produce and supply components with fine and accurate (and only negative) tolerances, he could avoid the adaptation of components on the assembly floor (in the building industry: on the building site). This made the difference between the former automobile ateliers where cars were hand-fitted after most of the time was lost in refitting the components and an industrial and almost 'blind' assembly only focussed on the assembly activities and not any more on the component care. From that moment on, Ford could even employ a running belt as the continuous production base of assembly-only.

*Fig. 46-47. Preparation and hoisting of the upper and lower wing of the Library in August 2005*

*Fig. 48-49. Assembly of the roof segments by gluing and bolting glass fibre polyester plates on the seams before applying the finishing layer*

The glass facades were developed separately form the roof wings. They were based on more than a decade of experience with designing and realizing of frameless glazing. The original design was a standard mullion façade, which was redesigned as a frameless glazing façade. The architect required a specially fritted glass in order to influence the daylight penetration and the solar entrance. This part of the building was not as interesting scientifically.

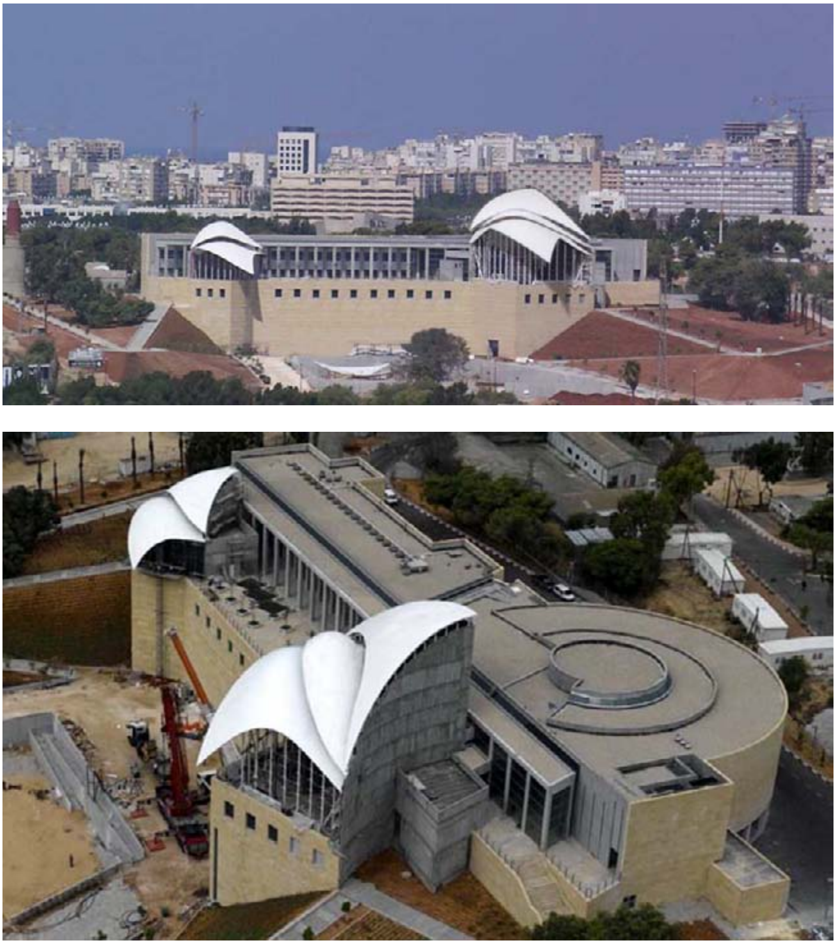


*Fig. 50-51. View of the building site on the 6th of November 2005, photographed by Ardon Bar Hama.*

*Fig. 52. View of the building site in April 2006.*

*Fig. 53. The Library – Interior view*

*Fig. 54. Overview of the building site just after completiont of the roofs by Octatube.*

*Fig. 55. Finishing of the top layer of the roof by "airborne builders"*

*Fig. 56. The Great Hall Interior view*

## 14. Carbon Fibre Blob Shells, as Yet One Bridge Too Far

The above described sandwich construction shells of the Rabin Center form a renaissance of the shell structures of the 1960's. In those days, due to simple mathematical hand calculations shells were thin, followed the ideal spherical, conical, cylindrical or hyperboloidal forms. Results were mostly 50 mm thin concrete shells with only one central reinforcement layer of steel bars. Many shells had an Hispanic origin: Eduardo Torroja, Spain, and Felix Candela, Mexico were the prominent pioneers. The shells were built in countries with high material and low labour costs. In the 1970's the pioneer's retired and the concrete shell fashion stopped. Crafted carpenters retired after that and nowadays making a concrete shell would again become an experiment. Heinz Isler from Switzerland built his concrete shells with re-usable timber moulding on scaffolding in the 1980's. He also retired and closed his company. These concrete shells have now to be designed in open en direct collaboration between architect en engineer.

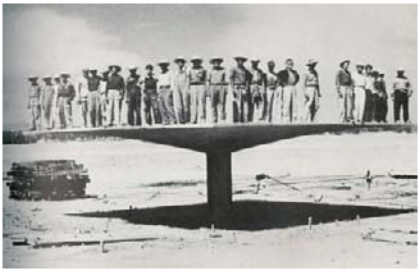



*Fig. 57–58. Works by Felix Candela: a mould for concrete (left) and a prototype for a cantilever made of concrete (right)*

Blob architecture emerging in the late 1990's (Guggenheim Museum Frank O. Gehry, 1998) changed these conditions, as the architect designs either directly in models or on the computer as if he is a sculptor. The dramatic 3D effect dominates architectural thinking. The structural designer has not an equal position, but is asked subsequently after the architect has found out a model or geometry, which suits him out of visual design considerations. Alas there are usually no direct feedbacks, no improvement feedback loop from structure to architecture. That is to say the engineer has to realize the sculptural whims of the architect to a trustworthy architectural structure, safe in use. This has as a consequence that the form of the new generation of shells are much more arbitrary in structural sense and hence have a more unfavourable structural behaviour.

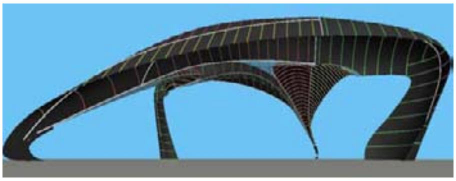
*Fig. 59. Guggenheim Museum Bilbao, architect: Frank Gehry*

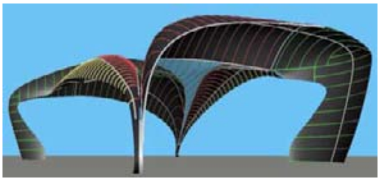
Many of these new shells are now governed by bending moments due to their unfavourable form and supports, rather than by normal forces and shear forces in the plane of the shell as in the first generation of shells. The constructional solution of the new generation of composite shells is in principle the one developed for the Rabin project and now the system solution: a double stressed skin sandwich composite construction in free form with a structural core. The two skins enable bending moments to be taken, caused by unfavourable loading conditions, column or support positions and, structurally speaking, arbitrary or rare shell forms. We would still call these roof forms 'shells' as a reminiscence to the thin-walled shells from the 1960's, but mathematicians and methodologists suggest to invent and publish a new name. The answer is: Blob-shells or Free Form shells.

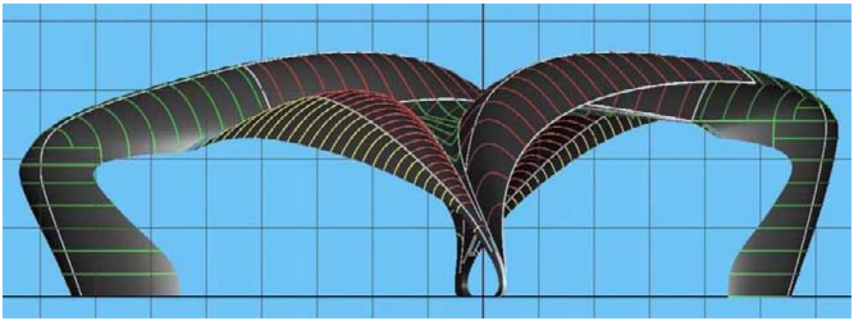
The next step in development is caused by the differences in loading behaviour between conventional structures in steel of concrete and glass fibre reinforced polyester shells. Blob shells, made of glass fibre reinforced polyester are usually much more flexible, and cannot reach the stiffness and rigidity of conventional structures. For sailing yachts, often prestressed by its masts and riggings, rigidity is a relative connotation. As long as the doors and cupboard doors still close and open only a few sailors would mind the distortion in the hulls of their yachts. The consequences and joys of trimming in speed govern. However, buildings components like windows and doors, often have vulnerable, annealed glass components directly attached to the roof structure. These are influenced by the stiffness of the load bearing structure. Depending of the details, this requires the engineer's attention. Cantilevering blob-shells are more flexible than in conventional structure. The cantilever of the tip of the largest wing at Rabin was analyzed as 100mm upwards and 210mm downwards. The total sandwich thickness was 314 mm. This fits in the general shell theory of Thimoshenko, so that this composite shell still behaves as a shell. Alternatives in steel and in concrete were analyzed to show deformations of 200 respectively 100 mm only. The engineering line-of-thought was that, as long as the movements of the roof under loading do not cause brittle fracture, de-lamination or other handicaps in the blob-shells internally and as long as the flexibility of the blob-shell does not lead to problems in the technical composition of the building around the blob-shells, for example by crushing glass panels or causing leakages due to too much movements in the silicone joints, a larger movement would be acceptable. So no rules yet, but intelligent and responsible building technical engineering, characterizing the experimentation phase. The standardization and normalization phase of newly developed technologies will follow after 5 tot 10 years only. But new projects involving blob-shells in future will show up with no doubt more strict requirements as to the anticipated deformations in GRP.

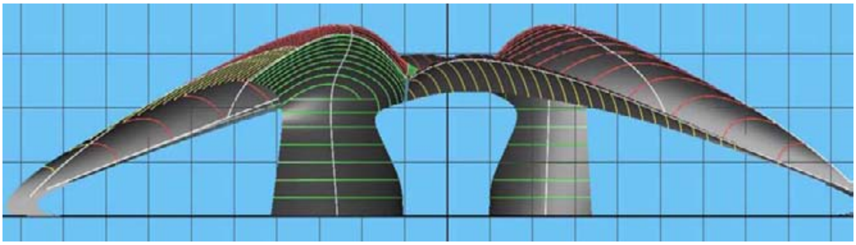
Other materials are interesting in this respect as well. Epoxy and carbon fiber is the alternative usually employed in the production of high-tech sail yachts. The next generation will probably be blob-shells in carbon fiber reinforced epoxy. This material is much more rigid, does hardly expand as the modulus of elasticity of carbon fiber reinforced epoxy is much lower than that of glass fiber polyester. However, these advantages are accompanied by a much more strict production process including curing in a tempering oven, which limits the sizes of components. For transfer of technology from the yacht building industry (for example used in the black and white ABN AMRO yachts of the Volvo Ocean Race 2005/2006 were built in Lelystad NL using this technology in vacuum injection), the costs play an important role. As the thresholds in the building industry are quite low and the price of carbon fiber reinforced epoxy shells are high, clients could prefer to go back to reinforced concrete after studying the price of carbon fiber epoxy shells. Yet amongst architects a strange mechanism works: the 'first-of-the-block' effect. The first guy of the block who buys a pink Cadillac is celebrated, the second one is a looser. So at least he has to buy himself a Cadillac of a different colour. Moshe Safdie designed shells that were realized as white shells in original material. The next architect would prefer a black shell to distinguish himself or herself. In this case the famous London-based architect Zaha Hadid designed a Free Form Mediateque in Pau, France, near the Pyrénées. Her initial design images show the 'Mediateque' in white, but the tender documents of 2005 show now a black design with carbon fiber as the basic material.

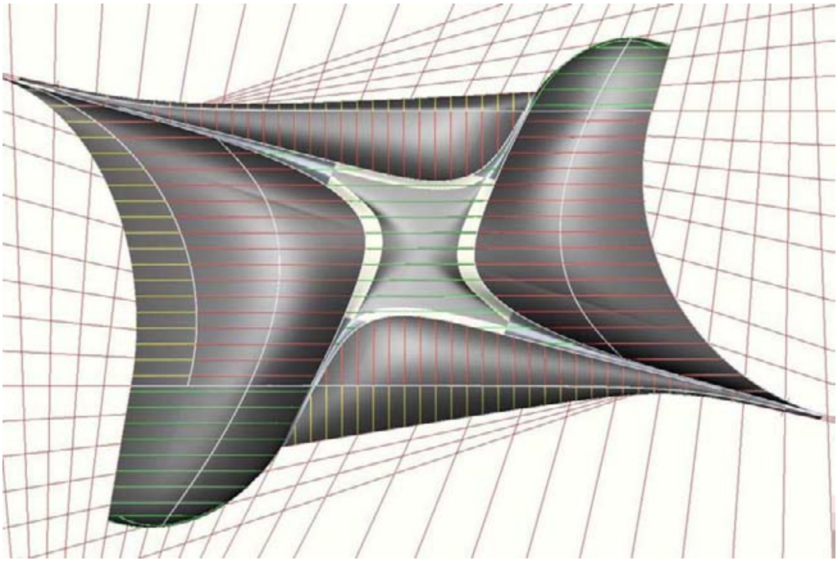
In the development of the Mediateque tender design in the proposal of the author, accompanied by co-makers in the Netherlands and England, the idea was production of the segments of the carbon fibre epoxy blob shell segments locally in a temporary factory shed, a re-assembled curing oven, next to the site. The process of tendering did not allow for any prototyping on the side of the client or architect. Rather this extremely experimental project was tendered as a standard building project. The resulting tender price was 4 times that of the client's budget and, may be as a blessing in disguise for this extremely experimental project on a giant scale, the project champion, Pau's mayor André Labarrère, who wanted to realize his '8ième Grande Project' died the day before the tender date. The project was cancelled. The design drawings indicate the design proposals in carbon fibre epoxy blob shells, which will probably be illustrated in a next Delft Science in Design conference at TU Delft if the experimentation course could be continued.











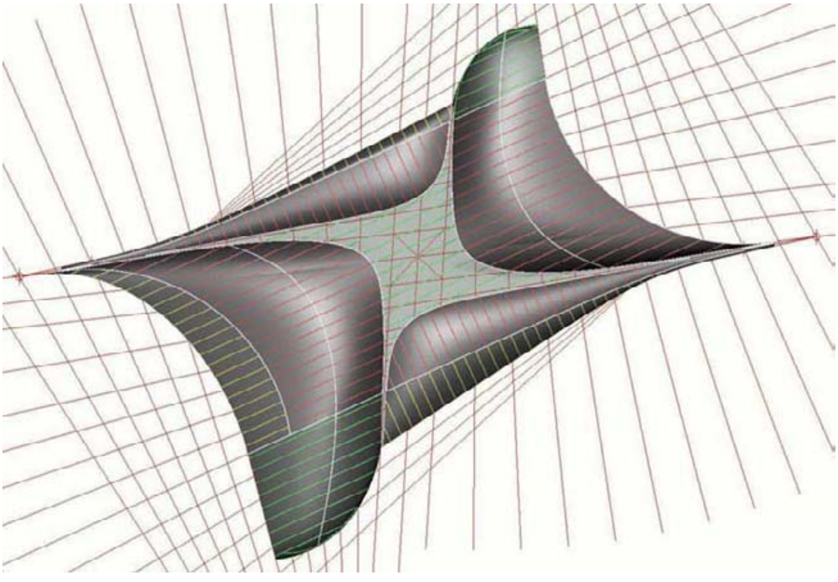


*Fig. 60-65. Preliminairy engineering drawings of the Mediatheque in Pau by Octatube*

## 15. Conclusion

The resulting design in this contribution shows that building technical design can lead to an integrated and innovative process. In such processes many disciplines are collaborating and have to be co-ordinated throughout the entire process inclusive all of its unforeseen and experimental stages. The results of this process have to be integrated into one technical artefact that satisfies all requirements and gives efficient answers or compromises in all of its life phases, be it conceptual design, material design, detail design, engineering, productions, assembly, installation, loading behaviour, functional use as a building, meaning of the artefact as a building, (even as Architecture) and in its (global) context/surroundings, in its meaning as integral part of the building.

Society expects perfect solutions from scientific designers. These solutions are not only the functional and technical solutions. It may be true that the well-known restrictions in the volume prices of the building industry, as posed by the clients in the building industry, lead to traditional and well-known technologies. Yet the thresholds to enter the building industry are low and competition is fierce. Sometimes experiments are persistent, initiated by technical designers who are willing to wander though the entire experimental development process and are able to analyse and solve all foreseen and unforeseen problems. It requires an experimental mind set.

In this case the interdisciplinary collaboration from Architecture with Industrial Design Engineering, the Maritime Engineering and Aeronautical Engineering proved to be essential and an enrichment in the field of Architecture in order to introduce the renaissance of the shell as 'Blob shells' of 'free form shells' for the world.

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# Design in the Chair AeroSpace for Sustainable Engineering and Technology (ASSET)

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**Abstract**

This paper gives an overview of the design work being performed in the chair Aerospace for Sustainable Engineering and Technology. The research of the chair is focusing on the themes sustainable energy conversion and sustainable transport. The work of the chair is organized in projects. For both research themes this paper gives an overview of two projects each.

Key words: design, sustainability energy conversion, transport

## 1. Introduction

The chair Aerospace for Sustainable Engineering and Technology was started in 2003 by professor Wubbo Ockels. The chair aims at applying hi-tech technology from aerospace for sustainable development. The chair does this from the vision saying that nature has no mercy and that humanity in the future needs to play the game with nature, rather than against nature. In this process technological means are essential, and in particular the technologies developed in the field of aerospace engineering can play an essential role. It is in this respect that ASSET sees an opportunity, namely to initiate activities where the capabilities and results of aerospace engineering are particularly used for sustainable developments. As this field is new, no previous experience existed. The strategy proposed was to initiate a number of highly visible and relevant topics that will lead to subjects for education and further research.

The Faculty of Aerospace engineering strives towards organizing its research and education in an object oriented way. In fact for ASSET the objects are formed by highly visible, challenging and stimulating projects from which the education and research forms a spin-off. The research is both applied and fundamental. This policy fits in the general approach of the Aerospace Faculty and has proven its merits in the past making the faculty very successful.

The two main research themes are:

1. Sustainable energy conversion

2. Sustainable transport

The most visible projects in each of the research themes are

Research theme 1 - sustainable energy conversion

- Ladder mill
- Kite propelled ships

Research theme 2 - sustainable transport

- Nuna solar cars
- Superbus

This paper will focus on the description of the projects and design related aspects. The paper will not focus on the societal and economic impact and viability since this is considered to be outside the scope of this paper.

## 2. Ladder mill

The Ladder mill is a concept to harvest electricity from high altitude winds. The concept's operating principle is to drive a ground based generator using a series of kites. Several kites fly high in the air at altitudes of more than one km. All kites are connected to one single cable that connects to a drum in the ground station. The lower part of the cable is wound around this drum. A generator is connected to this drum. When the kites fly in kite mode they develop a relatively large lifting force with which they pull the rope from the drum, which in its turn drives the generator and thus creates electricity. At the top of the cycle the kites change to a glider like flying mode. In that configuration they generate substantially less lift and can be reeled in using relatively small amounts of energy. At the end of the cycle the kites again change to the kite ode and start pulling again. This cycle produces net energy.

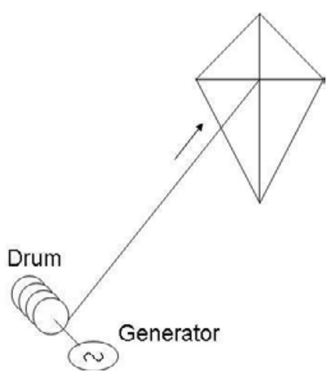


*Fig. 1. Principle of the Ladder mill with ground based generator (source: Bas Lansdorp)*

*Fig. 2. Artists impression of the Ladder mill (source: Jeroen Breukels)*

The forces acting on the kites in the two flight phases can be best illustrated using standard airfoil theory. The following two figures show the two basic flying conditions. The first figure shows the kite mode. The second one the glider mode. In the kite mode the design should be made such that the net resulting pulling force created is high. In order to be able to achieve this the lift force has to be considerably higher than the weight of the kite. Next to that the drag force has to be as small as possible since that has to be compensated by a forward component of the pulling force. The larger the component of pulling force in forward direction has to be, the more area the Ladder mill will need. Thus the ratio between the lift and the drag has to be maximized while the weight of the kites has to be minimized.

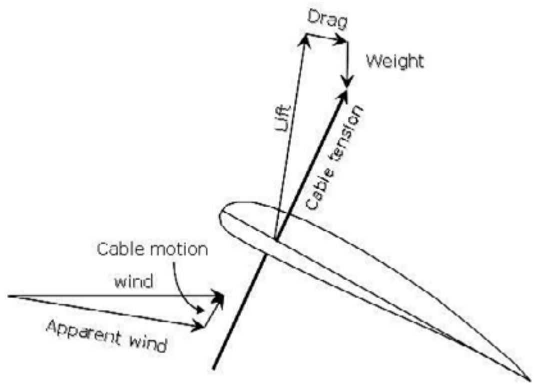


*Fig. 3. Kite flying in kite mode (source: Bas Lansdorp)*

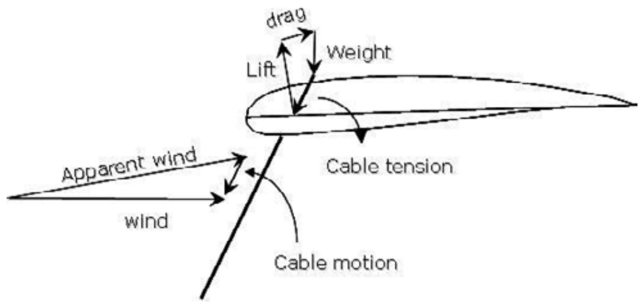


*Fig. 4. Kite flying in glider mode (source: Bas Lansdorp)*

In the glider mode the pulling force in the rope has to be minimized but may not become negative. Therefore a small resulting pulling force will be required. In this phase of the flight the weight will be helpful in moving the kite down with as little pulling force as possible. The mass of the cable also has an effect on the performance of the system. Since he Ladder mill consists of a series of kites the pulling force increases with an increasing number of kites of the same size. The pulling force will be lowest between the top two kites and will be highest between he lowest kite and the ground station. The cross sectional area of the cable can be adjusted for this. As a result the mass of each cable segment will change as well. In optimizing the configuration this can be taken into account as well.

The amount of energy is depending on the number of kites, the design of each kite and the wind at altitude. The wind speeds change considerably with altitude. While wind speeds at altitudes below 100 m are rather unpredictable the wind speeds at higher altitudes are more predictable. The following figure shows an overview of average wind speeds as a function of altitude in the Netherlands.

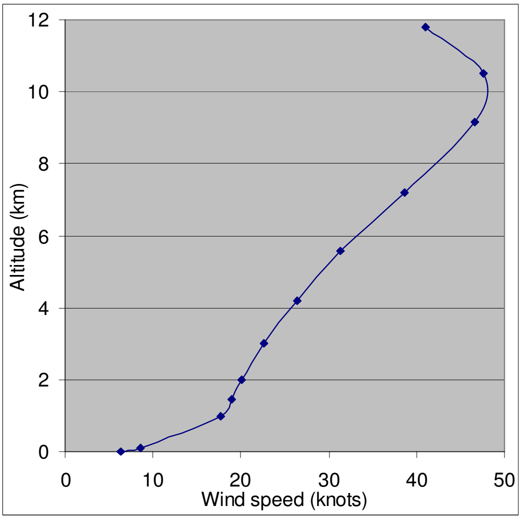


*Fig. 5. Average wind speeds over altitude in the Netherlands (source: Royal Dutch Meteorological Institute)*

The figure shows that the wind speeds increases rather rapidly when moving out of the boundary layer of the Earth. At altitudes above 1 km the wind speed changes gradient and keeps increasing until an altitude of approximately 10 km is reached.

The design of the kites can be based on a number of concepts. Within the research program two main designs are under consideration. The first is the surf kite configuration as shown in the following figure. These kites are well known for their ability to generate large pulling forces and controllability. In general the mass of these kites is relatively small and they are controlled by at least four wires, two on either side. Manual control is the normal way of operation. The lift to drag ratio of these type of kites is significantly smaller than that from aircraft.

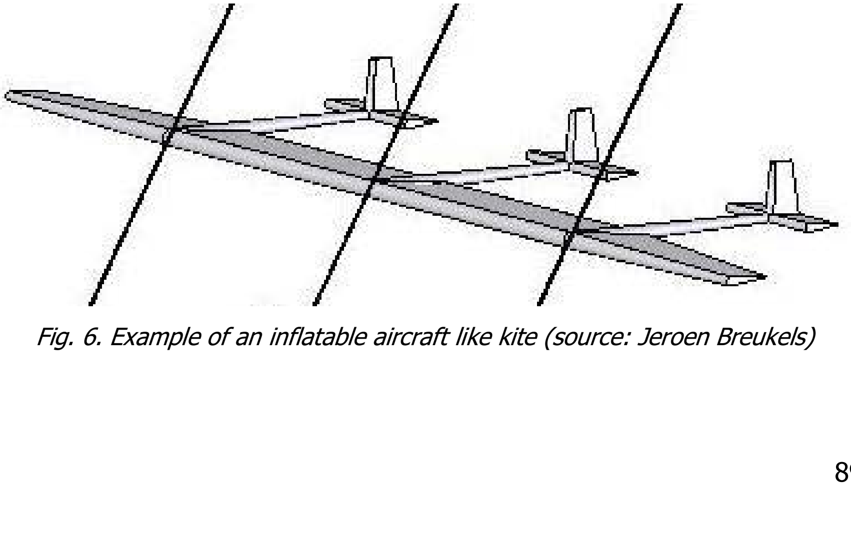

*Fig. 6. Example of an inflatable aircraft like kite (source: Jeroen Breukels)*

*Fig. 7. Standard surf kite (source: Bas Lansdorp)*

The second approach in the design of the kites is the aircraft approach. Kites can be seen as towed aircraft. In towing gliders this is being done on a regular basis. Towing an aircraft will have consequences for its stability. Aircraft in general can reach higher lift to drag ratios than kites. On the other hand the mass is also higher. In the development program therefore aircraft like structures are being considered but they are being designed as inflatable structures.

One of the factors of primary importance is the control of the kites. Therefore much effort is being put this. The practical part of the research now focuses on control designs of surf kites. The theoretical part of the design focuses on control of aircraft like kites as well. In the control of surf kites a system has been designed in which the control can be performed by two instead of four control wires. One wire on either side of the kite is being moved along a rail. It has been demonstrated that accurate computerized remote control is now possible.

Another part of the Ladder mill project is focusing on he design of the ground station. In this ground station the drum and generator have to be located. Depending on the power being generated the size of both the drum and the generator change. Design requirements of the ground station include issues like controllability, mass and efficiency of the generator being used. The following figure gives an overview of the current design of a 3 kW ground station which is currently undergoing testing.

*Fig. 8. Surf kite control by two wires only (source: Bas Lansdorp, Richard Ruiterkamp)*

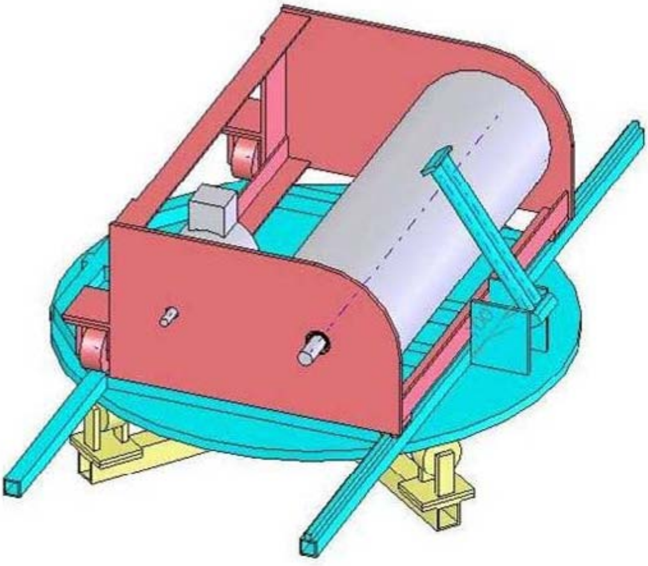

*Fig. 9. The 3 kW ground station (source: Bas Lansdorp)*

## 3. Kite propelled ships

One of the more recent developments is the application of kite propulsion on ships. Next to aircraft, ships can be considered as one of the most difficult means of transport to shift towards sustainability. The main reason for this that for the majority of their journey there will be no energy supply station nearby. This makes it impossible to propel them by electricity since the battery capacity would require too much space onboard. Nowadays the main source of energy is heavy fuel oil. One possibility would be to look at the use of wind energy conversion systems. On the oceans there will be wind power available quite often. This could be used for propulsion. Traditional sailing using tall masts will most probably not be an option for commercial shipping but kite like propulsion devices might become feasible. The German company Sky Sails is currently developing systems like this.

*Fig. 10. Artists impression of the Ladder mill ship sailing into the wind (source: Jeroen Breukels)*


*Fig 11. Applying a kite to a ship (source: sky sails, Germany)*

The ASSET chair is looking into the possibility to apply the Ladder mill technology to shipping. The potential benefit of this would be the possibility to use the kite system for generating electricity. This electricity then powers the engine of the ship or can be stored in an onboard battery pack of limited size. Theoretical research has shown that it would be possible to use this concept not only to propel the ship in tail wind conditions but also in head wind conditions. The following figure gives an artists impression of a Ladder mill powered ship. Currently research is being performed in developing a demonstrator.

## 4. Nuna solar cars

The most well known project of the ASSET chair is the series of NUNA solar cars. The Nuna solar cars were developed for taking part in the World Solar Challenge in Australia. This World Solar Challenge is a race from Darwin in the North all the way to Adelaide in the South of the country. The race has a length of 3021 km and normally takes place every two years. The race was first held in 1987. The first Nuna car took part in the 2001 race.

During the race the use of solar energy is the only source of energy allowed. The cars do have limited battery capacity but they are not allowed to recharge them other than using solar energy. The race is a multi day race. Racing times are between 8 am and 5 pm. The available solar light during the remainder of the day may be used to recharge the batteries.

The size of the solar cars is limited such that they fit into a 5 m long x 1.8 m wide x 1.7 m high box. For the race editions up to the 2005 race the amount of solar cells was not limited. During he 2007 race the amount of solar cells was reduced to 6 $m^2$.


*Fig. 12. Overview of the World Solar Challenge route (source: WSC)*


*Fig. 13. Nuna 1 solar car*

The Nuna 1 team approached professor Ockels in 2000 for his help. They developed a solar car which was designed using aerospace technology as much as possible. The aerodynamic design played a major role in he design of the whole car. The design was made such that the drag was minimized. Next to that the structural design was based on a light weight truss covered with the aerodynamically shaped outer shell. The leading edge of the vehicle was made rounded such that cross wind conditions would not have a detrimental effect on the performance. Next to that a computer based race strategy was designed such that the speed of the vehicle was optimized using he available light, the expected available light and the state of charge of the battery pack. The strategy algorithm was based on genetic optimization. This resulted in a winning performance where the average speed was 92 km/h. This speed was considerably higher that previous cars had ever achieved. Nuna 1 was the first car to finish the race within four days. Nuna 1 was considered an outsider. The alleged winner was the Australian solar car Aurora.

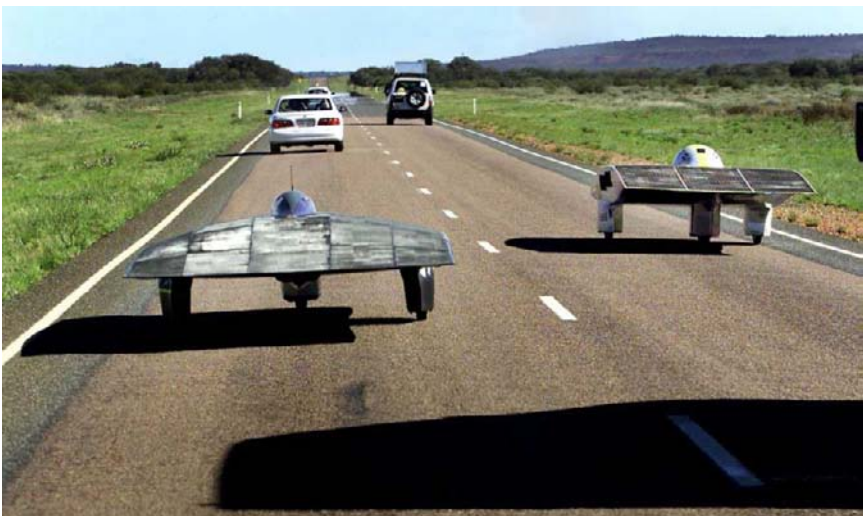

*Fig. 14. Nuna 1 (driving on the right) overtaking the Aurora solar car (on the left)*

After he success of the Nuna 1 a new team started the development of a new car in 2002. It was decided not to optimize the previous Nuna but to start from scratch since there were too many areas in which he design could be made better. The result was the Nuna 2 which became a car with a full carbon fiber epoxy composite body. The truss structure used in Nuna 1 had been considered too heavy and therefore not used anymore. The aerodynamic design was changed in the sense that the top view showed a more square car. This would give more area for placing solar cells. The expected detrimental effect of cross wind had not occurred and therefore this more square design could be applied. The result was an even faster solar car which again managed to finish he race within four days, now averaging a speed of 97 km/h. The Australian solar car Aurora came in second again. However their average speed was already higher than that of Nuna 1.

*Fig. 15. Nuna 2 solar car*


*Fig. 16. Mission control vehicle*

In 2004 it was decided to take part in the 2005 race as well. The organization had decided that it would move the race more towards the Australian winter. It had decided so because they were afraid of the high average speeds the cars had reached in the last two editions of the race. The 2005 race would take place in September. The new Nuna team decided to start all over again with designing a new car. All aspects of the care were redesigned where again aerodynamics, structural weight and control strategy formed the major design areas. The aerodynamic design was changed such that the cockpit was moved aft. This created a larger area of undisturbed flow. The attachment of the solar cells was made such that a large part of the top surface of the vehicle could operate in laminar flow conditions. Research was also performed in the area of boundary layer suction. Although initial test results were promising it was decided that this technology came too early and was not mature enough. Eventually the researcher who performed this research started his own company in laminar flow control for the automotive sector.

Another aerodynamic design change was the design of the two front wheel fairings. Since in the period of the race quite some cross wind was expected the design was changed such that the vehicle could benefit from this. The shape of the fairings was made such that in cross wind conditions they would start acting as sails. They would create a forward force contributing to the thrust of the vehicle.

*Fig. 17. Wind tunnel model of Nuna 3*

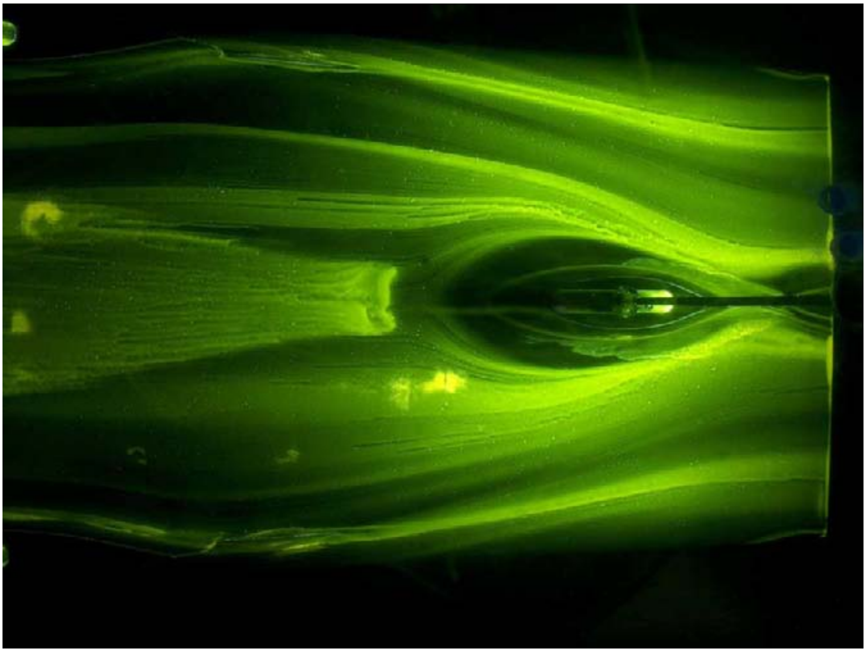

*Fig. 18. Flow visualization tests on Nuna 3*

The structural design was changed in the sense that the body was made as light weight as possible. Nuna 2 had made the step towards a full carbon body. The structural method applied was that of a sandwich structure over the whole of the body. This resulted in a strong and stiff body, also in places where this strength and stiffness was not required. The body of Nuna 3 was designed such that the center part was shaped like as a sandwich monocoque structure. The remainder of the body was made out of a thin carbon fiber laminate without the sandwich core material.

The race took place in September. This meant that there was more low incoming solar radiation. Therefore not only he top surface was covered with solar cells, also the side panels were covered with solar cells as much as possible. In the control system a fully remote cruise control was incorporated. This had been tested in the Nuna 2 after he 2003 race had taken place. In principle the driver only had to steer the vehicle. The speed of he vehicle was optimized by the control strategy software and then fed into the cruise control of the vehicle via remote control. In the end this resulted in a winning average speed of 103 km/h.


*Fig. 19. Nuna 3 during qualification trials in Darwin*

The regulations for the 2007 race have changed considerably. The maximum area of solar cells allowed has been reduced to 6 $m^2$. Furthermore it is required that the driver sits n an upright position. Where the drivers in Nuna 1, 2 and 3 more or less were lying down the driver in Nuna 4 may not lean back more than 27 degrees. Next to that the steering control must be performed by a steering wheel. The sliding control sticks used before are banned. Finally the vehicle must have a roll bar to protect the driver in a roll over situation.

## 5. The Superbus

The Superbus is a concept for a streamlined electric vehicle, which can operate at cruise speeds of up to 250 kilometers per hour. Such speeds can be reached on special designated tracks, but the Superbus can also be driven at lower speeds on existing roads and bus lanes. Professor Wubbo Ockels has invented the Superbus concept in 2004. The ASSET chair is now designing and building a full scale demonstration vehicle. This demonstration vehicle is to be displayed at the 2008 Beijing Olympics.

The Superbus combines Aerospace Technology and Information and Communication Technology (ICT). The Aerospace technologies included are:

- low drag design
- light weight design
- aviation levels of safety
- aircraft control
- aircraft reliability
- The ICT technologies included are
- detailed knowledge of the road
- accurate navigation
- surveillance radar
- flexible logistics


*Fig. 20. Front view of the Superbus*

**General description**

With a length of 15 meters and a width of 2.5 meters, the Superbus has similar dimensions as a conventional bus. Due to the seating arrangement without a centre aisle however, the height is just 1.7 meters. Instead of a few large doors, 8 doors are placed along both sides of the vehicle to allow direct access to all seats. The seats can be arranged such that compartments of 2, 3 and 5 passengers are created. This reduces the frontal area of the vehicle. This is combined with a highly streamlined body shape resulting in a coefficient of aerodynamic drag of approximately 0.3, compared to 0.6 for a conventional bus or around 0.35 for an advanced passenger car. The combination of a low drag coefficient and a small frontal area result in a low aerodynamic drag force. The low aerodynamic drag makes the Superbus more efficient than a passenger car. The energy use of the vehicle at 250 km/h is the same as a normal bus would have at 100 km/h.

*Fig. 21. Side view of the Superbus*

The Superbus has three axles with a total of six rubber-tired wheels. The Superbus will be electrically driven. For this the Superbus will use a set of onboard Lithium-Polymer batteries.

The Superbus will be operated by the combined use of a driver and electronic guidance of the vehicle. For example a radar system in the front can detect obstacles up to a few hundred meters down the road and accordingly brake or steer the vehicle to avoid a collision. Lateral guidance will also be provided with the use of radar technology.

**Propulsion**

The Superbus will be driven electrically. This makes it possible to control the emissions of the vehicle. In some situations emissions are not desired, like in inner cities. In that case electricity will be taken from the onboard batteries like hybrid cars do. Electricity can be generated using sustainable sources like sun and wind.

Today’s battery technology allows a range of around 200 km. For long range performance an onboard generator will be required. This generator will be preferably powered using a bio-fuel. Possible options are bio-ethanol or bio-diesel.

The electric motors used in the Superbus will be high performance, direct-drive motors. The expected efficiency is around 95%. It is decided not to make use of in-wheel electric motors since they would increase the so-called unsprung mass. The unsprung mass is the mass of the wheels. A high unsprung mass has a detrimental effect on vehicle dynamics and passenger comfort.

**Infrastructure**

The Superbus can make use of existing infrastructure. It can drive in cities and on the highways. The length and the all wheel steering system make that it complies with current regulations such that is can pass roundabouts as well. When the Superbus starts driving at high speeds it must be separated from other traffic for safety reasons. For this a dedicated infrastructure is needed, called Super track. Since the Superbus is a lightweight vehicle the Super tracks can also be light weight. This has two benefits. Firstly the road construction can be relatively cheap. Secondly the building of the road has minimal environmental impact. This is especially important since in the traditional public transport systems half of the total environmental impact of a transport system comes from the building of the infrastructure. The other half is generated by the driving of the vehicles itself.

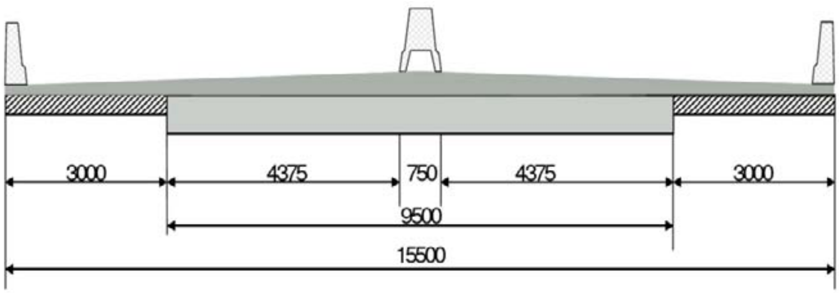


*Fig. 22. Possible lay-out of the Super tracks*

The road surface of the designated Super tracks can be heated during winter. This will be required for melting snow and ice. A possible way to do this is to make use of the so-called WinnerWay system. In this system the heat of the sun is collected in summer. This heat is stored in deep water layers in the soil. In winter this warm water is used to raise the temperature of the road to a level where the snow and ice melt. The concept has been tested successfully in the Netherlands. Making use of this method eliminates the need for spraying salt.

This seems an expensive solution but in fact it may result in a lower total life cycle cost. Because the road surface has a more stable temperature throughout the seasons, the road surface will have a lower tendency to crack. Furthermore the absence of the necessity to spray salt reduces maintenance cost and the negative effects it has on the road structure are avoided as well. In this way maintenance costs will be reduced.

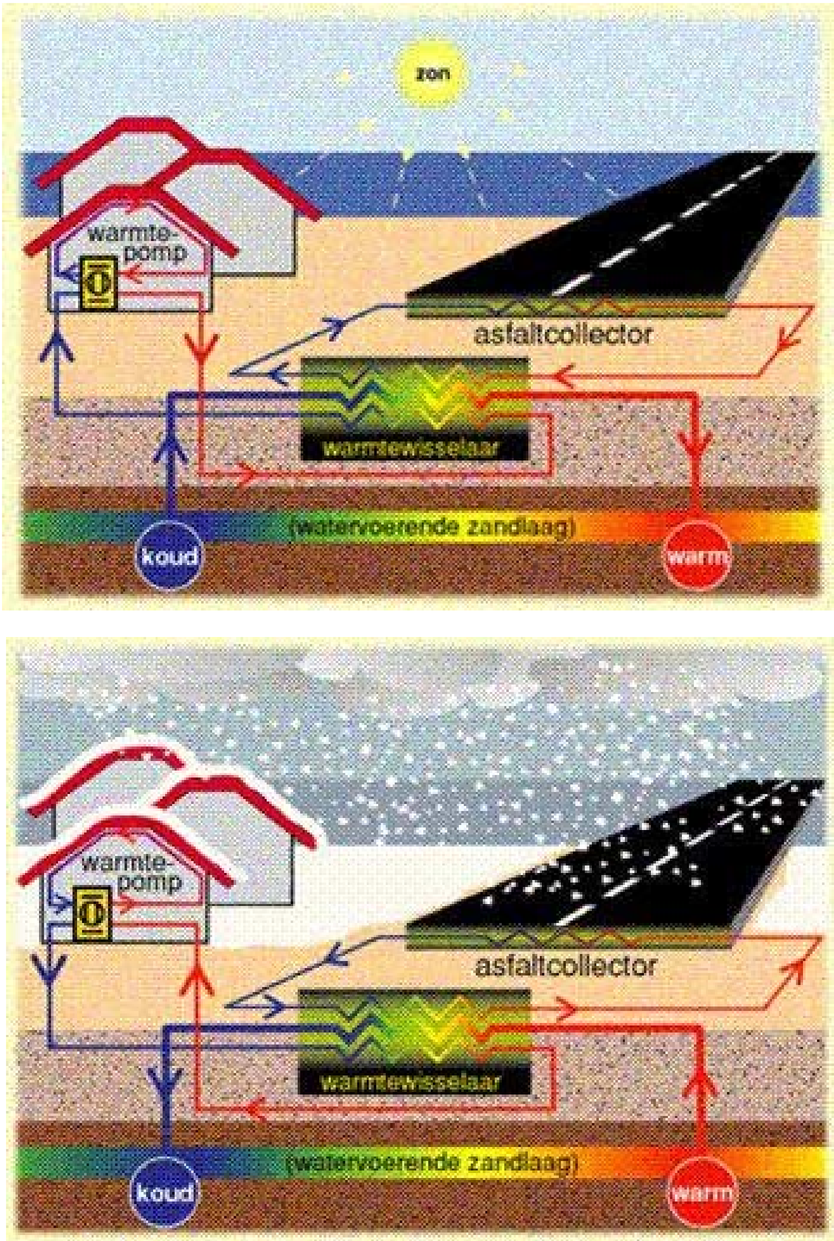


*Fig. 23. Winnerway heating system (source: Infratheker)*

## Flexible logistics

The Superbus is a transport system intended for distances above 30 km. In this way the best use can be made from its high speed potential. Applying the Superbus on shorter routes is possible but the high speed characteristics will not benefit the passengers in that case.

The Superbus logistic system will be a demand driven system. In this respect it will deviate from the standard supply driven public transport. Instead of using designated stops, the Superbus can be ordered anywhere along the route. This system will most likely work via mobile phone or internet and can be compared by the booking of an internet airline. Multiple passengers can also order a row of seats or a separated compartment in the vehicle.

The system will not be a door-to-door system. This would take too much time in the beginning and the end of the journey. The typical journey would start with the collection of passengers on a limited number of stops. The number of stops will have to be limited in order not to loose too much time in this part of the trip. After the passengers have been collected the vehicle will not stop anymore until the vicinity of the point of destination is reached. In this way the most benefit will be made form the high speed. At the end of the journey the Superbus will hold again at a limited number of points. The typical journey can be sketched as follows:

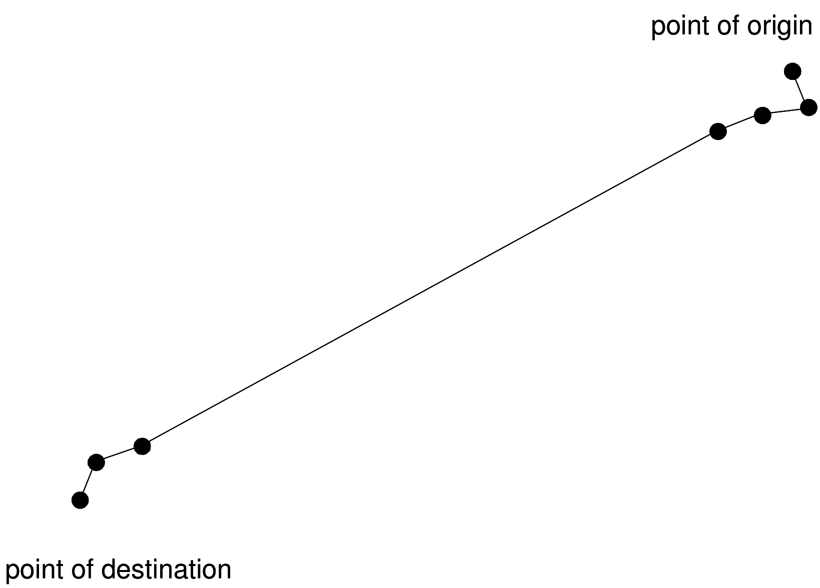


*Fig. 24. Lay-out of a typical journey*

## Safety

Safety is of prime importance in public transport. Therefore safety is an important issue in the design of both the Superbus vehicle and the Superbus transport system. Safety related to the vehicle has two aspects. The first aspect is the driver and the second aspect is the vehicle itself. It is chosen to make use of a human driver. He or she will be in full control of the vehicle. In inner cities and on highways he will drive the vehicle himself. On highways he will be supported by a number of advanced driver support systems. On the Super tracks the vehicle will be controlled electronically and the driver will have a supervisory role like the captain of an aircraft flown with the use of an automatic pilot.

In principal the vehicle could be controlled electronically in all speed regimes but experience has shown that this is not always the best way. The reason for this is that traffic in inner cities can be rather unpredictable because of crossing children and animals. Next to that the driver also plays a role in the so-called social control. He or she will supervise the vehicle and make sure no vandalism takes place. Finally the issue of liability makes it more convenient to have a human driver controlling the vehicle instead of an electronic system.

The vehicle itself will be supported by a number of advanced driver support systems. Research has shown that the safety increases significantly when the driver is supported by electronic support devices. Devices like these are under consideration at the moment. These systems will be radar supported.

If demand is high enough, vehicles can safely operate at high frequencies of up to 7 seconds. On normal highways a safe interval between manually controlled cars is believed to be 2 seconds. When the Superbus drives at 250 km/h an interval time of 7 seconds results in an interval distance of approximately 350 m. This more than sufficient to perform an emergency stop when needed since the Superbus drives on rubber tires. The friction between the road surface and a rubber tire is significantly higher than between a rail and an iron wheel of a train.

## TU Delft project

The Superbus project is a joint project of multiple faculties within the Delft University of Technology in the Netherlands, including Aerospace Engineering, Industrial Design Engineering, Electrical Engineering, Mechanical Engineering and Civil Engineering. The project is funded by the Dutch government, the bus company Connexxion and many other sponsors.. The aim of the project team is to have a fully functioning demonstration vehicle ready in due course of 2008.

## 6. Design challenges encountered

All the four design projects described have several design challenges in common. The one that poses the most problems is the fact that they all start from an original and in essence fairly simple idea and eventually have to reach a state of maturity where full scale demonstration becomes possible. For the projects Ladder mill, Nuna and Superbus it will be discussed how these design challenges are being handled. The project on kite propelled ships is still in the early design phase and will not be discussed further. For the Ladder mill the first mile stone is the practical demonstration of the concept. This proved to require a lot of trial-and-error work. For the Nuna the winning of the World Solar Challenge was the biggest challenge. For the Superbus the ability to show the working of the concept to the outside world within a reasonable amount of time but without getting into unfair competition with other parties in this outside world proves to be the major challenge.

### Ladder mill

The basic idea of the Ladder mill is very simple. Just combine the essential characteristics of a kite and a towed glider in a combined motion and link the cable to a generator. The technology of a kite is fairly old. The Chinese have been flying kite for thousands of years. The technology of a towed glider is at least 100 years old and the technology of an electric generator as well. The main problems encountered so far were in the control of the combination. Controlling kites is an area that is (almost) non-existent in literature. Available literature shows the theoretical basis but practical solutions have not been found in literature. This resulted in a search for possible practical solutions in combination with the existing theoretical basis. Since kites in general are very flexible structures the larger kites are controlled by many wires. The minimum amount of wires use for control of surf kites is four. The control motion of these wires is rather large. This would lead to premature conclusion that the best way to control the kites in the Ladder mill is to use at least four winches, each controlling a separate control wire.

However this conflicts with the idea of having only one wire going to the generator. The way in which this problem was solved was to look more into the fundamentals of the control system of the four wires. In essence they control the leading and trailing edge of the sides of the kite. These sides are normally made of flexible textile. The solution found for the problem so far was to make these sides rigid and having a small cart moving along this side. The position of the cart gives a specific combination of a tensile force on the leading and trailing edge of the side. The most forward position would lead to a tensile force on the leading edge only and no force at all on the trailing edge and vice versa. Positions in between give other combinations.

The next step in the design process was to really build and test this set-up. In the description of the Ladder mill this has been discussed. Here a new design problem was encountered. The problem of making the design in real, making it such that is weighs as little as possible, making it such that it is reliable and finally making it controllable via remote means. This was approached via a series of trial-and-error steps. First designs failed structurally or got damaged. Later designs were made more robust. Control was first achieved by use of standard remote control equipment for radio controlled airplanes. Later this was miniaturized using the development of dedicated printed circuit boards designed for computerized remote control.

Similar steps were taken in the development of the ground station. Again the basic idea is simple but the realization took quite some time. The first ground station was built on a simple trailer. It was chosen to make it movable in order to be able to transport it to any location in the country for testing and demonstration. A later development shows a ground station built onto a small truck. Future development will show the use of a larger truck and eventually a fixed base ground station.

**Nuna**

The basis idea of the Nuna solar cars is fairly simple as well. Make a vehicle that has solar cells on top and connect them to an electric motor to propel the vehicle. Again the essential technologies needed are not new. The design challenge in this design project is to make the vehicle as fast as possible. This requires an extensive search for the best technology and moreover the combination of them leading to the best performance. In this project the approach taken was to first make a thorough analysis on what would be the factors that would contribute to victory. The majority of them proved to be technical but some of them proved to be non-technical. Examples of them were the composition of the team and the funding available.

Technical aspects were for instance a low vehicle weight, low aerodynamic drag and high efficiency of the solar cells and the engine. They were all treated in combination in order to see interdependency effects. For instance one could decide to buy solar cells with a very high efficiency but thereby spending the whole budget available. Or one could decide use a higher efficiency engine but thereby increasing the vehicle weigh too much. For every major decision these so-called winning factors were used and the decision taken was based on the integrated analysis of them.

### Superbus

The basic idea of the Superbus concept is fairly simple as well. Make a road driven vehicle that is fast and sustainable, let it drive on simple light weight infrastructure and use a demand driven logistic system that is highly ICT supported. Again all basic technologies are available. The design challenge is to combine them in one transport concept and show this to the outside world which is rather skeptical and anxiously waiting for results.

The design approach taken in the Superbus project is to use the concept of a demonstration vehicle supported with a limited amount of additional research on the other aspects of the transport concept. The demonstration vehicle is definitely not a prototype. It will show the basis elements of the concept and makes it possible for everyone to "touch and feel" it. It will not be made such that it can move into series production but it will merely serve as a test bed.

This approach fits with the role a university has to play in society. A (technical) university is funded by society to create new inventions and show what is (technically) possible. It is not the role of university to produce things on a large scale and implement them in society. That role is the role of the general public, the politics and the commercial companies. Developing a test bed is therefore the ideal way for a university to play its role in a clear an fair way. In this way it will never end up in unfair competition with commercial companies. One thing that has to be watched closely in this process is that university does not give away its inventions too soon and too cheap. Using a (semi)commercial outlet of start-up companies might be the right way to protect the interests of universities.

## Conclusion

In all projects described the commonality is that based on a fairly simple idea it has to come to detailed full scale hardware. This involves a lot of trial and error in case of new things like the Ladder mill. In case of the drive to win a contest an thorough analysis of the winning factors like in the case of the Nuna solar cars can help. In case of larger projects like the Superbus it is very important to have university play its role in a clear and fair way. In this case the development of a demonstrator/test bed is the approach taken. For new project experience gained in these projects will of course be used.

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# Innovation-Focused Ship Design
## Developments and options from a European perspective

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**Abstract**

The European shipbuilding industry has been able to survive by focusing on building 'specials'. In order to maintain this position, it is an absolute necessity for the European shipbuilding industry to remain innovative. However, it is difficult to realise product innovations in this industry. The series are usually too small, the development time too short and the risks too high. This article will discuss several developments and some measures that should be taken in order to stimulate the realisation of product innovations.

Keywords: Ship Design, innovation, systems of systems, partnerships, goal-based regulation.

## 1. Introduction

At present the shipbuilding industry is flourishing. In spite of the strong position of countries in the Far East, to date European shipbuilding has been able to hold its own. As regards the total volume of ships built per year, in the last few years the European shipbuilding industry, united in the Community of European Shipyards Association (CESA), has been far outstripped by South Korea and Japan; but in terms of the financial value of the ships supplied Europe can still compete with its rivals in the Far East and until 2005 was even number one [1].

This is mainly because European shipbuilding has specialised in building 'specials' – complex ships which are custom designed and in which advanced and often new technology is used. These are ships such as dredgers, yachts, cable ships, patrol ships and cruise ships, for which there is little question of mass production. In contrast, shipbuilding in the Far East is mainly focused on building large to very large transport ships such as bulk carriers, oil tankers and container ships, usually of standard types. These ships vary in construction price, depending on the size, from EUR 25 to 100 million whereas the construction price of European 'specials' of comparable size is EUR 50 to 300 million.

However, the shipbuilding industry in the Far East is rapidly catching up as regards technology. The present European position can only be maintained and strengthened by ongoing innovation. Europe owes its present position mainly to its superior knowledge, embedded in a close network of shipyards, suppliers and knowledge centres. In countries outside Europe there is scarcely any network of this kind [2]. Unlike in the car and aircraft industries, prototypes can rarely be used in shipbuilding; the series are too small and the risks too high. Innovation is therefore not a simple matter in shipbuilding, especially in the case of custom-built ships.

*Figure 1a: Standard transport ship*

*Figure 1b: European 'special'*

## 2. Process innovation versus Product Innovation

Only a limited number of product innovations are implemented in shipbuilding because the financial consequences of these innovations would have to be calculated at the initial stage in order to allow for them accurately enough in the quote. In many cases there is not enough time for this. Ships are usually ordered on the basis of conceptual designs which have been created within a few weeks. In shipbuilding the prototype and the end product are frequently identical and there is little scope for introducing radical product innovations. As a rule the margins in shipbuilding are narrow and the risks associated with innovations therefore tend to be too high. Any innovations there are in ship design are more likely to be evolutionary than revolutionary in nature.

It is therefore not surprising that in shipbuilding attention is paid mainly to improving the engineering and production processes. In the past these processes were very labour intensive and often of a repetitive character. As a result, investing in improving and automating these processes yielded quicker results for shipyards. The European shipyards which still exist owe their survival mainly to the way they have rationalised and structured their engineering and production processes. The relatively high hourly pay in Europe in comparison with countries such South Korea and China is in fact largely compensated by using fewer workers and smarter production methods.

However, by specialising in certain types of ships, a shipyard can also increase the repetitive character in the development of the product. By using product experience gained from previous ships it is possible to realise product innovations which can yield quicker results. The fact that this formula can be successful is shown by the number of shipyards in Europe which have acquired a leading position in the market or even become market leaders.

*Figure 2: European 'specials'*

## 3. 'Systems of Systems' approach

The role of supply companies in shipbuilding is becoming increasingly important. In the past knowledge of both ship design and the design of systems to be placed on board was to a large extent available at the shipyard. The materials, components and sub-systems needed to build the ship were then ordered from the appropriate suppliers (see Figure 3a).

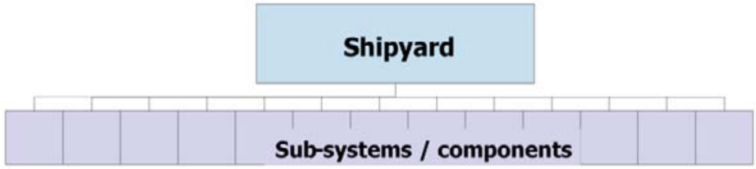


*Fig. 3a. Shipyard buying sub-systems & components (old situation)*

During recent years there has been a clear trend in shipbuilding towards shipyards hiving off more and more areas of knowledge to supply companies. This is a logical consequence of the fact that the knowledge needed to design and build complex, innovative ships has become more and more varied, so that the number of areas of specialist knowledge involved in these processes has grown rapidly in recent years. Many companies with specialist knowledge they do not need directly for their own core activities have placed this knowledge outside the company because it is more efficient to concentrate this capacity in new specialised companies.

On the other hand there is also a trend whereby system-related companies are entering into new forms of collaboration in order to gain a stronger market position together. In this way a large number of groups of companies have emerged which are able to take on the responsibility of supplying complete ship systems (See Figure 3b).

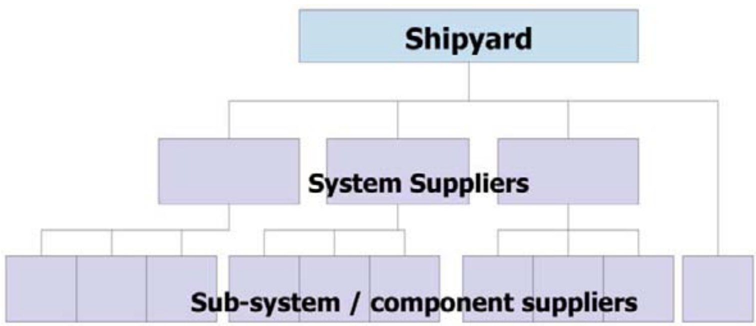


*Fig. 3b. Shipyard buying systems & components (present situation)*

Examples of this are companies such as Wärtsilä and Rolls Royce which are now able to supply complete propulsion and manoeuvring systems to the shipyard as a turn-key system. As a result, not only the scope of delivery, which was previously limited to supplying only diesel engines or gas turbines, has risen considerably, but also the responsibility. By taking on the responsibility of supplying the intake and exhaust systems, propellers, rudders and the integrated operating and monitoring systems as well, these companies also make themselves responsible for the integration of these sub-systems into the whole system. The main systems such as the integrated generation and distribution of electrical energy on board ships, accommodation and the concomitant 'hotel systems' are now often delivered by one supplier.

This system-bound grouping of companies enables the companies to combine their developmental capacities and to harmonise and standardise their products beforehand, thus reducing integration risks. Because they also take over part of the integration and project management tasks from the shipyards, these groups have the strength and power to be attractive, innovative and robust partners. Not surprisingly, it is becoming more and more common for groups like this to initiate developments of their own towards new, integrated solutions for application on board ships (see Figure 4).

This means that as regards developments and innovations in the area of materials, components and sub-systems the shipyards have become more and more dependent on supply companies. On the other hand it also means that shipyards can focus more on the important role of ship integrator and on the project and process management that goes with it.

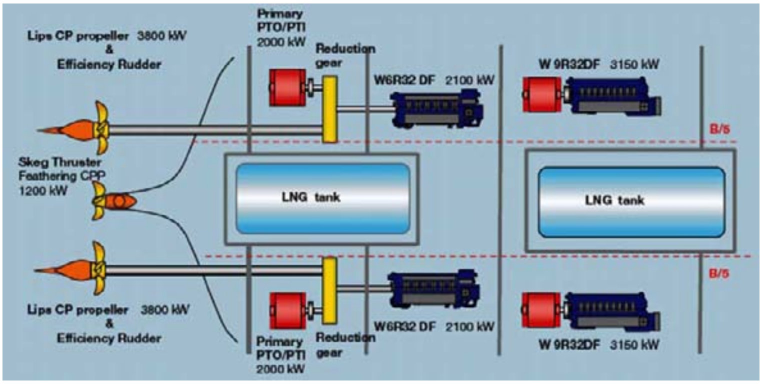


*Fig. 4. Design study by Wärtsilä Corporation [3] for an LNG propulsion plant for application on board a cruise ferry.*

Another important development is that to an increasing extent shipyards are focusing on the customer. Because the shipyards are becoming more and more dependent on supply companies for new technology their own product innovation will be driven mainly by clever combination and integration of new technologies. Knowledge of operational processes is of crucial importance in creating better designs. Regarding ships as part of an overarching process or system (systems or systems approach) broadens the scope for finding innovative solutions and reduces the chance of sub-optimisation. This approach also makes it easier to design on the basis of life-cycle approximations.

In the case of transport ships, first considering the entire logistic transport chain opens up a creative scope which facilitates the generation of more effective solutions. Recent examples of this – though developed in the framework of a European project – are the IPSI concept [4] and the recently launched Project CREATE3S.  In both cases the innovation has to do with improving the competitive position of European short sea shipping by reducing the conventional loading and unloading times of 8 to 12 hours or longer entailed in loading and unloading container ships with cranes to less than 2 hours.

The key element in CREATE3S is to be able to develop a cargo-carrying platform that can be loaded onto or unloaded from the ship in one move. This approach will also improve the possibilities of gearing the vessels to specific trades and help to develop a standard hydrodynamic platform that can be optimised for industrial mass production.

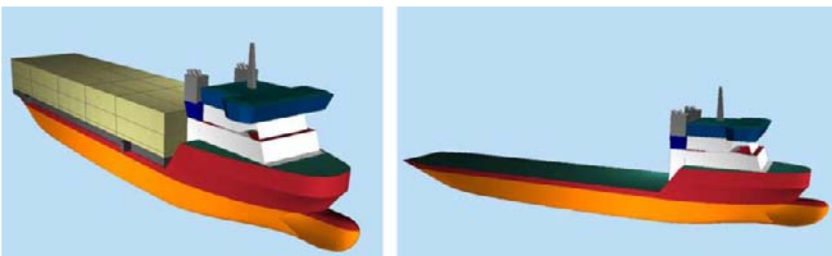

*Fig. 5. Conceptual impression of a solution for a new shipping concept based on large cargo modules to be loaded / unloaded in one move.*

## 4. Partnerships

Nowadays the only way to realise complex projects is to set up collaborative groups which enter into agreements on the basis of equality and shared responsibility. In this way risks are reduced to an acceptable level for all parties involved and the foundation is laid to work in a joint win-win situation.

It is therefore interesting to observe that larger-scale innovations in shipbuilding have nearly all come about through close collaboration between shipowners and shipyards, often supplemented by contributions from supply companies and knowledge centres. The risks entailed in developing new products may be high; but the same is true of interdependence with respect to knowledge. 'Launch customers' are essential if innovations are to be applied successfully.

It is not surprising that collaborative ventures and partnerships are common in the development of naval ships and ships for offshore operations. What these ships have in common is that their designs, unlike those of transport ships, are strongly dominated by systems which must be placed on board in combination with the operational management needed for them.

What collaboration between industry and a knowledge centre can lead to is best illustrated by the success of the 'enlarged ship concept' (see Figure 6) and the 'axe bow' which was a further development of this concept [5].

*Fig. 6. Enlarged Ship concept (left) and Axe Bow (right) (by Damen Shipyards)*

## 5. Construction standards

The International Maritime Organisation (IMO) is responsible for the development of safety standards for constructing and operating ships. The enforcement of these standards, however, is the responsibility of the national authorities. The standards are usually formulated as prescriptive regulations which are often a distillation of past experience and as such tend to become less and less relevant over time. They are also often unable to cope with a wide range of design solutions and, at worst, may create unnecessary dangers. At the time they were written prescriptive regulations encoded best engineering practices, but with evolving technologies they may rapidly become inadequate. In fact, it is quite probable that in the long run prescriptive regulations prevent industry from adopting current best practices or – even worse – safer solutions.

To discharge their legal responsibilities designers applying such regulations are only required to carry out the mandated actions. If these actions prove to be insufficient to prevent a subsequent accident, at present it is the regulations and those that set them that are seen to be deficient, not the designer applying them, even though in law it is actually the designer's responsibility.

In May 2004 it was agreed that an IMO Maritime Safety Committee (MSC) should start to develop a so-called 'goal-based' approach. Goal-based regulation does not specify the means of achieving compliance but sets goals that allow alternative ways of achieving compliance. Such an approach gives greater freedom in developing technical solutions and accommodating different standards under the assumption that it is the innovator who is best placed to ensure the safety of their design, not the regulator. This development will make designers more aware of the risks they introduce in their designs as a result of decisions made during the design process. More important, however, is that the use of goal-based standards not only supports innovation but should also result in safer solutions.

For defining criteria the MSC is considering the use of a probabilistic risk-based methodology based on the ALARP (As Low As Reasonably Practicable) principle. This methodology divides risks into three categories: unacceptable, tolerable and negligible (or broadly acceptable). For the tolerable risk category the ALARP principle is to compare the cost of further risk reduction with the costs which would be incurred in the event of an accident. This means that when the cost per life saved by a further risk reduction within the tolerable region exceeds the assigned value, the implementation of this extra reduction measure will not be required. An example of an ALARP diagram is given in Figure 7.

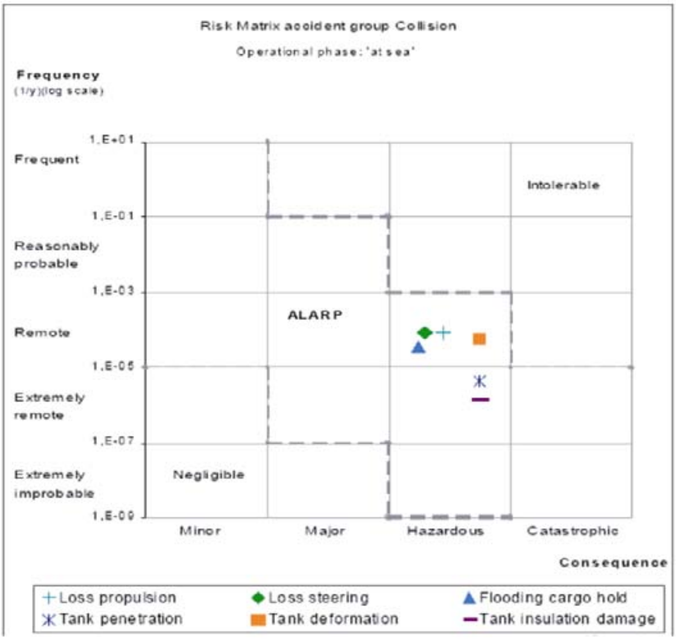


*Fig. 7. Example of an LPG carrier's risk matrix for collisions at sea*

Although some first steps have been taken such as agreement as to basic principles and goals, there is still a long way to go in order to arrive at consensus on goal-based standards for new ship construction.

Another development related to standards is the need for safer and more environmentally friendly ships. New legislation is coming into force that will stimulate investment in better and safer ships. This need for so-called 'quality shipping' will also entail the development of new technologies and innovations.

## 6. Process for the creation of systems

The designing process in shipbuilding is a creative and complex process and is an important part of the whole production process (see Figure 8).

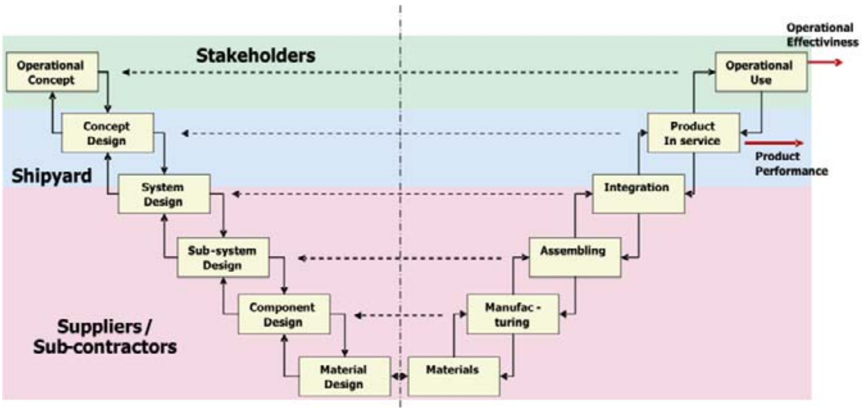


*Fig. 8. Generic model for the creation of systems*

Contracts for the construction of new ships are usually entered into on the basis of conceptual designs which have been developed within a very short space of time, in most cases a few weeks. As Figure 8 shows, after the conceptual design has been completed there are many further stages before the physical product can actually be tested with regard to its required performance. However, risks can be minimised for instance by using familiar and proved production methods, components and subsystems. In addition, calculation models are often used to predict the performance of the product as accurately as possible in advance.

In Figure 9 the 'left part' of the production process as shown in Figure 8 is shown in more detail and two parallel development paths are distinguished:

- the development of the operational architecture (the requirement package), and
- the development of the physical architecture (the solution).

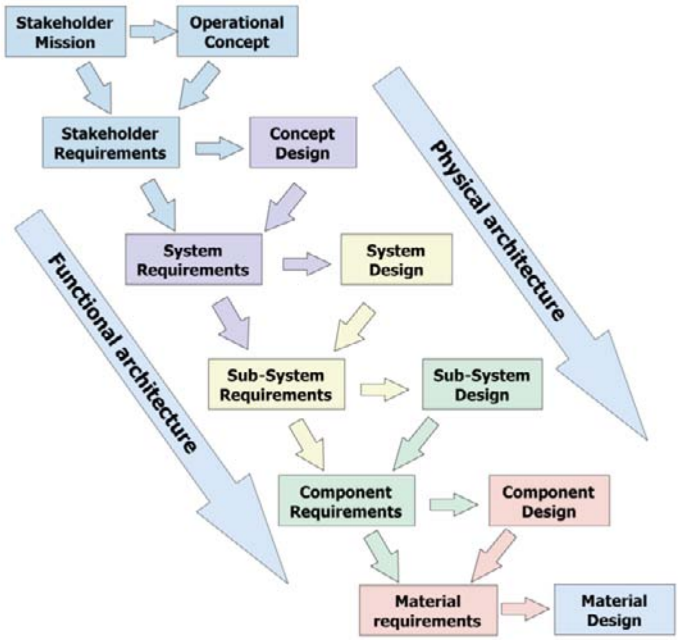


*Fig. 9. Generic design process based on a 'systems of systems' approach*

Figure 9 also shows the processes which take place before the conceptual design is generated. These processes entail the design of the best operational concept on the basis of which the requirements can then be drawn up for the ship needed. The importance of this stage is being recognised to an increasing extent, since it is not only important for the ship to achieve the desired performance but also for the ship to realise or support its user's operational objectives in this performance.

In most cases not all steps of the process have to be traversed for every aspect of a new ship design. If optimal use is made of standard requirements (SOLAS, classification bureaus etc.) and suitable off-the-shelf solutions for the materials, components, sub-systems etc., the process can be very much simplified. The innovative part of the design process is usually focused on generating concept and system designs and on the quality and safety standards which must be met.

However, if new technology is going to be introduced in the ship design, the design will have to be worked out at a corresponding level of detail. To be able to take this information into account in preparing a quote requires greater detail in the design in the pre-contract phase. However, modern software in combination with increasingly powerful computers now make it possible to include more and more design details and variations in the initial plan.

## 7. Computer tools

In the design process analysis or simulation tools are often used to show how the design's performance measures up to the requirements. In the initial phase analysis tools are usually based on regression analyses of previously constructed designs. This means that these tools lose their validity as the information on which the analysis is based ages or if the new design is too different. As a rule these tools are not suitable for analysing product innovations.

However, with the help of analysis tools based on 'first principles' it is now becoming easier to analyse the feasibility and consequences of new, different solutions for both the product and the process. For example, it is now possible to determine a ship's resistance on the basis of a 'first principles' tool (see Figure 10).

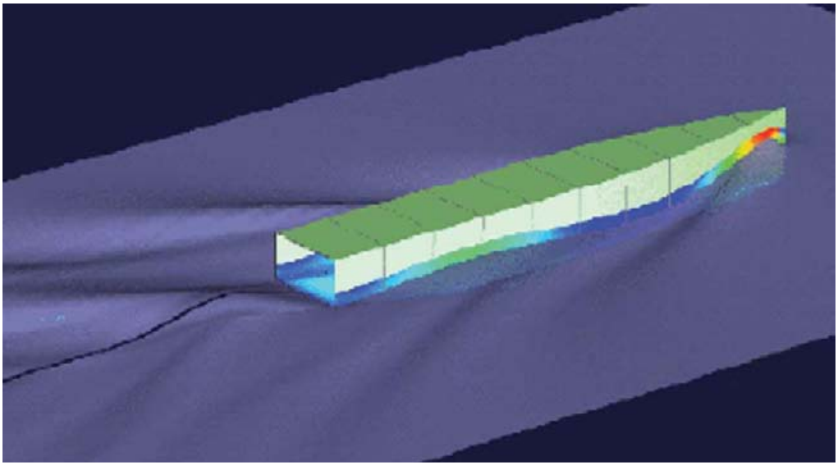

*Fig. 10. Result of a CFD-calculation for a new ship design (RAPID–MARIN)*

First principle tools usually require a more detailed description of the design and in the conceptual phase this information is not always available or there is not enough time to generate it. This has often led to opportunities for innovation being lost. However, new CAD tools and more powerful computers are now making it easier and easier to obtain more detailed design information in the initial phase of the design, to generate several alternatives and therefore to arrive at better designs.

An example of a recent CAD tool still under development at Delft University of Technology [6] is a genetic optimisation algorithm for space allocation in the conceptual design phase of naval ships. Some preliminary 2-D results of this tool are shown in Figure 11.

Another possibility is to make a division at the various levels of detail in the design between the topological description and the geometric description, as shown in Figure 9. The topological description refers to the structure of the design while the geometric description defines the dimensions that go with it. In principle the structure is determined by the designer and this work is creative in nature; the optimal dimensions to go with the particular structure are calculated by the computer.

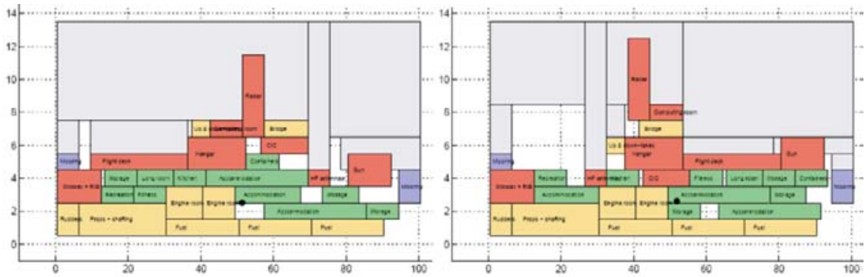

*Fig. 11. Computer-generated arrangements for an Offshore Patrol Vessel using a genetic optimisation algorithm.*

This approach enables designers to make alterations in the dimensions even at quite a late stage of the design process with minimal consequences for the completion time of that process. This makes it easier to apply concurrent engineering. It is also possible to copy the detailed topology of detail solutions used in previous designs in the description of the new design. In this way the details of a design can be realised more quickly.

## 9. Systems Engineering

The increasing complexity of man-made systems has led to new opportunities, but also to growing challenges for the organisations that create and utilise these systems. There is therefore a need for a common framework to improve communication and cooperation among parties which create, utilise and manage modern systems so that they can work in an integrated, coherent fashion.

An example of such a framework is Systems Engineering, a common process framework which covers the whole life-cycle of man-made systems. Several standards [7] have been developed based on the process framework as shown in figure 12. This representation of the process framework is also known as the V diagram and has some features in common with the diagrams shown in Figures 8 and 9.


*Fig. 12. The Systems Engineering process framework*

At present very little use is made of Systems Engineering in shipbuilding. One approach might be to limit its introduction to just a few processes.

## 10. Conclusion

Europe owes its present market position largely to its superior knowledge, embedded in a close network of shipyards, suppliers and knowledge centres. The present European position can only be maintained and strengthened by ongoing innovation.

Innovations which lead to more effective and more efficient engineering and production processes can yield results more quickly because of their repetitive character. It is not so easy to realise product innovations in the European shipbuilding industry, because the series are too small, the development times too short and the risks too high.

Nevertheless, there are certain developments which may stimulate product innovations in European shipbuilding or certain measures may be taken to that end. The following measures and developments may play an important role:

- specialisation in certain types of ships
- forming collaborative groups or partnerships with supply companies and knowledge centres
- focusing more on the customer's processes
- the development of goal-based standards
- the promotion of safer and more environmentally friendly ships
- the development of first principles analysis tools and new design methods.

Provided it is applied selectively, an additional option is Systems Engineering, which is specifically intended for the realisation of complex systems of a multidisciplinary character.

Finally, of course other, more political factors also play a role in strengthening the position of European shipbuilding. For example, an important precondition if shipbuilding is to remain attractive to entrepreneurs is the creation of a level playing field.

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# Integrated Design
# Integrated Design in Architecture - and what comes next?

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**Abstract**

This article describes the basic demands on architectural design such as function, aesthetic and technology with a focus on how to integrate the different disciples in the design process. One solution is the "integrated design" where the design team develops the design in collaboration and comes to mutual conclusions. This method is described on the basis of two projects where the author was responsible for the design and the planning process. Lastly this paper discusses a vision for future developments of the design process with a focus on value orientated results.

## 1. Introduction

A personal statement to start with: my interest in architecture derives from its combination of aesthetic form, functional aspect and technical solution: the task at hand is always to design a building within an architectural content, with a specific organization and function, at expected costs and for certain technical demands. Here we have to make decisions for or against formal aspects and technical solutions. Sometimes the technological method provides the starting point for a design idea, which ends in a formal discussion about positioning and relations of structural and enveloping components. In other situations the formal idea leads to constructional solutions for the structure – like skeleton or massive constructions depending on the expected appearance. Finally the functionality and its organization within the building will control the design.

These aspects make designing architecture a challenge – the engineer in the architect sees right or wrong and wants to come to a technically correct solution; the artist within however searches for the final and perfect combination of elements and formats. In the end the entire unit has to work as an organism, in which people can live or work and last, but not least, feel comfortable. This leads to the point that different architects come to different solutions for the same project – and the tradition of project competitions is therefore very exiting: to find the best possible solution for a given situation, reflecting all above mentioned aspects by different architects and design teams with their various starting points and influences.

In addition to the personal and historically positioned formal objectives, trends and fashions in architecture there are some basic developments worth mentioning: architects are well trained in integrating new technology in their design work. New materials and technical solutions are always welcome – even if the building has to be built as a 1:1 model in order to prove the theory.

Secondly, today's buildings' energy demands have led to the development of energy standards – in principle a well intended and needed request. However, the issue lies in improving promised results and the interaction with the user – not everyone needs a formula 1 car for traveling. The question in this case is how to fulfill energy saving demands in an understandable, practical and technically sensible manner.

Finally the line of communication between client, user and planner is an aspect of interest. The traditional process of creating architecture was orientated on a limited amount of technical solutions and required only the collaboration of a small group of consultants. Current architectural design requires comprehensive integration of all technical and functional demands reflecting the formal aspects starting right in the planning process. The architect is therefore trained to communicate with consultants such as structural engineers, climate designers, building physicians, facade planners, cost consultants, logistic and facility management planners – just to mention a few of the disciplines involved. Considering the growing number of new technologies available in the industry and increasing overall demands the architect is challenged to keep on top of this knowledge, isolate sensible solutions and integrate them in the design concept. In the subsequent design process the concept needs to be developed from the initial planning draft into an executable building. The last step of the design process is the control of the building process itself: here the architect and the design team have to guide the construction on site and find solutions for issues not previously defined and any problems occurring during the actual execution. This process of so called "integrated design" requires a technical and formal education as well as the capability of abstraction and reflection, overview, interest in detail solution and communication.

In terms of the appearance of a building; the described planning process includes the development of a basic aesthetic idea with general suggestions for technical solutions, which the architect then gives to the general contractor. The planning process is concluded by the contractor deciding on the final structure, construction and quality of materials – a process, which might provide a cheaper building but can not guarantee the best solution – the differences in objectives between the client and the contractor are just too big. As an alternative the architect could accept more responsibility by acting as the general planner in the process. This would mean to include all the other planning disciplines into his contractual responsibilities. The architecture would therefore have to integrate as well as control all aspects of the planning disciplines involved. Besides the risk for and the additional demands on the architect, the overall positive aspect would be that the control and decision making of the entire project would lie in the hands of the architect providing a better inclusion of his design concept. And the design of the process is also part of the design – virtual in terms of the relationship between the parties involved, and real in terms of the built result. Controlling the flow of money in a project means controlling the final result and its quality (1, 2, 3).

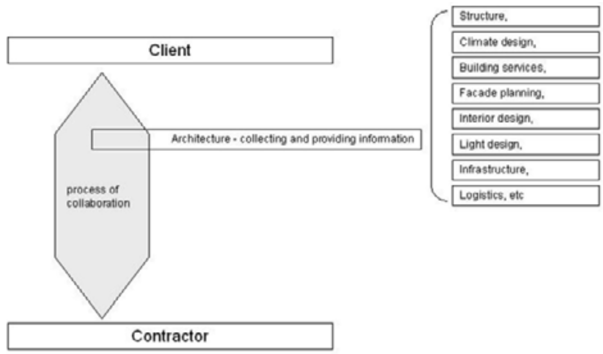


*Figure 1 – Classic design process: the main drivers of the process are the client and the contractor. Planning parties provide information and determine quality standards. The conflict is direct and predestined. Quality has to be controlled both by the client and the planning partners.*

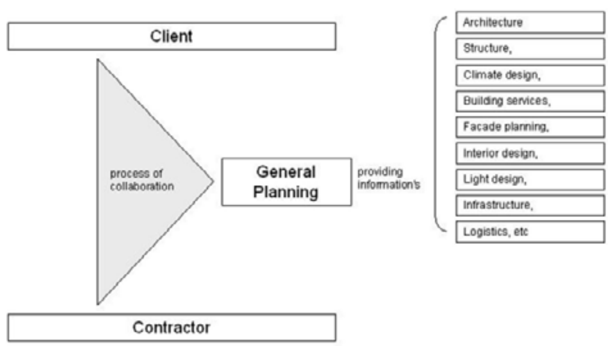


*Figure 2 – Design process with general planning: the main drivers of the system are the client, the contractor and the general planer, who combines the planning parties. This shift in the system gives the planning parties power to control parts of the process.*

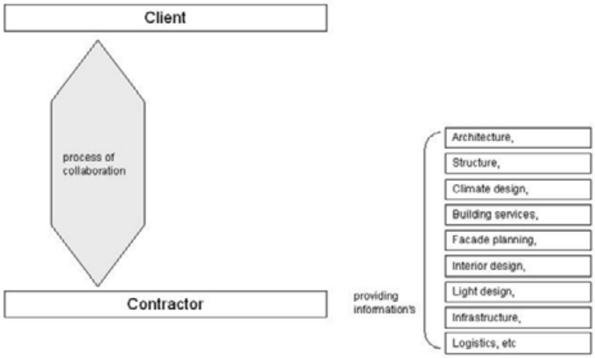


*Figure 3 – Design and building process: the main drivers are the client and the contractor, who uses the planning disciplines to provide information. Quality is controlled be the contractors. The conflicts in this scenario are also direct. Loss of quality control can result, depending on the positioning disadvantage of the process.*

## 2. Two Projects – Debitel / Stuttgart and König Arena / Krefeld

The following two examples are given to explain the possibilities of integrated design process and general planning under consideration of the building objective, the strategies for the planning process and the final architectural results. Both projects were executed with the architectural company RKW – Architektur und Städtebau / Düsseldorf where the author owned responsibility for a profit centre. Both projects were executed as "fast track projects" with an extremely limited time schedule.

*Figure 4 - Bird's eye view of the development Debitel headquarters*

**Debitel headquarters in Stuttgart**

For the German mobile phone company Debitel this 40,000 m² headquarters facility was developed on an existing business park location. The initial objective was to find a functional organization for a growing company providing easy communication and interactivity between the different departments. The design translation of these goals was a series of connecting elements between the office units. Secondly the company needed some manner of identification to express its position within the city and the market. To address this issue a part of the building was developed as a high-rise in the centre of the business park.

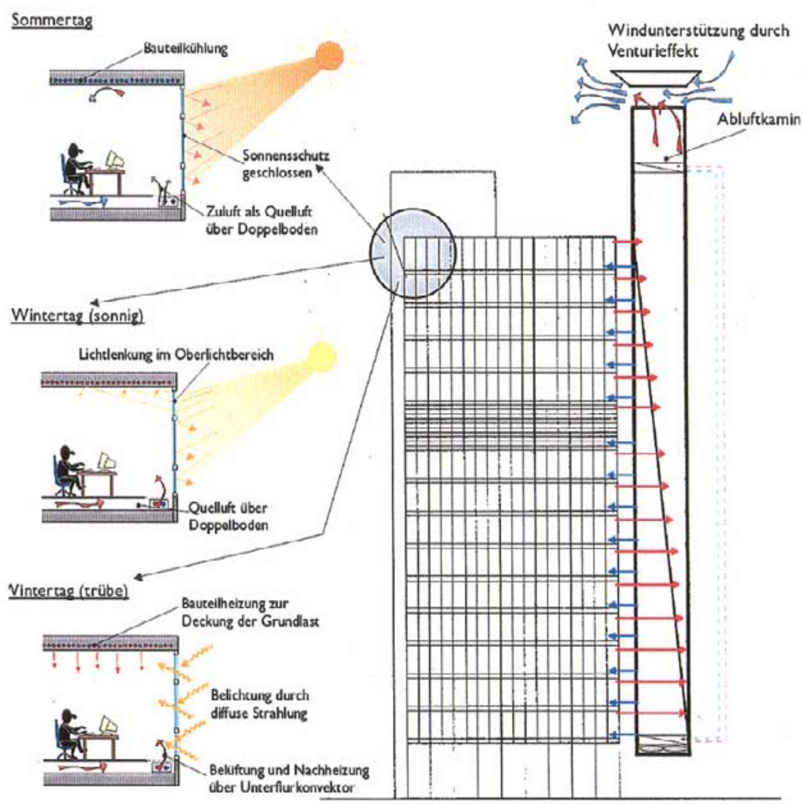


*Figure 5 – Concept of ventilation and facades in different climate situations for the high-rise part of the building complex debitel. (Picture by Transsolar / Stuttgart)*

By integrating disciplines such as climate designs and structural engineering right from the beginning of the project, the architects designed the project in an interdisciplinary team. One example of this interaction is the "solar chimney" in front of the high-rise part of the complex:

The architect wanted to include natural ventilation in the project. To address this request the climate designer developed a "solar chimney", described its function and suggested the position within the building. Following a team discussion he suggested its integration into the façade: By positioning the chimney on the outside of the building, not only do the pressure differences in the chimney generate air transport in the system; but the thermal impulse also implements pressure differences - a principle, which was not used for such purposes before. With the described pressure in the system, the solar chimney provides natural ventilation of the building by exhausting the offices spaces (4).

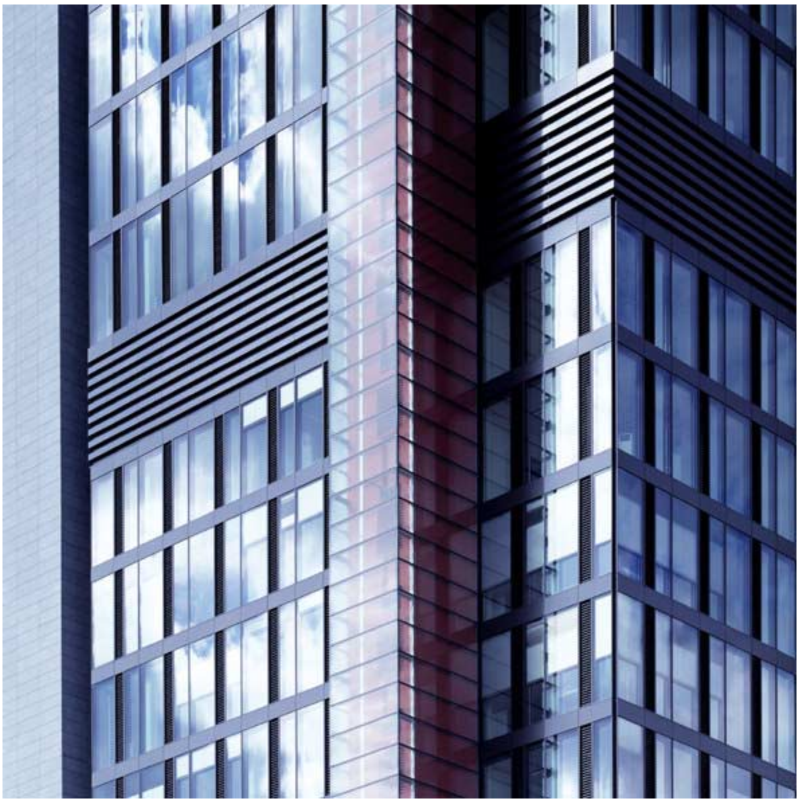

*Figure 6 – Solar chimney as part of the façade*

At this point the architect again got involved, worked on the aesthetic design of this new solution and developed the chimney into a formal object giving the geometric body of the high-rise building an aesthetic shape. The conclusion was to not only expose the chimney but also the stairs and elevators – with the result that the body of the high-rise was divided into segments. This changed the visual impression to emphasize the building's vertical orientation. The chimney was placed – in correct orientation to the sun – centered on the main entrance of the building. So in its technical function it acts as the driving force of the mechanical ventilation and in its form-giving function as an exclamation mark for the entrance and the building in its urban surroundings.

*Figure 7 – Main entrance and solar chimney of the high-rise part of the building complex debitel*

The design of the twin-face façade underwent a similar development. Current technology divides between four different principles of twin-face facades: boxed windows, adding a signal glazed window in front of an inner window; a second skin façade where the extra layer of glass covers the entire façade; corridor facades with a glazed corridor with vertical slots in front of the inner facade; and finally the integration of a story-spanning chimney in the façade cavity.

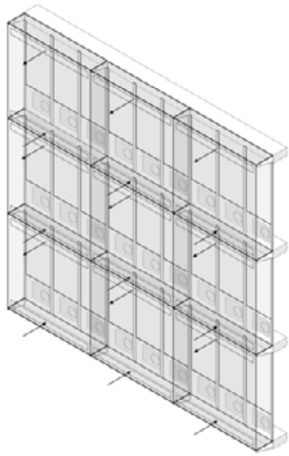

*Figure 8 – Boxed Window*

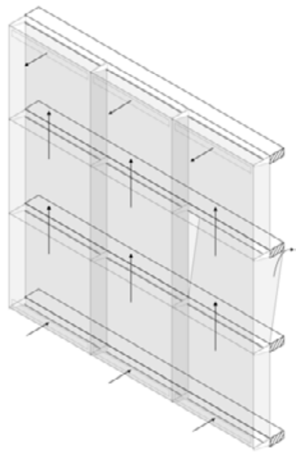

*Figure 9 - Second skin façade*

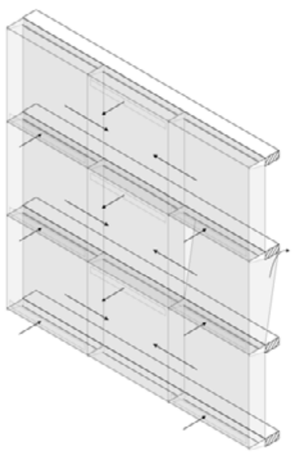

*Figure 10 – Corridor façade*

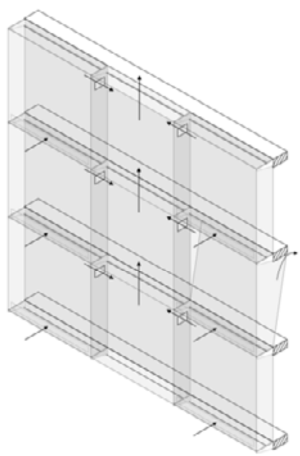

*Figure 11 – Chimney façade*

For the Debitel project the design team of architects and climate designers chose a combination of standard facades with fixed sun screens and boxed windows – a system, especially developed for this project and later used in various versions as a so called "hybrid façade". This system was developed to provide the user with the options of controlled natural ventilation and personal access to the outside air, if required. But at the same time, the advantages of twin-face facades were to be maintained: control for sun protection during high wind situations with an inner sunscreen and sound protection. This part of the design process was executed in the way previously described: combining ideas and knowledge within the team without distrust or one-sided control. The result provides the requirements for maximal protection of twin-face facades and combines them with the simplicity of single layered facades and the possibilities of individual control (5)

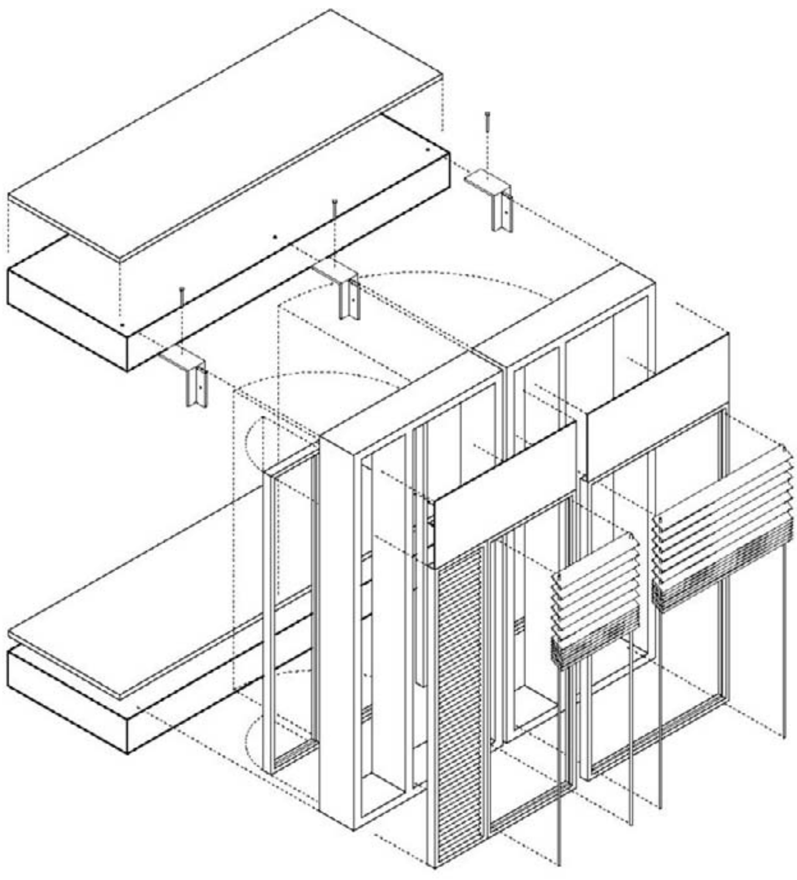

*Figure 12 –Principle of the hybrid façade*

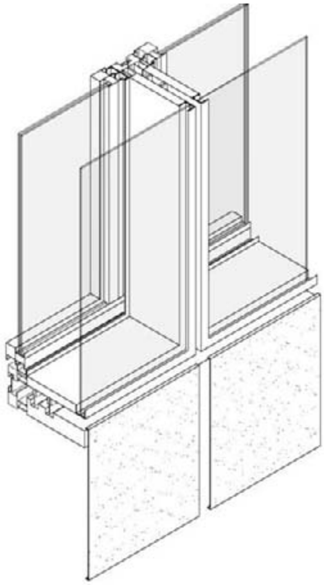

*Figure 13 – Detail solution of the hybrid façade: developed as an element façade, serpentine and prefabricated elements are suspended from the floor/ceiling slab.*

*Figure 14 – Final hybrid façade with twin faces façade parts with integrated movable sunscreen and individual operable windows behind the fixed sunscreens*

*Figure 15 – Construction side of the hybrid façade*

All this takes place right at the beginning of the project – when the client still needs to be convinced. This means that emotional/sensual aspects of the design will have to be positioned and explained; construction and its functionality to be improved upon and costs to be guaranteed. During this initial period of the project the design team might not yet be in its final configuration; additional members might be needed and others reappointed or exchanged. Such changes might influence the later design, impacting all other aspects. But it is also the time during which the quality of the team becomes apparent – can it handle the ideas, the technology and the appearance? And the cost?

My solution for this period of the project and for guaranteeing aesthetic quality for the remaining design and building process is to implement "general planning". General planning means that the architect as leader of the integral design team takes on the responsibilities for the entire team and transports the final design including all aspects. With this strategy he will guide the team members, control the solutions being presented and the money flow within the project. Especially this last aspect - money flow – is important: even though it seems counterproductive to the aesthetic design finding process, it is one of the most important topics to control architectural quality.

**König Arena Krefeld**

The second project to be described is the ice stadium in Krefeld. It is a stadium with standard use for ice hockey and the optional use as a stage, either centric or eccentric. About 8,000 seats and 20 VIP lounges with a business club are available. In the process the client was requiring an architectural design and a contractor proposal as an integrated solution – a "design and build" project. This means that besides the architect and the consultancies the contractor himself participates in the design process.

The final design's goal was to express the purpose of the stadium as a place for ice hockey as the main objective and concerts as a secondary use. The facade was therefore designed as a glass layer, with different lighting expressing the current use: blue for ice and amber for concerts. In addition the façade had to be kept within tight cost limits since competitors were developing without a façade and therefore entirely without façade related cost. You can imagine the discussions taking place due to inherent conflicts of interest within the design team willing to win the race.

*Figure 16 - Interior during construction process*

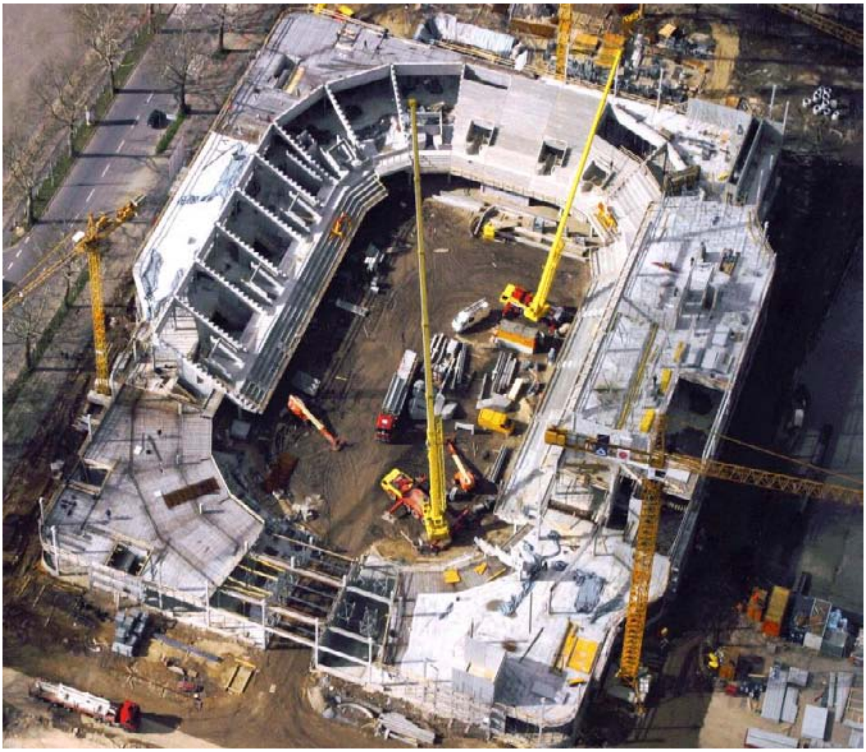

*Figure 17 Bird's eye view of the ice stadium / Krefeld during building process.*

An additional issue worth mentioning was the solution for the climate design. When developing office buildings we have to improve the quality of cooling and natural ventilation due to an already good insulation of our current facades. When designing housing we have to insure the quality of insulation and try to keep as much energy as possible within the building. The demands for a stadium are entirely different since this building type is being used only short periods at a time with a huge demand on ventilation during these periods. Consequently the ventilation system is the main instrument to control climate in the building and we need to focus on several mechanical ventilation units that condition the building simultaneously. For the architectural design this means building without massive structural constructions and without trying to integrate natural ventilation – obviously, this influences the design.

To conclude this part I would like to emphasize that designing and building architecture is always related to the personal relationships between the participants: the members of the design team have to accept and understand each other. And even though most members are educated to do so this requirement remains a critical point in the process, specifically when financial aspects are involved. Then the relationship with the contractor and builders has to improve since final decisions are made when these parties are involved, and the design idea is finally executed on site. And lastly the client has to be impressed by the building because he will be the one using the building and paying for it. The conclusion is that – in addition to an aesthetic, functional and technologically sound idea – the communication and working process such as "integrated design" is an important aspect of architectural quality.

*Figure 18 - 19 - Main façade of the ice stadium with the alternative illumination scenarios to generate branding for different uses – ice hockey games or concerts. The change of the colors of the lightning expresses the different uses: ice blue for hokey to amber for concerts.*

## 3. Value as an orientation and task for design process

Even when the described process is an "integrated design" it might not really integrate all possible aspects. The next question is how to develop future strategies for the design process. "Integrated design" focuses on the demands of the building and the user and tries to develop design solutions for both. We can divide this into two basic demand qualities: the direct need to improve minimal features of the building such as heating or natural daylight, and the indirect need. This would include enrichment of the building features by adding extras like cooling during summer time or a natural light system to control reflections etc.. The task for the integral design process is to find and improve upon such aspects and provide solutions in the design proposal.

*Figure 20 - Guggenheim Museum by Frank O. Gerry in Bilbao*

Now focusing on the next step of development within the design process we have to find solutions for unexpected demands. This could include the possibilities of a re-use of the building to increase its live span, or – even more interesting for the decision making process – potential added value that can be generated by the building. This can be achieved by focusing on the building's branding and possible interaction between the architectural object and its positioning within the city and the market. Projects like the Guggenheim Museum in Bilbao, a city in Northern Spain previously not well known throughout Europe, can explain this so-called "Bilbao effect": Architecture can be used as an instrument for positioning and can generate added value. But the added value that, for example, the Guggenheim Museum generates for the city of Bilbao, can not be directly aligned with the building costs – how should this be evaluated, even if it is measurable? For the design team the conclusion of this reflection is that this added value will have a positive influence on the project and therefore needs to be part of the considerations during the design process. Finally added value can be just as much a benefit for the client and the user; improved quality - even at higher cost - results in more than just the sum of all elements (6).

To extend on the above mentioned aspects and to develop ideas for the next steps it seems reasonable to ask what additional values will be expected in the future. Here begins the interesting part of the assumption: do we expect more comfort or more space? Will individualization and personalization be a future requirement or are we going to focus on the quality of space and design?

Besides the more marketing related aspects of "fashions and interests", the most important driving force for future building development will be energy: its accessibility, production and consumption. The reasons are obvious; but the important question is in how far the building structure and architectural design need to be geared to this development. Secondly, ecology will gain even bigger importance than it has today. Architecture already deals with climate as a design tool and an ecological and energetic concept for the design proposal is becoming a standard. But aspects such as the energy used to produce constructional materials or the disassembly possibilities of buildings need to be further investigated and implemented into the design process. Finally, efficiency will be another important topic for the planning process to give the design a livelong attractiveness - not only related to limitations of energy consumption or financial savings; but rather as a concept for efficient design solutions in terms of organization, synergies between functions and capacity for individuality .

But if we define the topics energy, ecology and efficiency as key items for demands of design, how can we apply values to them? Energy savings alone with better insulations or new and more efficient technical units can be called solutions for some demands. The added value could lie in the option of reusing buildings with different, not yet known functions: today a building's useful lifespan is considered to be a minimum of 20 years; but this could be extended to 100 years or more. Here we would add a value, which is not noticeable at present but guarantees a benefit for society and the client. Secondly, the reuse of existing buildings is a topic to consider:

60% of future building budgets are going to be used in the field of refurbishment and renovation, only the remaining 40% will be invested in new constructions. These numbers show that there is a need to focus on this topic and to find solutions for existing buildings as well as the redesign for current or even future expected uses (7)

Of course architects are always interested in new technologies – here they can find new topics to draw attention to their designs and new influences to give impulses for certain developments. At the same time the building industry is conservative in principle. The reasons are that on the one hand established methods of constructions exist that builders and users are used to and feel comfortable with. On the other hand the building itself has to stay and function for a certain period of time and is mostly an individual development – which means that the possibilities of serial production and copying are limited compared to other industrial products. Still, there is a trend in architecture of using new materials and the application for materials to be used in constructions. We can define two directions – a structural use, which requires knowledge and material improvement and its application in the building. This is an inherently slow process. The alternative option, which is well established and executed, is the use of newly developed materials for the interior – without any risks and only fire safety concerns – or for facades, where a certain risk of failure is acceptable due to their accessibility and the limited risk for the entire building.

Again, the approaches described above serve specific demands; and again we have the opportunity to find added value for the project and society to give an impulse. The difficulty is that we have to develop results for demands not even known yet or to define values from unexpected viewpoints and tasks. A fundamental solution to this problem requires a system, which will accept changing demands and can adapt to influences for alternative solutions. To cerate such a system we have to think in completely open structures and to try to develop elements and connections. The structure itself can only be a schematic of collaboration and linking, not a physical construction. Secondly, the elements have to be developed on an existing technology base to be integrated and usable right now. Finally, in order to create a solution that is adaptable for any future integration, the individual elements need to be connectable. It has to be an open system – we all know this technology from network systems or, for example WIKIPEDIA, where anybody can insert his information and the public has simultaneous access. The question is how this can be achieved for architecture.

## 4. Conclusion

Considering this approach the strategy for developing architectural design has to be an open minded collaboration between the involved parties – concept developers, planners, builders, users and clients – led by an architect who understands and respects the partners. This will be the only way to reach the goal of an emotionally impressive and technically sound object to be used for specific functions: the architectural building. The Netherlands can look back on a long tradition in this regard – architecture is respected as an important part of society and the number of internationally known and very well respected architects is enormous for such a small country. But at the same time fear exists that limited technological knowledge combined with a narrowed focus on only the aesthetic design aspects will guide architecture to be solely responsible for the creative emotional aspect and other disciplines for the actual realization. The result will be a situation as it is developing in Sweden, where the leading role in the design process was taken from architects and placed with the contractors – with the result of decreasing building quality. It is interesting to see that now, after 20 years of this development the clients – and not the architects - are asking for well integrated and technically oriented architects to be the person responsible in the process and are taking action in educational programs for this redevelopment – certainly not for social reasons but with an positive impulse for society in mind.

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# Offshore Structures: Hidden Treasures for Designers

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**Abstract**

Structures for the production of oil and gas placed in relatively shallow offshore waters are generally fixed structures which are piled to the seafloor. With increasing water depths these structures tend to become more sensitive to dynamic response and fatigue. When entering water depths exceeding approximately 300 meters these conventional fixed platforms are generally not capable to cope with the offshore environment and being replaced by floating platforms. As under certain functional design considerations bottom founded platforms may be preferred over floating platforms the industry developed the so called 'compliant tower': a bottom founded platform capable of carrying topside loads up to 30,000 t in water depths ranging from 300 meters to approximately 500 meters. This paper describes the basics of conventional bottom founded fixed platform design followed by the fascinating design and installation aspects of compliant towers and will conclude with the challenging statement that, contrary to the belief of many in the industry, under certain conditions conventional fixed bottom founded platforms may be feasible in water depths up 400m.

Key words Offshore, Oil – and gas production, Offshore Engineering, Fixed Platforms, Compliant Towers, Fixed deep water platforms, Fatigue.

## 1. Introduction

When the production of oil and gas moved offshore starting in the Gulf of Mexico the first platforms were designed for and installed in very shallow waters of a few meters. Gradually oil and gas fields were found and exploited in deeper waters resulting in more advanced designs of the platforms which were generally fixed to the seabed using driven hollow tubular piles. With increasing water depths the wave loading and resulting overturning moments on the platforms increased significantly leading the designers to focus on platform designs which, apart from the required strength and stability considerations, were specifically aimed at being as transparent as possible to reduce the wave excitation as much as possible. As a rule of thumb it can be assumed that of the total maximum horizontal design load on such a platform the contribution of the wind load is only approximately 15%, the remainder of the horizontal design load being caused by wave and current.

Moving to more hostile environments, like the North sea, not only caused the design criteria to become more severe, also the transportation and offshore installation of the composing parts of these offshore facilities became increasingly difficult whereas simultaneously the industry aimed at reducing the amount of man hours to be spent offshore. The latter clearly for safety, efficiency and planning reasons. That is why the accepted way of designing, fabricating, transporting and installation of these facilities is generally by using a small number of large and heavy components, as complete as possible, requiring a minimum amount of work offshore.

Generally the stiffness of the bottom founded Fixed Platforms in water depths up to approximately 150 meters is such that dynamic response and associated fatigue are not decisive for the platform substructure design. The supporting structures are generally designed for the extreme environmental condition, a combination of maximum wave, wind and current. Typical designs and the associated fabrication, transportation and installation aspects are being addressed in the first part of this paper.

Subsequently the problems associated with the moving of the bottom founded Fixed Platforms into deeper waters are being addressed and how the industry came up with a solution to cope with the dynamic response problem. The emergence of the so called "Compliant Tower", also bottom founded using steel piles. The design methodology will be highlighted and a recent application in a water depth of approximately 400 meters will be used to illustrate the resulting structural dimensions and method of installation.

The paper will be concluded by presenting the results of a study revealing that a conventional bottom founded Fixed Platform may after all be competitive for the same design conditions as used for the Compliant Tower as described.

## 2. Bottom founded Fixed Platforms in relatively shallow water

In a typical example of a bottom founded Fixed Platform (fig. 1) the three main elements are the topsides accommodating all the required functions of the platform, the supporting structure or jacket and the piled foundation.

The functions and size of the topsides are determined by the size and characteristics of the oil and / or gas reservoir which may be located up to a few kilometers below the sea bed. Generally the wells to produce the oil and gas are already being drilled during the period of designing and fabricating of the facilities that will be used for the eventual production.

*Fig. 1. Production facilities on a bottom founded fixed platform.*

The substructure, or jacket in the industry terminology, provides the necessary strength and stability for the platform to operate safely during its lifetime, generally ranging from 20 to 40 years.

It is obvious that certainly for increasing water depths the designer has a clear incentive to make the structure as transparent as possible to minimize the magnitude of the acting wave load and the resulting overturning moment (fig. 2).

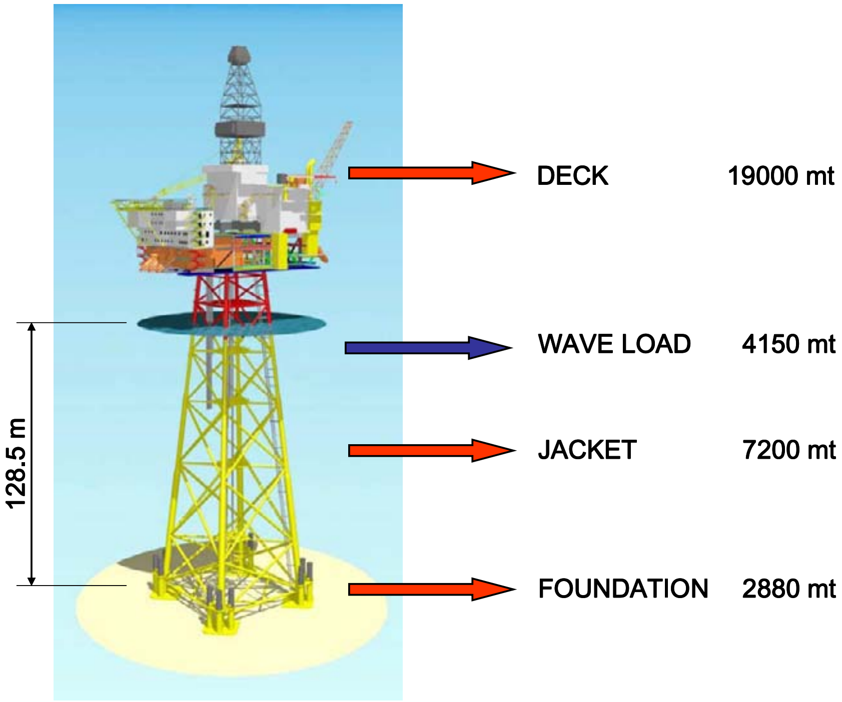


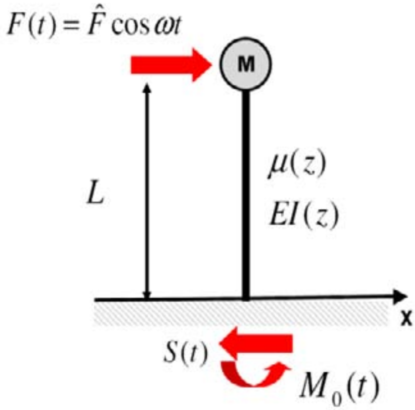

*Fig. 2. Main dimensions, masses and wave load for a typical bottom founded Platform.*

The shear is predominantly being transferred via the braces whereas the overturning moment is to a great extent determining the required dimensions of the jacket legs. To efficiently support the topside structure and to minimize wave loading which is most severe close to the water surface the aim is to minimize the width of the jacket at the top. Making the base of the jacket wider clearly will reduce the pile loads and the required pile size and or pile penetration.

The dimensions of the jacket components are determined by the permanent weight of the structure and very important the maximum design wave applicable in the area of application. For the structure as shown in fig 1, the maximum design wave amounted to approximately 36 meters, also determining the elevation of the bottom of the deck at a certain height above the still water level.

For initial design purposes the first natural period of the structure can easily be assessed by some simple modeling (fig. 3). For relatively shallow water platforms the first natural period is generally less than 3 seconds.

## Modeling of fixed structure as a one mass spring system




$$
\begin{aligned}
L &= 100 \quad m \\
M &= 20000 \quad ton \\
\mu &= 100 \quad ton/m \\
EI &= 30 \cdot 10^6 \quad MNm^2 \\
\hat{F} &= 45 \quad MN \\
\xi &= 0.05 \quad [-]
\end{aligned}
$$

$$k = \frac{3EI}{L^3} = \frac{90 \cdot 10^6 MNm^2}{1 \cdot 10^6 m^3} = 90 MN/m$$

$$x_S = \frac{\hat{F}}{k} = \frac{45 MN}{90 MN/m} = 0.5 m$$

$$\omega_n = \sqrt{\frac{k}{M}} \qquad (if\, \mu = 0) \rightarrow \omega_n = 2.12 \ rad/s \rightarrow T_n = 2.96\, s$$

*Fig. 3. Simple model of fixed structure to calculate first natural period.*

The loading is therefore considered to be quasi static and the members and joints of the structure have to be checked for all relevant load combinations and various positions of the wave when passing through the structure.

More rigorous dynamic response and fatigue analysis is only required when the first natural period is getting too close to the peak of the wave spectrum. This may be the case in water depths nearing some 150 meters in combination with high topside loads and a hostile environment.

For reasons as explained the prefabrication of this type of offshore facilities is such that as large and complete sections as possible will be brought offshore. For the platform design as shown (fig. 1) the composing elements are the integral substructure (fig. 4), the piles to fix the structure to the seabed using a hydraulic underwater hammer (fig. 5) and the topsides facilities.

The production facility is composed of a huge deck section (fig. 6) only to be complemented by a drilling and an accommodation module to complete the topsides.

*Fig. 4. Prefabricated integral substructure of fixed bottom founded platform.*

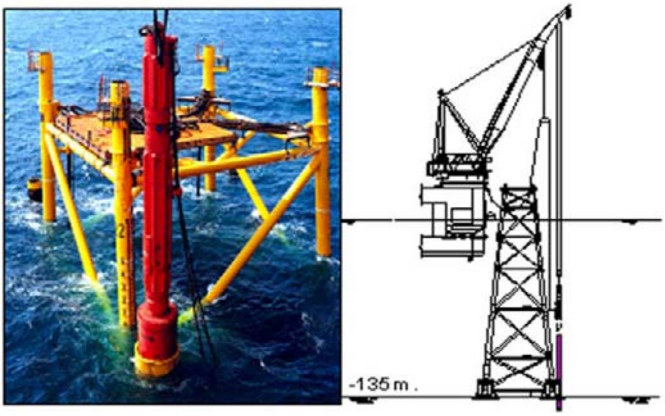



*Fig. 5. Pile installation using hydraulic underwater hammer.*


*Fig. 6 Installation of prefabricated integral topside facilities.*

It goes without saying that the load-out, transportation and installation of these huge structures have to be engineered thoroughly and where appropriate these phases may have an impact on the design, certainly on certain details of the design (fig. 7).

*Fig. 7. Node of a jacket structure with provisions for offshore lifting.*

## 3. Bottom founded Compliant Towers in deeper water

In water depths exceeding 200 to 300 m oil and gas production is generally achieved by using floating platforms (fig. 8).

When operating considerations lead to the wish of developing reservoirs in deeper water using a bottom founded platform rather than a floating platform a so called Compliant Tower may be a cost effective solution in water depths up to some 500m.

Designing a conventional Fixed Platform with a relatively low first natural period for a large topsides mass in combination with deep water will lead to an extremely costly solution in view of the amount of structural steel required for the substructure to be stiff enough provided it would be possible to fabricate, transport and /or install such a structure in the first place.

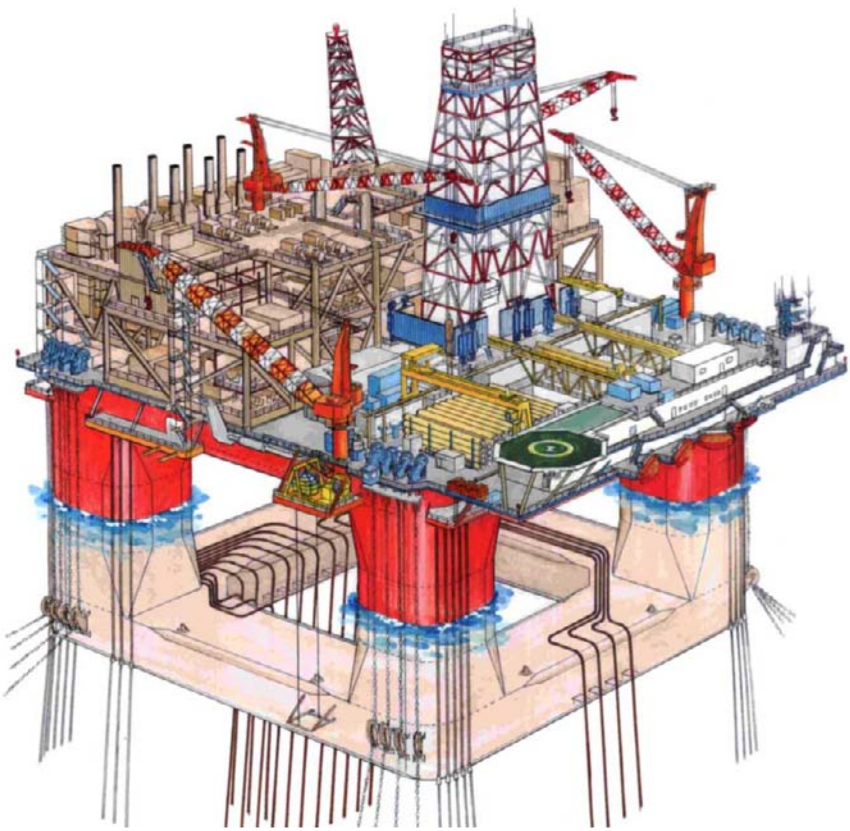


*Fig. 8. Typical example of a floating – semi submersible- platform.*

When looking at the envelope of the wave spectra applicable at the location of interest (fig. 9) it can be seen that the aim for conventional fixed platforms is to ensure the natural period to be outside the frequency range of significant wave excitation by designing the jacket to be adequately stiff.

The basic design principle of a Compliant Tower is to arrive at a first natural period of the structure high enough to be located on the other side of the peak in the wave spectrum envelope (fig. 10). This can be obtained by finding the right balance between topside mass, stiffness of the substructure and the water depth.

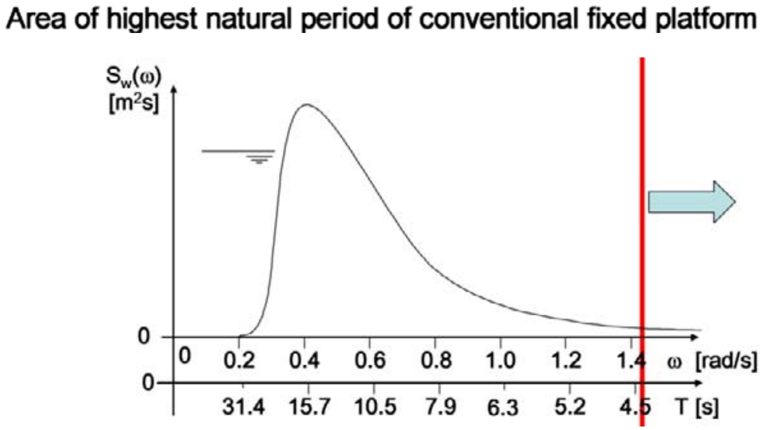



*Fig. 9. First natural period of fixed platform in relation to wave spectrum.*

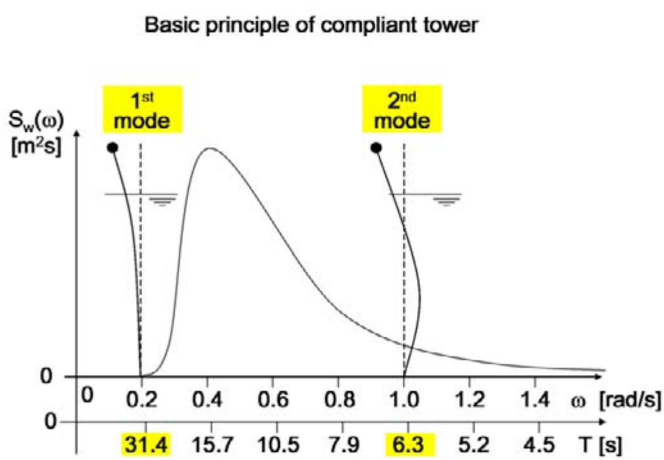



*Fig. 10. First and second natural period of compliant platform in relation to wave spectrum.*

A typical example of a Compliant Tower is shown in fig. 11 where it can be seen that the flexibility requirement results in a very slender structure which may have an associated highest natural period in excess of 30 second. To obtain a sufficiently high natural period is quite a challenge for the designer, but the problem becomes even more interesting since the second natural period of the structure should also be well outside the peak in the spectrum, generally being less than 5 to 6 seconds, depending on the applicable offshore environment (fig.10).

When looking at the first natural period of the structure the designer has to accommodate the required topsides mass and the water depth at the envisaged site. What remains for her or him is the stiffness of the supporting structure.

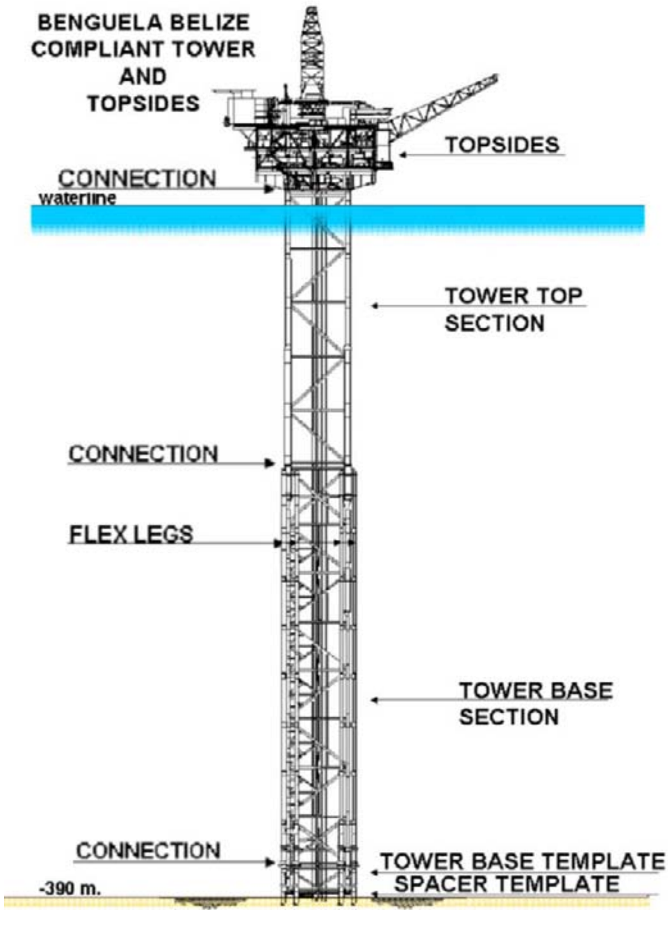



*Fig. 11. Typical example of a compliant tower.*

We are now faced with two important requirements: firstly, the structure should be **strong** enough to cope with the maximum extreme loading case, a quasi static requirement. Secondly, the structure is also required to have the adequate **flexibility** to ensure its capability to resist the shorter waves by inertia rather than by stiffness. Generally this strength and stiffness requirements lead the designer to look for additional means to ensure sufficient flexibility without sacrificing strength.

A way to increase the flexibility of the tower is not to fix the foundation piles to the base of the structure but have them extending upwards parallel to the tower only to be connected to the tower at a higher elevation; this can be a few hundred meters. This measure results in the vertical reaction forces of the foundation being transferred at a higher elevation causing the tower to be supported by softer vertical springs than would be the case when connected at the base. Clearly also the bending moments in the tower are being influenced by this contrary to the shear forces which always have to be transferred by the braces (fig. 12).

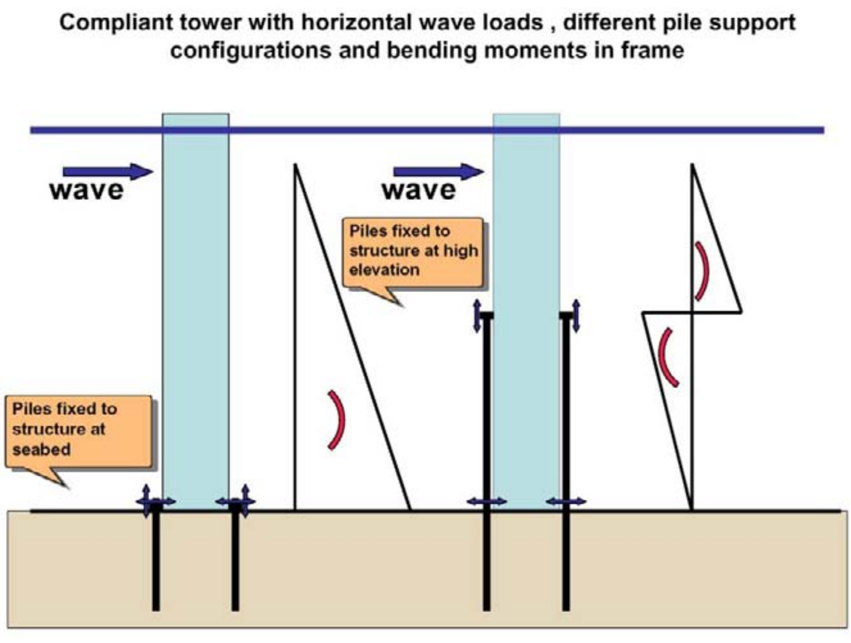



*Fig. 12. Influence of the level of the pile-tower connection on the tower's behavior.*

It goes without saying that this type of design approach has only been made possible due to the improved quality of materials and welding, due to the advanced calculation tools and knowledge of fatigue behavior and due to the capabilities of the industry to fabricate, transport and install this type of structures. The latter requires a significant amount of advanced engineering to ensure the structure is capable to withstand all the relevant stages ranging from fabrication to final installation (fig. 13-15).

*Fig. 13. Preparation for launching the compliant tower.*

*Fig. 14. Compliant tower sliding from the barge.*

*Fig. 15. Compliant tower just before leaving the barge.*

## 4 Fixed Platform as an alternative to a Compliant Tower ?

As has been shown, the elegance of a Compliant Tower brings along a relatively complex installation procedure which in turn adds to the cost and total installation time of the structure. When taking a closer look at the design of a Compliant Tower that has most recently been installed off the coast of West Africa it appears that the great majority of wave loading is coming from the same direction (fig. 16).

This raises the question whether or not it would be possible to design a bottom founded Fixed Structure at that particular location considering this unidirectional wave climate. The installation of such a structure in one piece is feasible by means of launching and the foundation piles can be driven and connected to the structure in the conventional manner resulting in significant time and cost savings. Whether or not the total installed cost of such a substructure will be competitive and will thus totally depend on its cost to fabricate which is mainly determined by its weight.

Given the earlier mentioned unidirectional wave climate a Fixed Structure (jacket) should have adequate stiffness in this direction to guarantee a sufficiently low natural period estimated to be approximately 6 seconds for this particular offshore site.

Can a conventional jacket be designed such that it:

1. has the required stiffness in the direction of maximum dynamic wave excitation,
2. is capable to withstand the maximum quasi static loading,
3. requires an amount of steel equal to or less than the Compliant Tower designed for the same conditions ?

To answer the above question a study has been carried out to design and optimize a jacket configuration meeting the design criteria as used for the Compliant Tower.

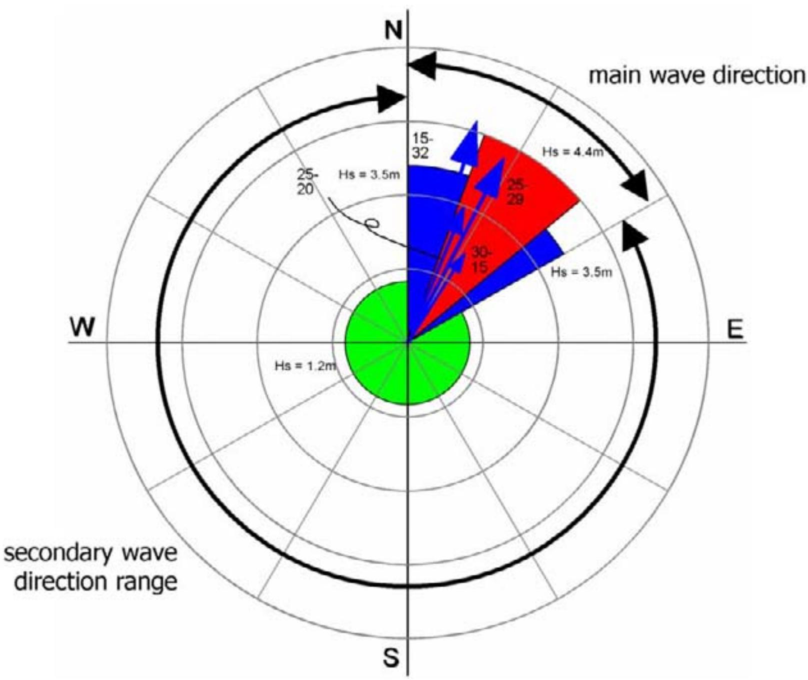



*Fig. 16 Unidirectional wave loading on structure in West Africa.*

### 4.1. Substructure optimization

To investigate the possibility of a substructure (jacket) to cope with the environmental conditions at the site of interest the influence of geometrical properties - like base dimensions, number of legs, bracing configuration, member dimensions, number and size of piles, etc.- on the natural periods of the structure and the associated material use has been investigated [1].

## 4.2. Bottom layout of the jacket structure

The stiffness of the jacket structure largely depends on the dimensions of the base.

For highly unidirectional loading the base length and base width can be chosen such that the reaction forces (pile loads) are being optimized. Assuming the foundation piles being located at the corners of the jacket and given the environmental conditions at the site of interest, an optimal base configuration in terms of quasi static pile loading has been found to be approx. 1.5 ( fig. 17).

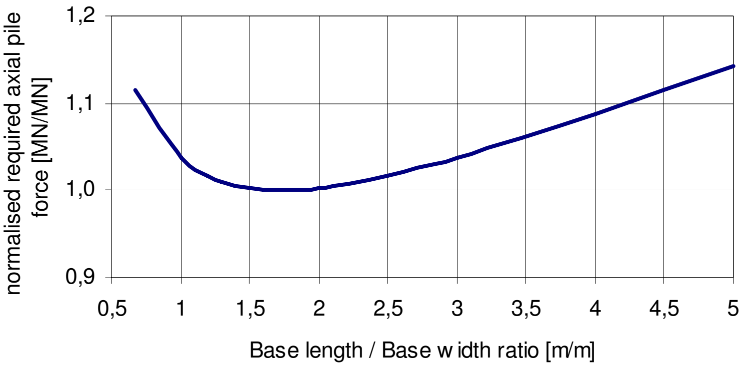



*Fig. 17 Normalized pile force for a constant base area and different base length / base width ratios.*

## 4.3. Layout of the top of the jacket structure

The center to center leg distances at the top of the jacket have initially been assumed to be the same as at the top of the reference compliant tower.

## 4.4. Member layout of the jacket structure

The legs have to withstand two main types of loading: the permanent and variable vertical load caused by the mass of the jacket and topsides and the overturning moment caused by environmental actions. The braces are loaded by the corresponding horizontal forces. Regarding the initial dimensions of the leg and brace members (fig. 18), the following ratios can be applied based on practical experience:

$$\frac{A_{brace}}{A_{leg}} = 0.1 - 0.2 \quad \frac{d_{brace}}{l_{brace}} = 0.03 \quad \frac{d_{brace}}{t_{brace}} = 40 \quad \frac{d_{leg}}{t_{leg}} = 24 \qquad (1)$$

For design considerations as well as construction reasons an angle of $30^o < \theta_{brace} < 60^o$ should be applied.

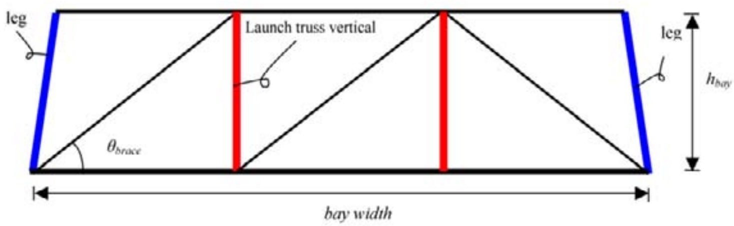



*Fig. 18. Member layout for a single bay.*

From these initial dimensions an estimate of the material use can be made. As an example, using a leg diameter of 3.0m and varying the number of vertical members in a single plane (shown for 4 in fig. 18) the resulting steel mass per unit height can be determined as shown in fig. 19.

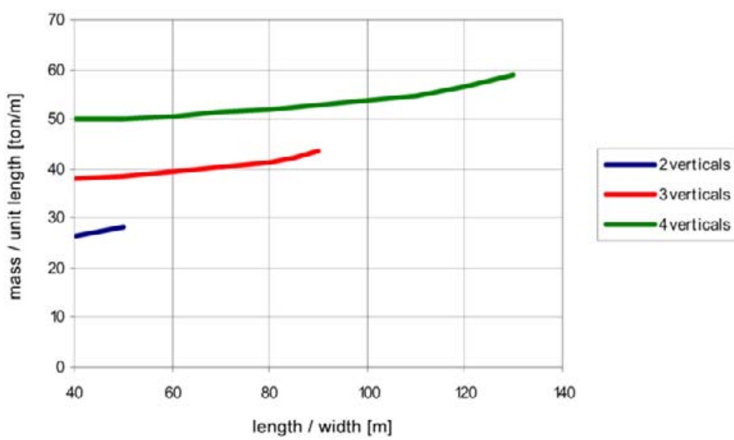



*Fig. 19. Mass structural steel per unit height.*

As shown in fig. 19, for a bay width of 70m a configuration with 3 vertical members results in a minimum of material used (the use of 2 vertical members is not meeting the relevant criteria at this bay width).

### 4.5. Natural period of the jacket structure

The flexibility of the structure largely influences its first natural period. In general, a jacket in shallow water has a low natural period compared to the peak of the wave energy spectrum. As a result they experience a relatively low dynamic amplification of the wave forces due to the absence of resonance effects. For a deep water situation the wave force periods may be close to the natural period of the jacket resulting in higher dynamic loads which need to be taken into account when considering the fatigue life of the structure.

One of the governing parameters in determining the natural periods is the mass of the structure. The topside mass is dictated by functional requirements and the mass of the supporting structure, the jacket, results from its eventual design. The mass of the reference Benguela Belize Compliant Tower is shown in table 1.

**Table 1 Mass of the reference structure related to the dynamic behavior.**

| Part | Self-weight [mton] |
|---|---|
| Equivalent topsides mass | 45.000 |
| Jacket mass | 50.000 |
| Hydrodynamic mass | 50.000 |
| Entrapped mass | 15.000 |
| Conductors | 20.000 |

As the centre of gravity of the topsides mass is located 26 m above the top of the jacket, an equivalent mass which results in similar dynamic behavior should be used. The equivalent mass is defined by considering the following approach, see fig. 20.

$$M_{eq} = \left( \frac{u_1 + \Delta\ell \cdot \theta_1}{u_1} \right) \cdot M \qquad (2)$$

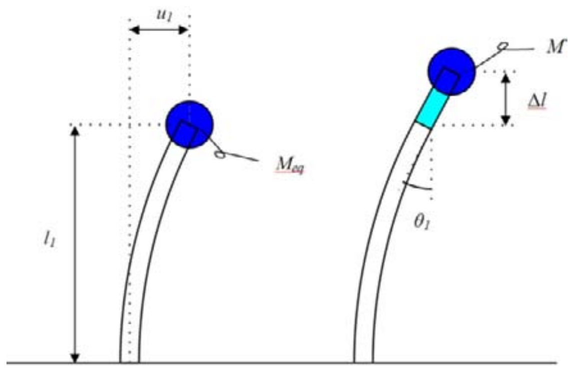



*Fig. 20 Lower bound determination of equivalent mass; topsides assumed infinitely stiff.*

For a first estimate of the first natural period of the alternative jacket structure (excl. the foundation flexibility) its behavior is assumed to be determined by a bending mode and a shear mode. For both modes, the natural period can be estimated by the application of the Rayleigh method. Subsequently, the natural period is obtained by

$$T^2_{total;jacket} = T^2_{shear} + T^2_{bending} \tag{3}$$

The effect of varying base dimensions (excl. foundation flexibility) on the first natural period is presented in table 2.

**Table 2 Natural period estimates for different base dimensions, excluding the foundation flexibility.**

| | | y - direction | | | x - direction | | |
|---|---|---|---|---|---|---|---|
| Base dimension | [m] | 80 | 87 | 95 | 110 | 120 | 130 |
| $T_{jacket}$ (lower bound stiffness) | [s] | 8.7 | 7.9 | 7.3 | 6.7 | 6.5 | 6.2 |
| $T_{jacket}$ (upper bound stiffness) | [s] | 6.8 | 6.4 | 6.1 | 6.2 | 6.0 | 5.7 |

In table 2 a lower bound based on an analysis of the 4 corner legs participating and an upper bound based on all verticals participating is given. The natural period should be in-between the estimations made for these two cases. The stiffness reducing effects of the foundation will increase the natural period of 5 – 35%. As frequently occurring waves have a period of about 7s – 8s, the natural period of the jacket structure should preferably be lower than 6s, which means a minimum base length in the x-direction of 120 m.

### 4.6. Design of a jacket with a base area of 120 m by 95 m

The jacket configuration is shown in fig. 21. For the broad side of the jacket a symmetric bracing pattern is desirable to ensure a balanced transfer of the jacket mass to the barge during transportation and launching. This resulted in a K-bracing for the outer part and an X-bracing for the centre part of this frame.

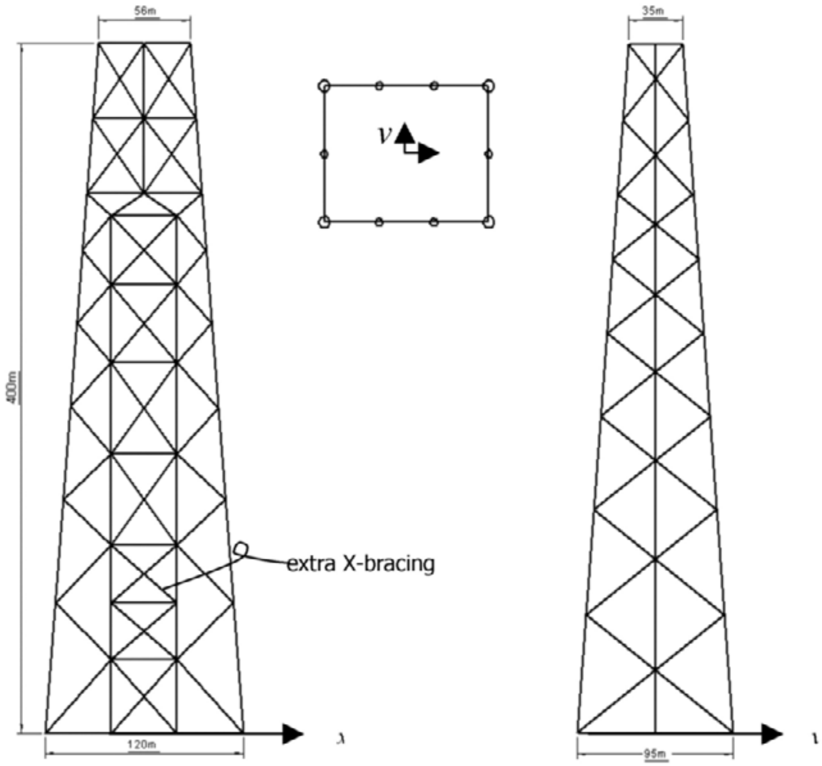



*Fig. 21 Jacket view in x- and y-direction.*

From the model as shown a finite element model has been made to be used in the program SACS. For the jacket structure the wave and current loading incl. their time percentage of occurrence and the foundation stiffness parameters (lateral as well as axial) have been estimated and the natural periods been determined. Also, a fatigue life assessment based on the API recommendations has been carried out.

The natural periods as obtained by the computer analyses are shown in table 3.

**Table 3 Natural periods of the jacket structure with and without foundation flexibilities.**

| SACS model; $T_{jacket}$ | | y - direction | x - direction |
|---|---|---|---|
| Without foundation flexibilities | [s] | 5.4 | 6.5 |
| With foundation flexibilities | [s] | 7.6 | 8.7 |

Because of the preliminary requirement of the first natural period being lower than 6s, it is concluded that the total structure is too slender. Therefore, a parameter study is performed in order to meet the natural period criterion at a minimal material use.

The main parameters which have been varied are: base dimensions, foundation parameters, dimensions of the legs of the jacket and topside payload. The first three parameters are intended to improve the dynamic behavior or to improve the efficiency of the structure regarding the magnitude of the natural period and the associated material mass.

### 4.6.1. Fatigue assessment

Regarding the fatigue assessment, as illustrated by fig. 22, the fatigue damage increases linearly with the natural period of the structure in x-direction when this period exceeds the value of 5.8s. The fatigue damage caused by loads in y-direction seems to be very low compared to the x-direction; clearly due to the unidirectional wave climate.

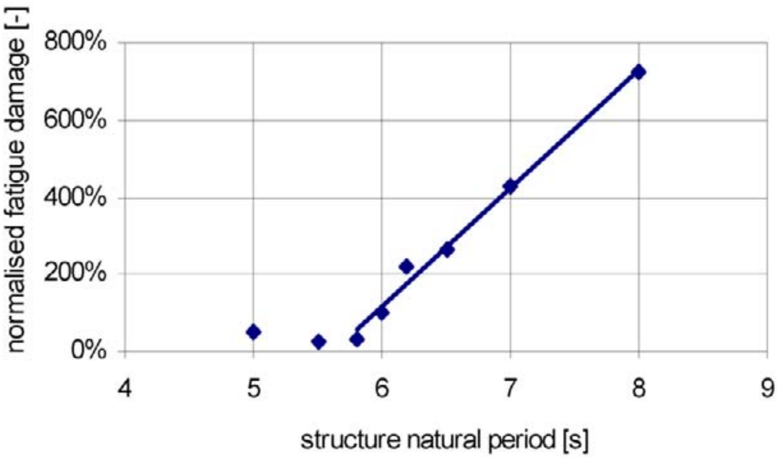



*Fig. 22 Influence of the natural period on fatigue damage for the x-direction, when incorporating wave directionality, dynamic amplification and using the API X' Wöhler curve.*

### 4.6.2. Varying the base plan dimensions

The rotational stiffness of the foundation and the bending stiffness of the jacket are strongly influenced by the base dimensions of the structure. The effects of different base lengths on the natural period and the material requirement is shown in table 4. A maximum base length of 140m is being proposed, which is 10m larger than the base length of the largest jacket ever transported.

**Table 4 Effects of different base length on natural period and material requirement (compared to the 120 m base case).**

| Base length | $T_x$ [s] | $T_{jacket;x}$ [s] | $T_{foundation;x}$ [s] | Material requirement [mton] |
|---|---|---|---|---|
| 110 | 8.0 | 5.7 | 5.6 | -750 |
| 130 | 7.3 | 5.1 | 5.2 | +750 |
| 140 | 7.0 | 4.9 | 5.0 | +1.500 |

### 4.6.3. Varying foundation properties

A large number of parameters influence the stiffness of the foundation, like: pile wall thickness, number of piles, position of piles, penetration depth and the batter of the piles. Some main conclusions obtained are:

- in terms of material use an increase of the number of piles is more effective than increasing the wall thickness; this requires more installation time, however
- increasing the number of piles to an amount larger than 20 reduces the effectiveness of this measure, so a number of 20 seems to be a practical upper limit
- applying battered piles seems a rather effective solution; the installation of these piles is relatively complex when compared to installation of vertical piles.

### 4.6.4. Varying the leg area

The third major contributor to the stiffness of the structure, apart from the foundation stiffness and the base dimensions, is the steel area of the legs. The base case of the parameter study has a ratio of $A_{brace}$ / $A_{leg}$ = 0.10, which is a lower bound. The upper range $A_{brace}$ / $A_{leg}$ = 0.25 is about the minimum value to withstand the permanent load of the structure.

**Table 5 Effects of leg area on natural period and material requirement.**

| $A_{brace}/A_{leg}$ | $T_x$ [s] | $T_{jacket;x}$ [s] | $T_{foundation;x}$ [s] | Material requirement [mton] |
|---|---|---|---|---|
| 0.10 | 5.7 | 4.9 | 3.0 | - |
| 0.15 | 6.0 | 5.3 | 2.8 | -6.500 |
| 0.20 | 6.3 | 5.7 | 2.8 | -10.000 |
| 0.25 | 6.9 | 6.4 | 2.7 | -12.800 |

4.6.5. Varying topside mass

Although the variation of this parameter is inconsistent with a main functional requirement, the effect of this parameter is considered. Removing some parts of the topsides and placing these parts on for instance a floating structure might be an economical solution. An upper bound estimate can be made for the effects of a topsides mass reduction by considering the total structure as a single-degree-of-freedom system with a weightless beam and a lumped top mass. The variation of the natural period is then related to the square root of the variation of the topsides mass. A reduction of the topside mass by 5.000 mton results into a decrease of natural period of 6%. For a reduction of 10.000 mton, the natural period decreases by 13%. As the effects on the natural period of the key parameters are known, the base can be modified such that a lower natural period is achieved with a relatively low amount of material.

Since the relation between the jacket mass and the natural period is known, also the relation between the normalized fatigue damage and the mass of the structure can be estimated, see fig. 23.

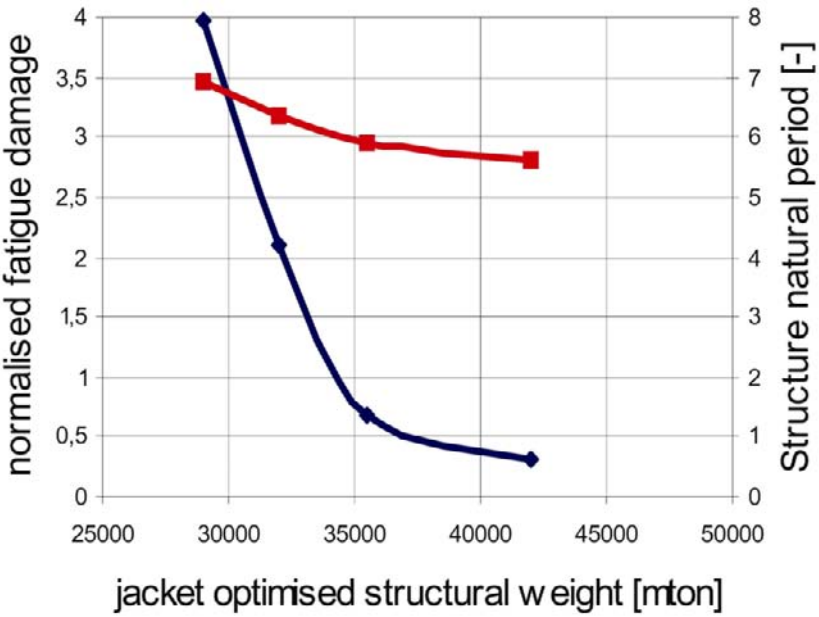



*Fig. 23 Optimized structural mass of the jacket versus the natural period and the fatigue damage.*

## 4.7 Comparing the economics of the compliant tower and the proposed jacket structure

### 4.7.1. Transportation

Transport of the compliant tower has been carried out in nine phases; five separate transports of topsides components, three for the main sections of the tower and one transport for the foundation template and piles. The total transportation costs of the Benguela Belize compliant tower was approximately $ 19 million USD.

The estimated transportation cost for a single piece jacket and foundation piles is estimated to be $ 16.5 million USD resulting in a reduction in transportation costs of roughly USD 2.5 million.

### 4.7.2. Installation

Regarding the installation of the topsides, the difference in cost for the two types of structures is assumed to be negligible. Installation of the substructure of the compliant tower has been carried out in 4 major phases, which can be reduced to 2 in case of a single piece jacket. Only the launching from a barge and positioning on the seabed is required followed by the pile installation. Result of this shorter installation scenario is an estimated reduction in installation costs of USD 2.0 million.

### 4.7.3. Fabrication

Table 6 shows a summary of the fabrication costs of the compliant tower.

**Table 6 Fabrication costs of the compliant tower.**

| | Quantity | Unit price | Total [million USD] |
|---|---|---|---|
| Tower | 30.500 [mton] | $ 6.875 | $ 210 |
| Piling | 10.800 [mton] | $ 3.250 | $ 35 |
| Temporary ballast tank | 900 [mton] | $ 6.875 | $ 6 |
| Fabrication specific complex parts | 4% of fabrication costs | | $ 8 |
| Total | | | $ 259 |

Based on the total mass of the compliant tower the mass of a competitive jacket should be less than 33.000 mton, which will probably result in a structure with a first natural period its stiff direction of approx. 6.2s.

## 5. Conclusions

The following conclusions can be drawn when comparing the proposed jacket design with the compliant tower:

- West-African environmental conditions are rather unidirectional, which makes a jacket design with a stiff and a relatively flexible orthogonal direction economically attractive.
- A first natural period of a jacket structure of approximately 6.3s does not result in serious fatigue problems when positioned in benign deepwater areas with a strong wave directionality.
- The jacket structure as designed is considered to break even with the compliant tower when considering the integral costs and taking into account 10% contingency on the main structural steel of the jacket. Many conservative assumptions have been made during the initial jacket design and the structure is not fully optimized, however. An optimized jacket structure is therefore very likely to have lower integral costs than a compliant tower.
- Since the total material use of the compliant tower and jacket designs are almost equal, an increase or decrease in material costs will not significantly influence the previous conclusion.
- For the unidirectional benign sea states as applicable in this study it has been concluded that the application of a jacket is even feasible with a slightly larger topsides mass or water depth than was the case for the reference compliant tower.

## References

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Delft Science in Design 2
M. Eekhout et al. (Eds.)
IOS Press, 2008


# Soft Mobility Products
## the Experiences of the Delft Design Institute

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**Abstract**

Design oriented faculties of the TU Delft today partly gain new knowledge by advanced product development, next to regular research. The "Research by Design" approach enables the answering of research questions that otherwise would be difficult to deal with: in addition to disciplinary problem solution and simulation models, the integration of multiple elements in an advanced, real product design indicates if and under what circumstances user benefits can be realized.

The role of the industrial designer consists here in fostering the transition of the potentialities of new principles and technologies to superior product functionalities.

In the SoftMob program of the Delft Design Institute and the section Design for Sustainability of the Faculty of Industrial Design Engineering, this approach is being applied on problems and opportunities in the transport area. Particularly, the question has been raised (1) if and how new inter-modal, soft mobility product concepts can contribute to more sustainable transport systems of the future; and (2) how these concepts could be embedded in economically sound service systems.

The paper describes the background of the SoftMob program as well as the lessons learnt from quite a number of previous studies and designs. From market research it was found that an emerging need exists from commuters for a small portable device, like the folding bike, but with more comfort and auto-propulsion. Therefore, the Link concept has been developed, a foldable small scooter ready for electrical assistance and/or an advanced battery system or a small hydrogen fuel cell.

In order to be able to build the Link, extensive studies had to be undertaken in the areas of novel materials, fuel cells, new battery development, energy management etc. Furthermore, a network of companies, design practitioners and experts has been established. Only via the design of a prototype the research question could be answered if and how these new technologies and principles could be integrated in a product with superior characteristics. Although further testing is needed and niche experiments should give more definite answers, Link is considered to be a feasible and attractive new concept.

Implementation is foreseen in Friesland, where the conditions for introduction of Link in a future, sustainable transport system are favourable. Besides, the project fostered the knowledge building on new materials, emerging energy technologies and comfort. By systematically applying a variety of industrial design methods and tools, additional valuable new insights on development methodology could be gained.

The positive experiences with the SoftMob program and the Link concept in particular have confirmed the Delft Design Institute and the Design for Sustainability program' management decision to continue their parallel research and design quest aimed at deepening and integrating design knowledge and creating solutions for societal –sustainable mobility- problems at the same time.

Keywords: soft mobility, research by design product design, product service systems, fuel cells

## 1. Introduction

Within the Faculty of Industrial Design Engineering (IDE), the Delft Design Institute (DDI) aims at a scientific contribution to product innovation by building complex prototypes and creating related niche experiments. An important ambition of the IDE Faculty research program is to foster the success rate of novel product development in relation to the demands of society, now and in the future. During recent years it has been acknowledged that so many aspects are relevant in this regard, like future contexts, user orientation, ergonomics, aesthetics, materialization, and construction etc. that the risk occurs of sub-optimization: in some areas the IDE Faculty acquires extensive knowledge, while other areas would be underdeveloped. As a consequence, methodologies and guidelines for appropriate product development might appear to be partly unsatisfactory in business practice.

In addition, nowadays so many new product technologies[1] emerge, like from nano sciences, energy transformation theory and biomedical approaches, that the amount of potentialities for future product functionalities is booming, increasing the complexity of the field. In a global society in which also the speed of -and the time to- the market is more and more decisive for success, this requires additional inputs from technical universities. In order to enable "consistent brilliant innovation", Larsson and Feland et all [11] argue that we need a new, comprehensive design engineering approach that supports engineers' capabilities in transitioning new technologies from R&D centers into product architectures.

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[1]Product technologies are defined here as the entities realizing product functions [20]

One of the responses to this challenge from universities, and the IDE Faculty in Delft in particular, is to create explicit possibilities for experiments with advanced product prototyping, testing and evaluating, based upon new principles, technologies and/or methodologies. In this way, not only research questions, dealing with an integral development approach, can be answered by –potentially- solving all problems by a real product design ("Research by Design"), but at the same time attempts are being made in demonstrating far reaching solutions for societal problems. These potential solutions not only consist of the prototypes and the answers they give to scientific questions and challenges from society, but also in the development of design methods and tools that can help designers to systematically apply gained knowledge in future development processes. To a large extent, the activities in the DDI Institute are being performed by PhD candidates and MSc graduate students, guided by teams of research professors and design practitioners.

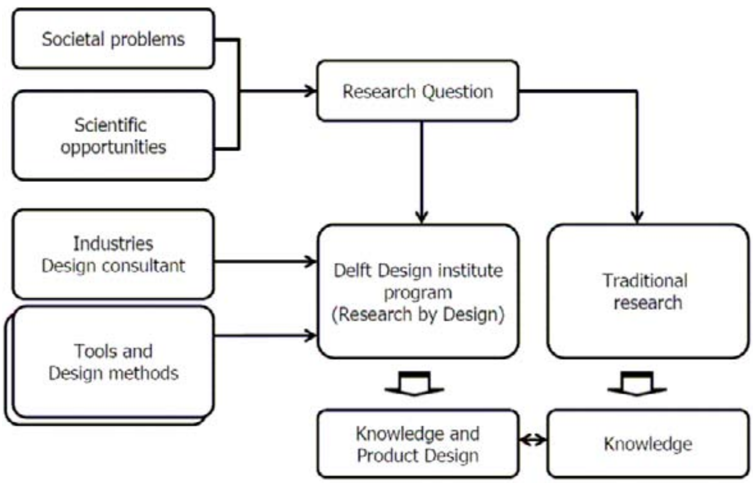


*Fig. 1 An overview of the DDI approach*

The DDI organizes it's research and design program in close connection with large and small industries, with design consultants and experts and of course with the research groups and programmes of the IDE Faculty. The activities are concentrated around the two following themes:

- Health & Care
- Mobility and Energy.

One of the research groups that have joined the DDI program is the Design for Sustainability (DfS) section.

The DfS program of the Faculty of Industrial Design Engineering aims at contributing to sustainable development by designing advanced artefacts and services with superior life cycle characteristics [10]. The focus of today's research and design program is on renewable energy (photo voltaics, human power) for portable products and mobility systems, renewable materials (cork, bamboo) for high-end applications and on sustainable product innovation in a global c.q. international context. In cooperation with the DDI, within the SoftMob program a series of new concepts for soft mobility are being developed and tested, as potential enabling elements in tomorrow's sustainable transport system.

## 2. Goal, scope and history of the SoftMob program

### 2.1 Goal

Goal of the SoftMob program is to develop scientific knowledge and know how for product-service design based solutions for today's and future mobility problems, by (1) prototyping, demonstrating, experimenting and evaluating advanced –soft[2]- mobility products; (2) integrating existing disciplinary product development knowledge from IDE's Faculty and external knowledge sources and (3) focussing on solutions that potentially contribute to the transition to sustainable societal systems.

### 2.2 Scope

The scope of the program is on new personal transport means that are soft by nature, i.c. that can replace car use, while optimizing sustainability, comfort and other functionalities as well as profiting from the potentialities of new energy technologies.

Advanced "bike-up" design solutions are the point of departure of the activities, including future context and use research, the creation of concepts, product prototyping and testing in experimental markets.

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2 The attribute "soft" points here at those person and goods' transport modes and chains –such as inter-modal, waterborne, rail, other public transport, human powered etc.- that in most circumstances are more sustainable than motorised individual mobility. It can also include traditional transport modes with a breakthrough in terms of performance and energy efficiency.

## 3. The SoftMob program

The search of alternatives for urban car transport is one of the starting points of DfS chain mobility program, as can be seen in figure 2. It went through several iterations within the DfS program, before entering the joint venture with the DDI Institute.

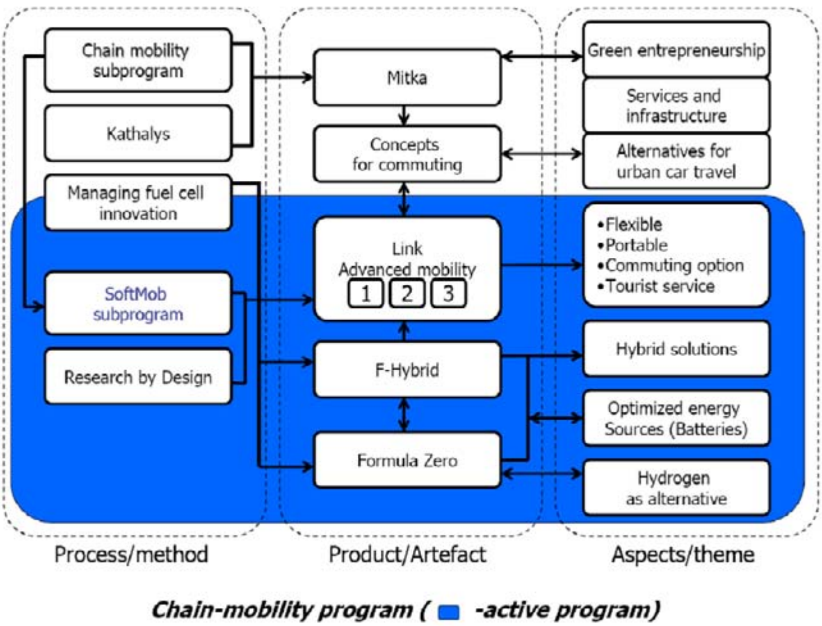


*Fig. 2 Chain mobility program*

Short distance mobility in urban areas is one of the problem areas in the Netherlands. Most commuters use their bike for a maximum home-work distance up to 5-10 km. A study [4] carried out at sports' company Nike headquarters in Hilversum revealed that lack of comfort was one of the mean reasons for avoiding a wider range. Therefore, a trajectory was set in motion, in close cooperation with the Nike, Gazelle bicycle company, TNO/Kathalys, van der Veer designers, Freewheel and others, to create an attractive and comfortable solution for short distance commuting (10-20 km home-work distance). The aim was to find an attractive alternative for the urban car use at wider distances.

After extensive studies and surveys, a prototype of MITKA was realised (see Figure 3) including a help motor for pedalling, novel seat position, three-wheel architecture and a tilting steering mechanism in the front. The idea was to build a full test series for demonstration by Nike's employee's in their daily commuting.

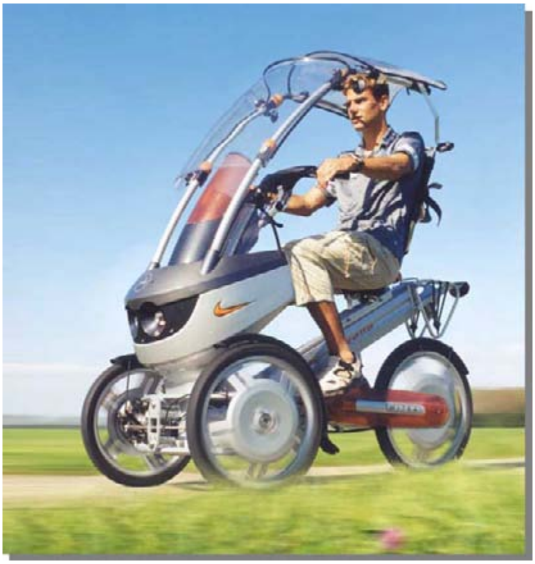

*Fig. 3 Mitka, alternative for urban car transport*

However, due to both technical, design and managerial reasons the MITKA never exploited the prototype stage. The three-wheel vehicle was very comfortable for the user, but too big to manoeuvre on small bicycle roads and too slow for the main road. Moreover, it's features were considered to be too expensive for a huge market, keeping investors and business implementation away. Although novel elements of MITKA, such as the seat, found their way to the market, no possibilities emerged to test other essential elements of the new mobility concept, such as financial services, maintenance and repair services, health benefits etc. However for the SoftMob program, several lessons for future design could be learnt from the MITKA project [4]:

- Radical design projects -with a high environmental ambition- should preferably apply a bricolage approach, including a flexible versus an ideological vision, capacity building via ready-to-use experimentation and a series of small incremental steps rather than one big jump. In this way technological risks can be reduced.
- From a business perspective, at least three questions should be answered at the start of a Soft Mob project: "what is our business?", "who is the customer?" and "what is the customer value?"

Parallel to MITKA, several other alternatives were explored that could lead to reduction in car use, either for commuting or in tourism and recreation. Some of these studies were focussing on artefacts, others more on service and infrastructure solutions, in line with the study of Mont [19], indicating that an integrated combination of novel products, services, infrastructure and organization is a precondition for sustainable solutions at system level.

| *Project* | *Type* | *Commuting* | *Chain mobility* | *System design* | *Output* | *Advantage* | *Technology* | *Aesthetics* | *Portable* | *Features* |
|---|---|---|---|---|---|---|---|---|---|---|
| **1.** *Mitka (combination of three projects)* | Design and Research | √ | - | √ | Working prototype | Alternative for car | Battery (optional) | √ | - | Three wheel; comfort; weather protection |
| **2.** *Slim Forensen met Fiets en OV* | Research | √ | √ | √ | Scenarios | Stimulants for chain mobility | - | - | - | Chain mobility |
| **3.** *Ontwerp van een Vouw fiets* | Design | √ | √ | - | Working prototype | Mix between robust city bike and handy vouwfiets | - | √ | √ | Minimal elements; portable; comfort; multifunctional |
| **4.** *Nieuw concept voor een driewieler Ligfiets* | Design | √ | - | - | First evaluation prototype | Aerodynamic design and weather protection | - | √ | - | Three wheels; weather protection |
| **5.** *Een toekomstig mobiliteitsconcept met betrekking tot individueel vervoer voor afstanden tot 20 kilometer* | Research | √ | - | √ | Concept sketches and future vision | Commuting without traffic jams | Diesel engine and regenerative power options | √ | - | 9project under progress) |
| **6.** *Design of an advanced portable solution* | Design | √ | √ | | Concept sketches and evaluation prototype | Foldable and portable to carry in personal/public transportation | Battery or Fuel cell | √ | √ | Portable; flexible; powered; easy to fold; link to chain mobility; |
| **7.** *De ontwikkeling van een brandstofcelfiets* | Design/ Demo | - | - | - | Evaluation prototype | Fuel cell demonstration project | Fuel cell | - | - | Fuel cell; bakfiets |
| **8.** Ontwerp van een fiets met one size fits all frame | Design | √ | √ | - | Working prototype | Light weight, one size fits all bike concept | - | √ | √ | Light weight; new materials |

*Fig. 4 Overview of design studies aimed at alternatives for car*

Maas [17] and Koenderink [15] found several new options for comfort, including novel options for weather protection and aerodynamic design, while van der Woning [22] focussed on the opportunities of new materials for a light weight – one size fits all bike concept. Cordozo [8] studied the possibility of a mix between a robust city bike and a handy foldable device: with the design of the foldable bike he demonstrated that with minimal elements a portable, comfortable and multifunctional bike concept is feasible.

While aforementioned studies focussed on the soft mobility artefacts, others studied the service and infrastructure context. Worm [23] found several options to stimulate sustainable chain mobility, such as 'Fietsdubble', 'Fietsforward' and 'cybervoertuigen', etc. Iraci [14] and Boelens [7] sketched today's and future opportunities for superior chain mobility systems, and particularly the role of advanced bikes and information and communication technology, to foster easy transition for the user from one type of mobility (train, bus etc.) to others (bike etc.) and vice versa. They concluded that the need exists to foresee the whole service system, than to develop the system itself and customize the artefact accordingly. Along the same line, van de Goot [12] stresses the importance of an appropriate physical and informational infrastructure to enable sustainable chain mobility solutions.

## 4. Today's SoftMob program

From the previous studies, several conclusions for the roadmap of the SoftMob program can be drawn. The most important are:

- Design demonstration: The general product design is seen as combination of disciplines of form-giving, engineering, ergonomics and innovation management. The product needs to demonstrate the optimal combination of these disciplines for intended purpose and market. Product development and demonstration gives more opportunities for integral testing and for improvement of the market worthiness of artefacts;
- Need for advanced concepts: The finding is also that there is a pressing need for advanced concepts which could be using advanced technologies and materials to overcome the issues with traditional technologies. The application of advanced technologies for functionalities like light-weight commuting and inter-modal chain mobility options;
- Expertise in the field: The cooperation of knowledge institutes and companies in the initial stages of product development gives the practitioners help and reflection from policy, design, market feasibility and engineering;
- Sustainability and system perspective: Available knowledge on sustainable mobility at faculty IDE in the form of experts and previous projects could be a head start in coming forward with more practical solutions. The system perspective is aimed at the enabling of a particular function (e.g., door to door) and not at just bringing another product on the market. The combination of the sustainable perspective and system thinking should result in a more complete solution;
- The scope of the program is mainly based on soft mobility designs, chain mobility options, product-service systems and sustainable urban infrastructure.

The DDI design activities that are undertaken by researchers and students, in cooperation with the DDI external partners, are the basis of the program. At the same time the designer-researcher team will describe, analyze, assess and reflect upon the progress made, specifically from the perspective of the research questions. This also includes the development of a framework and -living- program of requirements for design evaluation and optimization. In this program it is also proposed that research will follow a reflective-practice approach. The coexistence of design and research cycles need to be further clarified in the research trajectory.

### 4.1 Advanced Mobility

Within the project several studies on the future of mobility systems and users' needs have been undertaken, leading to a scope on small, foldable concepts for short distance commuting. The assumptions and research findings are summarized as below:

- Portable and light vehicles could be solutions for the transport of people and their luggage in specific markets and certain niche circumstances (where a quick, clean and individual transfer over a limited number of kilometres is required).
- In inter-modal situations, like commuting and tourist trips, the concept should be easily distributed, handled and stored as own personal luggage.
- Battery and fuel cell technologies, as alternative energy systems, offer the potential of significantly decreasing local carbon dioxide emissions.

After extensive benchmark studies [1], idea finding and the creation of a number of design concepts, the elaboration of one of them has been chosen: the "Link" concept. The Link is a foldable vehicle (close to a moped) that can be brought as luggage in public transport or in a car trunk, and is used as before- and after-transport. The Link is designed to be powered by advanced batteries, high-capacitors and/or in combination with a fuel cell. Among other advantages Link adds as functionality that it can be driven seated as well as standing: changing between these modes can be performed easily by folding the saddle bar.

### 4.2 Role of artefact design and services

In close connection to the design of the actual artefact and an accurate description and analysis of the design process, several research questions emerge. Particularly, the PhD study of Beella [3] focuses on the following main research questions:

How to foster innovation by integration of emerging new technologies and creative service systems for sustainable mobility?

- What role can emerging technologies and its intelligent combinations play in the artefact design?
- What is the relation between the design of the artefact and its surrounding service packages?

The two sub-research questions, mentioned above, are formulated in such a way that the first question helps in creating the initial designs with the help of previous projects (see figure 4). Design assignments are carried out during the process. A functional prototype, Link1 (see figure 5, 6), has been developed and tested, leading to further insights in folding possibilities, construction, propulsion, driving dynamics, aesthetics and other aspects. At the moment the Link2 is being constructed, including propulsion and electrical systems, to be tested in DfS regional innovation program in the Province of Fryslan [3]. In addition to the users' tests, further implementation research takes place to find out how Link2 and it's follow-ups might best fit into a sustainable mobility Product-Service-System [16]. In other words: how could the product be further optimized and re-designed to fit the ideal sustainable system?

The *urban mobility concept* uses a battery as energy source for immediate implementation and fuel cell in long term. It has 50 km of action radius and maximum speed of 25 km/hr.

*Main features*

Two riding positions: Standing (while saddle folded) and Sitting
Footprint in folded state: 30X35cm
Carrying capacity: 100kg
Weight: ~17kg
250W motor

*Fig. 5 Specification of Link1*

Relation between artefact design and surrounding service packages would be realized with the help of development of a business case. Service criteria, which are output of the envisaged Fryslan analysis and business case, will be used in order to relate artefact design to its surrounding service packages. The business case also includes the further design assigment to relate the service criteria to the final artefact design and service creation.


*Fig. 6 Illustartion of Link1 interaction [1]*

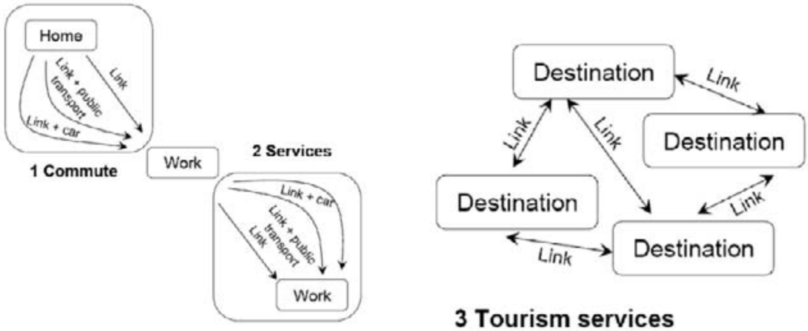


*Fig. 7 Illustartion of Link1 use scenarios with market combinations*

### 4.3 Advanced Design and methodology

Figure 8 shows different methods involved in the product development process and simultaneously the features developed. In the case of MITKA, Lead user technique is used to find the user requirements where the product is radically new and needs technological development. The method indicators are specified by (1) finding a market or technological trend and related measures, and (2) defining measures of potential benefit. The product is seen as need based and the potential market is screened based on measures specified in previous step (by means of a questionnaire) to identify a lead user group.

| | Method | features | output |
|---|---|---|---|
| Mitka  | • Lead user technique | • Alternative for car<br>• Product service system<br>• Green entrepreneurship | • Awareness for sus transport<br>• Learning<br>• Spin-off for several alternatives for urban car travel |
| Link  | • Morphological analysis<br>• Conjoint analysis | • Foldable and portable to carry in personal/public transportation<br>• Chain-mobility option | • In development stages<br>• Design tool based on functionality<br>• Market ready product |
| F Hybrid  | • Emerging technology<br>• Optimised energy sources | • Demonstration of Fuel cell technology<br>• Role of technology in artefact topology | • Technology demonstration<br>• Spin-off for hybrid two wheelers<br>• Further dev with Hogeschool Rdm |

*Fig. 8 Methods involved in product development stages*

In the case of Link, methods like morphological analysis and conjoint analysis are used, where the product semantics are well known. The design embodies a novel functionality (i.e., to carry around the vehicle with comfort in folded state) which needs attributes relevant to the product category and their relative importance.

In the case of FHybrid, the role of emerging technologies and optimised energy sources were explored [2]. The main aim is to demonstrate the fuel cell technology and its subsequent role in artefact typology, which is also one of the point of departures in the case of 'Link'.

## 5. Reflection and future

From the Link's scientific adventure it is clear that the DDI approach have several benefits, in addition to a more traditional PhD study. First answers could be found for the research questions posed, not only by thorough user research and the assessment of new technologies, but also by actually building several prototypes.

It's evident now that emerging technologies, such as fuel cells and novel batteries, play a decisive role in the functionality of the final product. But only by building the Link artefact, it becomes clear how industrial designers can successfully translate the potentialities of these new technologies into a product that is attractive for use in inter-modal, more sustainable transport systems. In the case of Link new folding principles, light-weight construction, flexible seating and innovative energy management have proven to be crucial elements for today's design success. Also learning from existing alternatives, i.c. product benchmarking, is significant for the development. The use of a variety of advanced design methods and tools has not only enriched the outcomes, but also given interesting feedback for the optimization of industrial design methodology.

Although many specific questions still have to be answered and further testing in more detail is necessary, Link should be considered as both a design and research success. The concept has the potential of stimulating a significant part of individual car commuters to change to chain mobility, allowing high performing, comfortable and energy efficient individual inter-links. Several industrial partners have shown interest in participating in a follow-up. In addition, the Fryslan region in the North of the Netherlands has expressed it's ambition to integrate Link into it's future sustainable mobility system. Particularly, an experiment on the island of Ameland with a first series of Links is one of the proposals here.

However, if in the end Link also will become a national market success like for instance the folding bike is a question that is hard to answer in advance.

Within the SoftMob program of the DDI Institute the Link project has proven to be an important carrier project that stimulates research in different other technology and design areas. Therefore, follow-up PhD and master studies are being undertaken in the following areas:

- Fuel cells and super capacitors for bikes, scooters and small boats [5, 6 and 13]
- Advanced bike design (comfort, form, aesthetics, GPS, wind-powering) [18]
- Photovoltaic energy for small energy systems in soft mobility
- Product Services Systems for sustainable mobility (such as the national train-bike scheme, advanced rickshaw services) [5 and 21]

Together with the researchers from the Design for Sustainability program, with inputs of new technologies from within TU Delft and from industrial partners the Delft Design Institute definitely will continue the SoftMob program, exploring the edge of product innovation knowledge by advanced design.

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# DELFT SCIENCE IN DESIGN 2

## DESIGN PROCESSES

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# AI Techniques for Conceptual Design

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**Abstract**

The conceptual design of complex products may be improved by applying knowledge available in existing designs (analogues), pre-defined components (parametric models), and functional models (rules). To represent and re-use this knowledge, AI techniques may be applied such as Case-Based Reasoning (CBR), Constraint-Based Modeling (CBM) and Rule-Based Reasoning (RBR). Case-Based Reasoning indexes a database with existing products with known performance characteristics, to suggest a first prototype solution that fits the requirements. The prototype can then be modelled and dimensioned with Constraint-Based Modeling, and its performance be verified with a network of functional relations derived by Rule-Based Reasoning and optimized with a numeric solver. In this way a first design concept can be quickly generated and evaluated as a first step towards a more elaborated design.

Keywords: Conceptual Design, Artificial Intelligence, Case-Based Reasoning, Constraint-Based Modeling, Rule-Based Reasoning

## 1. Introduction

Conceptual design is the first phase of the design process. Its role is to come up with a first proposal that satisfies the functional requirements. Conceptual design  is difficult in particular for complex objects such as aircraft, ships, and industrial appliances. The list of requirement is generally quite long and it often takes a full detailed design to assess whether the proposed solution satisfies the functional requirements, only to learn in the end that it does not. So we need a system that can quickly generate a proposed solution and that can evaluate whether it satisfies the posed requirements without extensive detailing effort.

In this paper, we propose a design methodology for conceptual design, using several AI techniques, which in combination support the total design cycle of proposing and evaluating solutions.

We will first discuss conceptual design and how AI techniques can be used to implement the required qualitative kind of reasoning needed for suggesting and analysing design concepts. Then we describe the application of these techniques within the AIDA system (AI supported Design of

Aircraft) and show how this system can be used for the design of aircraft. A more elaborate version of the case can be found in [Rentema 2004].

## 2. Conceptual Design

Design is an activity that generates a 'materialised' solution for a 'functional' problem, i.e. it proposes a system or 'structure' that shows some 'behaviour' that satisfies the 'functional' demands. However, there is no direct reasoning possible from functions to behaviour and structure, i.e. a logical, straightforward deduction of the structure from the function is not possible. It is even feasible that more than one structure is capable of realising the demanded functions, or none at all. Hence, designing is a non-deterministic process.

Designing has more challenging features. Typically, it is often an 'ill-defined' process, meaning that the functional requirements may change during the process, for example when they appear to be too conflicting. Also time and resources may be limited, and we may have to decide in a situation of uncertainty. Another challenge is to define the optimality criteria based on the diversity of design specifications, in order to generate an optimal design or select the best feasible design.

Because straightforward reasoning is not feasible, a 'generate-and-test' strategy is often applied. This strategy leads to a number of iterations through the design cycle which is visualized in Figure 1.

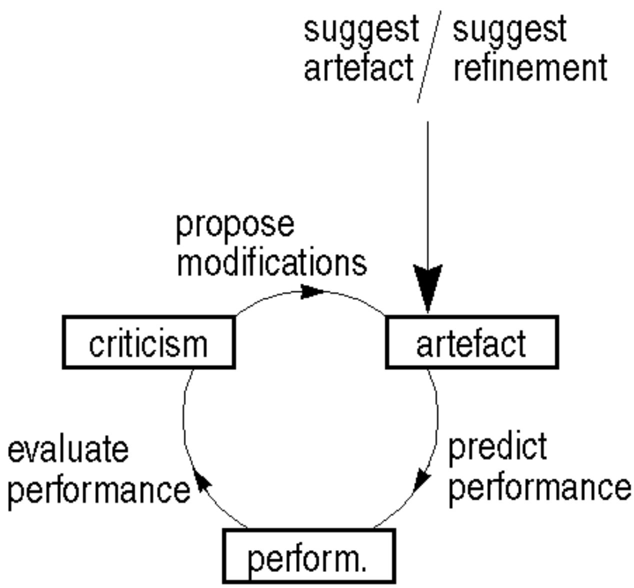


*Figure 1. The Design cycle*

Using his experience, the designer first suggests a solution, then the performances are predicted/estimated. This may be done with some formalized knowledge such as physics, statistical data or empirical 'rules-of-thumb'. A full analysis is often not possible due to lack of a detailed description. After the performances are evaluated with respect to the requirements, then modifications may be proposed to remedy the shortcomings, and the cycle starts over again. When the solution is deemed to be good enough, the designer suggests refinements. This means that the artefact will be described more completely by adding details, for example by focusing on one of the components.

An often applied strategy to avoid exhaustive generate-and-test search is the 'divide-and-conquer' method. The problem is decomposed into several sub-problems that are easier to solve and the different sub-solutions are then combined into one integrated solution. An example of such a decomposition strategy is the 'function-means' method. Requirements are recursively decomposed until a solution can be provided and the part-solutions are then successively combined. This decomposition strategy does not solve the design problem itself but transposes it to the 'integration' activity; however, the initial decomposition and analysis may provide some useful clues for the integration phase. The decomposition-integration cycle can be repeated for different levels of detail, or different functional decompositions.

The integration step can be avoided when an existing solution is taken as a starting point. The chosen solution, which partly satisfies the new functional requirements, is then refined via a 'reuse-and-adapt' or 'diagnosis-and-repair' cycle. The solution is analysed and modifications are proposed that relieve some of its weaknesses.

This approach is better suited for so-called 'routine design' problems than for 'creative' designs where new principles are applied in a new context. Most designs fall in between routine design and creative design: a new design is often a new composition of existing components. According to [Mittal, 1989] this type of design can be classified as 'configuration design'. Typically large-scale design problems such as design of aircraft, buildings, ships and industrial appliances fall into this category: certain aspects of a new design may be 'innovative' but in most cases there will be quite some similarity with earlier designs.

Although the reuse of existing components greatly benefits the design process, the number of possible combinations is still far too large to be fully elaborated. Hence a good initial choice is very important. In the next section we will review to what extent AI techniques can be used to cope with these issues.

## 3. AI and design

Artificial Intelligence (AI) is concerned with the application of knowledge. Within AI, three main directions of reasoning can be distinguished: reasoning by logic, reasoning by learning, and reasoning by analogy. Expert systems apply rule-based reasoning (RBR) technique, a form of reasoning by logic. An expert system is useful when the domain knowledge can be formalised into simple rules, such as mathematical problems, and when common sense does not play an important role. Unfortunately, design can not be formalized this way.

Reasoning by learning can be implemented with Artificial Neural Networks (ANN). An ANN consists of a network of nodes (processing elements) connected via adjustable weights (connections). By training the network with a large set of input-output pairs, the system learns the functional relation between the input and the output space. This type of generalized learning can not be applied to the design problem because the solution space is sparse and discontinuous.

The third form of reasoning, reasoning by analogy, is best exemplified by Cased-Based Reasoning (CBR). Cases are stored in a case-base to create a reservoir of problem-solution combinations. When a new problem is presented, CBR searches for cases with similar problem descriptions. Although the retrieved case usually does not completely fit the new problem, the retrieved solution may be a good starting point for further adaptation and optimization. The difference with the other AI methodologies is that CBR does not use generalized domain knowledge but knowledge which is locally valid: the implicit knowledge within a case which relates a problem with a solution only holds for that particular case. See Figure 2.

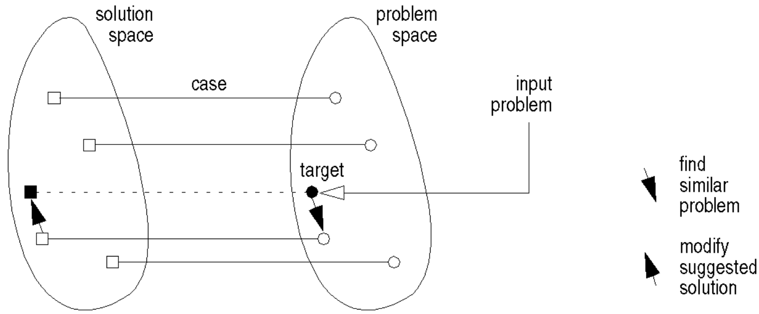


*Figure 2. Principles of problem-solving with Case-Based Reasoning (from [Leake,1996])*

Considering the characteristics of conceptual design, reasoning by analogy seems to be a helpful method to assist the suggestion of a concept. Because CBR applies implicit knowledge, this paradigm offers interesting possibilities to overcome the lack of (quantitative) knowledge at this design phase. CBR in design, however, differs from other CBR applications where the number of cases is generally quite large but each individual case is relatively simple. In design the examples are few but often complex and may cover a large diversity of the functions. Hence, to be able to use CBR properly, the information about the design cases will have to be encoded in a flexible way.

A useful representation scheme for design cases is with the triad Function-Behaviour-Structure [Gero, 1992]. Structure represents the materialized version of the design: the geometry, the components and the assembly. Function represents the performances of the functional aspects of the model. Behaviour describes more explicitly how the structure is able to accomplish the functions; i.e. the mechanism by which the (functional) problem is solved. The behaviour component is very much dependent on the structure. Given two different design configurations, there may be a completely different set of behaviour data to evaluate each of them.

To make things complex we should be aware that, in addition to functional requirements, the list of specifications may also contain explicit requirements for the behaviour and structure of the design (i.e. the use of certain components). Some functionality may therefore be an indirect result of behavioral and structural choices given by the list of requirements, and not directly prescribed in the list of requirements.

For the evaluation of the structure via behaviour and function, explicit (physical and mechanical) domain knowledge can be applied. Since its logical character, the RBR technique seems suitable for controlling this knowledge. Compared with the conventional techniques implemented in a static manner in existing computer support tools, rule-based techniques may improve flexible use of domain knowledge. By logical reasoning, the input and output of the calculation methods can easily be matched in order to determine a proper evaluation sequence. Also the transparency of the applied knowledge will be improved. Instead of performing complicated calculations within a module, RBR can be used to split up these calculations into basic functions and connect them on-line by logical reasoning (and helped by interactive specification of the user).

Strongly associated with the evaluation functions are constraints and relations imposed on the (standard) components of the structure. These constraints keep the structure functionally consistent, encode some form of parametrization of the structure, and/or be part of the interface specification between components. These constraints are not directly used to evaluate the design but to model the design and put some intelligence into the configuration and adaptation process.

The next section we will describe how these techniques can be applied for conceptual design of aircraft. A system set-up is presented based on the use of case-based reasoning to propose design concepts, rule-based-techniques for the functional evaluation, and constraint-based geometric modeling for the geometrical evaluation of these concepts.

## 4. The AIDA system

The AIDA system (AI-supported Design of Aircraft) is built of three modules and a central interface; see Figure 3:

- Case-based reasoning (CBR) module
  In this module case-based reasoning techniques are implemented to generate an acceptable initial concept which can be modified in the Functional module.
- Functional module
  In this module rule-based reasoning techniques are implemented to perform sensitivity studies on the primary parameters of the concept. With these studies a feasible concept is designed.
- Geometrical module
  This module automatically models and visualizes the concept. It uses feature-based and constraint-based modeling techniques.
- Central user interface (CUI)
  This module handles the communication between the other three modules.

For each module existing tools have been used. The following paragraphs describe the separate modules. We will illustrate their function with a case taken from aircraft design. It is based on a conceptual design study for a 70 passenger regional airliner [Franssen, 1996].

### 4.1. Case-based reasoning module

As suggested by its name, the Case-based reasoning (CBR) module applies case-based reasoning techniques to generate an acceptable concept from the design specifications. These techniques enable the use of design experience which is implicitly available in existing cases. Also, case-based reasoning is an approach to learning, since the result of succeeded design sessions can be added to the case-base, making it available for future design problems.

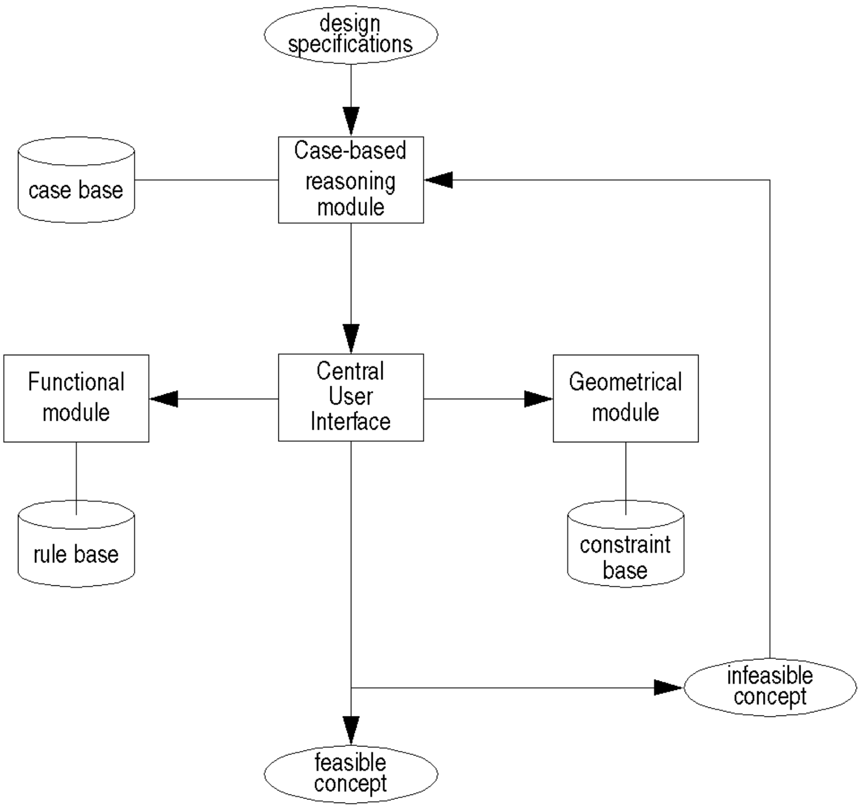


*Figure 3. Modular set-up of the AIDA-tool.*

A complete case-based reasoning process can be considered as a cycle of four sequential steps; see [Aamodt, 1994] and Figure 4:

- retrieval: find cases in the case-base which resembles the problem description;
- reuse: copy case-data or combine data of more cases;
- revision: evaluate the proposed solution; and
- retaining: put successful 'learned case' in the case-base.

The problem description defines the 'new case'. In the retrieval step the case-base is searched for cases with data matching the 'new case'. The cases with most similar data are retrieved. In this step the matching process is most critical.

In the reuse step data is copied from a 'retrieved case'. Usual the 'retrieved case' does not completely match the 'new case', i.e. the best matching case does not completely solve the problem. In that situation the data of other 'retrieved cases' can be combined. In other words, the best matching case is changed/adapted with data of other selected cases. This adaptation process requires domain knowledge and is very complex.

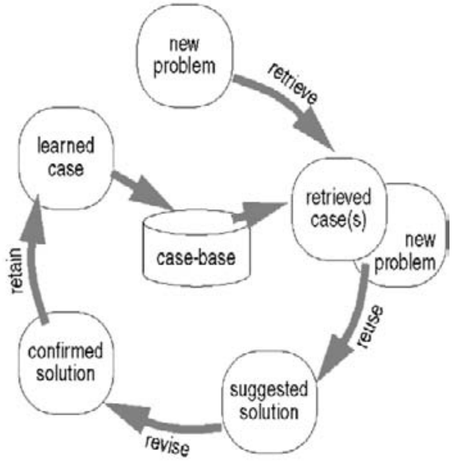


*Figure 4. The CBR cycle (adapted from [Aamodt, 1994]).*

The result of the reuse step, the 'solved case', is a suggested solution to the problem. It is evaluated and repaired when necessary in the revise step. The evaluation process is often performed by numerical tools. This process also requires domain knowledge, as does the repair process. The result is a 'tested/ repaired case', or a confirmed solution to the problem

The learning aspect is implemented by adding information about the confirmed solution to the case-base. The retain step handles the transformation from the 'tested/repaired case' into the 'learned case'.

In AIDA, only the retrieve, the reuse and the retain steps are implemented in the Case-based reasoning module. The evaluation in the revise step is taken care of by the Functional module, using rule-based reasoning techniques; see next paragraph. The CBR module has been developed in EADOCS [Netten, 1997, 1998], a design system for composite sandwich panels. In this CBR module the retrieve step, as well as the reuse and the retain steps have been implemented (see section 3); the revise step has been implemented in another module.

In aircraft design, the cases contain data about their function or performances, such as the range and speed, and data about their structure or physics, such as the weights and sizes. Also data which numerically expresses the quality of the aircraft is added, such as the wing-loading and maximum lift-coefficient; according to [Rosenman, 1994] these can be considered as behavioural data.

The CBR module consists of two parts. The first part generates an indexing network. This network provides an index to the cases by the use of parameter domains. These parameter domains allow qualitative labelling of the continuous parameter values, such as 'small and 'moderate' etc., to enable a kind of qualitative matching. The network is created off-line to improve the efficiency.

The second part uses the network to search for cases similar to the specified 'target set'. This is done on-line. For each part of the target set the matching results are shown, and the cases are ranked accordingly. The importance of each part of the target set is given by priority-values. Figure 5 shows a list of best-matching aircraft configurations.

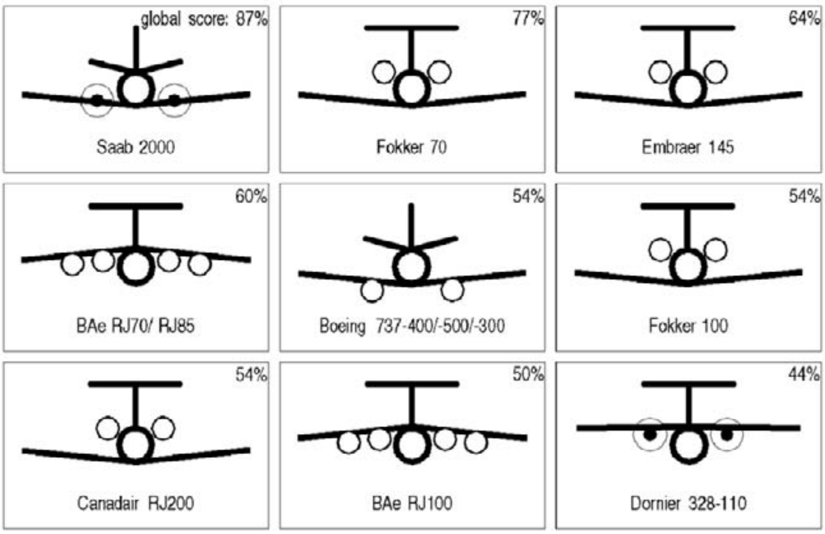


*Figure 5. An example of best-matching aircraft configurations.*

The strategy used for the CBR module is to first retrieve a 'best-matching' case, and then to reuse parts of other cases for adaptations. The adaptation process, however, disrupts the link between the functional and the structural data. Therefore the adapted case is probably not valid anymore. The adapted case should be evaluated before other adaptations can be usefully applied.

To adapt the case properly is difficult, due to the many interactions between the functional data and the structural data. Therefore a strategy is followed which should lead to as little adaptations as possible. A secondary target set is defined, consisting of the rest of the specifications which the 'best-matching' case does not satisfy, together with the most important structural and behavioural data of the 'best-matching' case. The result of the new matching process will give cases which resemble the structure of the 'best-matching' case, and which (partly) satisfy the functional requirements that the best-matching case does not meet. In Figure 6 this strategy is summarized.

Domain knowledge is used to support the adaptation process. Expert rules have been collected which may help with focusing on the relevant data. For instance, when the 'best-matching' case does not reach the specified speed (function), the designer should focus on the thickness of the wing and its sweepback angle (structure).

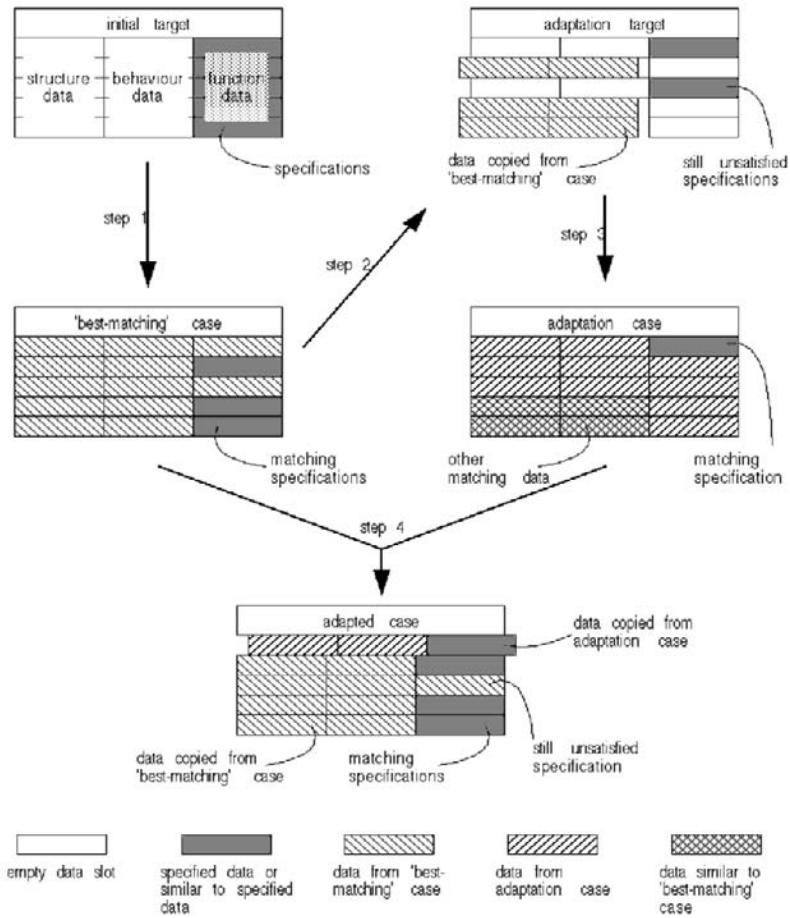


*Figure 6. Case adaptation strategy.*

The CBR module delivers a complete case, which may be inconsistent due to the adaptations. The complete structural data set is required by the Geometrical module in order to make a solid model of the concept. Some structural and some behavioural data is required by the Functional module when generating a relational network. They provide proper initial estimations which can be evaluated and modified.

### 4.2. Functional module

The Functional module supports the execution of parameter studies. These are used to evaluate and modify the adapted case as produced by the CBR module. The result is a feasible concept, according to the available knowledge. This knowledge is represented by numerical relations which express the heuristics such as collected in books on aircraft design [Roskam, 1987] [Torenbeek, 1982].

In the Functional module rule-based reasoning techniques are applied to generate a network of numerical relations. The rules implement heuristic knowledge and simplified physics in an algebraic format. The network of these rules links functional parameters (from the specifications) to structural parameters (from the designed object). With this network sensitivity studies can be performed to estimate the structural parameter values. This reasoning technique offers the flexibility to easily generate a different network for a different set of specifications.

The Functional module is implemented in Quaestor [van Hees, 1997], an expert governed system for the assembly, execution and maintenance of parametric design models. This tool has been developed to support ship design in the early phases of design by improving access to and control over design related knowledge.

Before Quaestor can be used, the rule-base has to be built. The rules represent numerical relations in an algebraic format. To each rule, conditions can be added to incorporate its limited validity. This is often the case with the heuristics and simplified physics. Within Quaestor the conditions are called 'constraints'. The third type of element within Quaestor is the parameter. The rule-base is built by one or more experts, which do not have to be the same persons as the designer which uses the Functional module.

The designer starts a Quaestor session selecting the parameters to be calculated, for example the desired functional performance characteristics. These are called the goal parameters. The inference engine of Quaestor searches the rule-base for relations which do calculate this goal parameter. The designer selects one of the suggested relations. Usually the new relation introduces other, unknown parameters. The designer can make the unknown independent or dependent. The parameter becomes independent when it gets a value, for instance a value generated by the CBR module. When the parameter is a function of other parameters then the parameter is set to be dependent and it becomes a new goal parameter for which other relations have to be found. So, a backward chaining strategy is applied.

The creation of the relational network is finished when no goal parameters are left. When the network is completed, the number of dependent parameters is equal to the number of relations. Quaestor uses Newton-Raphson and simplex methods to solve the set of relations, and calculate the goal parameters. Figure 7 shows a simple numerical link.

It is important to notice that Quaestor also searches for relations with the goal parameter on the right-hand side of the algebraic notation. This makes Quaestor very flexible. Instead of an algebraic relation also an external application can be part of the network. This possibility makes the module even more powerful. However, the input and output parameters of these applications have to be known in advance.

To perform parameter studies, independent parameters can be given an array of values. The resulting arrays of the goal parameters can be saved in an file, to be viewed graphically by the Central User Interface (CUI).

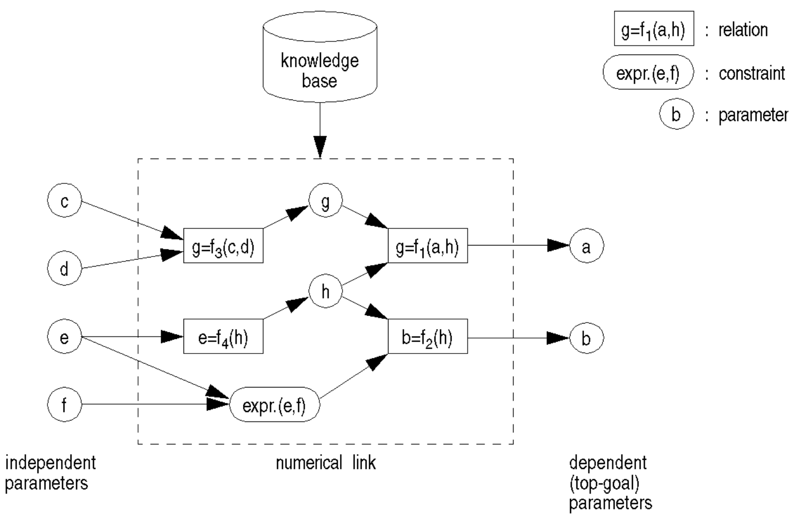


*Figure 7. A Quaestor template, linking independent with dependent parameters.*

### 4.3. Geometrical module

The Geometrical module models and visualizes the suggested aircraft concept. This gives the designer a visual feedback of the concept. The module can also deduce some geometrical properties, such as volumes and areas.

The module is implemented in Pro/Engineer [PTC, 1999], a commercial feature based solid modeller. In this modeller the solids are constructed with engineering features, such as holes, protrusions, rounds etc. Features can be combined into parts, which can be combined into assemblies. The features are defined and located by parameters and by constraints between parameters and features. With these relations Pro/Engineer is able to preserve the consistency of the model when parameter values are changed.

Pro/Engineer can handle the variation of continuous parameters very well. However, to change the definition of features, parts and assemblies requires knowledge of the package, which is not the intention of the Geometrical modeller. Therefore the aircraft concept model is constructed with pre-defined parts, such as the fuselage, the wing, the engines, the horizontal and the vertical tail-surfaces. The geometrical constraints between these parts keep them properly located.

It is possible to visualize different types of these pre-defined parts, for example turbofan and turboprop engines. Both types are pre-defined, and the parameter which defines the type of engine will automatically suppress the other types. This way the variation of the discrete parameters is managed.

This strategy of using standard aircraft parts is practicable because it is known which configuration elements are in the case-base. Figure 8 shows the hierarchical structure of the aircraft model.

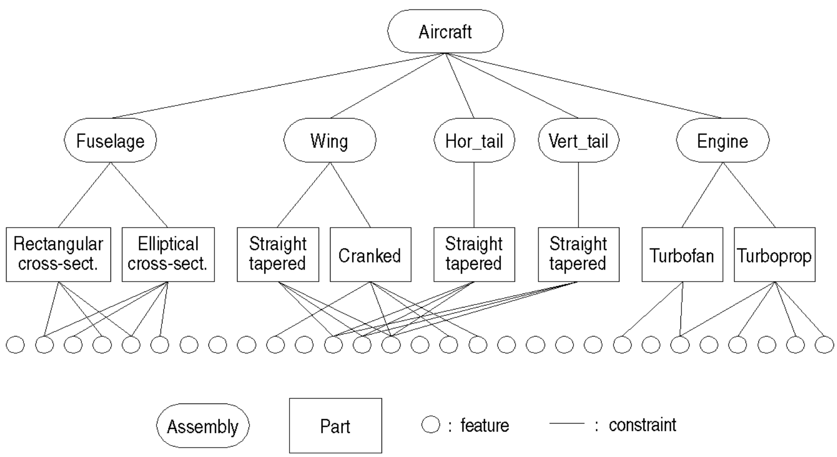


*Figure 8. The hierarchical structure of the aircraft.*

The Geometrical module is able to show a three-dimensional view as well as three side-views of the model. Figure 9 gives an example of a three-dimensional view. The model can also saved in several graphical formats, for use of other computer programs.

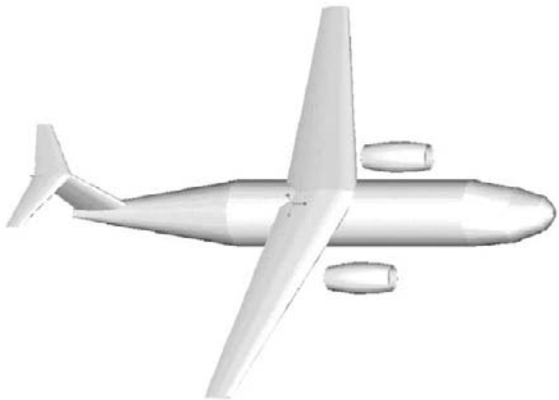

*Figure 9. A shaded, 3-dimensional view of a concept design.*

### 4.4. Central user interface

The Central User Interface (CUI) handles the interaction between the other three modules and the designer.

It reads the data generated by the CBR module, of the adapted case, filters it and directs the required data to the Geometrical module. The CUI is also able to present the results of the sensitivity studies, performed by the Functional module, in a graphical format. See Figure 10.

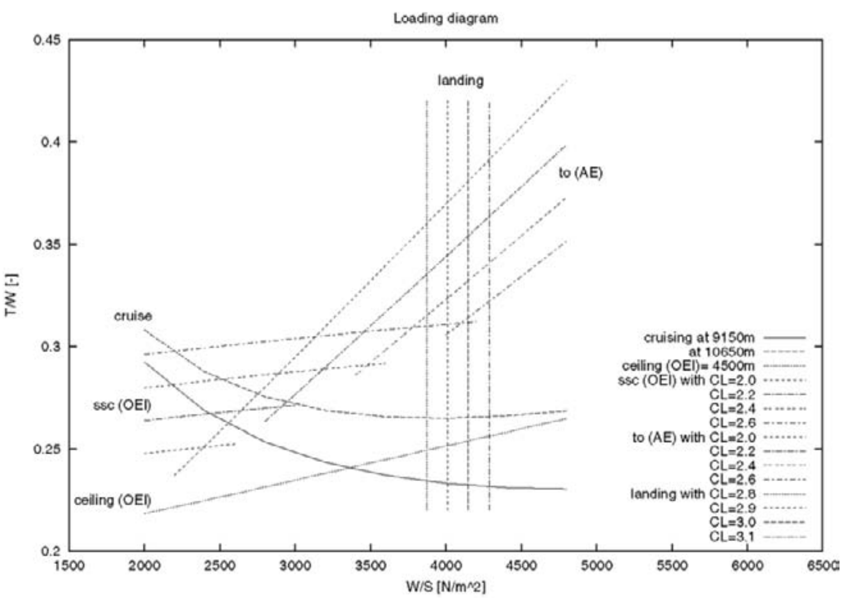


*Figure 10. Sensitivity studies of some behaviour parameters in aircraft conceptual design.*

## 5. Conclusion

We have analysed the conceptual design process, and suggested a design cycle that uses CBR-techniques to propose and adapt initial concepts, RBR-techniques to analyse and evaluate the concept, and geometric modeling techniques that model the concept automatically. These three techniques are implemented in three independent modules, with a central user interface to connect the modules.

The system has been evaluated for the conceptual design of aircraft. This application allows the decomposition of the design product into basic components. The current approach therefore relies heavily on the decomposition of the design product into basic components. For a more general approach without the basic components the case representation will need to be more comprehensive.

Another aspect of further research will be the implementation of the separate modules into one integrated framework.

## Acknowledgements

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# Construction Safety: At the Crossroads of Building and Design.
## The Case of the multifunctional Bos & Lommerplein estate, Amsterdam.

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**Abstract**

Bos & Lommer is a district in the west of Amsterdam. The spatial plan for Bos & Lommer was based on the General Extension Plan (*Algemeen Uitbreidingsplan /AUP*), which was designed by Van Eesteren in 1935. In the 1960s this plan was seriously impaired by the E10 motorway, which cut the area in two, leaving it without a heart – until 2004, when it was reunited by a complex of buildings constructed on viaducts. The new centre, consisting of the district office, 96 apartments, a few dozen businesses and shops, a two-storey parking lot with capacity for more than 500 cars, and a market place, was completed in the same year. Less than two years later, in July 2006, this whole multifunctional complex had to be urgently cleared, because its safety could not be guaranteed. Serious cracks had appeared in the parking deck – so serious that it caved in under the weight of a beer lorry. Further investigations exposed even more design and construction errors.

The residents had to wait until Christmas 2006 before they could return to their homes. In the meantime, some additional and costly operations had to be carried out. The shops and businesses re-opened in January 2007.

On 20 July 2006, Amsterdam's mayor, Job Cohen, set up an Investigatory Commission consisting of former housing minister Margreeth de Boer (Chair), Lex Michiels (Professor of Public Law, Tilburg University) and the author. This Commission published its final report on 15 January 2007.

The remit of the Bos & Lommer Commission was to establish the course of the decision-making on the complex since 1990, to ascertain how the responsibilities were allocated and to identify the causes of the errors. The emphasis had to rest on the 'safety' aspects and on ways of preventing similar situations in the future.

The investigations revealed that the planning and realisation of the Bos & Lommer complex were anything but exceptional. What happened there could have happened anywhere in the Netherlands and elsewhere. So, some important lessons can be learned from this case. This paper traces the causes of this new planning disaster and try to specify guidelines for designing and building complex projects, based on an operational risk analysis, introducing more quality management in the contributions of each participant and strengthening the system responsibilities for the whole project. There is certainly scope for a better integration of design and building construction, to improve the construction safety of complex building projects.

Keywords: Construction safety, planning disaster, structural disaster, Amsterdam.

## 1. Introduction

Real-estate development has always been fraught with risks. Public values such as safety, health, and the environment are covered by European building regulations. Theoretically, the safety of real-estate development is guaranteed by national building regulations, but this is not how things work in reality – for a number of reasons:

- The information which the plan assessors (mostly municipal) have at their disposal is usually incomplete [see e.g., report by Van Overveld Bouwbesluit Advies];
- The plan assessors lack the time (and sometimes the expertise) to check everything. They work within constraints and often miss important points because of pressure of time [ideally: a risk analysis should form the basis] [see Van Overveld Bouwbesluit Advies];
- Frequently, the building department (mostly municipal) also lacks the time and expertise to check everything. They too work within constraints and miss important points. The construction certainly does not always match the plans [again, ideally, a risk analysis should form the basis] [e.g., roof struts, façade fixation; impact-resistant pillars in parking lots, impacts of gas explosion];
- The chief architects, structural engineers, contractors and subcontractors act strategically to try to prevent their plans and construction work from being rejected. The ISO certification which is held by many businesses in the Netherlands implies that certain procedures are followed but does not guarantee quality. ISO approval seems to be more of a marketing tool than anything else;
- The market players tend to concentrate primarily on returns and cost-cutting in a bid to survive the price competition;
- The market players try to avoid duplicate work, despite the fact that the 'double-check' principle is essential to proper supervision. Cut-throat competition often prompts them to economise on activities designed to safeguard continuity between the building process and the building project. Construction firms and other players often create the impression that they are performing a thorough risk analysis, but experience indicates that this is scarcely ever the case.

These alarming conclusions have not been plucked from thin air. On the contrary, they were reached after an examination of the planning and construction process for the recently built multifunctional Bos & Lommerplein complex in Amsterdam. The decision-making for the development of the Bos & Lommerplein complex plays a central role in this paper. The findings will be placed in a broader context and eventually lead to a number of conclusions and recommendations.

Many years ago, Peter Hall published his seminal work Great Planning Disasters (Hall, 1980). Since then, a great many structural disasters have occurred in the world. On 11 July 2006, less than two years after its completion, the multifunctional Bos & Lommerplein in Amsterdam had to be evacuated. The district office, 27 shops and businesses, 96 apartments and a covered two-storey parking lot (over 500 places) lay empty from 11 July till 21 December 2006. The evacuation cost the municipality over 8 million euros, which it is now trying to reclaim from the builders.

Bos & Lommerplein certainly qualifies as a serious candidate for 'planning disaster' status. In this paper we shall trace the project planning and decision-making process and identify the factors that enlarged the technical risks. We shall end with recommendations on how to improve the planning and construction of multifunctional estates in the risk society.

Section 2 describes the origins of the Bos & Lommerplein complex. Section 3 concentrates on the many changes in the functional programme. Section 4 presents the description of the project as eventually realised. Section 5 sketches the dramatic developments between the completion of the project and the emergency evacuation. Section 6 summarises the technical problems which have appeared in Bos & Lommerplein. Section 7 deals with recent building disasters and shows that Bos & Lommerplein is not unique in the Netherlands. Sections 8 and 9 present conclusions and recommendations.

## 2. Origins of the Bos & Lommerplein complex

The Bos & Lommer district in the west of Amsterdam forms part of the General Extension Plan (Dutch abbreviation: AUP) for Amsterdam, which was designed by the city planner Cor van Eesteren and approved by the Municipal Council in 1935.

In 1965 and 1966 the western edge of the Amsterdam Ring Road – the A10 – was built. Thise road cut straight through the planning area from south to north. The site that was originally designated as the heart of Bos & Lommer was now a motorway and, for a long time, was dominated by a viaduct and a vast, open stretch of urban space with a few scattered buildings tormented by the noise of the traffic.

In 1988 a decision was taken to develop the central area of Bos & Lommer. This led to a Statement of Intent entitled 'Bos & Lommer: a district without a heart' which was published on 24 October 1990. It was followed some time later, on 19 May 1992, by a Preliminary Report entitled 'Heart's Desire for Bos & Lommer', which elaborated on the Statement of Intent. In 1994 the starting specifications were published in a document entitled: 'Take Heart'. The functional programme for the entire planning area was as follows:

- a minimum of 300 homes;
- a maximum of 15,000 $m^2$ of gross surface area for offices;
- a maximum of 5,000 $m^2$ of gross surface area for central functions;
- around 2,500 $m^2$ of gross surface area for socio-cultural amenities;
- a maximum of 7,000 $m^2$ of hotel space (3-star);
- a restaurant with a jetty along the Erasmusgracht;
- parking places, according to the set norms, inside and outside;
- recreational space on the Bos & Lommerplantsoen;
- a market with space for 125 stalls on the Gulden Winckelplantsoen.

Some of the building would take place across the A10: two viaducts, upon which office premises would be built (bridge buildings).

On 25 April 1994, the District Council, the real-estate developer Multi Vastgoed, and the building firm Hillen & Roosen signed a partnership agreement under which Multi Vastgoed would develop the offices, the socio-cultural amenities and the parking garage, and Hillen & Roosen would take charge of the housing. The agreements between the District and the market players were confirmed and fleshed out in an Agreement Document of 16 January 1997.

## 3. Changes in the functional programme

In 1998, when the Urban Planning Programme was published, the functional programme turned out to be a lot more intensive than was envisaged in the original specifications:

- the number of homes had increased from 300 to 395;
- the gross surface area for offices had risen from 15,000 to 24,000 $m^2$;
- the gross surface area for central functions (shops etc.) had risen from 5,000 to 6,000 $m^2$;
- the space for socio-cultural amenities had risen from 2,500 to 3,500 $m^2$.

The total site consisted of five sub-areas (see Figure 1):

| | |
|---|---|
| Sub-area 1: | Gulden Winckelplantsoen |
| Sub-area 1a: | Foyer |
| Sub-area 2: | Viaduct with bridge buildings |
| Sub-area 3: | Bos & Lommerplantsoen |
| Sub-area 4: | Jan van Schaffelaarplantsoen |

The Bos & Lommerplein complex falls into sub-area 1. According to the Urban Planning Programme (1998), this sub-area would accommodate 52 homes, 5,000 $m^2$ of office space, 5,000 $m^2$ of central functions and 2,100 $m^2$ of socio-cultural amenities.

In 2000 the Urban Plan for Bos & Lommerplein and the surroundings was published under the title 'The Heart on the A10'. Again, it turned out that the functional programme had been intensified. Table 1 compares the functional specifications of the Urban Planning Programme (1998) and the Urban Plan (2000).

### 3.1. Changes in the housing programme (2000-2001)

According to reports by the Bos & Lommerplein Steering Group, the number of homes in sub-area 1 increased from 52 to 77 to 96 in a relatively short time and the most frequent apartment breadth of 8.10 metres shrunk to 5.40 metres. The latter change, which became effective in January 2001, had profound structural implications. Prior to 2001 it was consistently maintained that the apartments had to have a load-bearing structure with a centre-to-centre distance of 8.10 metres, as this was also the measurement for the shops on the floor below.

**Table 1: The Urban Planning Programme (SPvE) compared with the Urban Plan (SP) for sub-area 1**

| Function | Urban Planning Programme (SPvE, 1998) | Urban Plan (SP, 2000) | Difference |
|---|---|---|---|
| Central functions* (shops) | 5,000 $m^2$ | 5,500 $m^2$ | + 500 $m^2$ |
| Other central functions | 5,000 $m^2$ | 7,700 $m^2$ | + 2,700 $m^2$ |
| Blue Tower | 6,500 $m^2$ | 6,500 $m^2$ | - |
| Socio-cultural | 2,100 $m^2$ | 3,500 $m^2$ | + 1,400 $m^2$ |
| Homes | 52 | 77 | + 25 |
| | Current situation | New situation | |
| Parking* | 195 | 490 in parking garage + ground level | + 305 |

* The area for the Albert Heijn (1800 $m^2$) and Marca/Vomar (2600 $m^2$) supermarkets is not included in the programme.

Source: Urban Plan (*Stedebouwkundig Plan*), 2000.

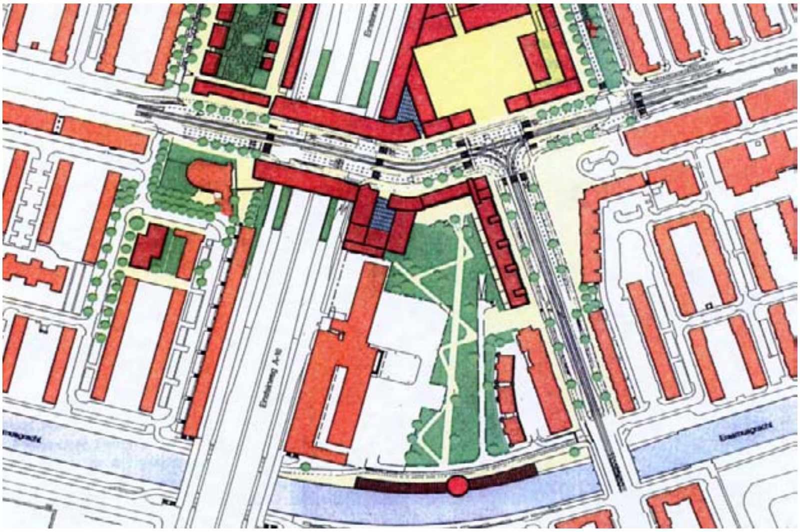

*Fig. 1a. Urban Plan for Bos & Lommerplein and the surroundings Source: Urban Plan (Stedebouwkundig Plan, 2000)*

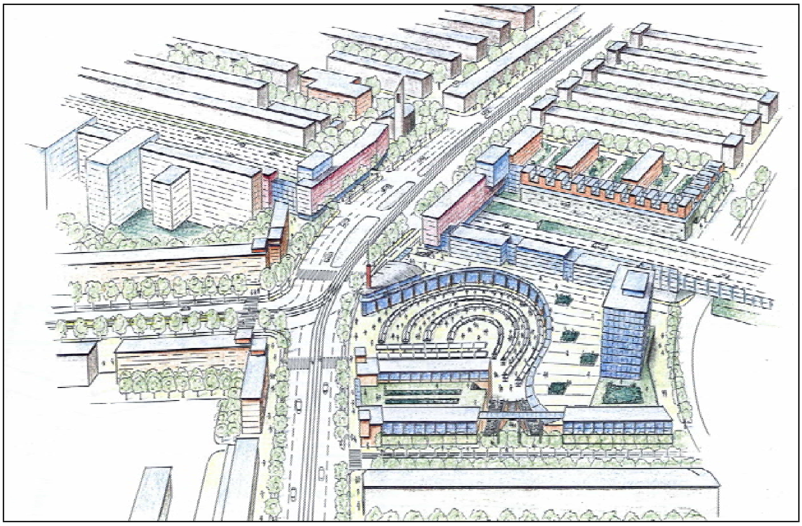

*Fig. 1b. Birds-eye impression Bos en Lommerplein and surroundings according to SpvE (1998) Source: Borough of Bos and Lommer, Hillen & Roosen and Multi Vastgoed, 1998*

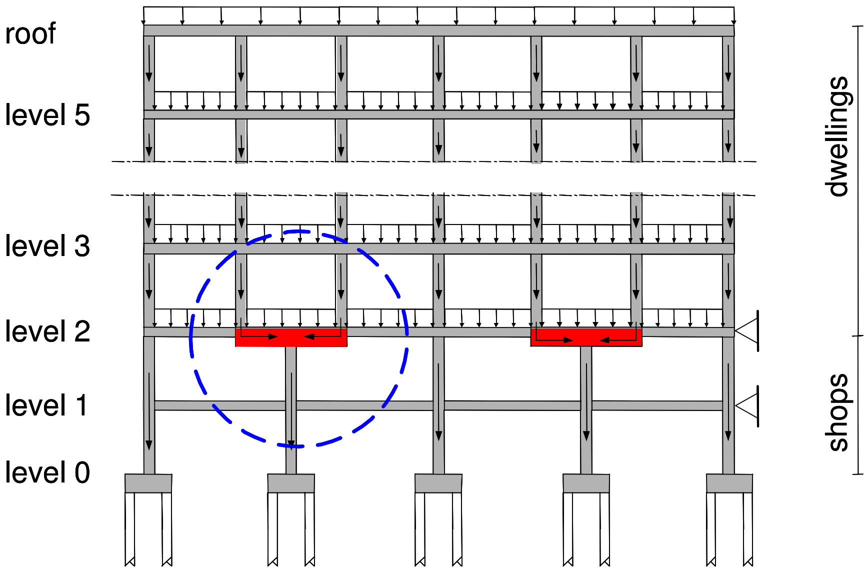


*Fig. 2. Cross-section of the Bos & Lommerplein apartment complex*
*Source: Bos & Lommerplein Commission, 2007a: 155.*

After the centre-to-centre distance of the apartments had been shortened from 8.10 to 5.4 metres, only one of the three load-bearing walls on the floor above extended down to the shops. The load-bearing function of the two other walls was now taken over by a floor approximately one metre thick. Later, Professor Cees S. Kleinman, technical advisor to the Municipality of Amsterdam, discovered that the reinforcement for this thick floor had been wrongly calculated. The Municipality had, however, approved these calculations when assessing the structural design.

It is clear from the cross-sectional diagram of the apartment complex in Figure 2 that the thick floor between the apartments and the shops had to bear the strain of two of the three load-bearing walls in the dwellings.

### 3.2. Changes in the functional programme for the district office and the socio-cultural amenities

On 15 January 2002 the District signed a purchasing contract with Multi Vastgoed developers. Over seven months later, the District Executive made some robust changes to the functional programme (see Table 2).

**Table 2 Surface area of the District Office and the socio-cultural amenities as recorded in the Purchasing Contract with Multi Vastgoed (15-1-2002) and in the letter to Multi Vastgoed (27-8-2002)**

| | Purchasing contract with Multi Vastgoed 15-1-2002 | Letter to Multi Vastgoed 27-8-2002 |
|---|---|---|
| District office | 6,645 | 5,997 |
| Vacant | - | 1,446 |
| Library | 1,760 | 1,471 |
| Impuls, Community Centre | 1,564 | 1,000 |
| Crèche | 409 | 602 |
| Total (m2 net free rentable space) | 10,378 | 10,516 |

*Source: Bos & Lommerplein Commission, 2007b: 56.*

When the rents were announced, the Impuls Foundation backed out and the crèche was shelved.

The rent for the crèche also proved too steep for the municipal Welfare & Education sector, so the crèche disappeared altogether, adding another 602 $m^2$ to the vacant space. Lastly, the Bos & Lommer social services department (*Stichting Maatschappelijke Dienstverlening Bos & Lommer*) withdrew as well.

These setbacks were partly counterbalanced by one modest stroke of luck: the PCH (*Parkeer Combinatie Holland*) parking association wanted to rent more space inside the district office building.

It seems therefore that, during the preparation phase, the Bos & Lommer Executive Board had no realistic idea of the demand for socio-cultural amenities. In effect, the functional programme for Bos & Lommerplein appears to have been more of a gap-filler than a guiding factor.

## 4. Project description

A total of three building permits were requested and granted for the Bos & Lommerplein complex. The first application (parking garage + floors 1 and 2) was submitted on 13 September 2001 and granted on 7 December 2001. The second (office and shops) was submitted on 16 November 2001 and granted on 15 May 2002. The third (96 apartments) was submitted on 27 November 2001 and granted on 7 June 2006. The complex was therefore split into three components, built partly on top of one another.

Figure 3 shows the layout of the complex and Figure 4 presents a cross-sectional view of the three components.

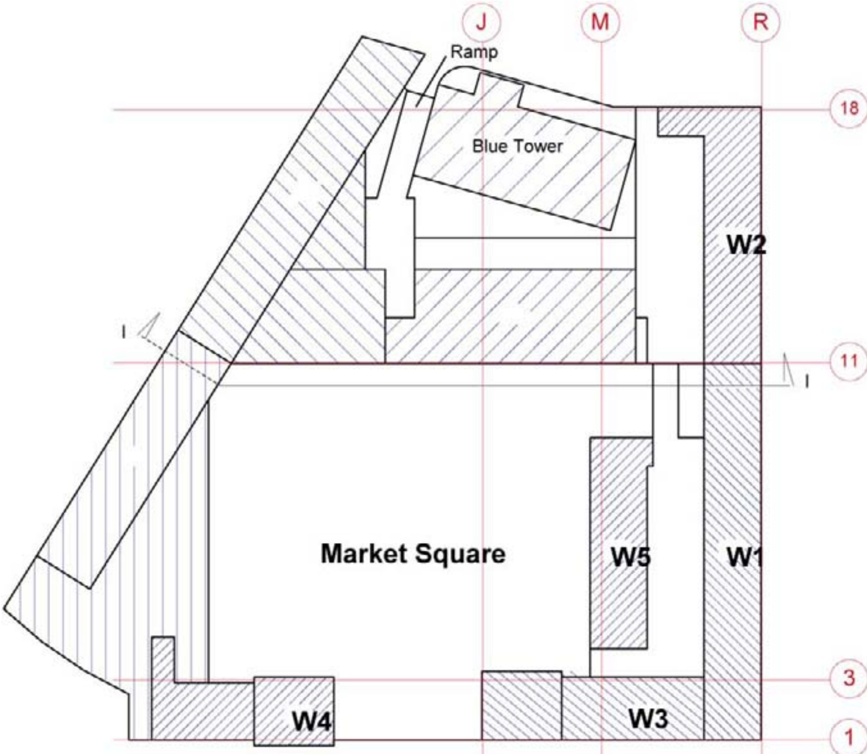


*Fig. 3. Scematic plan of the Bos and Lommerplein complex*
*W1 – Dwellings, W2 - Shops underneath dwellings,*
*W3 – Offices, W4 - Shops underneath offices,*
*W5 - Parking Garage and Market Square*
*Source: Wijte, 2006*

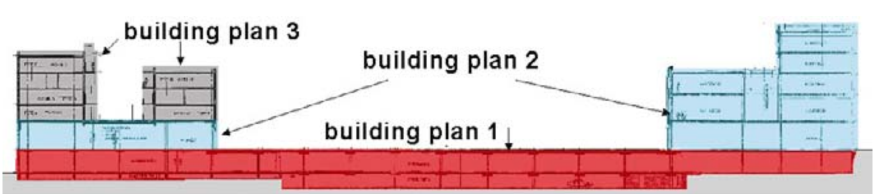


*Fig. 4. Cross-section of the Bos & Lommerplein complex*
*Source: Bos & Lommerplein Commission, 2007a: 216.*

## 5. From handover to evacuation (2004-2006)

The festive opening of Bos & Lommerplein took place on 3 June 2004. The district office became operational over six months later on 17 January 2005.

Another year later, on 1 February 2006, a lorry carrying barrels of Bavaria beer (weighing 11 tons) drove across the market place – also the roof of the parking garage – and caused structural damage. Four centimetres of local subsidence were discovered in the roof of the parking garage. The struts under the concrete slabs had given way. Several apartments in the complex had to be evacuated. Once the roof had been shored up and once a maximum axle weight of five tons per vehicle had been introduced and specific enforcement arrangements were in place, the authorities pronounced the complex safe and the market place re-opened to vendors, shopkeepers and the public on 3 February 2006. By then, the evacuated residents had returned to their apartments.

The report by GAB Robins Risk Analysis Services BV (G-RAS, 2006), commissioned by the Municipality of Amsterdam and the Bos & Lommer Executive, appeared on 21 February 2006. It was experienced as reassuring. The report by TNO on the construction of the parking garage (Gijsbers *et al.*, 2006) was also interpreted as an indication that the structural problem (wrongly constructed struts for the roof slabs) was local and incidental. To make extra sure (and because the District insisted on it) Fortis, the owner of the parking garage, the shops and the offices in Bos & Lommerplein, instructed Intron BV to test the structure at other points in the complex. Intron's report appeared on 5 July 2006 (Boutz, 2006). The conclusions were disquieting: the concrete reinforcement at various places deviated from the specifications in the drawings. The safety of the complex could no longer be guaranteed. The verdict was presented to the District Executive on 10 July 2006.

The reinforcement deviated from the specifications in the drawings at 12 of the 14 tested locations. Similar discrepancies were discovered in concrete beams which formed part of the construction above ground level. In some cases the discrepancies were so great that urgent restoration was needed. By now, the research findings had also prompted the conclusion that the defects were not merely incidental; in fact, the structural safety of the entire complex was at risk. Besides emergency restoration, the construction of the complex would have to be appraised in order to get a clear picture of the safety situation. Right up to the moment that these research findings were published, there was no demonstrated level of safety. There was incontestable evidence that various structural components were unsound.

On Tuesday 11 July 2006 the Bos & Lommer Executive ordered the evacuation of the apartments and shops on Bos & Lommerplein. The mayor issued an emergency decree to vacate the area immediately. The area was then closed off to everyone, apart from officials in the performance of their duty.

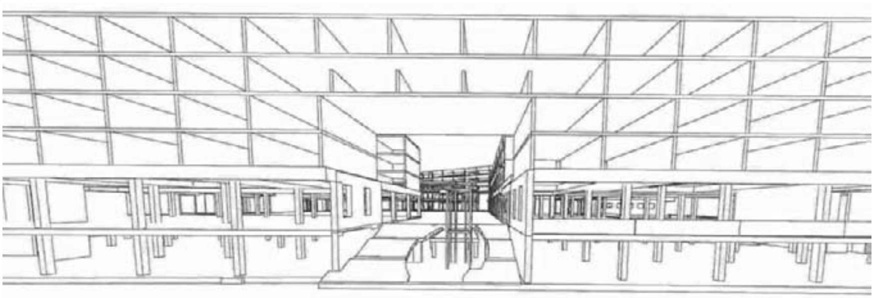

*Fig. 5. 3D view of the structure of the dwellings and the storeys below on the east side. Source: Wijte, 2006.*

## 6. Technical problems

After the evacuation the technical aspects of the Bos & Lommerplein complex were examined in detail by three structural engineering firms: Hageman; Cunningham & Lindsey; and Intron. They diagnosed the following technical problems:

1. Contrary to the specifications in the drawings: insufficient reinforcement in the struts under the roof of the parking garage;
2. At a number of selected locations the actual reinforcement differed from the reinforcement prescribed in the drawings. Professor Kleinman, technical advisor to the Municipality of Amsterdam, diagnosed two more problems:
3. Wrong design for the reinforcement in the thick floor between the apartments and the shops (Figure 2);
4. Questionable details in the reinforcement in the struts referred to in (1) (see Kleinman, 2006).

The Bos & Lommerplein Investigatory Commission endeavoured to identify the causes of these technical defects and submitted the following observations:

1. The preparation phase was dynamic: it was not driven by the functional programme, which changed constantly. The programme became more intensive as time progressed. The logic in the design was seriously undermined by some of these alterations. One typical example is the changes to the support structure for the shops and the apartments, and the emergency measure in the form of the thick floor (see Figure 2).
2. The market players had a relatively strong position in the preparation phase whereas the Municipal District's position was relatively weak. There was no sign of any form of competition. The decision to do business with Multi Vastgoed and Hillen & Roosen was not based on market conditions. No explicit go/no-go moments were introduced into the process. The maxim seemed to be 'all friends together from cradle to grave'. In the contract that was concluded between the private companies and the District in 1994, the responsibility for the functional programme rests primarily with the private companies. Presumably, a lot of competitive tendering went on between the main contractor Hillen & Roosen and the 50 or so subcontractors. Multi Vastgoed and Hillen & Roosen economised so heavily on the costs that the preparations were not internally supervised. The so-called 'double-check' principle was not applied. Hillen & Roosen's ISO certification proved no guarantee for quality. Neither Hillen & Roosen nor the District performed a risk analysis to serve as a basis for their activities.
3. Another – not unfamiliar – problem which emerged (Vambersky, 2003) was the approach to Bos & Lommerplein: there was too much fragmentation and no clear all-encompassing final responsibility. Three firms of architects and two construction agencies were recruited. But there was no senior coordinating construction engineer. The complex was split abruptly into three parts for which building permits were separately requested and granted.
4. There are no records of supervision by the contractor, the director or the District. The same goes for the plan assessment. No 'Black Box' to report the plan assessment, the building work or the supervision.

5. Steel-fixing is apparently a highly strategic and fragile activity. The documentation from the Bos & Lommerplein Investigatory Commission (2007a) indicates that reinforcing steel was stolen at least once from the building site, that some steel-fixers were unable to read drawings, and that the wrong reinforcement bars were repeatedly lying ready when fixing was due to start. As if that were not enough, one of the two steel-fixers went bankrupt during the project. So, there was an unusual amount of improvisation in the steel-fixing. The timetable for pouring the concrete placed the steel-fixers under huge pressure. The main contractor does not appear to have regularly checked the steel-fixing. The communication between the steel-fixer and the main contractor left much to be desired. Nothing at all is known of the Municipal District's role in supervising the construction and approving the steel-fixing.
6. It may be concluded from an independent plan assessment performed later by Van Overveld Bouwbesluit Advies, who used the same documents as the municipal plan assessors in 2001-2002, that some crucial information was missing. This related to the following assessment items (Onderzoekscommissie Bos & Lommerplein, 2007a: 220):
    - Resistance to fundamental stress on floor partitions, windows (wind load) and roofing (fastening);
    - Resistance to exceptional stress on floor partitions and roofs (impact load);
    - Electricity and (emergency) lighting facilities;
    - Gas facilities;
    - Soundproofing between the rooms in the apartments;
    - Running (hot) water facilities.

There were no energy performance calculations for the apartments; the application for a building permit for the apartments (plan 3) should therefore have been rejected.

## 7. Recent structural disasters

The Investigatory Commission realised that it could not submit broad policy recommendations for the construction industry and the government on the basis of one single case without raising methodological questions. It therefore made a close study of the context of the case and looked at a number of recent developments in the Netherlands and elsewhere.

Though building standards are tightly regulated by the Housing Act, there have been regular instances of very serious structural problems in the Netherlands in the past five years.

For example:

- Collapsed balconies in an apartment block in Maastricht, which claimed two lives;
- The roof of a supermarket in Klazienaveen, which caved in under the weight of snow during the night of 2 March 2005, after a very busy day;
- A TNT Post distribution centre in Hengelo: the warehouse roof (measuring 20,000 square metres) could not cope with a 40-centimetre layer of snow in November 2005;
- The collapse of a car deck built above a reception hall in the Van der Valk hotel in Tiel in February 2002 did not cause any serious casualties, but if the concrete block of 15 x 40 metres had fallen one hour earlier, the consequences would have been catastrophic: a busy computer fair had just ended in the space below;
- The flight tower that was being built for Het Park Theatre in Hoorn collapsed at around 4 a.m. on 11 April 2000. Dozens of workmen had been in the building during the day;
- On 5 August 2002 the roof of the Leysdream event centre and indoor tennis hall in Roosendaal collapsed;
- In 2002 and 2003 the facade elements of the Bonnematoren in Leeuwarden became loose and felt down.

Many of these incidents only just escaped becoming a major catastrophe. The Bos & Lommer problems would not be out of place in this list.

All these incidents point to structural defects in the building. The literature (Derkink & Mans, 2006: 6) concludes that these are often caused by:

- clients who do not pay enough attention during the management of the (sub)projects;
- miscommunication between the parties on matters of structural design;
- lack of coordination and overall management across the various parties (designers, contractors, suppliers, building firms);
- a fixation on price at the expense of quality;
- design errors, including insufficient warning and redundancy in the construction;
- incomplete information and inadequate checks in the building permit applications;
- inadequate treatment of alterations during design and execution;
- poor quality control: internally and by the project organisers;
- focusing on the apportionment of blame rather than on feedback or useful lessons when problems arise.

The report *Leren van instortingen* (Learning from Collapses) (Derkink *et al.,* 2005) also indicates that the causes of such incidents lie mainly in the organisation of the building process. Structural safety is the duty of many different players: the client, the architect, the structural engineer, the local authority, the building department and its inspectors, the contractors, the suppliers and the sub-contractors. The responsibilities are diffuse and communication and coordination are often haphazard. A recent report by the Dutch Safety Board (*Onderzoeksraad voor Veiligheid/OVV*) entitled *Veiligheidsproblemen met gevelbekleding* (Safety problems with gable cladding, OVV, 2006a) highlighted the existence of certain structural problems in a great many buildings. Two VROM reports *Bouwkundige schades t.g.v. sneeuwval* (Structural Damage from Snowfall, 2006) and 'Collapses of Light Flat Roofs /2003b) deal specifically with the (dangers of) collapsing roofs after heavy snow and rainfall respectively. Heavy downpours caused the roofs of several large buildings to collapse on 24 August 2002. Within a single weekend snow caused over 90 buildings to collapse entirely or partly in the Netherlands or it permanently buckled the structure of the roof. The VROM Inspectorate holds that flat roofs need special treatment. But many thousands of buildings have flat roofs – around 20 cave in every year in the Netherlands.

The reports on the fireworks tragedy in Enschede (Oosting Commission, 2001), the pub fire in Volendam (Alders Commission, 2001) and the fire in the cell complex at Schiphol-Oost (Dutch Safety Board: OVV, 2006b) are also relevant in this context as they provide insight into the problems of supervision – not least structural supervision.

The Oosting Commission, which investigated the fireworks tragedy in Enschede, concluded that when an accident implies multiple responsibility, there is a risk that those involved will claim that they played only a minor part in the whole. The same conclusion appeared in the report on the fire in the cell complex (Dutch Safety Board: OVV, 2006b). Tight orchestration is imperative wherever responsibility is widespread. The Dutch Safety Board also concluded that the respective organisations were not critical enough of their responsibilities and how to fulfil them. A similar pattern emerges in earlier reports by the Dutch Safety Board and in the investigations into the pub fire in Volendam and the fireworks tragedy in Enschede (Dutch Safety Board: OVV, 206b).

Van Leeuwen (2006a) maintains that the fragmentation of tasks and responsibilities has become commonplace in the Dutch building sector. Beekhuis (2006) also points to the problems which arise when one main contractor engages many separate sub-contractors: "All of them, regardless of their remit, go in search of the cheapest sheet-piles, floors, pillars and roof constructions. Hopefully, this will all come together at the building site and result in a safe building. But who checks on the client's behalf that all the elements are combined in a safe and responsible way? Usually no-one! So the structural cohesion is lost. The safety that sounds so good on paper is actually undermined in practice. This is why the board is so adamant about appointing a coordinating consultant engineer."

Vambersky concedes that there are certainly plausible reasons for outsourcing parts of the work to sub-contractors and suppliers:

> *"This has evolved partly through the desire for specialisation; in other words, expertise in a specific part of the construction process so that you can deliver a top-quality product. On the other hand, it is a question of costs. For instance, if the contractor employs his own steel-fixer, he will probably have too much work for him at some moments and not enough at others. Wages still need to be paid during periods of surplus capacity and this, in turn, drives up the costs. Hence, the contractors need to outsource as much work as they can to sub-contractors, suppliers et cetera. They also try to prefabricate many more elements off-site. I expect these trends to get stronger in the future."* (Interview Vambersky, 27 October 2006)

In the *Cobouw,* Vambersky singles out another factor (Vambersky, 2003)

> *"All designers are driven by an ambition to realise their designs in new, ground-breaking forms, materials, technologies and constructions. They are encouraged by clients and users who want to make a name for themselves with their buildings and constructions. The building specifications are also getting more complex and demanding, and more and more disciplines are becoming involved."*

So, many parties want more expedient and more complex construction. But that requires time and attention. The Commission again quotes Vambersky (2003):

> *"The paradox is, however, that, for several decades now, the trend seems to have been moving in the opposite direction. Monitoring, supervision and enforcement are subject to cost-cutting on all fronts. The structural engineers are selected on the basis of price instead of quality – prices that do not even cover the standard work, let alone support the ground-breaking ambitions, the monitoring of structural cohesion and the accompanying safety. People are under the impression that somewhere in the process someone is monitoring quality and safety. However, this needs to be organised, and often it is not… It is a matter of misplaced economising, culture and underestimation at many levels in and around the design, construction and preparation process."*

# 8. Conclusions and recommendations

## 8.1 General conclusions

Most of the time responsibility in and around the construction industry is badly organised. In the Netherlands responsibility is usually commensurate with the size of the pay packet. Parties often try to avoid responsibility by erasing traces of potential errors. It is in their interest to get rid of 'the evidence' (e.g. daily and weekly construction reports; building inspection reports). Solution: regulations which ensure that information on plan assessment, execution and inspection is stored safely for a long period of time (at least ten years). The Black Box.

The more complex the project, the more important it is to clearly and effectively allocate responsibility in the system: to the client, the designer, the engineer, the contractor, the plan assessor and the building inspector. It is not only the quality of the components that needs to be guaranteed but also – and perhaps above all – how the components and the tasks fit together: each responsibility in the process requires, amongst other things, proper interface management.

Uncertainties and risks must be addressed in a professional and businesslike manner. Risks need to be quantified as far as possible, so the appropriate empirical references need to be on hand. The building sector should learn from the mindset of insurance companies. The sections that follow set out the recommendations of the Bos & Lommerplein Investigatory Commission on the role of the public authority as a principal (Section 8.2), public-private partnerships (Section 8.3), cohesion and quality in the preparations (Section 8.4) and execution of the building plan (Section 8.5). Finally, Section 8.6 discusses the phenomenon of the fatal deadline.

## 8.2 Public authority as a principal

1. Strengthen the administrative and the political role of the public authority as a principal. Set a well-prepared functional programme for inner city locations which serves as a guideline for the further development of the plan. This programme should be flexible enough to keep pace with market trends.
2. Base the budgets more on recently realised projects. This will enhance the democratic nature of the decision-making and provide the market players and members of the public with an anchor.
3. Rationalise more in terms of alternatives, also in relation to the costs and benefits in each phase. When interim choices are made on the basis of an explicit balance of the costs and benefits of each alternative, make sure that proper attention is paid to the uncertainties and risks.

## 8.3 Public-private partnership

1. Sign contracts with market players only after drawing the benefits of market forces. It is not a question of the candidate with the cheapest tender but the candidate with the most added value (returns minus costs).
2. Base the choice of market players as little as possible on land positions or ground lease rights. Be guided by the functional programme. Compulsory sales are tiresome but an effective tool for owners who are unwilling or unable to realise the official designation for the land.
3. Explain explicitly in the functional programme for a development area how you intend to safeguard the public values (including safety, healthy, energy saving and sustainability).
4. Reach agreement with the market players on a process architecture which includes a phasing system with some go/no-go moments when the project and/or the alliance can be abandoned or adapted.

## 8.4 Strengthen cohesion and quality in the preparation phase

1. The parties involved in the preparation phase should, where possible, demand recognised building-sector certification. The employees should be properly trained and have sufficient experience. These requirements present major tasks for institutes of secondary and further education and, especially, post-initial education (lifelong learning).
2. The parties involved in the preparation phase should follow procedures which guarantee competent internal supervision. This supervision should be reflected in documents authenticated by the author/compiler and supervisor/controller.
3. One architects' firm should be engaged to design and work out as many of the projects as possible.
4. The services of a coordinating structural engineer should be enlisted for building projects (above a specific value), who should also inspect the building work at crucial moments.
5. Make the recruitment of a coordinating structural engineer a legal obligation in complex building projects to prevent this essential position from being shelved due to price competition.
6. Provide architects and engineers with as many complete assignments as possible to prevent tasks from becoming owner-less.
7. If possible, design complex building projects as one cohesive project, requiring one (umbrella) permit.

8. Obviously, new circumstances or fresh insights may lead to changes during the preparations for a building project. Take the time to implement these changes in such a way that a consistent whole is maintained. Any changes during the actual building activities should relate only to the installations.

## 8.5 Strengthen cohesion and quality in the implementation of the building plan

1. Demand a building-sector certificate from an institution which is recognised by the Accreditation Board. Contractors and subcontractors should be as far as possible certified. ISO certification is too general and process-oriented to count in this context.
2. Safeguard the structural quality by engaging professional and experienced personnel and by the consistent profiling and deployment of competent, relatively independent supervision. Again, there is an important task here for vocational educational at different levels, and post-initial education (lifelong learning) in particular. More generally, knowledge in the construction segment is in need of significant enhancement.
3. Cohesion needs to be constantly monitored during the implementation of (complex) building projects. This is the task of the inspector appointed by the main contractor, the building coordinator appointed by the client and – at crucial moments – the coordinating structural engineer.
4. The execution of a complex construction project should be based on a serious risk analysis. The building sector needs to mobilise a lot of knowledge and data to make the phenomenon of 'risk analysis' operational. A lot can be learned from experience gained in some other sectors and from the expertise of insurance organisations.
5. Fix key moments in the building process: on paper, in drawings and/or photos. Photos of the steel-fixing, as approved by the supervisor of the main contractor, immediately before the concrete is poured, constitute important documentation of the building work.
6. Pay more systematic attention to the steel-fixing activities. First, prompt and intensive measures should be taken to ensure the availability of reinforcing steel and steel nets before the steel-fixer starts work. The steel-fixers should mark (yellow flag) the work when they believe it ready. The inspector from the main contractor and (as far as possible) the inspector engaged by the municipality should then approve and photograph the completed work (recording the time and date) and mark it again (green flag). Only then may the concrete be poured.

7. Consider using non-destructive methods to examine the actual steel reinforcement in recent complex projects which involved a lot of (complicated) steel-fixing. This may help to identify potentially dangerous situations. One must not assume that the problems in the Bos & Lommerplein are unique.

### 8.6 Fatal deadline

One separate, but typically Dutch problem which did not manifest itself in Bos & Lommer is the obligatory fatal deadline. If the municipality fails to reach a conclusion within 13 weeks of receiving an application for a building permit, the permit is automatically deemed to have been granted. The deadline can be extended once by six weeks.If a building permit is automatically granted, there is no guarantee whatsoever for safety and quality. The risk of an unsafe building can be limited by demanding that, after the permit has automatically gone through, the building is supervised by a certified organisation at the expense of the negligent municipality. It is much more attractive to link the broken deadline to another consequence, such as a fine that the municipality is required to pay to the applicant (and not the automatic granting of a permit). After all, it is downright absurd that laxity on the part of the municipality should result in the realisation of a building with no safety or quality guarantees.

## 9. Conclusions

In the introduction we cited some circumstances that might explain why the safety of many buildings cannot be guaranteed. An inordinately large number of building disasters have occurred in the Netherlands in the past five years (Section 7). The technical problems which appeared in the Bos & Lommerplein complex are not a one-off: similar problems appear repeatedly in complex building projects. On the basis of an investigation of the preparation phase and building work at Bos & Lommerplein, the Investigatory Commission drew up a list of recommendations regarding the role of the contracting public authority, public-private partnerships, building plan preparations and building activities (Section 8). Specific attention was devoted to the phenomenon of the fatal deadline (Section 8.6). Everything indicates that these recommendations are important not only to the Municipality of Amsterdam and those who are directly involved but also to construction and development in general, including the municipal services in the rest of the Netherlands and many other countries.

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# Design as an Integral Part of the Innovation Process

## Connecting Technical Capabilities with Societal Needs

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**Abstract**

Innovation models should give insight into the success and failure of generating new business. Considering the high degree of complexity, it is proposed to view such models at different levels of abstraction. It is also proposed to make feedback an essential property of the process model. The result of this new line of thinking is an integrated environment for the creation of new business. In this multilayer environment, innovation is positioned as the interconnecting activity between the development of new technology and the provision for unsatisfied needs, and the involved process model is represented by a circle of change. In this circle of change, creative design plays a dominant role.

## 1. Introduction

Traditional innovation models describe the processes along the transition path as a pipeline: government investments in scientific research must lead to application-oriented development routes which subsequently – with the aid of risk capital – ought to result in successful market introductions. If  we invest enough in science and technology then the rest will work out all right, that is the reasoning . Such a linear knowledge-push approach in innovation policies is still taking place on a large scale, with the result that the innovation system cannot florish.

Chesbrough (2003) shows that the in-house stage-gate model, a pipeline where promising ideas are developed towards successful products and services, can be extended to a more open version that allows external interactions from outside the pipeline. This pipeline was extended by Robert Kirschbaum by introducing the possibility of spin-in and spin-out (2005).

Successful innovation processes are not a matter of one-way pipelines, but rather of interlocking cycles with feedforward and feedback connections: from linear to nonlinear thinking. In that way, a dynamic environment is created in which the soft sciences are linked to engineering, and where the hard sciences connect with valorization goals. The links, which go forwards and backwards (cyclic processes), are an essential feature of dynamic systems (Forrester, 1961; Senge 1994). To improve the scientific insight in innovation processes, we should make feedback more explicit in our models.

In the foregoing we have argued that in innovation the transition path should represent a voyage of discovery (new innovations build on existing ones) and, therefore, any strategic planning should not be biased towards old thinking but should be wide open for new concepts. Breakthroughs are the result of surprises.

In addition, we have argued that in innovation large emphasis should be given to the quality of the process and the capability of the organization to execute those processes. Therefore, the remainder of this chapter will be devoted to the process model. We will focus on the nonlinear behavior of innovation processes as they occur along the different stages of a transition path. We will see that improved understanding leads to new insight in how to organize those processes.

## 2. The principle of cyclical interaction.

With the explicit addition of feedback paths, models of transitions are represented by two-way interactions, leading to cyclic processes . With the presence of feedback, organizations are continuously exposed to reactions of their environment, providing them with an important source of information and inspiration. In addition – thanks to feedback – organizations are constantly confronted with the consequences of their actions, preferably through built-in 'early signals'. In that way quick adjustments can be made in the event of unexpected occurrances. And, last but not least, the cyclical architecture also ensures that mistakes can be learned from, a very important property for innovation.

In summary, the combination of feedforward and feedback – cyclic interaction – is a fundamental property of dynamic systems. It also provides the basic elements to model the culture in innovative organizations: start quickly, adjust quickly and learn quickly .

### 2.1. Elementary building block

Figure 1 illustrates the basic principle. A represents an entity that maintains a cyclical interaction with entity X. Examples are interactions between governments and their citizens, commercial organizations and their customers, hospitals and their patients, etc. A particularly interesting example is the innovation strategy of large companies with respect to spinning-out (A-to-X) and spinning-in (X-to-A) start-ups. New in-house ideas are developed outside the original business unit and, after successful prototyping, reintroduced in the organization where it all started. It is interesting to note that by including the time axis Figure 1 transforms into a helix.

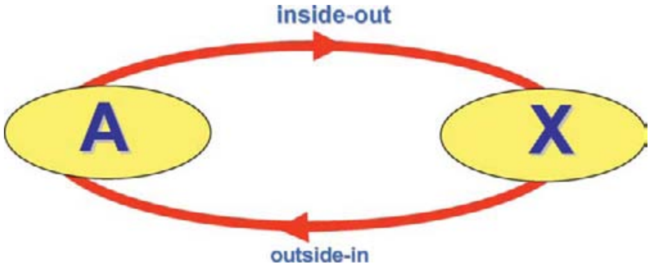


*Fig. 1. Cyclical interaction is the basis for open innovation and a precondition for operational flexibility. It is also a necessary condition for sustainability. Here, A and X represent two interacting entities.*

The cycle in Figure 1 is proposed as an elementary building block (basic unit) for designing nonlinear models to represent innovation systems, similar to those we find everywhere in ecological systems. In particular, open innovation models for technical, economic and socio-cultural change can be constructed from the basic unit in Figure 2

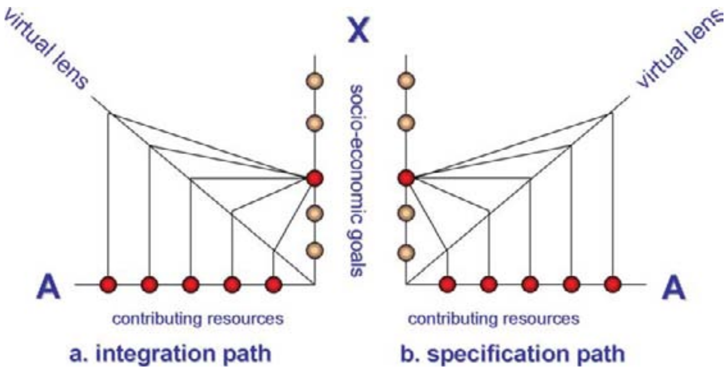


*Fig. 2. The network version of one cycle, showing the integration and specification of resources for one specific goal. The involved processes are many-to-one (A-to-X) and one-to-many (X-to-A). Using an optical metaphor, the cycle functions as a lens and the goals represent focal points. The network represents focusing (A-to-X) and defocusing (X-to-A).*

Looking closer at the basic unit, Figure 2 shows the network version of one cycle. The integration of different resources realizes a preset goal (A-to-X), and the specifications of a preset goal determine the resources that are needed to be successful (X-to-A). Figure 2 llustrates that collaboration of skills is the key to success. Using an optical metaphor, the network acts as a lens that enhances the resources to an optimum in the focal point, representing a high socio-economic value. In a fragmented organization there is no coherence between the resources, and the result will be out of focus.

Note that Figure 2 can also be represented by a spreadsheet or matrix, the columns referring to the resources and each row representing a selection of resources that contributes to a specific goal (Berkhout, 2000).

## 2.2. Double dynamics around technological research

Figure 3 shows two linked basic units – the double loop – in which technological research plays a central role. The cyclical interaction processes for the development of new technology take place in the so-called technical-oriented sciences cycle (the left-hand side of Figure 3 with the help of a wide range of disciplines from the hard sciences . Technological research in this cycle is a multi-disciplinary activity: a team of scientists from different disciplines of the hard sciences is needed to develop a new technology (many-to-one relationship).

Similarly, the cyclical interaction processes for the development of new products take place in the integrated engineering cycle (the right-hand side of Figure 3). Modern product development is a multi-technology activity: a package of different – often patented – technologies is needed to design and prototype a new product (many-to-one relationship). Like multi-disciplinary science, here too we see that many different specialists are needed to succeed. In most industrial sectors the creativity, knowledge and skills of specialized suppliers play an important role in making the engineering process successful. This is consistent with the open innovation concept.


*Fig. 3. The dynamics surrounding technological research are driven by the cyclical interaction between new scientific insights into technical-oriented processes (left-hand side) and new functional requirements for process-product combinations (right-hand side).*

Figure 3 visualizes that in the hard sciences cycle technological research is driven by new scientific insights: 'science push'. It also shows that in the engineering cycle technological research is driven by new functional requirements in product development: 'function pull'. The dynamics in technological research are therefore driven by new scientific insights as well as new functional requirements. In a well-functioning technological infrastructure, scientists and engineers must constantly inspire one another.

To achieve this, research must be organized in a different manner: no more barriers between the two cycles. The Technological Top Institutes (TTIs) in The Netherlands are a good example of how this can be addressed: scientists from the hard sciences work together with engineers from industry to create new technical functions ('products'). The Commission of the European Union (EU) has announced plans to start a European Institute of Technology (EIT) at supranational level, based on the push and pull in Figure 3.

It is important to realize that the concept 'products' is used here in the widest sense: everything mankind designs and builds. Hence, it includes immaterial products such as databases, computer software, financial instruments, artistic productions, governmental regulations and governance models. This means that the concept 'technology' is also used in the widest sense: knowledge – both implicit and explicit – on how to design, manufacture and maintain products in the widest sense. Broadening the concept of technology and product is characteristic of the proposed open technological infrastructure. The open campus of Philips in Eindhoven is a good example of such a infrastructure.

### 2.3. Double dynamics around market transitions

Figure 4 also shows two linked cycles, but in this case it is the world of social change rather than the world of technical change that plays the central role. The cyclical interaction processes for the development of new insights into changes in demand – causing emerging and receding markets – take place in the social-oriented sciences cycle (left-hand side of Figure 4) with the help of a wide range of different disciplines from the soft sciences . With these insights, new socio-technical solutions can be developed faster and with less economic risk. Anticipating changes in demand is very much a multi-disciplinary activity: a team of disciplinary experts from the soft sciences is needed to explain and extrapolate shifts in societal needs and concerns as well as shifts in trade conditions (many-to-one relationship). This type of research means a shift in traditional market studies.


*Fig. 4. The dynamics around market transitions are driven by the cyclical interaction between new scientific insights in changing socio-economic behavior (left hand side) and industrial investments in new product-service combinations (right-hand side).*

Likewise, the cyclical interaction processes required to serve the changing society with new product-service combinations take place in the differentiated valorization cycle (right-hand side of Figure 4). Experience shows that in this cycle, users play an important role in making the innovation process successful. This means making use of the creativity of customers: 'democratizing innovation' (Von Hippel, 2005). It is interesting to note that in recent years the services sector has expanded considerably, not only because of the greater demand for services from the consumer but also because industry has outsourced many of its support processes. This trend is still going on. If a branch of industry disappears, it is important to realize that the accompanying services will disappear with it.

In the soft sciences cycle, market transitions are seen as a dynamic socio-economic process in which the changing demand for product-service combinations is determined by the dynamics of the needs and concerns of society. On the other hand, in the differentiated valorization cycle market transitions are seen as a dynamic commercial process in which the change in the supply of product-service combinations is determined by the innovative capability of the business community. In an innovation economy both components, scientific insight into changing demand (left-hand side of Figure 4) and commercial investment in changing supply (right-hand side of Figure 4), should be constantly inspiring and reinforcing one another.

In industrial innovation programs a lot of implicit knowledge concerning new technological possibilities is created in the engineering cycle, and the task of the hard sciences cycle is then to make this knowledge explicit: feedback of engineering to the hard sciences. Likewise, a lot of implicit knowledge about market dynamics is created in the valorization cycle, and the soft sciences cycle then has the task of making this knowledge explicit: feedback of valorization to the soft sciences. The explication of implicit knowledge is a important role for science in innovation.

As far as we know, no formal organization has yet been established with the aim of trying to understand, influence and exploit the regime of both technical and social changes in innovation research. This confirms the current imbalance between investment in scientific knowledge for new technology and investment in scientific knowledge of emerging markets, where markets are seen as an integral part of society.

## 3. The cyclic process model.

If we compare Figures 3 and 4, the dual nature of scientific exploration and product creation becomes clear: science has both hard and soft aspects and product creation has both technical and social aspects. Figure 5 combines Figures 3 and 4. The result is the Cyclic Innovation Model

(CIM), a systems view of change processes – and their interactions – as they take place in an open innovation arena: hard and soft sciences as well as engineering and valorization are brought together in a coherent system of processes. The combination of the involved changes leads to a wealth of opportunities. Here, entrepreneurship plays a central role: making use of those opportunities. Without the drive of entrepreneurs there is no innovation, and without innovation there is not new business.

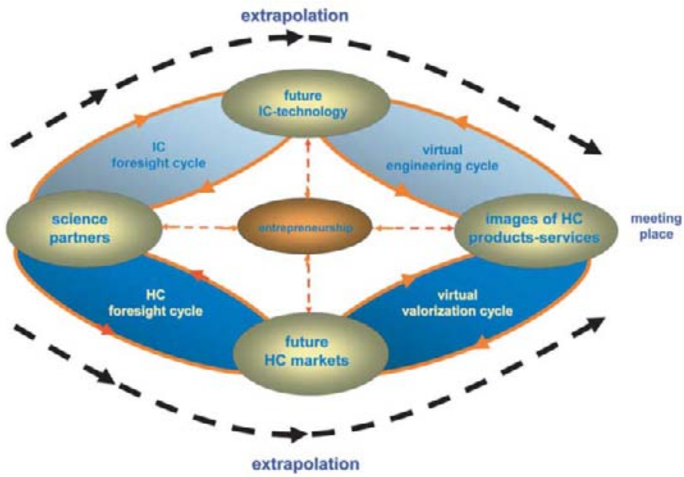


*Fig. 5. Cyclic Innovation Model (CIM), presenting the processes in innovation by a circle of change. In the model, changes in science (left) and industry (right) and changes in technology (top) and markets (bottom) are cyclically interconnected. It requires an open society to realize a rapid circulation along the circle, clockwise and anti-clockwise. The combination of all these changes creates an abundance of opportunities and it requires entrepreneurship to transform those opportunities into value for society (valorization).*

The first striking feature of Figure 5 is that the architecture is not a chain but a circle: innovations build on innovations. Ideas create new developments, successes create new challenges and failures create new insights. The creation of value is constantly accumulating.

New instruments will be needed to preserve the strength of the dynamics in the circle. Large-scale failures like the dotcom debacle in 2000 undermine the confidence in the innovation economy and cause investment capital to become scarce. In terms of the cyclic process model: the processes of change are decoupled. The economy enters a phase of stagnation in which companies focus on existing business at lower cost (life-cycle management), until institutional adaptations are made and investment capital becomes available again to spur innovation. The dynamics in the circle then accelerate again. Carlota Perez (2002) calls this phase the turning point in a technological revolution.

Figure 5 also shows that the proposed model portrays a system of dynamic processes – circle of change – with four 'nodes of change': scientific exploration, technological research, product creation and market transitions. But more importantly, between these nodes there are 'cycles of change' by which the dynamic processes in the nodes influence each other. In other words, they inspire, correct and supplement each other (first-order dependency).

This produces a system of linked cycles, which in turn also influence each other (higher-order dependencies). The result is a more or less synchronized regime of interconnected dynamic processes that spark a creative interaction between changes in science (left-hand side) and industry (right-hand side), and between changes in technology (top) and market (bottom). The combination of change and entrepreneurship is at the basis of innovation. We can attach the names of prominent entrepreneurial scientists to the cycles of the process model, with the objective to increase the understanding of the fundamental concepts depicted in this model. This aspect of CIM will not be discussed in this paper.

Autonomous social transitions manifest themselves in markets as changes in the need for products and services (the demand). Think of the huge influence of education and emancipation on a society. On the other hand, autonomous technological developments generate new products and services (the supply). Think of the huge influence of internet and mobile communication technology on a society. It is the cyclic interaction of both autonomous innovation drivers, social and technical, that will create new business with a maximum value for society.

Several variations exist in the proposed cyclic process model, depending on which goals we would like to achieve. For instance, if we would like to emphasize changes in society at large – combining economic and social values – then 'market transitions' should be replaced by 'societal transitions' in Figure 5. Similar, if we would like to emphasize changes in today's energy system – aiming at renewable sources – then 'market transitions' should be replaced by 'energy transitions'.

For the coming decades, environmental values will become one of the biggest drivers in innovation worldwide. This means that the transition node in the cyclic process model should be focused on changes in the global ecological system: 'ecological transitions'.

### 3.1. Meeting place for science and industry

Returning to Von Hippel's democratizing innovation concept, it is clear that in the valorization cycle users should play a vital role. This is represented by the feedback loop in the lower right part of the circle. If we extend this concept with the aid of the cyclic process model, it means that the democratizing concept is applicable to all cycles. Every node is an open node and every feedback loop contains a contribution by users in the neighboring nodes.

It is important to realize that all cycles in Figure 5 may also function in a virtual space. If we focus on foresighting, the hard sciences cycle should give a view of what kind of technological possibilities we may expect in the future. The result provides input to the virtual engineering cycle, to create – with the help of prominent designers – images of new product-service combinations (clockwise extrapolation starting from the hard sciences).

Similarly, the soft sciences cycle should give a view on what kind of needs and concerns we may expect in the future. The result provides input to the virtual valorization cycle, to create – with the help of motivated users – product-service combinations (anti-clockwise extrapolation starting from the soft sciences). It is the virtual space of product-service images where science and industry should meet each other. Those images do not present rational constructions but they tell emotional stories.

Take, for example, innovations in the healthcare sector that will be made possible by new developments in the IC sector (transsectoral innovations): the top half of Figure 6 (future developments in information and communication technology) meets the bottom half of Figure 6 (future needs and concerns in the healthcare market).

Universities, together with industry, could already start similar exercises for the sixth technological revolution. Governments should stimulate those future-oriented initiatives.

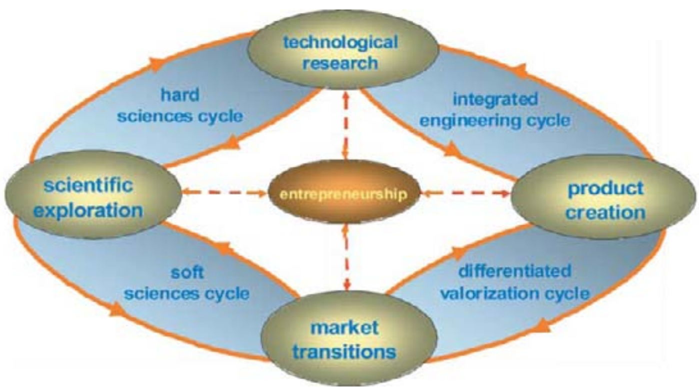


*Fig. 6. Example of sector-crossing foresighting. The upper part of the process model shows the extrapolation activities of hard scientists in the Information and Communication (IC) sector; the lower part shows the extrapolation activities of soft scientists in the Health Care (HC) sector. The result is a common virtual product-service space. This is the preferred space where science and industry should meet to innovate healthcare.*

Foresighting with the Cyclic Innovation Model will not be discussed in this paper. Note that by including the time axis, the 'circle of change' is extended to a four-fold 'helix of change'.

### 3.2. Networks of skills

Looking closer at the cyclic process model opens up the nodes and cycles. This is similar to what was already shown in Figure 2. Every node represents a collection of different resources that form cyclical networks with other resources in neighboring nodes.

Figure 7 visualizes that innovation processes take place along a circle with more or less synchronized networks – so-called CIM networks – in which knowledge suppliers, design firms, supply companies, production companies, marketing organizations and user communities reinforce each other's activities. The communication in these open networks of skills is increasingly empowered by new capabilities of the information and communication sector. Institutional factors, in particular governmental regulations, have a dramatic effect on the dynamics within and between the CIM networks. Ultimately, institutional factors determine the maximum rate of circulation that can be realized along the circle. The way a society is organized and regulated can exercise an enormous influence on this process, in both a positive and a negative sense.

Figure 7 also visualizes how the multitude of highly diverse processes can be organized to reinforce each other. Using again the optical metaphor, Figure 7 can be represented by four lenses that focus the multi-resource input. A focal point of one lens acts again as a new resource for the next lens. Note that one lens represents the capability of a network. If lenses don't work well, the points are blurred and the socio-economic goals will be out of focus.

Note that Figure 7 can also be viewed by four interconnected spreadsheets or matrices. Using the multi-matrix presentation, the necessity of interconnectivity of skills can be well visualized (Berkhout, 2000).

## 4. Classification of innovations.

The circular arena in Figure 5 shows that new innovations arise from previous generations. New innovations are therefore a mixture of the old and the new, and the ensuing impact can be large or small; the terms generally used are incremental and radical innovations. This is not a very clear distinction. The process model of CIM shows that innovations can be subdivided into different classes. This classification may be more informative. We will use the terminology of Carlota Perez (2002) – utilization of existing technology or 'deployment' – and Edward Cornish (2004), development of new technology or 'futuring'.

### 4.1. Deployment category

Class 1 innovations are the result of new developments in a single node. These involve existing product-service combinations where only the market concept is radically changed. Examples are switching to internet shops, focusing on a different market segment and responding to a new lifestyle. It appears that the 'Second Life' movement is the most exciting recent development for Class 1 innovations.

Class 2 innovations are the result of new developments in two nodes. These involve the development of new product-service combinations together with a unique market concept. Examples include technical installations with intelligent sensors connected directly to the internet (connected products). This new combination creates significant added value since information about access, use/abuse and the physical condition of installations becomes available wherever and whenever it is needed (early warning signals). The result is that entirely new services become possible, which in turn means that the traditional product-oriented market concepts will have to be replaced. Other examples are capabilities in mobile identification technology (RFID), which will bring about major improvements in logistics as well as a major change in the battle against crime and terrorism.

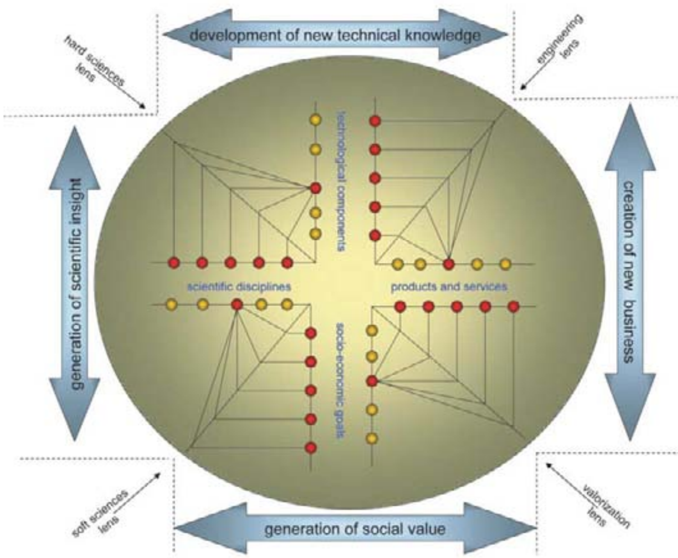


*Fig. 7. Looking closer at the cyclic process model, the circle of change represents interacting networks of skills, showing the complexity of an open innovation system (beyond the pipeline architecture). The output of one network generates the resources for the neighboring network. Here, this process is visualized in a clockwise fashion. Organizational flexibility is the key to success.*

### 4.2. Futuring category

Class 3 innovations follow from new developments in three nodes. They involve the development of new technologies, which in turn make new product-service combinations possible, which for their part call for new market concepts. Many emerging information and communication technologies in broadband interaction will make spectacular Class 3 innovations possible, such as telecare in the widest sense. And recent developments in the life sciences have generated new opportunities in biotechnology, which in turn set off a revolution in the development of new product-service combinations in the pharmaceutical and food industries. But spectacular progress is also being made in the nanosciences, where technical building blocks are on a molecular scale. Nanosciences have already produced radical new knowledge for material-oriented nanotechnologies, which will in turn cause a revolution in the development of product-service combinations in all technical-industrial sectors. An example would be nanotechnology for the new energy era, characterized by internet-like decentralized networks.

Class 4 innovations follow from new developments in all nodes. Innovations based on the scientific research in genetics, nanosciences and artificial intelligence will change society so radically that the overwhelming increase in technological possibilities (top half of Figure 5) will have to be accompanied by a major effort to increase our understanding of society's needs and, above all, society's concerns (bottom half of Figure 5). Climate change, for example, will require a great deal of cohesion in the development of knowledge in the hard and soft sciences.

## 5. System faults in the innovation arena.

In a closed society there exist principal barriers in creating new business, usually owing to institutions that were established in the previous technological revolution. Figures 8 and 9 illustrate two notorious obstacles that are referred to here as 'scientific isolation' and 'technology push'. Scientific isolation refers to a society that may be excellent in scientific research, but still underperforms economically because of a communication barrier between the science and industry community (Figure 8). The two worlds make their own choices and plans, and throw their wishes and results over the fence to the other side. Technology push refers to a society that may be excellent in designing and building technical functions but still underperforms socially because of a communication barrier between the technical and social community (Figure 9). Both worlds make their own choices and plans; here too they throw their wishes and results over the fence to the other side.

The failure of the Lisbon strategy of the European Union is a consequence of the existence of these obstacles in the European innovation system. The huge emphasis on more research and more technology is a too one-sided and simplistic approach. The proposed multilayer environment for new business shows that the real problem lies elsewhere: little emphasis on nonlinear processes (Figure 5) and insufficient trans-border interactions (Figures 8 and 9).

The solution lies in connecting technological progress with societal needs as well as loosening top down control and tightening bottom-up collaboration. In a recent article, Rosabeth Moss Kanter (2006) summarizes many years of her consulting experience on innovation for a large diversity of companies. Her extensive practical experiences are confirmed by the theoretical considerations in this paper.

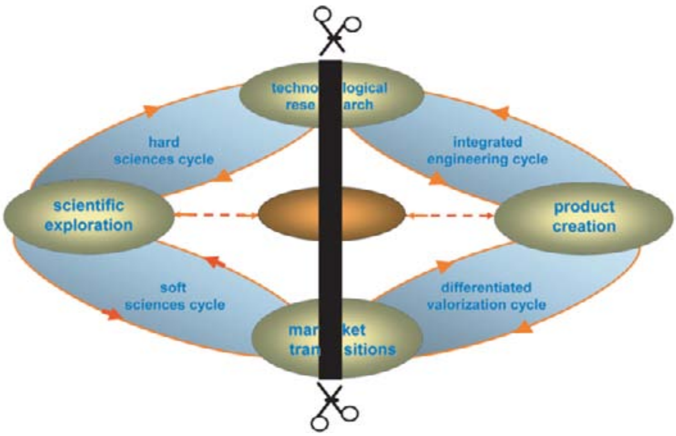


*Fig. 8. A society can be excellent in science, but still may underperform economically (vertical communication barrier)*

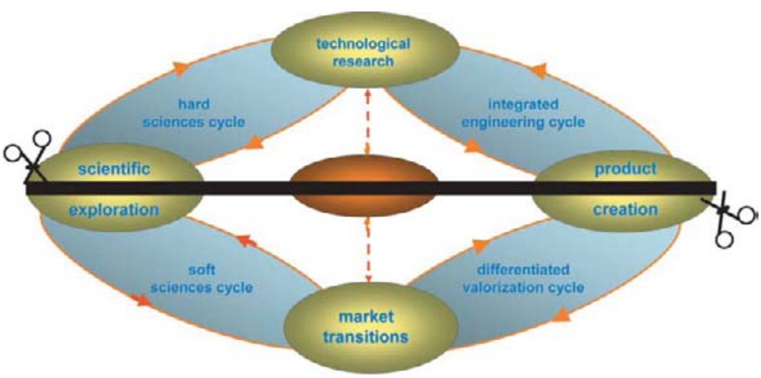


*Fig. 9. A society can be excellent in technology, but still may underperform economically (horizontal communication barrier)*

## 6. Example: hearing spectacles, designing the unimaginable

The cyclic concept of innovation will be illustrated with an example. A new hearing device has been designed, prototyped, beta-tested and introduced into the market. By using acoustic antenna's in the sides of a pair of spectacles, a very high directivity can be reached: 'what you see is what you hear'. This property turns out to be vital for the speech intelligibility of elderly people.

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# Designing Complex Systems
# A Contradiction in Terms

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**Abstract**

Networked infrastructures are complex socio-technical systems. The complexity shows in the physical networks, in the actor networks, and in their combination. This paper addresses the question how these systems should be designed. For the physical networks as well as the actor networks, design processes exist that could be applied separately. However, for these integrated networks an integrated approach is proposed. Three cases studies of designs are discussed concerning a district heating system, a gas network and a seaport development. The studies lead to the conclusion that an integrated socio-technical complex system design process must be applied.

Keywords: complex systems, engineering design, systems engineering, infrastructures

## 1. Introduction

Socio-technical systems are systems that exhibit both physical and social complexity. Networked infrastructures, such as those for transportation of people and goods and for provision of telecommunication, water and energy services, are prime examples of socio-technical systems. Infrastructure systems are *complex* systems in view of their combined social, economic and physical complexity.

Most of the public utility and infrastructure systems of today were not designed as integrated systems. They gradually evolved into the patchwork of physical networks, the patchwork of old and new technologies and the patchwork of actor networks and institutions they are now. They have adapted to changing economic conditions, societal demands and end-user requirements. The development of Europe's critical infrastructures is not centrally planned and coordinated but governed by many actors who optimise their management decisions and investment strategies for their own subsystem, in their own interest.

Complex adaptive systems *design* may therefore be considered a contradiction in terms: how should the future complex system be modelled, how should the design process be set up among this multitude of actors and who, if anyone, is responsible for the overall design and design process?

Nevertheless, many design engineers are involved in infrastructure development. How do they cope with the physical and social network complexity and the emergent behaviour of infrastructures? How should they be equipped to cope with complex adaptive systems and how can the designers' performance and thereby the future performance of the infrastructures be improved?

## 2. Complexity in infrastructure systems

### 2.1 Infrastructure systems as socio-technical systems

The notion of 'infrastructure' generally refers only to the physical network that connects the suppliers and end users of an infrastructure-bound service. However, in our view an infrastructure system includes – besides the transport and distribution network – the carriers, conversion and storage facilities as well as the governance, management and control systems that are needed to make the system meet its functional specifications and its social objectives.

Any infrastructure is in itself a highly complex networked system, that includes both a physical and a social network, or actor network (see figure 1). The behaviour of an infrastructure cannot be understood by merely studying the structure and behaviour of either. Both are interconnected in many ways. The physical network and the social network are complex in themselves – and their interaction, at the level of the integrated socio-technical system, presents another domain of complexity.

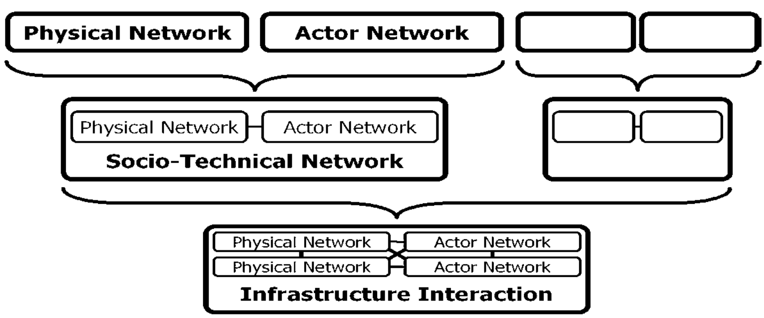


*Fig. 1. Domains of complexity in infrastructures (from [1]).*

## 2.2 Complexity in the physical network

The physical networks of infrastructure systems consist of many nodes and links. Large-scale systems, such as the European electricity infrastructure, comprise a huge number of subsystems, links and nodes, all of which are interdependent in several ways. If one subsystem is not functioning well, this may have far-reaching repercussions on the functioning of the overall system. The interdependence of the subsystems can take various forms, from simple linear dependencies to multiple, non-synchronous dependencies (see [2]).

Moreover, the nodes of the network interact with and adapt themselves to their surroundings. Their reaction to external changes is often non-linear, which can result in unpredictable behaviour of the system as a whole. Deterministic chaos is one form of such unpredictable behaviour [3]. As the number of subsystems and interrelationships increases, and as those interrelationships become more diverse, it becomes more difficult to gain an overall view of the system and to model it. Eventually, the system will become so complex that the analyst can no longer recognise or model it at all. Chaos theory shows that even if it were possible to accurately describe the changes in the nodes as they are influenced by their environment, the prediction of the state of the system could gradually diverge from its actual state, due to the exponential growth of tiny errors in the measurement of the system's initial state. Chaos theory can, however, give insight in the general behaviour of the system and the system states that can be expected.

Studies on complex systems often use the concept of agents for interacting elements in the system. In general, an agent is a model for any entity in reality that acts according to a set of rules, depending on input from the outside world. Agent Based Modelling theory uses agents that act and interact according to a given set of rules to get a better insight into system behaviour (see [4] for examples). The emergent behaviour, which is the behaviour of the system seen as a whole, follows from the behaviour of the agents at the lowest level. In many cases, emergent behaviour can be described by new rules, new laws, at higher levels of aggregation, disregarding the actions at the lowest level of the agents. This coincides with the notion that the value of a physical infrastructure is determined by the physical system's performance at the top level only. The end users do not care what switches or cables are used, as long as they can make a phone call, watch the television, and have a comfortably heated home.

## 2.3 Complexity in the social network

In a multi-actor system such as the European electric power infrastructure, many actors are involved with different, possibly conflicting, interests and hence different perceptions of 'reality'. Again, agents may be used to model the system's elements, which in this case are people and organisations. In analogy with the agents in the physical network, each actor in the social network can be described as an agent that acts according to a set of rules determined by legislation and regulation, moral and cultural codes, etc. In addition to these more explicit rules, each actor will have its own strategy. In the case of, e.g., a driver on the motorway, behavioural psychology may shed light on the determinants of individual driver behaviour. If the actor is a firm competing in an infrastructure-related market, business economics and strategy will influence the actor's behaviour. Actors, however, may also show reflection and learning: when faced with a similar situation for a second time, their behaviour will be influenced by the lessons drawn from the first time. This specific characteristic of actors makes modelling them as rule-abiding agents an extremely complicated, if not impossible, task.

The actors are interdependent: each needs the cooperation of the others. As in the case of the physical subsystem, the interdependencies can take various forms. As the number of actors involved in a problem increases, conflicts of interest grow and there is greater variation in interdependencies. Eventually, it may become impossible for any one actor to understand the situation in its entirety and the predictability of the actions undertaken by any one actor is limited.

## 2.4 Evolution of infrastructure systems

Part of the problem with understanding the behaviour of infrastructures is that most of the physical systems were not designed as an integrated system, but gradually evolved over time. A typical example is the way the electricity infrastructure evolved in the Netherlands [5]. Like most infrastructures, it originated in local networks, established through private initiative. City networks were established around the beginning of the 20th century. Interconnection of local networks and network expansion to rural areas was forged through intervention of the public authorities. Over time, the density of inter- and end-user connections increased. Transport and processing functions in the infrastructure were intensified to serve an increasing number of users and an increasing demand per user. Grids were interconnected across national borders to improve the stability of the network and thereby the reliability of service. Today, all national grids of mainland Europe are interconnected.

During this evolution, ownership and governance of the electricity infrastructure shifted from the private sector to the public sector. Until about a decade ago, most infrastructures were run as public monopolies. The infrastructure value chain was fully integrated vertically (figure 2, left). This was justified by the fact that the transport and distribution network have the character of a natural monopoly. Whether directly or indirectly, the government controlled the realization of the infrastructure and the universal provision of the public utility service by central planning and allocation of funds.

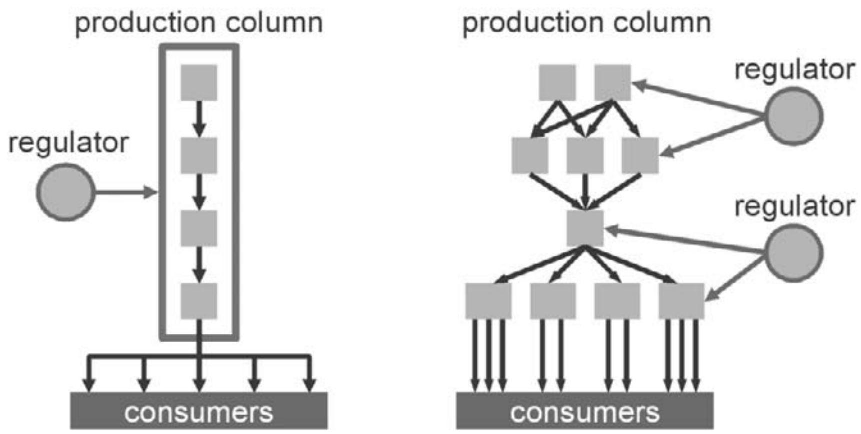


*Fig. 2. Model of infrastructure market before and after liberalization: vertically integrated monopoly (left) and unbundled infrastructure value chain (right), with competitive markets in non-monopoly segments (after [6]).*

This rather transparent situation has dramatically changed. Many infrastructures have gone through or are still in the midst of a transition from a vertically integrated monopoly structure to an unbundled value chain, with competitive markets being introduced in those segments of the chain that do not have a natural monopoly character. This transition does not directly impact the technical network, but mainly the social network (see figure 2, right). As a new playing field is defined, new actors enter, often in new roles. In the European electricity markets, traders and brokers have become active and new market places have emerged. National regulators have been created to ensure non-discriminatory access to the transmission and distribution networks.

It is evident that the social network has become much more complex with the larger number and variety of actors, and that the options to steer the development of the infrastructure have changed. In the old situation the government could directly interfere in the planning of the system. Nowadays, investment signals are established through market forces. Competition has been established in both the power generation market and the service provision market. Only the networks are treated as a natural monopoly, so that a precarious interface must be constructed between the competitive markets and the regulated networks.

## 2.5 Characterising the socio-technical system

From these analyses it is evident that there are both similarities and differences between the physical system and the social system at the conceptual level. The main difference is that the components of the physical system are technical or physical artefacts, while those of the social system are reflective actors. Reflectivity means that the actors have the ability to learn, and this has three significant implications for complex system design ([7], [8]).

- Actors display *strategic and opportunistic behaviour*. Their main motive is to realise their own objectives. Strategic behaviour (or 'game playing') refers to all actions that help the actors to do so. It can take the form of misinformation, hidden agendas, blocking decisions now in order to gain later, etc.
- Actors *learn how to neutralise interventions* by others. They learn the strategies and interventions used by other actors and, in time, may develop means to sidestep these strategies and interventions. This is known as the 'Law of Decreasing Effectiveness': every strategy is only temporarily effective because actors learn how to neutralise its effects. This enhances the dynamics of the network: actors are constantly developing new strategies to maximise their interests.
- Because actors are reflective, an *understanding of the process of interaction* that will eventually lead to a decision is crucial. In this process the actors interact, learn and display strategic behaviour. The final outcome cannot be fully understood without knowledge of the process itself. This represents a major difference compared to the physical system approach, in which the 'white box' of a system's functioning does not always have to be known in detail.

## 2.6 Design challenges for complex infrastructure systems

The overall demand for infrastructure services is increasing. At the same time, society demands an ever higher reliability of service as we grow more dependent on infrastructure-bound services. As the performance of the infrastructure system is determined by the interplay of the physical and social networks, ensuring high service reliability has become much more challenging.

Highly reliable services are more and more the outcome of networks of organizations, many with competing goals and interests. This creates new challenges for network design and for effective market and network regulation, and new needs for communication and information sharing. The California crisis, for example, could have been much worse than it was if the operators of the various subsystems had communicated less intensively [9].

In the design of new infrastructures, or in the redesign or expansion of existing infrastructures, the main challenge is how to deal with the many uncertainties that the system will face during its projected lifetime. Since infrastructures are deeply embedded in society, they are not only subject to rapid technological changes, but they also have to keep up with institutional and economic developments, such as deregulation, liberalisation, or increasing oil prices. The challenge is to provide technical flexibility and budget flexibility to ensure the adaptivity of the initial design to these changing requirements.

The market has a tendency towards capacity scarcity, because no private investor is prepared to invest in unprofitable overcapacity for the public good. This poses new demands on infrastructure capacity management. Innovations are needed to make better use of available capacity. Where central coordination mechanisms are lacking, making way for distributed control strategies, infrastructures might be equipped with self-organizing and self-healing properties so as to deal intelligently with disturbances and recover more effectively from incidents (e.g., see [10]).

For the longer term, the tendency towards under-investment in electricity generating capacity poses a serious threat to economic growth and social development. Research has shown that new mechanisms, such as a capacity market, must be brought in place to alleviate this risk [11]. Other concerns are emerging with respect to network quality on the longer term [12]. As the California power crisis has shown, excessive social cost may be incurred by a faulty market design.

Due to the limited possibilities to directly intervene in the established layout of the physical system, an important option is to ensure that the collective actions of players are steered towards the public interests through adequate market design, adequate network regulation (where the network has retained its monopoly character) and additional legislation and regulation for safety, health, environment, etc. Also, in view of private actors' interests, a better insight is needed into how individual investment decisions will perform as a subsystem of the complex infrastructure system.

## 3. Complex systems – addressing the design challenge

### 3.1 Designing complex physical systems

The system design of complex systems differs from that of a simpler system in the majority of the general design process components ([13], [14]):

- *Functional requirements*: For a simple system design, this will be a straightforward description, e.g. 'the system must store data.' In a complex system design, the function will often be compound, possibly with different functions for different actors. The system may also be 'distorted' upon implementation, i.e. it will not be used in exactly the manner that the designers intended. The more complex the system, and the greater the number of actors in the 'implementation field', the more likely it is that distortion will occur.
- *Objectives and constraints*: The degree of complexity results in a massive number of objectives and constraints that the client and other actors can impose on the design. If the designer wishes to incorporate all these requirements, the system is very likely to suffer from over-specification, which precludes any real solutions, i.e. a realistic design. Moreover, the system designer will have to contend with conflicting objectives. The more complex the problem, the more difficult it will be to determine the 'solution space', let alone select the best design from the various options.
- *Design space*: Even in simple designs the design space can quickly take on enormous proportions. For large, complex systems, the design space is practically unbounded. Other actors may also attempt to incorporate subsystems into the design space, or to ensure that they are excluded. It then falls to the designer to define and delineate the design space as best as possible.
- *Starting points*: In complex system design it is very difficult to find starting points for a design. The transplantation of models and design options is not simple and will indeed often be impossible precisely because these are systems embedded in a (dynamic) multi-actor field in a specific institutional context. Given the high degree of context sensitivity, the designer of a complex system will often have very few starting points.
- *Models and modelling*: The models map the design space into the functions, objectives and constraints. The system models that play a role in this part of the process can vary from simple, mathematical linear system models to complex probabilistic models or game theory models. The designer may also use agent-based models in order to model the complex adaptive system.

Real Options theory and exploratory modelling are examples of methods that are employed for modelling the infrastructure system, given the enhanced design complexity described above. The former is a promising approach as it treats future uncertainty as a business opportunity, contrary to other methods, which take a risk-aversive stance: similar to financial options, it allows the designer to build a real option into the currently implemented design. The option may be executed or exploited if and only if it becomes (economically) viable to do so at a certain moment in the future. The already implemented real option would significantly reduce the cost of redesign in the future, justifying the investment up-front.

Research so far has shown that improvements of 10 to 20% in the NPV can be achieved. For the case of designing and building infrastructures, this would imply that options could be built into, e.g., a power plant, allowing it to operate on multiple fuels. The advantage in this example of using the real-options approach is that the cost of implementing of a multiple fuel burner can be traded off financially against the associated cost of the probability that different fuels will have to be used in the future. In other words, the cost of *flexibility* can be made tangible in terms of monetary value.

When the design and operation of infrastructures is required to be adaptive, in view of the deep uncertainties, the decision-making processes in this system also need to be adapted. Preferably, the operational stages of any system are already considered in the design stage (in terms of Reliability, Availability and Maintainability (RAM) optimisation – see [15]), but also in the case of changing ownerships, or distributed responsibilities, which is often the case in infrastructure systems, the operation and maintenance must be executed as flexibly as possible. The design challenges for infrastructures should therefore also focus on maintenance and replacement strategies, as these are so intricately related to (grassroots) design. In fact, maintenance and replacement could be considered as heavily constrained design problems. Innovative construction and maintenance contracts, asset management and risk management are just a few emerging strategies that deal with integrating the design and the operation/maintenance challenges for infrastructure systems.

### 3.2 Designing complex social systems

For complex social systems, the process of 'design' should not be regarded as a process of modelling a desired reality. For a network of actors, a model of the desired reality would only be authoritative if it would be accepted by a 'critical mass' of the actors. Within the network, this is precisely the problem: given all the differing interests, the likelihood of a model being accepted is extremely small. How can consensus regarding a desired reality be achieved nonetheless? The characteristics of a network of actors reveal that two familiar types of intervention will not be effective [16]:

- Hierarchy, or 'command and control' will be impossible since no actor is superior to any other. An actor who nevertheless attempts to manage the process through command and control will only generate opposition. Attention will then shift from the hierarchy itself to the processes of interaction between the actors.
- Management by 'expertise of management', based on a content-based analysis, is also unlikely to succeed. Knowledge and information will be contested; statements based on a content-based analysis are always open to rebuttal. There is no such thing as unambiguous information. In this situation, attention will shift from expertise and unambiguous information to the process intended to arrive at negotiated knowledge.

Attention therefore shifts to the *process* of decision-making. A set of game rules of this type is termed a 'process design'. Like the design of physical systems in the engineering design tradition, process design is based on a solid set of design principles [8]:

- In the interactive decision-making process, actors must be sufficiently open with each other.
- The core values of the actors should be protected during the process.
- The process contains incentives for progress and speed.

The risk inherent in an interaction or negotiation process is that in order to reach consensus, actual content-based expertise will not be fully taken into consideration. There can be no 'negotiated knowledge', only 'negotiated nonsense'. The fourth design principle therefore is:

- The result of the interaction process must stand up to expert scrutiny.

### 3.3 Designing socio-technical systems

It will be evident that any design in the context of a socio-technical system should acknowledge and respect both the physical and the social reality and their respective rationalities. The socio-technical complexity of infrastructure systems calls for a synthesis between the two design perspectives or, if not a synthesis, for a systematic confrontation or combination of the two perspectives. The diagram below provides a framework for the confrontation and combination of the physical and social system design perspectives.

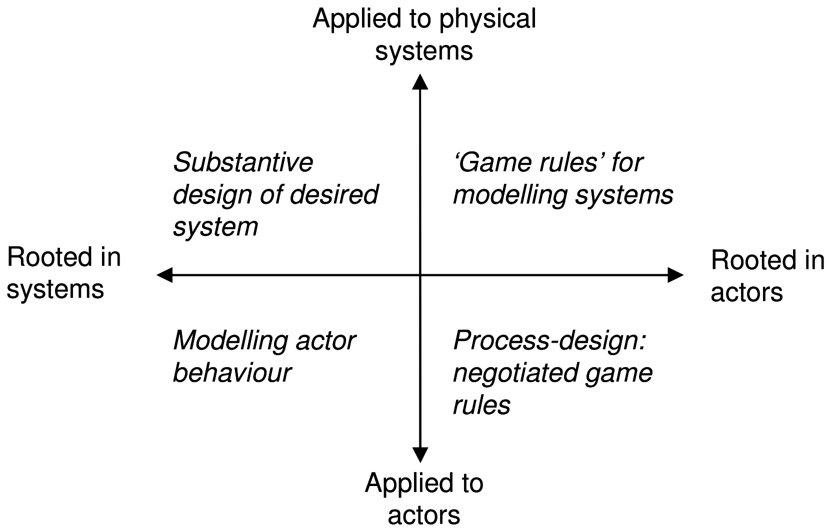


*Fig. 3. Pure and hybrid forms of design methods and tools for complex socio-technical systems design and modelling (from [2]).*

As shown in figure 3, various hybrid modelling techniques have been developed that help combine the physical system perspective and the social system perspective. Hybrid modelling approaches are conducive to a meaningful dialogue between the engineering design professionals who are the experts in physical system design, and the social scientists who engineer the decision-making processes between the actors. Hybrid modelling techniques that apply rational modelling techniques to the social system are used to model the network of actors, including the sub-actors, resources, interests, strategies and interrelationships. Even though actors are not inclined to allow themselves to be modelled, the application of rational modelling techniques to actor networks performs a number of valuable functions [16]:

- It forces the modeller to consider the problems from the actor perspective.
- It provides an insight into the known and the unknown variables. In some cases, for example, the relations maintained by certain actors will be unclear, as will be their underlying interests, etc.
- If the modelling process is undertaken by several modellers (e.g. modellers playing the role of specific actors), an understanding of the differences in perception among the actors will be gained.
- A modelled actor network can facilitate the discussion and decision making with regard to the strategies to be followed.

Conversely, the question is what contribution the process-oriented modelling of the actor approach can make to the physical system perspective. As previously stated, complex systems abound with uncertainties. A model of the system will therefore always be 'contested', with various experts holding diverse opinions regarding the way the system functions. If there is a marked divergence of views, this is likely to obstruct successful interventions. In cases where the model is contested, it is necessary to pay attention to the process in order to arrive at a negotiated model. This process requires the experts to enter into a structured form of interaction. In the ideal situation, this process will reveal exactly what the experts already agree on, and where the differences of opinion lie.

## 4. Infrastructure design as complex system design: applications

### 4.1 Introduction

For each of the design challenges described in the previous section, a design case study has been performed. The first case comprises the design of a district heating infrastructure system in which the focus was on the physical design challenge: design an infrastructure with the most appropriate network topology that can stand the test of time and that takes into account any requirements that are set on the system from an institutional or social system's perspective.

The second case study describes the results of a design performed by a group of MSc students, in which the physical and social subsystems were considered simultaneously during the design process. The resulting syngas infrastructure for the Port of Rotterdam area is a prime example of an integrated complex system design.

The third case study demonstrates the value and necessity of a good process design in order to arrive at a conceptual socio-technical system design of a bio based industrial cluster. The process allowed for strong actor commitment to the Agent Based Model that was developed for this design challenge.

### 4.2 District heating system

District Heating Systems (DHS) provide an efficient method for house and space heating. In such systems, heat is produced and/or thermally upgraded in a central plant and distributed to the consumers through a pipeline network. An integrated conceptual design was made of the technical, economic, and institutional subsystems for using low-level residual industrial waste heat for district or city heating [17].

The technical part of the integrated conceptual design consisted of the heat demands, the design of the heat upgrading system, equipment size, the network topology and/or spatial connectivity of the needed infrastructure as well as the economic viability of the system. For modelling purposes, thermodynamic models and life cycle costing methods were used. Figure 4 shows the resulting physical subsystem.

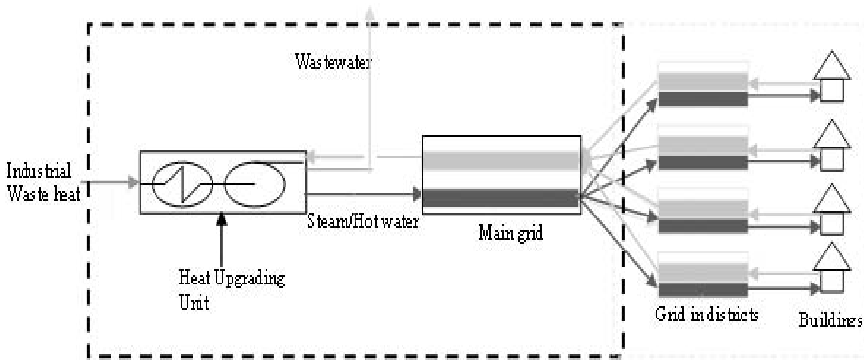


*Fig. 4: System diagram of the physical subsystem (from [17])*

The low-level temperature industrial waste heat is routed to the heat-upgrading unit where the temperature is raised to the required level by heat pumps before being led to the central grid. To enhance the system effectiveness and flexibility, the steam from the main grid is taken to a modular (district) grid where the possible connections to the houses and offices are made.

The social subsystem design had to take into account institutional aspects that could impact the design and realization of the heating infrastructures. Equally, the institutional design would impact the design choices made for the design of the physical subsystem. It was, therefore, crucial to design the physical and social subsystems in parallel, by frequently switching between both designs and confronting them with each other. During the design of the social subsystem, the nature and impact of (future) regulation in the heating sector was one of the most important constraints that needed to be taken into account. It is obvious that many uncertainties pervade the future of regulation, requiring a process design in addition to the institutional design. During the design process, such legislations were simulated and their present and future impacts on the design were assessed.

The institutional design comprised the building, operation and ownership of the infrastructure and supply of heat. Secondly, a DBFO (Design, Build, Finance and Operate) contract between public and private parties involved in a project like this was selected and designed. Due to the financial risk sharing between public and private parties in a DBFO contract, incentives are created for fulfilling requirements such as efficiency, profitability and quality of service to consumers. The assets for owning and using the grid have to be allocated ex ante by the municipality and not by the market. It was deemed most efficient that the owner and user of the grid are one actor or at least function as one. The contract and the process conditions designed helped to establish this.

### 4.3 Syngas infrastructure

The Port of Rotterdam has a large petrochemical cluster that processes incoming crude oil into numerous end products. In the coming decades the cluster may find itself increasingly at risk of not being supplied with enough coal and crude oil, on which it so heavily relies. Since the current cluster is quite inflexible in its need for crude oil as a feedstock, security of supply issues for crude oil threaten the operations of all cluster partners. In order to safeguard the competitiveness of the cluster as a whole, it is important to reduce the dependency on fossil fuels by increasing the feedstock flexibility.

As a solution to the feedstock inflexibility problem an industrial cluster feeding on synthesis gas has been designed [18]. Synthesis gas (or syngas in short) is a mixture of carbon monoxide and hydrogen and is widely used for methanol and ammonia synthesis as well as in the production of their derivatives. Moreover, the conventional Fischer-Tropsch process that produces liquid transport fuels from syngas has recently been modernized. The resulting designer fuels contain less sulphur and hence are relatively environmentally friendly. Carbon monoxide and hydrogen also find other applications, for example in the direct reduction of iron.

It is obvious that for the design of the cluster, a physical as well as a social subsystem had to be designed, and that both subsystems can be considered to be complex (e.g. emergent behaviour, deep uncertainty, strong interaction between physical and social subsystem). In the initial physical design space, network topologies such as ring, bus and star networks were considered. For the governance, three archetypical structure types were evaluated: hierarchy, market and network. After confining the overall design space to three combinations of the physical and social subsystem (i.e. network-bus, market-ring and hierarchy-star), the network-bus structure was chosen as the basis for further design.

The final proposed design consisted of a double bus network (see figure 5): one pipeline contains pressurized 'high-quality' (HQ) syngas with a high $H_2/CO$ ratio, enough to satisfy the most demanding production processes. The other bus contains syngas with a lower ratio that supplies to users with a lower demand for high-ratio syngas.

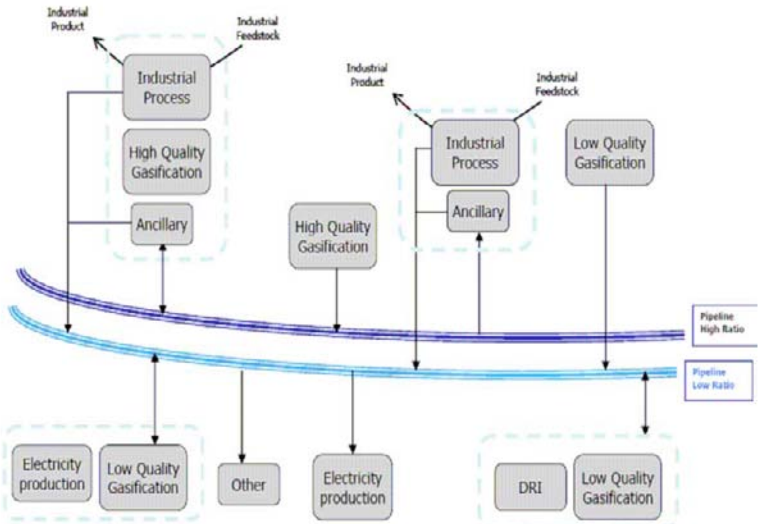


*Fig. 5. The physical subsystem design: double bus network (from [18])*

The social subsystem for this grid (i.e. local syngas market design) comprised a specially devised set of rules to play by. For suppliers and users on the HQ line two options were designed: transactions through bilateral contracts or syngas trading on a syngas spot market. For actors on the LQ pipeline bilateral deals and a syngas pool were created, from which users can buy the quantities they need. In addition, market balancing tasks were assigned to specific actors (see figure 6).

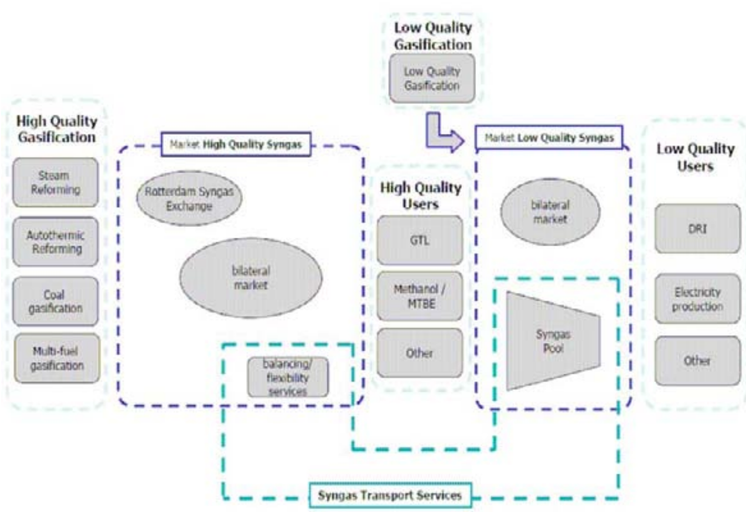


*Fig. 6. The social subsystem design: institutional design (from [18])*

Finally, the process design concentrated on commitment to the development process and on creating a sense of urgency by dividing the entire evolutionary process to the final cluster into a number of distinct rounds in which the conceptual technical and institutional designs would be adapted and detailed. With the inherent decrease in uncertainty with time passing by, the final design of this socio-technical complex system will evolve into one that can stand the test of time.

### 4.4 Seaport Groningen

Around the world, industrial areas have developed that are known for their concentration of heavy industry. Many of these industrial clusters evolved as a result of favourable geographic conditions, resource availability and infrastructure. Industrial clusters are complex socio-technical systems, being a network of physical assets controlled and maintained by an extensive social network [19]. Generally, a regional development authority has the responsibility to ensure the progress of the industrial cluster.

Groningen Seaports is the regional development authority in the Eems delta region in the north of the Netherlands. In the older of the two seaports in the region, the one around Delfzijl, a prosperous cluster has developed over time. Port, railroad, pipeline and utility infrastructures were developed to facilitate heavy industry, such as base chemicals production and alumina smelting. The available local resources, rock salt and natural gas, provided ample incentive for the development of what has become a successful chlorine-chemical cluster [20].

Following initial rapid growth and investments in heavy infrastructure in the 1970s, the economic development slowed down in the 1980s and 1990s. In 2000, the Groningen Seaports organisation was created to market the region's infrastructure pro-actively. The "Costa Due dialogue process" was then formulated in cooperation with the county, with the mission to create a sustainable bio based industrial cluster in the Eems delta. The cluster design was to comprise an initial high-level design of the technological system and the formation of a social network. To this end, the Costa Due partners approached a variety of scientists, entrepreneurs and energy companies to take part in a dialogue process, and they were all challenged to bring in innovative and feasible investment projects. The intention, of course, was to commit all these stakeholders to the project and to bring a healthily growing industrial cluster into being.

Equally important is that the Costa Due initiative also renewed the exposal of the Eems delta to potential investors. Whereas in the past both oil crises frustrated the region's development, global trends now support bio based and energy-related activities in the region. Since the Eems delta started to convey that it has a first-rate energy infrastructure and it has connections to both the national and the European gas and electricity grid, series of new investments have proved that this new tactic was successful.

It was then explored how the Costa Due partners could initiate and further the development of the cluster, building upon the success of the Costa Due dialogue process, where some 50 innovative project ideas emerged.

In the study an integrated approach was employed that comprised the physical system and the social network (with feedstock and product markets and regional and global trends as important inputs). To further explore the evolution of the Eems delta bio based cluster, an Agent-Based model was developed ([21], [22]) that accurately replicates the historic evolution of the cluster into the existing chlorine-cluster (see figure 7). Inclusion of the 50 project ideas from the dialogue process indicated that the existing industry network and infrastructure are required as a nucleus for further development of the bio based cluster.

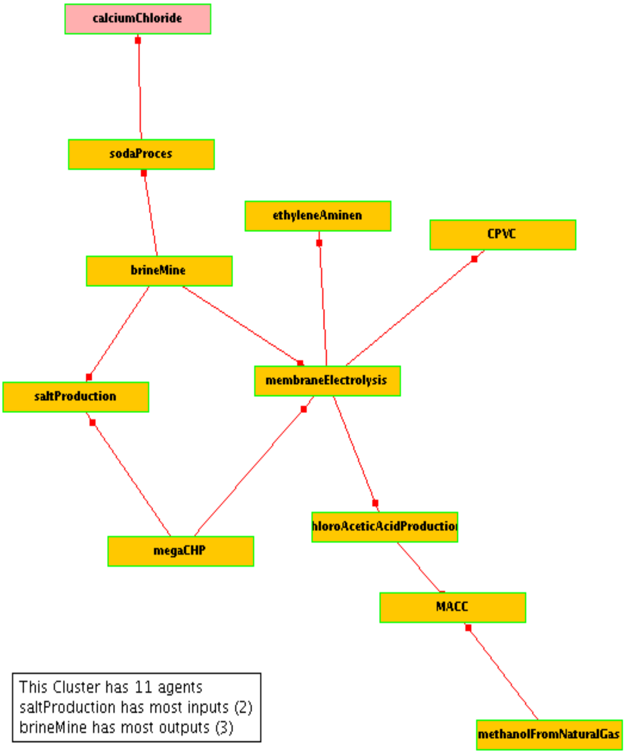


*Fig. 7. The existing chlorine cluster as a result from the Agent Based Model run (from [22]).*

It was concluded that the Costa Due project is perfectly positioned and timed to leverage the global interest in bio based energy conversion and production. To accelerate sustainable cluster development the socio-technical system should be allowed to evolve and expand to include also bio based specialties and life sciences. The geographic conditions and the present seaport and energy infrastructure, however, are predominantly attractive to heavy large-scale industry and energy companies. To engage local players and bring more value-added, knowledge-intensive investments to the cluster, an opportunity would be to connect the existing tangible infrastructure with the intangible knowledge infrastructure available in and around the region's capital Groningen.

## 5. Conclusion

Can physical system design and social system design be combined to acquire a better understanding of the behaviour of socio-technical, complex systems and to effectively support better designs and design processes? The answer to this question has been addressed in this paper. The design of such socio-technical systems has been illustrated by means of three case studies, which range from a relatively simple design of a physical infrastructure (taking into account constraints from the social system), to a combined approach of process and systems design for the design and development of a large industrial cluster.

It has been be shown that a combined approach is essential, as socio-technical complex systems cannot be understood or designed without knowledge of both the physical system and the constellation of actors, i.e. the social system. It was also argued that the two designs and design processes differ in nature, and that forcing the actor perspective into a framework of system thinking would allow too little opportunity for modelling the reflectivity of the actors. Conversely, the actor perspective offers a framework which is not intended for a full description and design of the physical systems. Concluding, an integrated approach that takes into account the typical characteristics of complex system design, such as its deep uncertainty, the emergent behaviour, and the strong, unpredictable interaction between both subsystems, must be applied in the design of complex systems.

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# LIVING BUILDING Environment for Sustainable Development in a fast Changing World

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**Abstract**

Development, construction and operation of buildings and structures are associated with disproportional consumption of energy, production of waste, emission of CO2 and transportation of materials. The first reason is the fragmented supply chain in the construction industry, that leads to sub-optimal buildings. The second reason is that buildings are built for long lifetime, where the world inside and around the buildings changes faster and faster. This also leads to suboptimal buildings. The third reason is that buildings are built as monoliths. All components are welded, poured, glued, sealed and cemented. This makes the building hard to change. These changes however are necessary to keep the building fit for use and up to date. The Living Building Concept is a business model for a more sustainable building industry. It is a business model which concentrates on the lifecycle of components and elements of buildings providing an economy of scale for innovative suppliers. Buildings can easily be kept up to date and fit for use with state of the art technology and in a sustainable way by changing parts and re-using the replaced parts in other buildings and structures. In that way buildings and structures show similarity with living organisms, changing slowly as a whole on the long term but changing fast and easy at cell level on short term. The characteristic "from cradle to grave" thinking of the construction sector then changes in a sustainable "cradle to cradle" thinking with substantial positive effects.

Keywords: Cradle to Cradle, Sustainable Built Environment, Living Building Concept

## 1. Introduction

In the Netherlands the contribution of the construction industry to the Gross National Product is about 11%. The negative effect on environmental issues of construction and operation of buildings and structures is disproportional. With respect to the national figures, the energy consumption is more than 45 %, the emission of CO2 is more than 45 %, the production of waste is 35 % and the total road transport is 25 % (Lichtenberg, 2006).

This poor performance is the result of the structure and culture of the construction industry. Three specific factors play a dominant role. The first factor is the fragmentation of the players involved in the development of buildings. Subsequently, the client determines the quantity, the architect determines the form and the technicians determine the quality. The players acting after the architect are allowed to work out the design of the architect and are selected on lowest price. In result, the buildings are suboptimal. The quality of the buildings is not what it could be when the supply chain works together on product development. Product development is only encountered at component and element level. The second factor is that buildings are unique, one shot fabrications with a long technical lifetime. Unfortunately the world inside and around buildings changes faster than the buildings itself. These changes refer to demography, social behavior, technology, regulations, climate, financial conditions, availability of resources etc. The static buildings can not cope with societal dynamics. The technical lifetime is substantially longer than the economical lifetime. In other words, the economical value degrades faster than the technical value. In fact, buildings are built with yesterday's technology and today's ideas for tomorrow's people. In most cases a series of interventions will be carried out during the lifetime of buildings to keep them fit for use, up to date and provided with state of the art technology. The effect of the interventions decreases in time. In other words, the older the building, the harder it is to upgrade the functionality. This process is sketched in Fig.1.

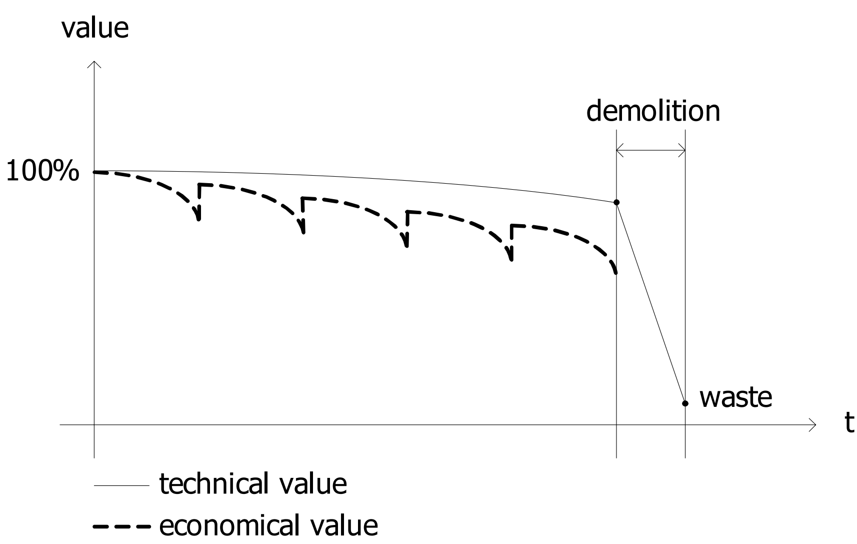


*Fig.1.Interventions in order to keep the buildings fit for use*

The interventions during the lifetime of buildings and structures in most cases are carried out with new materials and components. The removed components are considered as waste material, which can only be 'down cycled'. These interventions and also the eventual demolition of a building is a significant contribution to the poor performance of the construction industry with respect to environmental issues.

The third factor is that buildings are built as monoliths. All components are welded, poured, glued, sealed and cemented. This makes the building hard to change. These changes however are necessary to keep the building fit for use and up to date. There is no reason to assume that either the above figures or the factors behind these figures are significantly different for other countries. As the world on the one hand changes faster and faster where on the other hand there is a trend that contracts for construction cover longer periods with fixed output specifications, the above figures can be expected to become worse in the next decades.

The present performance of the construction industry with respect to environmental and climatologic problems can at the moment hardly be accepted, but will certainly not be accepted in the near future. A major change towards a more sustainable construction industry is necessary. Such a change can only be achieved with a business model that shows advantages for the three main parties involved: (1) Users, Clients and Owners (People), (2) Public Authority as Regulator and Client (Planet) and (3) Companies (profit).

## 2. Performance and sustainability in the construction industry

The performance of a building can be described by value at one side and cost at the other side (Bunge 2006, Vögtlander). This model originates from research of Total Quality Management and/or Continuous Improvement. The model emphasizes the creation of more value against less costs. This double objective opens new perspectives to support eco efficiency (Vollmann 1996, Porter 1995). This separation of value at one side and costs on the other side models the normal perception of goods in the daily life. Consumers are interested in "Value for money" and producers are interested in "Money for Value". Both parties are interested in a good performance, hereafter defined as the difference between value and costs of the building. When that difference is big enough, both parties can easily find a price which is beneficial for each. In this way the total performance is divided in two partial performances: (1) the benefit for the consumer which is defined as value minus price and (2) the profit for the producer which is defined as the price minus the costs (Fig.2).

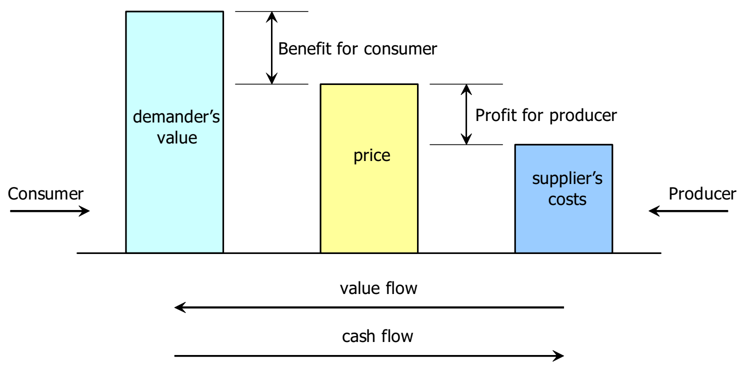


*Fig.2.Value price cost model combining consumers benefit and producers profit*

In the economical theory the value of a good equals the price from a producer's point of view. Here, value is money. However, from the consumer's point of view, value is consumed. As money can only be spent but not be consumed, consumer's value can not be money.

Value of buildings can be explored from different points of view. The classical theories refer to psychological, economical and technological value (Seni 2007). This can be used to define consumer's value of buildings. The psychological value is given by the architecture (form), the economical value is given by the function (capacity, quantity) and the technological value is given by quality.

Costs of buildings are related with capital costs, maintenance costs and operational costs.

## 3. Living Building Concept for sustainable buildings

The performance of the construction industry can only be improved by stimulating innovation on sustainable construction with competition. Instead of the generally accepted preference for extension the lifetime of the whole building or renovation of the building, it is better to concentrate on components rather than complete buildings. This is the level where the interest of users and the interest of innovative producers of components come close together, creating a viable market place which can be compared with the "normal" consumer market. In this view, buildings are considered as an aggregate of a large number of elements with different properties and lifetimes. In this context a construction work is considered as an intervention in the built environment. An intervention takes place at element, component or (sub)system level and is justified by calculating the change in value and the change in costs for the entire system over the design lifetime of these particular (sub)systems, components or elements. An intervention is sketched in Fig.3.

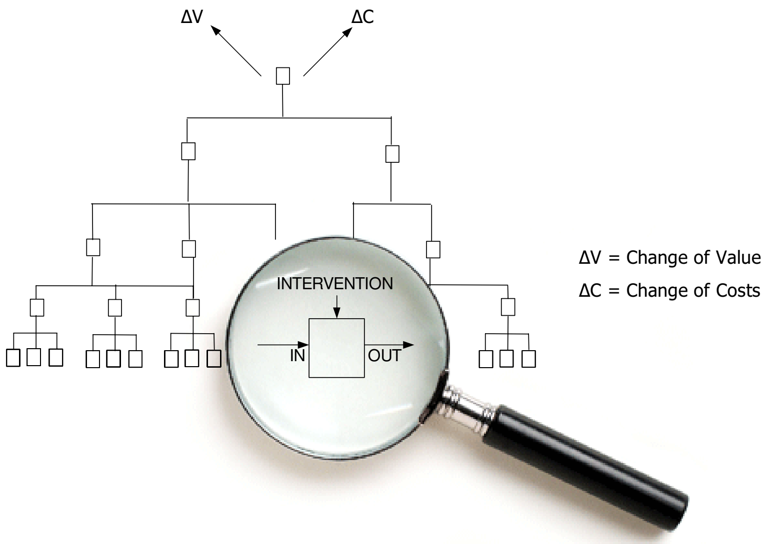


*Fig.3.Intervention with resulting change in value and costs*

The changed value as result of the intervention is subdivided in (1) architectural value (form), (2) functional value (quantity, capacity), (3) technical value (quality) and (4) the extracted value from the world around the building (system). The changed costs consists of: (1) the investment associated with the intervention and , (2) the savings in maintenance and operation due to the intervention over the design lifetime of the changed component or sub- system.

In such a setting, structures and buildings are comparable with living organisms, slowly getting older as a whole but rapidly and easily changing on cell level. The components and materials which come out are used in other buildings. In contrast to the current construction industry where value and price of buildings are fixed at the early start of a construction project, the "Living Building Concept" (de Ridder 2006) considers the value, price and cost as variables. In this approach buildings and structures remain fit for use and up to date with state of the art technology under fast changing circumstances. This dynamic control is sketched in Fig.4.

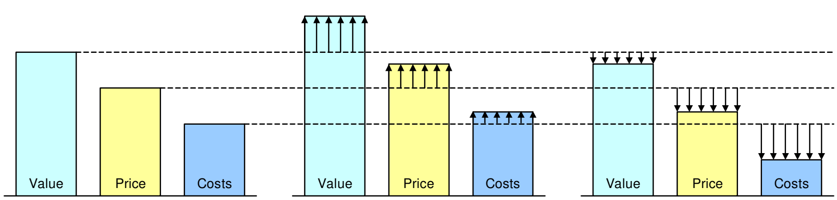


*Fig.4.Dynamic control of buildings*

The essence of dynamic control is that both parties strive either for substantial extra value against little extra costs or accepting little less value for a substantial reduction of costs. Both strategies are beneficial for the two involved parties.

## 4. Living Building Concept for sustainable built environment

The transaction model for individual construction projects can also be used for determining the value and costs  for a set of buildings. In an ideal situation all buildings generate value for consumers (clients, users, owners). These players pay a price for "consuming" this value, which result in an overall revenue. The set of producers (architects, engineers, contractors) gain profit which is the difference between the total revenue and the total costs. This picture for a set of buildings is given in Fig.5.

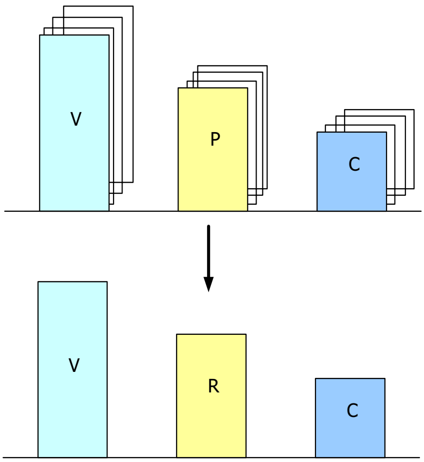


*Fig.5.Value, revenues and costs for a set of buildings*

With this model, construction works would lead to short term benefit between the parties involved. That does not lead to a sustainable built environment, because the long term value of the built environment as a whole is not included. It is also likely that value will be extracted from the environment. Therefore, the model should include a dominant role for the government. The role of the government is plural. Firstly, she takes care for the value of built environment as a whole by watching architectural value of individual buildings, developing public buildings and infrastructure and safeguarding the landscape. Secondly, she should take care for individual interests. What is valuable for one could be worthless or even threatening for another. Thirdly, she takes care for minimum requirements for the technical value by regulations. Fourthly, she takes care for a fair competition between the producing parties (Brown 1999). Last but not least, she should take care for the environment as a whole by taking into account the extraction of ecological value by construction activities.

As has been said before, a transition towards a sustainable building industry can only be achieved with an organized competition. The consumer is willing to pay a price for created value (architecture, quantity and quality). However, most of the consumers are not willing to pay a price for reduction of extracted value. Hence, the market relation between producers and consumers does not result in sustainable buildings. Therefore, the government should set a price on extracted value. The extracted value will be converted into eco-costs.

It is assumed that a small public charge on extracted value is enough incentive for producers to look for eco-friendly solutions. The conversion of extracted value into eco costs is sketched in Figure 6.

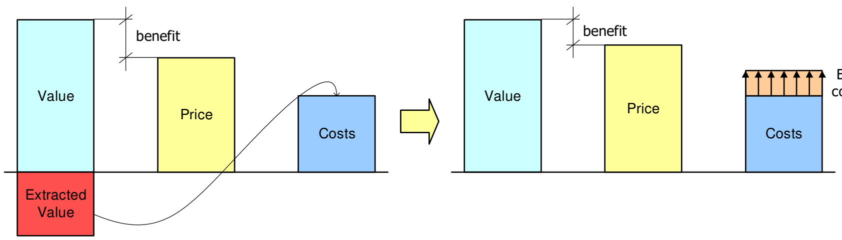


*Figure 6 Conversion of extracted value into eco-costs*

A producer will only apply the eco-friendly solution if its costs are lower than the charge. It can be seen that with a charge on extracted value the producer still has three variables available to create both added value for consumers as well as profit for himself. The eco-friendly innovations can only occur when producers are free to develop their own products and have opportunity to deliver these products in the market.

Based on the positions of the three main parties and the associated roles to be played by them, the connection with the three P's (People, Planet, Profit) of sustainable development (Elkington 1994) can easily be made (Figure 7), resulting in an overall business model. Three distinguished roles can be observed: (1) the Planet is safeguarded by the public authority that converts the extracted value into eco costs, (2) the People consume the total value and generate the total revenues by paying the prices and (3) the Profit is what companies have when controlling the cost benefit of projects.

The three parties indicated in Figure 7 have specific relations with each other. There is a political relation between the government and the people, a market relation with the people and the companies and a regulation relation between government and companies.

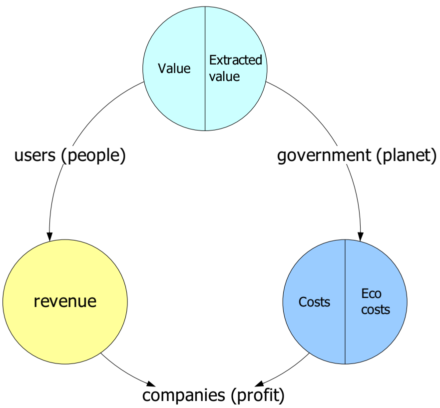


*Figure 7 People, Planet and Profit in an overall business model*

## 5. Four steps towards a sustainable built environment

The business model proposed by the Living Building Concept amounts to a paradigm shift for sustainable built environment. The present culture and structure based on a 'cradle to grave' approach for individual buildings and structures makes place for a new culture and structure based on 'cradle to cradle' approach [lit 9] for a large number of components and elements to be used in a set of buildings and structures. The Living Building Concept is a combination of the technical principles of IFD and the value/price/cost model. A paradigm shift can never be achieved without clear steps that can reduce the resistance against changes.. Four steps are necessary.

### Step 1: Convert extracted value into eco- costs

As already is discussed in section 4, the government should set a price on extracted value associated with the production of elements and components. In that way, use of resources and emissions will be paid. This will lead to trade in and reuse of components by the producer. In a later phase of this transition it could be imaginable that a second hand market will be developed in marketable components and elements such as beams, piles, floors, walls, columns, windows, pipes and elevators.

### Step 2: Introduce sustainable procurement

Secondly, the government should stimulate procurement procedures that provides design freedom for suppliers. In that way suppliers are enabled and challenged to come up with their own solutions. Unique, client specific solutions will be aggregated by a combination of fully developed products. Integrated supply chains formed by architects, contractors, suppliers, advisors and researchers together develop product modules and product families. This will transform the present capacity market of the construction industry into a product service market. In that type of market more thought is given to disassembly, reuse and recycling of components and modules because of the financial incentive for suppliers. The competitors will approach their clients with their trade mark, added value, discount, trade-in and guarantee. Buildings will be better, more beautiful, more diverse, more sustainable and substantially cheaper. That is because the partners in the integrated supply chain think and work together supported by research and development.

The proposed procurement procedure starts with defining a solution space spanned by a value axis and a price axis. Then the client sets boundaries in order to create a level playing field. The value is limited at the down side by a set of minimum requirements (internal) and at the top side by boundary conditions (external). The price is limited at the top side by the budget available (internal) and at the down side by a minimum price in order to prevent unprofessional bids. The solution space is sketched in Figure 8.

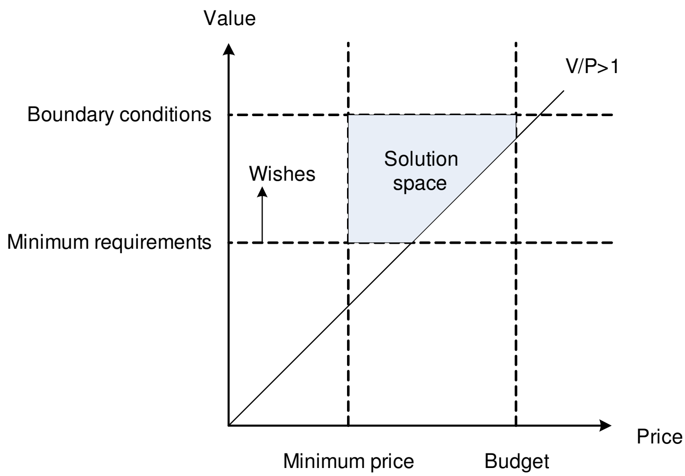


*Figure 8 Solution space for value based procurement*

Bids outside the solution space are not valid. The space between the minimum value (requirements) and the maximum value (boundary conditions) is spanned by the set of wishes (as much as, as beautiful as, as large as, etc). The client is now able to organize a competition on value against price. Wishes can be formulated on architecture, quantity and quality. The first step is a validation. The bids will be checked on a position inside or outside the solution space. Then, each bid is on the "value" side evaluated on the scores on the wishes. This can be done with a Multi Criteria Analysis. On the "cost" side it is obvious that eco costs, construction costs and operational costs can be added taking into account the discount rate and expenses in the future.

**Step 3: Introduction of dynamic control in construction contracts**

As has been said sustainable development means dynamic control of a series of interventions in order to cope with the fast changing world. As shown in Fig.3 an intervention results in a change of both the total value of a system as well as the total costs of a system over the design life time of the intervention. A change is always relative. The change can be measured with respect to the situation just before the intervention.

The total value is composed by three mainly independent sub-values: (1) architecture (form), (2) quantity (function) and (3) quality (technology). Quantification of change can be done by using dimensionless vectors. In a linear orthonormal vector space it is rather simple to calculate the value after the intervention with respect to the value before the intervention, expressed in a percentage. This is shown in an example. The situation before is determined by three unit vectors. The situation after the intervention is changed: (1) architecture is increased with 10%, (2) quantity is increased with 20 % and (3) quality is increased with 10 %. The change of value in percentages is:

$$\Delta Value = \frac{\sqrt{1.1^2 + 1.2^2 + 1.1^2}}{\sqrt{1^2 + 1^2 + 1^2}} = \frac{\sqrt{3.86}}{\sqrt{3}} = 1.13$$

The total costs is the sum of the present values of: investment costs (IC), eco-costs (EC), operational costs (OC) and maintenance costs (MC) over the expected lifetime of the intervention. The change of costs is:

$$\Delta Costs = \frac{present\_value\_of\_(IC + EC + OC + MC)\_after\_intervention}{present\_value\_of\_(IC + EC + OC + MC)\_before\_intervention}$$

The intervention is useful in case $\dfrac{\Delta Value}{\Delta Costs} > 1$

This dynamic quantification of both value as well costs can be the basis of a Living building contract aimed at continuous adaption of buildings. The adaption can be initiated by both the client as well as the contractor.

For the price forming the extra investments associated with the intervention can be considered as costs, whereas the savings can be considered as value.

**Step 4: Living city project**

Sustainable development can hardly start with only one building. It is better to start with a number of buildings, in order to create an economy of scale for components. In that way an integrated supply chain of architects, contractors, mechanical engineers and electrical engineers can not only develop product families and standard components, but are also able to keep the buildings fit for use under changing circumstances by taking out components of one building and reuse that component for another building. In that way the gap between the short functional lifetime of a building and the long technical lifetime of a building will disappear. Concentration on components makes that the components with a long technical lifetime also have a long functional lifetime. This could possibly lead to a stream of components and elements which can be used for any of set of buildings.

## 6. Conclusions

1. The contribution of the construction industry to the Gross National Product is about 11%. The negative effect on environmental issues of construction and operation of buildings and structures is disproportional. With respect to the national figures, the energy consumption is more than 45 %, the emission of $CO2$ is more than 45 %, the production of waste is 35 % and the total road transport is 25 %.

2. The poor performance is the result of the culture and structure of the construction industry. Buildings are sub optimized by different players that work subsequently on quantity, form and quality of buildings. The quality is less than it can be. Moreover buildings are built for long lifetime whereas the functional lifetime is substantially shorter. In result, buildings will frequently be adapted. For these interventions new materials must be produced with associated emissions and energy use. Interventions produce also a lot of waste material.

3. The Living Building Concept is a business model for sustainable built environment. Based on principles of IFD, it focuses on adaptable buildings by replacing non-functional components by new ones and re-using the old ones in other buildings, possibly after repairs and upgrades. LBC keeps the building fit for use, up to date with state of the art technology in a sustainable context with small amounts of waste and emissions.

4. The Living Building Concept requires continuous intervention that is dynamically controlled; added and extracted value at one side and investments and savings at the other side. This requires a systemic approach for the prediction of the performance in value and costs of the system in changing conditions.

5. Sustainable development needs a stepwise approach. The first step is the introduction of a charge on extracted value for the production of building components resulting in eco costs. The second step is a sustainable procurement procedure giving producers the freedom to offer their solutions. The third step is to introduce dynamic control in construction contracts. The fourth step is to start a "Living City" project to help integrated supply chains with the development of product families and components that can be used in a series of buildings.

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# Research by Design in Urbanism

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**Abstract**

There are only few periods in history in which architecture and urban planning acquired the speed of development they have today. This acceleration of development has to do with fundamental changes in our society. Cultural and economical changes in the framework of globalization and growing international dependencies, technological innovations like the establishment of new traffic and transportation systems, the introduction of automated production methods and robots in industry and the even broader application of information and communication technology in everyday life - all these developments are affecting the cities and city life - while environmental risks at a global scale are forcing us to consider the sustainability of our technologies, our life styles and our behavior.

At the same time, in designing our environment we are confronted with an unprecedented abundance of forms and possibilities, enlarged even further by the possibilities offered by the computer. We are being forced to learn, sometimes with great difficulties, to control this abundance and to restore it to a (more or less) consistent language.

The challenges of urban transformation no longer can be faced by analytical or regulative approaches (if they ever have been faced in that way). Conceptual thinking - design thinking – is necessary not only to make a plan, but even more to understand future opportunities and threatens. In this respect - maybe more than in the past - the process of design has become a process of exploration, a process of researching new spatial possibilities and investigating new methodological approaches. This process we could call research by design. In this article I will discuss the demands for research by design against the background of fundamental changes in the practice of designing the built environment.

## 1. Function follows space: the explorative role of design

'I am convinced that space not only makes intended use possible, but is also offering and giving rise to new and unexpected forms of use. Function follows space.' [1] With this remark, Fumihiko Maki at the same time is awarding a special research dimension to the design of spatial configurations: Design becomes an instrument for the exploration of new and unexpected forms of use. The explorative role of design achieved a special importance during the last two or three decennia, when a new type of design task, a new type of assignment got a major influence on the development of cities all over the world: the development of large urban projects as strategic intervention for city branding and competition.[2]

The Centre Pompidou in Paris is a kind of prototype for this type of project. The municipality of Paris on purpose placed this project in a rather deteriorated area to stimulate private investments in the surroundings and to upgrade the whole district. And with success: The public intervention was accompanied by a range of private investments in the surroundings, by housing improvement and new building construction, to participate in the process of gentrification. Even more important was the effect for the city at all: Due to the challenging design the Centre became a landmark and an icon, many times repeatedly presented on the frontpages of the international magazines.

*Fig. 1. Centre Pompidou. Architects: Renzo Piano and Richard Rogers*

In the 1980s and 1990s we have seen a hausse of these projects all over the world. Paris itself contributed with a range of exceptional projects: La Defense with La Grande Arche, Bibliothéque Nationale de France, Parc de la Villette, Parc de Bercy and Parc André Citroën, to mention some of them. But also in other parts of the world the LUP-approach became popular. Nearly every self-respecting city developed 'big projects' - Grandes Projets - to participate in the growing competition of city development. A common characteristic of these projects is the attention that is being given to the quality of design. In the selection of architects, a tendency may be observed that was once described by Hans Hollein as the personalizing of architecture. With increasing frequency, municipalities and developers prefer to give assignments to internationally famous architects whose name alone is supposed not only to guarantee the architectural quality, but even more to give international fame and image to the project. Furthermore, in various large-scale urban renewal projects, well-known architects are engaged as supervisors, to oversee and co-ordinate the quality of the work of the individual architects contributing to the project.

*Fig. 2. La Grande Arche. Architect: Johann Otto von Spreckelsen*

*Fig. 3. Bibliothéque Nationale de France. Architect: Dominique Perrault*

*Fig. 4. Parc de la Villette. Architect: Bernard Tschumi*

*Fig. 5. Parc de Bercy.*
*Architects: Bernard Huet, Madeleine Ferrand, Jean-Pierre Feugas, Bernard Leroy.*
*Landscape architects: Ian Le Caisne, Philippe Raguin.*

*Fig. 6. Parc André Citroën*
*Landscape architects: Gilles Clément and Alain Provost. Architects: Patrick Berger, Jean-François Jodry and Jean-Paul Viguier*

In the Netherlands, a particularly interesting example of the growing significance being attached to architecture and design in public debates on large urban projects is the new bridge over the River Maas in Rotterdam, which connects the old docklands of the Kop van Zuid on the south bank of the river with the city centre of Rotterdam on the north bank. For this bridge (officially named the Erasmus Bridge, but in the meantime by the people of Rotterdam called De Zwaan - The Swan) there were initially two sketch designs, both of which met all the requirements as far as the bridge's functionality was concerned. The difference between them was that, whereas one limited itself essentially to fulfilling the bridge's function as a carrier of traffic, the other (designed by the architect Ben van Berkel), though substantially more expensive, created, with its highly original form, a remarkable feature in the urban environment.

In a public debate that lasted for months, in which the population of Rotterdam was also consulted, the proponents of the Van Berkel bridge finally won, and De Zwaan was opened for traffic in the spring of 1996.

*Fig. 7. Erasmus Bridge, Rotterdam. Architect: Ben van Berkel*

The example of the new bridge over the River Maas shows clearly the extent to which, in the public's views on urban development, too, evaluative categories such as beauty, style and inspirational quality are taking the place of purely functional considerations. That is also why cities often give so much attention to the selection of architects for the design of the new urban development projects. Architectural qualities have become important characteristics when it comes to arousing the interest of private investors and 'selling' a project. It is precisely large-scale public projects like the new bridge over the River Maas that highlight a special aspect: that the imaginative design of such projects is an important means of creating a positive effect that radiates out over its surroundings, improving the image of a district or even the city as a whole to such an extent that further revitalization follows almost automatically.

In other words: these projects do not only need to be able to succeed in their own right; they also have to stimulate the development of their environment, they have to make a contribution to the spatial (and economical) development of the city as a whole - sometimes to the whole region.

But this emphasis on design concepts is more than just a sales argument: it has developed into an independent factor of urban planning. In particular in large-scale urban reconstruction projects the design process is less and less based on a defined program. The task of design is no longer (or no longer exclusively) to fit a program into a form, which then only has to be realized; a new and important task lies in bringing forward new possibilities of use, exploring different programmatic interpretations. And - last but not least - an important task of design in this framework is to bring together the interests of different actors, different participants.

The spatial design is no longer just a plan, but at the same time has become a tool for the exploration of the potentials of the site and a means of communication and negotiation between parties involved. The traditional order, first research, then defining a program and finally making a design, is - at least partially - turned on its head. The process of planning has lost its linear character and has transformed into a process of multiple feedback. Form no longer follows function, but has its own capacity, its own potential, and its own value to deduct new programmatic conclusions.

In this framework we can distinguish two major manifestations of research by design: On the one hand research by design takes place in the search for a suitable site for a given or desired function in which advantages and disadvantages of different sites are evaluated by means of design. On the other hand research by design occurs when designing is used as a means of exploring the spatial possibilities of and developing new programmatic infills for a given site. In both cases design can be seen as an innovative tool for the exploration of spatial possibilities.

## 2. The role of design methods and design strategies

A second demand for research by design has to do with the changing position of the designer/architect in the process of design. The architect no longer is the only one defining the creative design process. Technical specialists are often involved in the design process from the very beginning; their influence is no longer limited to finding solutions for a given form on a technical/constructional level. On the contrary, their input permeates the entire design process. Designing more and more becomes a collective process of collaborating specialists, in which tasks are divided anew between design and construction process, between architect, constructor, developer and other actors. During the process of design and realization the architect is confronted with a variety of interventions and with contradictory rules and demands. The architect has lost his autonomy and is involved in a process of negotiation with changing conditions of power. [3]

In this new complexity, communication between the different parties involved gains even more importance. New - sometimes globally organized - forms of communication increasingly define the result, the built environment. The presentation of the design integrating a variety of different media - has become an important factor in the process of negotiation and decision-making. The role of the architect is stretched into that of a mediator in this process. [4]

But the new media used in the design process are not limited to a communication tool for the architect with other participants. The computer is not simply a new drawing instrument slowly but surely taking the place of the pencil. It is becoming even more clear that the new media techniques are going to fundamentally change design, both at the level of the process and at that of the final result - the form of buildings and space. Thinking in 'fields', the application of rhizome-like structures and the imitation of biological or organic processes in design are just a few examples of changing design conceptions based on new techniques.

Research by design in this respect occurs in the development and application of new design methods and new techniques that often lead to surprising and so far unknown results. Virtual simulations are exploring new forms and new spatial configurations, using huge flows of data and information that never before could be integrated into the design process so fast and so easily. [5] With the experience that the architecture of the program at least is defining the range and orientation of the architectural design the use of the computer is shifting from the application of existing programs to interventions into the structure of the programs and to the development of new programs. The difference between architectural design and program design in this framework is becoming superficial.

### 2.1. The conditions of the society: reflexive modernization

A third demand for research by design can be deduced from the changing conditions of social reproduction. In his book Die Erfindung des Politischen (The Invention of Politics) [6] Ulrich Beck describes the necessity of self-transformation of modern society that will have fundamental effects on all planning activities. The reasons for the necessary modernization of society in first respect are of an ecological nature. Modern industrial societies more and more are taking exception to their limits. On the one hand society is producing risks that no longer can be shifted onto nature, onto other countries or onto other (future) generations. On the other hand the natural resources no longer can be exploited without reproduction, because otherwise the conditions of human living will be destroyed. Both limitations are forcing to what Beck calls 'reflexive modernization': a process of self-transformation that continuously confronts society with itself, with its own conditions.

Within the new risk society (Beck) basic requirements of the industrial society are becoming obsolete: the idea of unlimited growth, the certainty of technological progress and the distinction between nature and human society. In their place a new uncertainty is appearing: the loss of belief in progress, science and expert knowledge, accompanied by a lack of safety (threats from ecological disasters, social conflicts and wars) and (social and economical) insecurities.

With the idea of make-ability (of society), also the idea of linear planning (of the built environment) became questionable. The planning of the future no longer can be based on the certainty of programs and conditions.

Instead the planner is confronted with changing conditions and shifting programs. On the other hand more than in the past the plan has to reflect the own conditions and the effects of the planned interventions. Therefore the process of planning had to be transformed into a process of multiple feedback, it became reflexive too. [7]

In the last fifteen years a large number of new urban plans have appeared in Europe which are reflecting the uncertainty of urban development. [8] These plans normally do not simply delineate future developments but integrate a large number of partial solutions into a spatial strategy for a city and its suburbs, linking these up with various activities and interventions. This new kind of planning is often also referred to as 'strategy' or 'strategic planning'. In contrast to the traditional approach of town planning, strategic planning is not limited to define a spatial arrangement at a given level of scale and on a pre-defined time-horizon. Rather, planning objectives are converted into groups of measures and implementational steps that may be located on different spatial and temporal levels. A strategy in this sense thus contains elements from the whole range of planning hierarchies, from the design of an individual bridge up to guidelines for regional development. It is not limited to activities relating to the organization of space, but encompasses various aspects of local government policy - at least, in as far as these are important or essential for attaining of the objectives.

In contrast to the traditional structural plan or master plan, strategic planning is typically not focused on an even or balanced examination of all parts of the city. Rather, it identifies 'focal areas', for which detailed proposals for solutions are drawn up, with other areas being described only in general terms. The detail in which the aspects of the plan are worked out depends first and foremost on the strategic importance of the various parts of the city and the appropriate planning elements, not on planning standards or planning legislation. In this way, urban planning becomes a cyclical process in which overall vision and details, the objectives and the means by which they are to be achieved are constantly refined in the light of their effect on each other, with in each case the effects of individual decisions on those different planning levels being made clear to all those involved.

Within these approaches design methods are used to explore spatial possibilities and to weigh up the effects of alternative interventions. In this respect research by design became an important element, which partly replaced the methods of trend exploration, and prognoses to generate desirable, maybe unexpected urban perspectives in place of probable, but less desirable urban developments. [9]

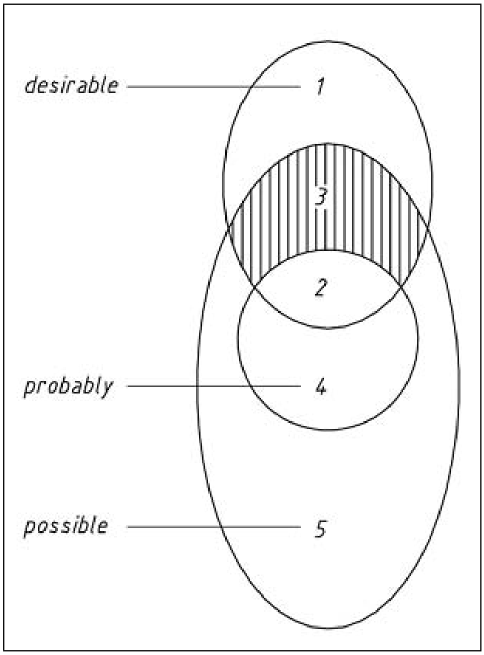


*Fig. 8. Taeke de Jong's scheme of the desirable, probable and possible future*

## 3. The conditions of practice

Specific to all approaches of research by design discussed above is that they were not created as theoretical concepts, yet are being developed in the practice of architects and urbanists. The practice of designing, the production of the built environment, became a field of experiments in which new knowledge and new methodological insights are generated on an almost daily basis. The dynamics of practice are yet so large that theory can hardly keep up.

Without doubt the explorative approaches of design fulfill important requirements of research. They are innovative, exceeding the limits of the body of knowledge both in a methodological and a theoretical way. On the other hand there are important differences compared with the approaches of traditional scientific research, in particular with empirical research. A main difference is related to the objectives. Contrary to traditional empirical research the main goal of research by design is not to analyze reality and find out the truth (or falsify wrong theories about it), but to explore possibilities and to generate new solutions. That means: creativity is more important than scientific correctness, to weigh more important than to measure. But traditional scientific research ran into its limits too. In the theory of science truth became relative, speculative approaches became serious methods for innovative research. From that point of view research and design are growing closer together.

A general limitation of research by design in the daily practice of professionals however is caused by the fact that the approaches barely are communicated, the methods barely are published. In most cases only the results are discussed in a broader way. The methodological discussion mainly is limited to the group of professionals involved. In my opinion here lies an important task for the academic institutions and a challenge for doctorates in architecture in the future.

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[3] Bart Lootsma, Superdutch: De tweede moderniteit van de Nederlandse architectuur, Nijmegen, 2000 p. 24.

[4] Nikolaus Kuhnert, Angelika Schnell, 'Die Moderne der Moderne', in Arch+ 143, 1998 p. 16.

[5] See i.e. Stan Allen, 'Terminal Velocities: The computer in the design studio', in Arch+ 128,1995 p. 83 ff.

[6] Ulrich Beck, Die Erfindung des Politischen, Frankfurt am Main, 1993.

[7] Ulrich Beck, 'The Reinvention of Politics: Towards a theory of reflexive modernization', in Ulrich Beck, Anthony Giddens, Scott Lash, Reflexive Modernization: Politics, tradition and aesthetics in the modern social order, Cambridge (UK), 1994.

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Delft Science in Design 2
M. Eekhout et al. (Eds.)
IOS Press, 2008


# Epilogue

In the second congress Delft Science in Design the opinions of prominent technical designers from all 8 different faculties of Delft University of Technology (TU Delft) were published. They form the top of the iceberg, a rather hidden part of the TU Delft. Up till now hard science or scientific research was higher valued and evaluated than design. Design seemed just application. But design is more than only applying what scientists once have researched. Designing is mediating between science and society, mediating between supplied potentialities (new and existing) and demanded functionalities (technical, but also economical, social psychological and cultural aspects play a role). Designing as an engineering activity is increasingly rewarded for the societal appraisal it deserves.

**Design is the tunnel though which science enters society.**

But it has its own laws and regulations. Sometimes, design is the 'valorization' of research, sometimes it is the satisfaction of societal needs.

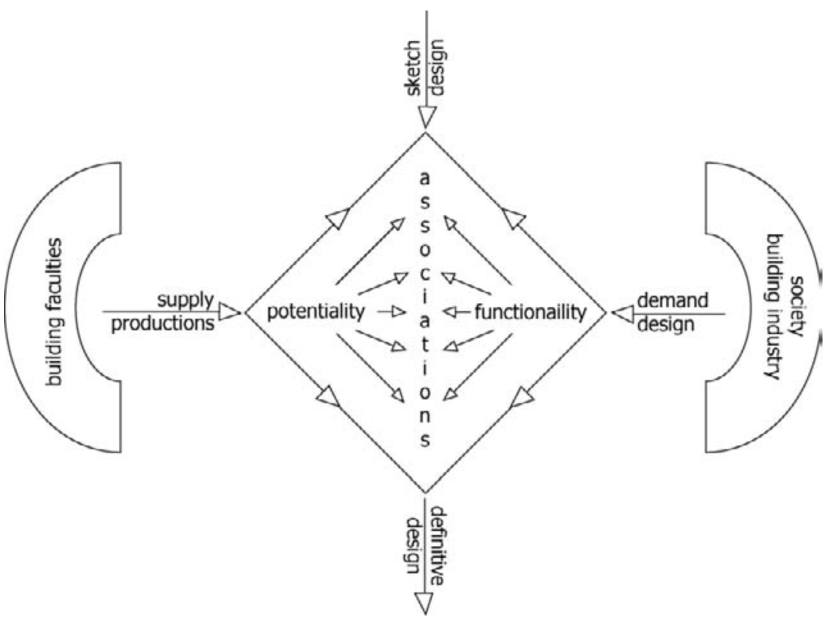



Fig. 1. Wim Poelman's match between potentialities and functionalities (adapted by Mick Eekhout)

The congress series Delft Science in Design has as its aim :

- To enlarge the understanding for (and the possibilities of) Design & Development as an attitude and bundle of activities;
- The stimulation of interaction between Design, Development and Research;
- To position the richness and diversity of the many mono-disciplinary approaches and to draw conclusions from similarities and differences, so that complimentary co-operations can be set up;
- To illustrate the possibilities of interdisciplinary collaborations in approaching societal design challenges, like airports in sea, train viaducts in cities, minimizing energy consumption, sustainability and traffic congestions;
- To enlarge towards society the impact from TU Delft wide inter-disciplinary and continuous design collaborations;
- To enlarge the status of the Delft engineer by emphasizing his/her design capacities;
- To anchor the TU Delft design capacities in the industry, to validate its know-how and to learn from the wishes of the industry;
- To use the adventurous image of prime examples of scientific design towards future students of the TU Delft.

TU Delft has four different types of faculties:

- Two mainly **designing** faculties at the TU Delft: Architecture and Industrial Design Engineering.
- Three mainly **engineering** faculties: Machine, Maritime & Material Engineering, Civil Engineering & Geosciences and Aerospace Engineering.
- Two mainly **researching** faculties: Electrical Engineering, Mathematics & Computer Science and Applied Sciences (Physics and Chemistry);
- One mainly **organizing** faculty: Technology, Policy and Management.

One can imagine that the four main characteristics: *'Design', 'Engineering', 'Research'* and *'Organization'* can be distinguished not only as the main characteristics of the eight TU Delft faculties. These aspects can also be read as aspects of the individual chairs in each faculty, in a mix of which chair has its own blend. It is also important to realize that the three core activities cannot exist without one another. Between Design and Engineering a changing relation is alive, as is the case between Design and Science and Science and Engineering. All three main characteristics are embedded in Organization. But also processes and organizations have to be designed. Processes are immaterial designs. Design influences many chairs of the TU Delft more or less. As one oversees the publications the amount of abstraction in design is prominent. I would like to comment on that later in the text.

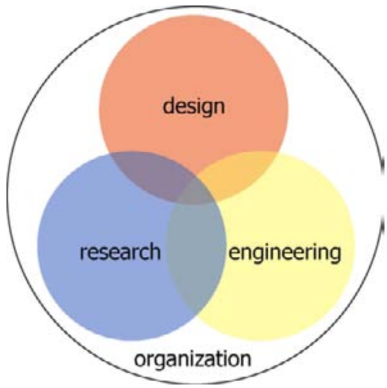



Fig. 2. Indication of the importance of the designing disciplines at TU Delft, in relation with the engineering, fundamental and organizing disciplines.

*Design, Engineering (or 'Construct') and Research,* enveloped by *Organization* are a well known 'Gordian Knot' of strongly intertwined rods. One could cut the knot open by a sword like Alexander the Great did in 333 BC, but by then the cut knot does not have the strength of the original knot any more. So design is intertwined with research and engineering and often difficult to recognize and make to solitaire. In Delft Scientific Designs, often highly technical, it is imperative that Design is present everywhere but at a low level of consciousness. This is the reason why half of the articles of this congress book were on Design Process and the other half on Design Products, this last category visually being the most outspoken.

Design as an academic activity is important for society. The importance of design is increasingly recognized, also as one of the virtues of the Delft engineer, who generally is seen as a hands-on, creative and original engineer, with varying skills in the 3 main directions plus organizational feeling encompassing it.

The average Delft engineer has a wide view on science, engineering and design and is able to concentrate on small specialist subjects as well. The model of the 'drawing-pin' (Figure 3). In some cases the head of the pin is smaller, in others larger and the pin may be deeper of less deep, depending of the faculty and of the interest of the engineer. On the one side the society position of the Delft engineer asks for a wide view. On the other side, the faculties of the TU Delft offer in itself (and in cooperation) a unique pallet of specialist possibilities for highly technical design. The Delft engineer is able to hover over possibilities and to pick out the best one for the job.

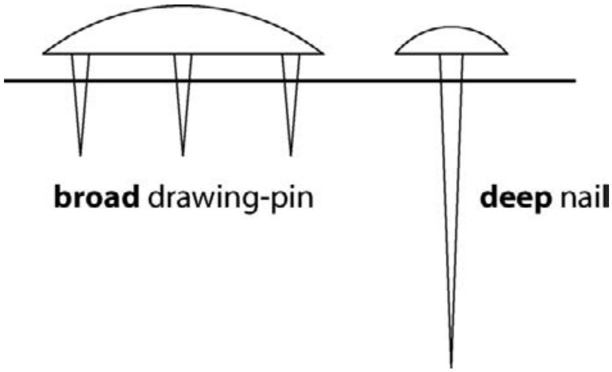



Fig. 3. Broad versus deep approach

Design is positioned between theory and praxis, between improbable and usual, between the extremes of her science and society, but also between ideas and concepts on the one side and materialization and engineering on the other side. Each design project knows a characteristic place between the four directions.

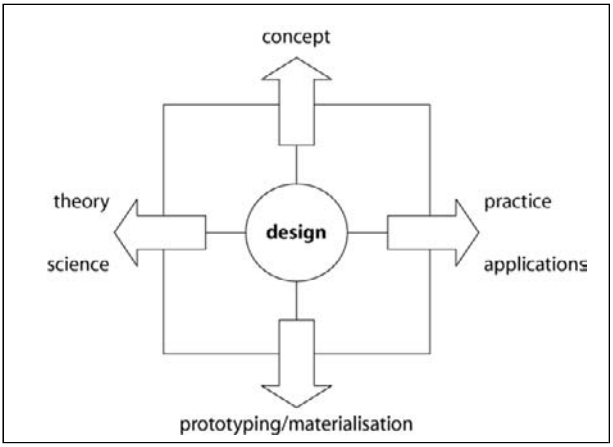



Fig. 4. Fields of tension in scientific design.

The Delft Science in Design congresses offer an opportunity for the more design-oriented staff and students to orient themselves on other professional fields, in multi- or interdisciplinary co-operations, sometimes with uniqueness only available in Delft. These multicoloured design disciplines are an immediate cause to set up typical Delft interfaculty co-operations or to widen these. This is a slow process and has to be announced repeatedly. There are opportunities both from the outside world of Medium and Small Enterprises (SME/MKB), whose president drs. Loek Hermans gave the key lecture in this congress. (Unfortunately this lecture has not been recorded.) But there are opportunities for the different faculties as well.

The Faculties of Architecture and Industrial Design Engineering have started a collaborative research program called the Delft Design Laboratories in which on 4 fields (Sustainability, Material Applications, Design Processes and Informatics) and in 4 Laboratories (Interactive Architecture, Public Space, industrial Architecture and Medesign) the best combinations of these two faculties are targeted.

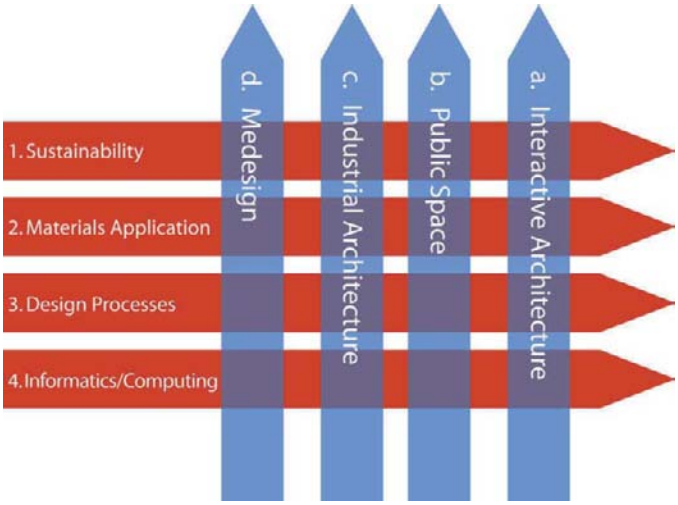



*Fig. 5. Wim Poelman's scheme of the Delft Design Laboratories*

The faculties of Civil Engineering, Architecture and Technology, Policy & Management are setting up a joint research programme in a future Delft Research Centre (DRC) called "3TU Spearhead Building Research", in which a match will be made between the demanding side of the building industry (clients, designers, makers and government) and the supplying side of the total research groups. This DRC is composed of three different levels of Urban Design & Infra Structure, Buildings & Constructions, Components & Materials. Each of these levels with their own deduction of specific research topics from societal problems, via technical challenges to building technical research topics, relevant to society. Since validation is a prime ministerial target for the universities, the match between the demanding side and the supplying side is sought and cared for.

Apart from the theory in teachings from full-time professors at the TU Delft, also real life design processes were presented as praxis examples, normally by part-time professors who have their own independent design practices. The best relationship is the complementary and mutually challenging twin phenomenon: theory and praxis. These two need each other to produce innovative designs. Theory implies design applications in practice. Problems from practice gear up to fundamental research. Both points of view can be found in the presentations.

## From Fundamental Technical Research to Application Design

Between the extremes of fundamental research and artistic functional design as displayed in Figure 6, once derived from the inspiring schemes of Guus Berkhout, one could distinguish a number of more or less independent domains. Each domain has its own rules and games, its own players and characteristics. But the domains are related as each left hand domain is the fundamental domain of the right hand one and each right hand one is the application domain of the left hand one. All of these domains can be found at the TU Delft. The extremes are seldom, though: fundamental research is done at the general universities and artistic design is done at the design academies. But our faculties have traces of these influences and they form a chain of mutually influencing working arenas. To quote Rudyard Kipling in *The Ladies:* they are "sisters under their skins".

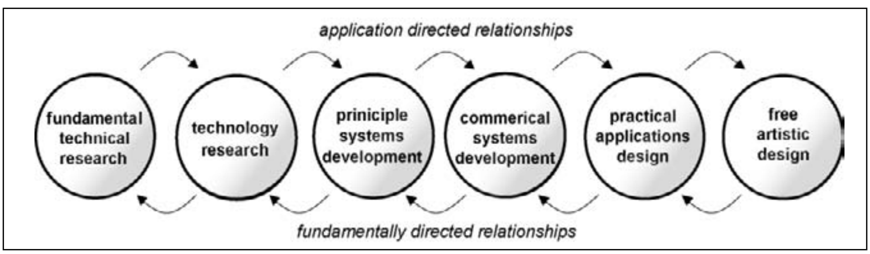



Fig. 6. Relationship between research and design as a linear model.

## Interdisciplinary Design Approach

Design problems are usually so complex and require so much specialized know-how from different disciplines that it is only logical to educate Delft engineers in different scientific fields at the same time, allow them to specialize and then to enter into the richer interdisciplinary collaborations. These set-ups allow both the required depth as well as width. Interdisciplinary collaborations are the pearl in the crown of the TU Delft, both in teachings as well as in research by design. From experience it appears that in doing so better use is made of specialists and better design results are obtained. Better designs and better performances is what the Dutch society needs to regain its position in the European and world industries.

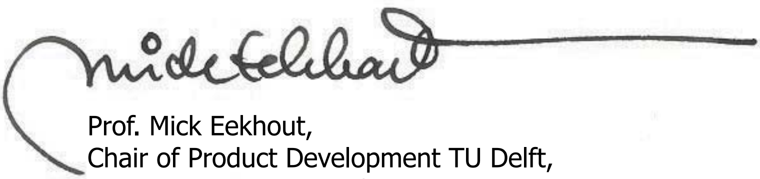
## Collaborations towards Delft Science in Design

These considerations have stimulated the Second congress of Delft Science in Design. TU Delft Rector Magnficus prof.dr. Jacob Fokkema sees the synergy from an hovering organization, so as to formalize the relationship and collaboration towards better scientific design results under the name of 'Delft Science in Design'. We have welcomed the visitors and lecturers of this congress and the readers of this book to participate more actively in collaborative and interdisciplinary design processes. It is for the future but we would like to close off the congress by announcing 'Delft Science in Design' will continue as an icon in the crown of the TU Delft, with the Rector Magnificus as its protector. It hopefully will produce design results of a higher quality, at a world novelty level. For the third congress in two years time we would welcome other designers from this university to present the results of their interdisciplinary design collaborations in 2009. Most probably , because of the 3TU Federation, 'Delft Science in Design' will be renamed 'Dutch Design in Science' and stay a regular topic on the agenda of the TU Delft and a strong point towards the Dutch industry.

To conclude I would like to give some observations from my 6 years of Delft Platform Design TU Delft that can be summed up as follows:

1. Research, development and design are strongly intertwined as in a Gordian Knot.
2. Delft Scientific Design is either quite abstract and focused on methodology and design tools or devoted to complicated technical design subjects.
3. Master students do design continuously during their graduation studies, supervised by staff and professors. This total TU Delft portfolio contains numerous designs on different fields. They should be saved and published on a TU Delft graduate site.
4. PhD students are focused on research and development and some fragments of design and development; There are occasionally mainly designing PhD students (research by design).
5. A 2 year (PdEng) multidisciplinary post master program for 'super-designers' would elevate the level of graduated designers and bring them into contact with the broad range of possibilities of TU Delft.

6. Practical object designs are made in the design and engineering offices of staff and professors outside the TU Delft and are debated within the university as practice designs.
7. Interdisciplinary design could be worked out as a strong point of the TU Delft with its many unique researchers and designers on the different designing and engineering faculties.
8. Complex design issues with their main core in Beta science, need the additional support from the Alpha and Gamma sciences in order to obtain a good match between societal demand and technical design supply.



Prof. Mick Eekhout,
Chair of Product Development TU Delft,
Presiding Congress Delft Science in Design 2,
Member Platform Design TU Delft

*The second congress concluded my mentorship of the Platform Design of the TU Delft. I took the liberty to inform you on my work on the novel technology of sandwich shell structures, to be considered as my farewell gift to the Platform.*

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