Vertical or Horizontal
Hoekse en Kabeljauwse Twisten

Inaugural Speech

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Mijnheer de Rector Magnificus, leden van het College van Bestuur,
Collegae hoogleraren en andere leden van de universitaire gemeenschap.
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Introduction

The development of science was equal to increase of knowledge. Our knowledge increases every time we discover new facts and laws. This takes place in two different directions. When we add new knowledge monotonically to our existing knowledge system, the entire knowledge system will explain phenomena more precisely but at the cost of universality. In other words, we deepen our knowledge vertically but the knowledge becomes always specialized and narrower. On the other hand, when we discover totally new facts and laws that have no relevance to existing knowledge, the knowledge system expands as a whole. The new added knowledge forms a new domain. Sometimes, we combine existing knowledge domains to form a new knowledge domain. Either by discovering a new domain or by forming a combined domain, our knowledge broadens up horizontally and its coverage becomes wider. Of course, "elke voordeel heb z'n nadeel" and the "nadeel" is that we need to learn a new knowledge system, which costs our time and effort.

Hoekse en Kabeljauwse Twisten

These two vertical and horizontal ways of increasing our knowledge sometimes creates a sharp contrast, if not a dichotomy, and remind me of the "Hoekse en Kabeljauwse Twisten", which took place in the Netherlands between 1345 and 1490, almost for one hundred and fifty years. According to Wikipedia, it is a conflict between so called "Hoekse" and "Kabeljauwse" parties. In 1345, Willem IV died without children [1]. The closest family member available was his eldest sister Margaretha who had been married to Keizer Lodewijk (or Ludwig IV) of Germany. Since particularly in Holland, Gravin was difficult, her young second son, later Willem V, was conferred de Graaf van Holland under the condition of annual payment to the mother. So started the "Hoekse en Kabeljauwse Twisten." We see here a universal source of conflict, i.e., tax. In 1350, those who didn't want to pay to the mother and wanted Willem V be disconnected from the mother formed "Kabeljauwse" party and those who were against, maybe not directly against Willem V but against those "Kabeljauwen", formed "Hoeken" which included the city of Delft.

This was the beginning of the story. After a while the original conflict disappeared, but only hatreds and curses remained. Aristocrats, cities, merchants, and guilds opportunistically switched parties depending on the issue of the time. In 1428, "De Zoen van Delft" once ended the conflict between the winner Kabeljauwen represented by Filips van Bourgondië and the loser Hoeken represented by Jacoba van Beieren, but the real final resolution did not come until 1490 with the victory of Kabeljauwen who pushed Jonker Frans van Brederode against Hoeken who supported the appointment of the Austrian Maximiliaan I.

But why Hoek (hook) and Kabeljauw (codfish)? One interesting theory is that a codfish eats a lot and grows enormously. Because it grows bigger, it eats even more, so you need a good hook to catch it. This explanation reminds me of a Japanese expression of "Tarafuku" which literally means, "eat like a cod fish".

The stomach of the fish somehow looks similar to the current status of our scientific knowledge. We have discovered and codified an enormous amount of knowledge both vertically in the depth and horizontally in the width. So, today's engineers and designers who develop a new product ideally need to master all domains of knowledge both vertically and horizontally. But there is always a limit.

Faculty Signboards

Very recently, our faculty disposed of classic mechanical but easy way of addressing classrooms and named them after great mechanical engineers, inventors, and scientists. All of them are universally famous and some are Dutch or related to the Netherlands (see Fig. 1).

Fig. 1. Faculty Signboards

Among them, the Renaissance scientist Leonardo Da Vinci (1452-1519) is the oldest. He was a painter, anatomist, physicist, military engineer, architect, and among other things great inventor, although his flying machines never really flew. About a century later, the Dutch mathematician Simon Stevin (1548-1620) introduced the word "wiskunde" to the Dutch language. At the same time he was a physicist who discovered the laws of force composition and resolution, and hydrostatic paradox. He even conducted experiments of falling balls much before Galileo Galilei at the Nieuwe Kerk here in Delft rather than at the Oude Kerk which looks similar to the Leaning Tower of Pisa. He was also a military advisor to Prince Maurits van Nassau who requested him to design a sailing car. Stevin held a number of patents as well, including one about water wheels.

Compared with Leonardo Da Vinci or Isaac Newton, Robert Hooke (1635-1703) is less recognized and appreciated. He was a natural philosopher and among other things was very much interested in microscopy. He was an important physicist whose name remains in the Hooke's law, but his work on vibration, gravity and astronomy must be equally acknowledged. In addition, he was a Curator of Experiments of the Royal Society that was established in the same period. In today's words, he was the editor of the first academic journal, the Transactions of the Royal Society. Later he became a professor in geometry of Gresham College where the Royal Society's meetings took place. He was a great inventor of the time and his inventions include the spring control of the balance wheel in watches and the first reflecting telescope. Robert Hooke's multiple talents in many different fields resulted in many competitors, followers, collaborators, and sometimes enemies including Isaac Newton over the universal law of gravity and optics, Antonie van Leeuwenhoek of Delft over microscopy, and Christiaan Huygens of The Hague over chronograph. Unfortunately, Robert Hooke's achievements were never valued more than any of these. However, the most astonishing thing about Robert Hooke was that, besides Curator of Experiments of the Royal Society, he was appointed City Surveyor of London after its Great Fire in 1666 and he himself was a busy architect. Although only a few buildings of his original design survived till today, he was helping Wren, as an assistant, who rebuilt London after the Great Fire.

It is very interesting to observe that already in the period of Isaac Newton (1643-1727), multiple talents of these great people in the history in science and technology started to shrink. Newton was a physicist, mathematician, astronomer, and perhaps an alchemist, but was never an engineer. In case of Daniel Bernoulli (1700-1782), the talents were exhibited mostly in mathematics and physics but of course this never means that Bernouilli's achievements were inferior to Newton's.

At the Dies Natlies this year, the university tried to explain to students the kinds of talent profile a contemporary TU Delft student is supposed to have. This is called "T-shaped profile" meaning that a student deeply masters one discipline with additional knowledge enough to be able to comprehend other domains, because solving multi-disciplinary approaches is a must for complex technical development under complex societal demands. But what does this horizontal direction mean? Knowing everything, a bit of piece here and another there? Or, the student can understand and communicate with experts from other disciplines very well? Maybe all of these are important. However, I would like to stress here that the most appreciated capability could be integration capability of different disciplines, on which this talk focuses.

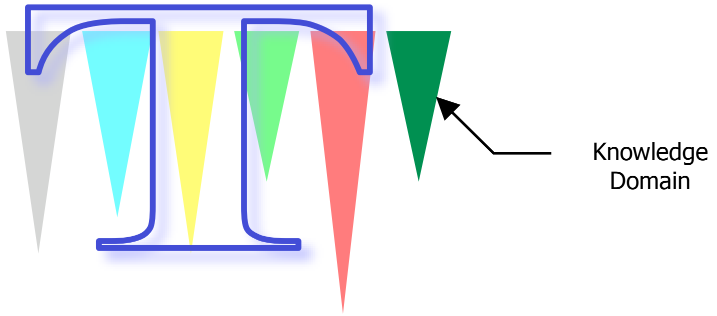

Fig. 2. T-Shaped Profile

The age of multiple talents like Leonardo Da Vinci, Simon Stevin and Robert Hooke has gone, because the amount of knowledge created so far by modern science is way beyond one can digest. This can be proven for instance by the fact that TU Delft has eight faculties in various engineering disciplines, and it takes nominally 40 years to study all of these, that means one may have seven years before he/she retires. Of course, according to the top secret of the university which took me more than a month to find out, in practice it will take 51.9 years, so the student never takes part in the labor market. However, one can do a bit cleverer, due to the so-called BaMa (Bachelor-Master) system. According to my findings, you first do three Bachelor studies, i.e., electrical engineering, mechanical engineering, and architecture[1]. These Bachelor studies will allow you to continue to any Master studies with a minimum effort, i.e., twice one-semester switch programs. In this way, theoretically you finish all studies within 26 years rather than 40 years. However, there is a pitfall, i.e., our Master programs have significantly expanded, so it is not just eight but 32. This will cost you minimum 74 years.

[1] Interested readers are invited to check at http://www.3tudoorstroommatrix.nl/.

Innovation by Integration

The model of scientific development suggests that innovation can be done in three ways (Fig. 3). The first one illustrated in Fig. 3 (A) is a classic approach that fundamental research will lead to a discovery of a new domain. Of course, this is dictated by serendipity and does not happen very often. Fig. 3 (B) depicts the second way to conduct deepening research in a narrow domain, which eventually can lead to a breakthrough. During this deepening process, one might hit very hard bedrock that retards any progress but once a breakthrough is made, we can expect not just gradual improvements but also disparately innovative achievements. In a way, this is a secured method for research and development, because we can use knowledge gained in our past experiences.

The third way depicted in Fig. 3 (C) is a bit different approach in that we try to combine several fields but the combination must be new. In the past, this was a pattern for success. As an example, we can point out mechatronics (i.e., mechanical engineering + electronics + control engineering), biochemistry (i.e., biology + molecular chemistry), biomechanics (i.e., biology + mechanics), and quantum computing (i.e., quantum physics + computer science). In a way, this approach can also be regarded as an application of one domain (X) to another (Y), i.e., X in Y. This method, i.e., X in Y, is a very guaranteed way to succeed, when knowledge in both X and Y is known and available. If you are the first one in the world who begins this combination, your success is almost certain. However, it is often the case that such a combination is already tried or it does not lead to real innovation, because X in Y cannot go beyond either X or Y.

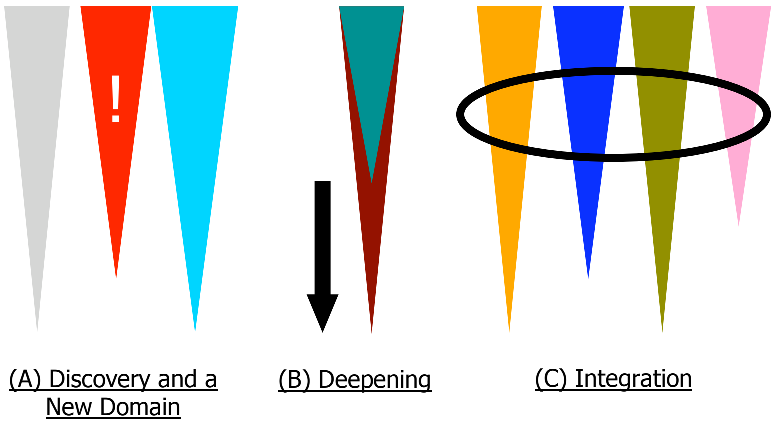

Fig. 3. Innovation Types

Innovation itself is not just about new discovery, invention, and breakthrough. In 1911 Joseph Schumpeter introduced the concept of "new combination" which is the origin of innovation [2]. His philosophy forms the basis for the entire discussions about valorization, entrepreneurship, and even EU's Lisbon Strategy. According to Schumpeter, besides new products, innovation can be triggered by new process, new market, new resources, new marketing, or even organization. In this context, for example, the concept of Product-Service System (PSS) is nothing but innovation, because it is a new combination of service and products.

Modern Multi-Disciplinary Products

Modern products are very much multi-disciplinary and their examples include cars, airplanes, mobile phones, machine tools, medical systems, and printers. Within these products, software plays a central role and its size has grown gigantically. One of the most recent Japanese mobile phone features, UMTS, 5.1 mega pixel camera both for still and movie pictures, TV, video telephone, PDA with various functionalities, full internet browser, music player, debit payment card, GPS, face recognition for security, voice recognition, barcode reader, IR, Bluetooth, and Japanese language front end, besides mobile phone capabilities that can cope with multiple standards. All of these do not come without a cost of eight million lines of software codes.

Within machine industry, automotive industry is the single biggest one in any measure. Modern cars are more "electronics in a moving box". In the luxury car segment, 50% of added value (not profit) comes from electronics[2]. The number of lines of the source codes of the control software for the latest Toyota Lexus's flagship, LS 600hL hybrid car, reaches ten million lines in addition to automatically generated software[3]. Generally such a hybrid car has 30% more movable components than a traditional car powered by an internal combustion engine. According to GM which developed a skateboard platform for future fuel cell cars, the number of movable components will be 50% less compared with a traditional one[4]. What this story scares me is the fact that in the future, at least a half of the job market for mechanical engineers would be then taken over by electrical and electronics engineers, chemists, software engineers and material scientists.

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[2] Private correspondence with a Volvo engineer.

[3] Private correspondences with a Toyota engineer and a Denso engineer.

[4] An oral presentation made by a GM engineer at the ASME 2006 International Design Engineering Technical Conferences in Philadelphia.

The complexity of modern product development, therefore, has significantly increased. There are three primary types of complexity. The first is product complexity due to technologies involved, sheer size of the product, and multi-disciplinarity, inter-disciplinarity, or cross-disciplinarity. The second one is process complexity of the development process, in which more stakeholders are involved. The development organization has also grown, due to various life cycle considerations in a competitive market that demand satisfaction in not only functions, cost, and quality, but also speed (e.g., time-to-market and time-to-delivery), sustainability, and product-service systems.

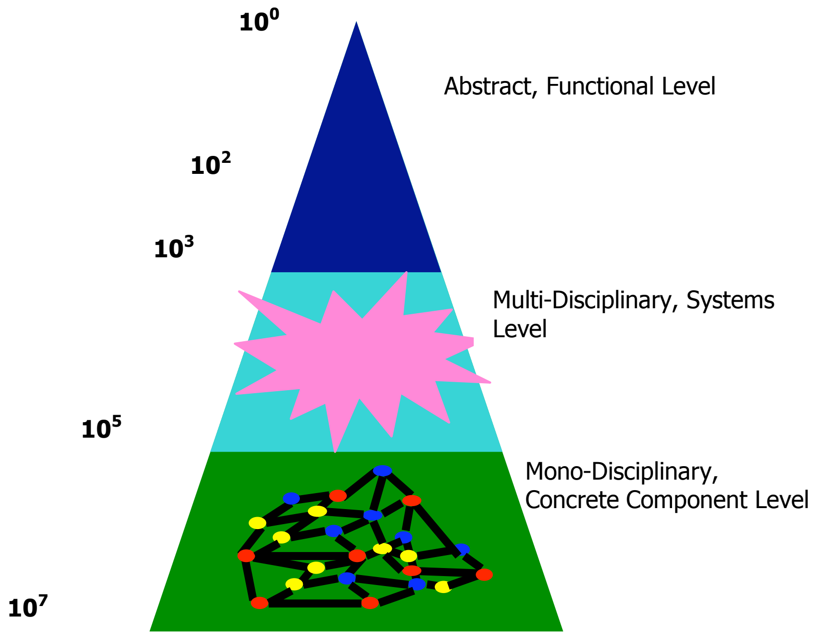

Fig. 4. Layers in Multi-Disciplinary Complex Product (by G. Muller, ESI, Eindhoven)

Inevitably, the architecture of modern products is very complex, because there are a huge number of components or details that count well up to $O(10^7)$ and because these details have interactions among them. This is represented in a triangle in Fig. 4. At the top layer, we have only very abstract descriptions about functions, requirements and modules. The bottom layer is very much mono-disciplinary and filled with technical details, such as components and program details. The middle layer is multi-disciplinary and describes relations among different subsystems in different domains. Contemporary engineers and designers are provided with good tools for the top and bottom levels in many engineering disciplines. We can imagine a CAD tool that can describe every detail of geometry. We have also function modeling methods for the top level. However, there is no tool between these two.

Some difficulties can be found in the development processes of complex high-tech products [3, 4]. First, due to sheer size, the whole product development exceeds the comprehension of a single engineer. Consequently there is no expert who truly understands every detail, because experts are educated and trained in mono-disciplines. This will force teamwork of experts from different disciplines, which will bring in other types of problems. For example, there is no common language among them, and this leads to communication problems.

Second, since every part of the system is interconnected, one little design change can easily propagate to so many other places. This will trigger unmanageable system-wide changes and result in unexpected design problems being found only in a later stage of the development.

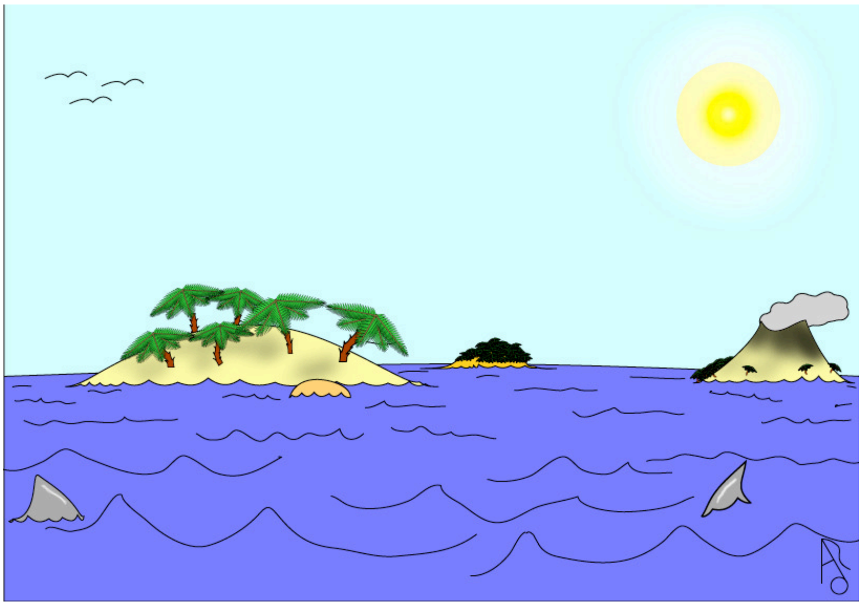

Fig. 5. Inter-Disciplinary Problems

A Western tradition in science is the "reductionist" approach which divides a problem into sub-problems of a manageable size. These sub-problems will be individually solved and their solutions are later integrated to form a solution for the whole problem. This "divide-and-conquer" approach requests that the sub-problems are clearly separated and have least interactions among them. However, this is not the case for many multi-disciplinary problems.

Multi-disciplinary product development causes inter-disciplinary problems illustrated in Fig. 5. We are residents of those isolated islands, and we have perfect knowledge on our own island to solve any problem found in the island. Multi-disciplinary product development by definition includes inter-disciplinary problems that fall in the sea between mono-disciplinary islands. In addition, there are even sharks in the sea. Since mechanical engineers have a view seen only from their mechanical engineering island, it is difficult for them even to find out the relative position of the problem in the sea. In other words, it is almost impossible to figure out how to attack a multi-disciplinary problem as long as we are viewing the problem from those mono-disciplinary islands.

Is there an alternative approach? One possibility is a bird's-eye view (Fig. 6) that clearly presents information about relative positioning of islands and the exact location of the problem. With such information, we can analyze the structure of knowledge and figure out methods to tackle the problem. However, the bird's-eye view does not directly solve inter-disciplinary problems. Instead, it offers useful hints for identifying a problem solving strategy. A bird's-eye view in the multi-disciplinary complex product architecture provides designers and engineers with clear top-down understanding about the system. It also helps a product development team composed of multi-disciplinary domain experts to coordinate their activities. The top level consists of functional level descriptions that should be linked to the systems level, then down to the component level.

Mechanical Engineering Education

Mechanical engineering largely deals with moving physical entities. These entities can be solid, liquid, or gas, with micro- to mega-scale structure. Reflecting this variety, mechanical engineering itself is multi-disciplinary, but within the whole engineering knowledge system mechanical engineering is merely one discipline. In a typical industrial situation, multi-disciplinarity means domain-wise disciplines, such as mechanical engineering, electrical engineering, electronics, chemical engineering, materials engineering, control engineering, software engineering and industrial design, as well as life-cycle-wise disciplines such as marketing, procurement, production, quality assurance, logistics, sales, operation, maintenance, service, and end-of-life activities.

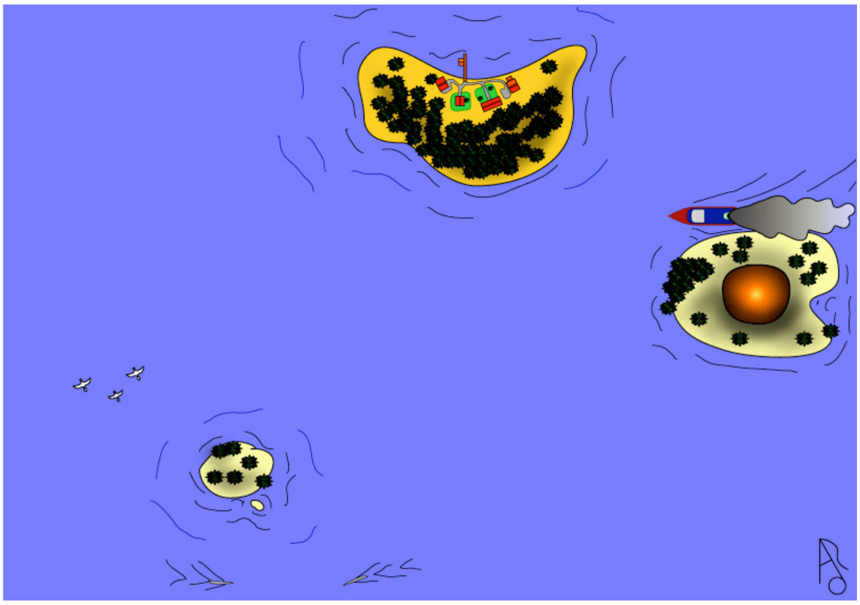

Fig. 6. Bird's-Eye View

Within mechanical engineering, traditional disciplines that deal with "motion" and "force" played a major role. These are strength of materials, mechanics, dynamics, thermodynamics, and fluid dynamics. Among other domains including production, materials, and control, design has been given a "horizontal" capstone position as opposed to vertical elements (Fig. 7).

More recently, many engineering disciplines had to address societal demands. In this sense, design is not the sole horizontal element in mechanical engineering any more (Fig. 8). First, computer technology or in a much wider sense, ICT plays a vital role at every corner of any engineering field. Second, issues addressing societal, legal, economic, cultural issues have rapidly been incorporated and formed separate, horizontal domains. For example, managerial science is becoming an indispensable component in design and manufacturing. Sustainability is another example of horizontal element and formed life cycle engineering. In my opinion, engineering ethics should be given more emphasis in university education, because it has also relevant to sustainability.

My research has been always horizontal. I started my research career about 25 years ago looking at the cross section of design and artificial intelligence, i.e., intelligent CAD. I looked more intensively at a branch of artificial intelligence, i.e.,

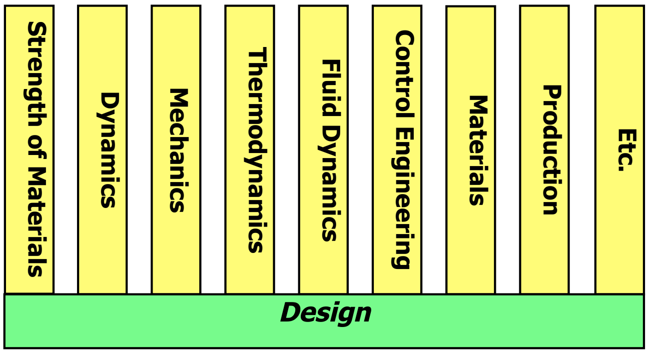

Fig. 7 .Mechanical Engineering

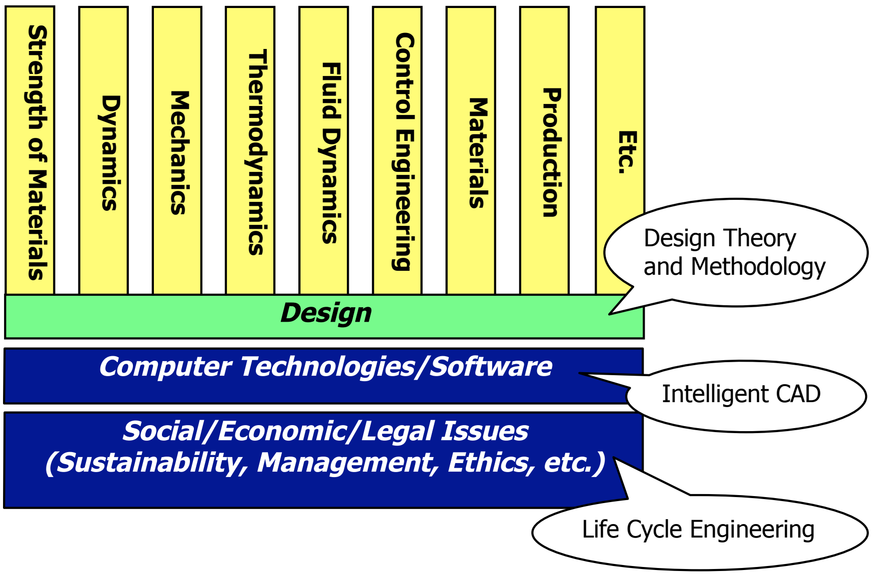

Fig. 8. My Research

qualitative physics, for two applications, i.e., model-based engineering for design and intelligent machines such as self-maintenance machines. Triggered by maintenance, I also started to look at life cycle engineering, which is again a multi-disciplinary discipline that requires bits of design, systems simulation, manufacturing, economics, material engineering, and so forth (Fig. 8).

Any engineering has the dichotomy between vertical and horizontal elements, which often leads to a modern version of "Hoekse en Kabeljauwse Twisten"[5]. Why is it necessary to educate students not only vertically but also horizontally? Even if so, where do these hours needed for such horizontal education come from? If we would like to give them more knowledge and skills in new, horizontal disciplines, it would automatically mean reduction in classic, vertical disciplines. After all, in any case, it is difficult to believe that students can master every aspect of mechanical engineering within five years.

While these debates are just intra-mechanical engineering, we can extend the same arguments to engineering disciplines in general. Is it possible that students can study mechanical engineering and, for example, civil engineering or applied physics? It is not reasonable to expect modern designers and engineers to become multi-disciplinary talents like Leonardo Da Vinci or Robert Hooke due to the depth and amount of knowledge they need. However, we still would like to educate students to be capable of handling multi-disciplinary product development.

If it is very difficult to deeply teach various knowledge domains, what might be alternatives? One solution could be found in so-called major-minor system, although the idea of studying a totally different discipline does not seem to be widely accepted by students and faculties. Another alternative solution could be to teach knowledge structure, i.e., relationships among different knowledge domains. To do so, teaching bird's eye views (Fig. 6) could be useful.

Here, we must realize an important fact. Having only vertical and horizontal threads does not mean that we can make cloth. After spinning threads from fiber, we need to weave them to cloth. This is the integration process of various vertical and horizontal knowledge domains into a single useful knowledge system. Without this process, what we learned ends up with a collection of irrelevant knowledge. In other words, it is extremely important to study integration methods of various knowledge domains, which is what I call systems integration technology. It is different from so-called systems engineering, though. Suppose a student is confronted with a multi-disciplinary design task. When there is no integrated knowledge yet, we can teach him/her individual knowledge domains as well as methods to integrate knowledge domains. The rest of the work should be

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[5] Different versions of "Hoeksen" and "Kabeljauwsen" exist. At the department of The University of Tokyo where I worked between 1987 and 2002, it was "hardware vs. software". I heard in another department that it was "digital vs. analog". Somewhere else, it is "linear vs. non-linear" or "MS Word vs. Word Perfect" or "Windows vs. Linux vs. Macintosh".

done by the student while working on the task. This means that integration of different knowledge domains can only be taught through practices such as project-based learning. We should keep it in mind that great forerunners were always great practitioners, too.

Systems Integration Technology

Systems integration technology is something I distinguish from design engineering or systems engineering in some aspects. First, it is not just a discipline or decision-making process but a horizontal combination of variety of activities. It concerns about integration of different knowledge domains about all knowledge about the product and its life cycle. Second, it is largely a set of methods used for developing large-scale complex multi-disciplinary products, addressing both technical and managerial issues. It addresses decision-making, communication, negotiations, and compromises.

Systems integration technology has four elements and it might be easy to understand these elements within the context of product development process. The first element is the establishment of requirements and specifications of the systems architecture. The system architecture includes overall organization of the system at functional, behavioral, and physical layout levels. This will lead to hierarchical systems decomposition which defines subsystems, their boundaries, and interactions among them. As the system decomposition goes into details, we can clarify process and technology needed to build the system and components. We also consider product life cycle related issues, such as procurement, production, logistics, use and operation, maintenance, and end of life. At the same time, we discuss issues related to product platform, family, and generation.

The second element of systems integration technology is project coordination. This begins with coordination of mono-disciplinary design and engineering processes. It also addresses allocation and management of resources such as human, budget, technology, and knowledge. Project coordination facilitates communications and negotiations to coordinate cross-disciplinary activities, to resolve conflicts and contradictions, and to control engineering processes and human factors.

The third element of systems integration technology is systems integration in a narrow sense. The focus here is on the integration of individual elementary design results into a whole. At this stage, we may need to resolve conflicts and contradictions.

The fourth element of systems integration technology is knowledge integration. Now I must admit that although knowledge integration is the core of systems integration technology, its significant portion still remains as a research issue and we know very little about it. Previously I talked as if there exist methods for knowledge integration but this is not true. We can only learn knowledge integration through practices at least at this moment. However, there are some technical clues for knowledge integration, i.e., knowledge structuring and abduction [5, 6]. Knowledge structuring identifies relationships among different knowledge domains, whereas abduction is considered to be an algorithm for integrating knowledge domains.

Intelligent Mechanical Systems Research

The research activities of our group, Intelligent Mechanical Systems at the Department of Biomechanical Engineering, focus on design. More specifically, our interests reside within designing machines that can exhibit non-traditional features such as self-maintenance, self-organization, self-reconfiguration, distributed autonomous intelligence, and higher degree of collaboration with humans.

We are interested in design in two ways. The first is design theory and methodology of complex systems. For instance, we are currently participating in a project to develop machine architecture that can accept future changes and

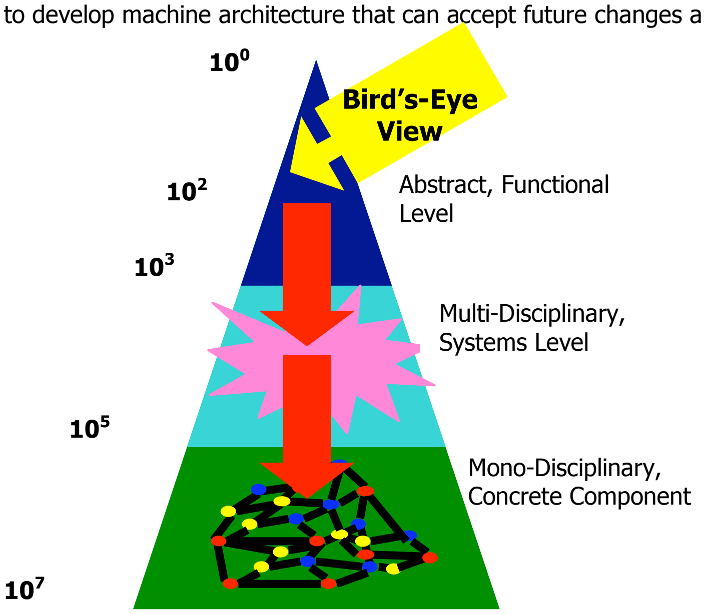

Fig. 9. Bird's-Eye View for Multi-Disciplinary Product Development

upgrades very easily. These capabilities are adaptability and evolvability of architecture and we believe that giving a clear-cur top down view of the system decomposition is helpful for designers to identify them (Fig. 9). In a way, this is more or less equivalent to developing a tool for a bird's-eye view. In another project, we are studying methods to reduce complexity of multi-disciplinary product development by detecting interference among different domains. We are also leading a project that aims at developing methods and tools to automatically generate control software from high-level requirements. Service CAD is a supporting tool to reduce complexity of designing product-service systems, which is by definition multi-disciplinary.

The second of our interests in design is design of machines themselves, especially of machine that exhibit non-traditional features. For example, we are a project member for a project to develop off-shore large scale windmills. Our role is to find out design methods to increase reliability, availability, maintainability, and serviceability of such off-shore windmills through reconfiguration. We are also interested in highly collaborative environments between human workers and robotic support systems, for example, for disassembling of post-use consumer products.

Conclusions

In a modern world, one of the competences of engineers is the capability to flexibly integrate different types of knowledge and apply them to practical complex applications. This is particularly explicit in, for instance, design and life cycle engineering. This stands in a sharp contrast with a classic, traditional image of engineers who are specialists in a narrow domain. Naturally, these two types of engineers are complimentary and equally important. However, increasing complexity of modern products, as well as increasing societal demands, request contemporary engineers and designers to be equipped with both vertical and horizontal capabilities.

The vertical and horizontal elements need "Zoen van Delft" in which I believe this university can play a leading role. The vertical and horizontal elements within mechanical engineering need more integration, not just because complex product development requires further integration, but because without mastering systems integration technology, we as a community will not be able to solve more socially important problems, such as sustainability. At this point, systems integration technology is crucial. The core of this business is knowledge integration, which is our research topic.

Final Words

Let me finish this talk by expressing my sincere thanks to people who supported me during my professional life. First, many thanks go to Rector Magnificus Professor Jacob Fokkema, Dean Professor Marco Waas, and my colleague professors in this university. Special thanks go to Professor Emeritus Klaas van der Werff and Professor Michel van Tooren. Delft University of Technology has wonderful colleagues at every corner. Among others, I would like to thank people at Department of Biomechanical Engineering who accepted me and allowed me to explore design research.

Outside the university, there are a number of people who really believed in me, guided me, helped me, and supported me. Especially I have many words of thanks for my friends in two other TUs, in particular, Professor Fred van Houten of Twente University, and old friends at Centrum voor Wiskunde en Informatica in Amsterdam. I should not forget to add my former colleagues and friends at the University of Tokyo, who even re-appointed me as a visiting professor. I should not forget to thank all project sponsors and project leaders who supported my research as well as my group.

Last not but least, I would like to thank my wife, Marleen, and children, Gianna and Julio, for their support, patience, and understanding about me being an academic.

Ik heb gezegd.

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