**INAUGURAL LECTURE**
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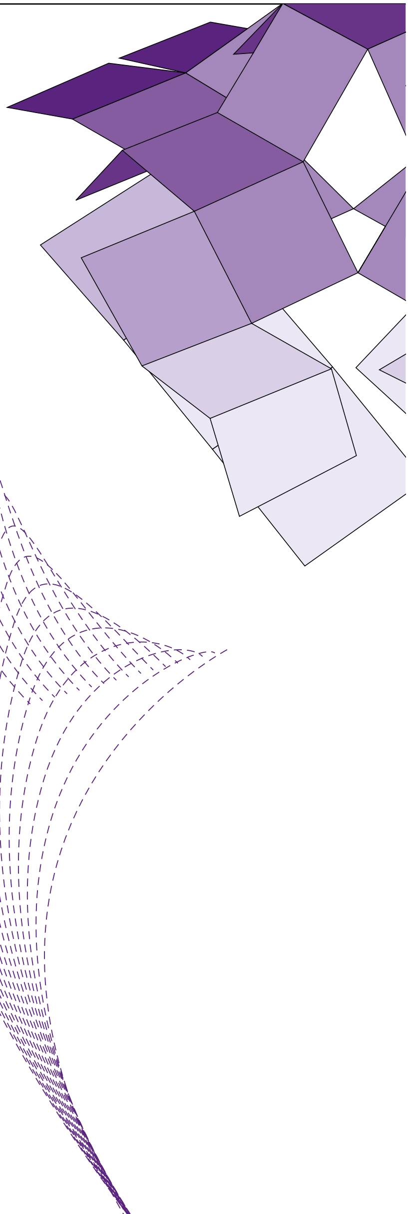

# COMPLEX TASKS – SIMPLE TOOLS

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## INAUGURAL LECTURE PROF. DR. IR. G. MAARTEN BONNEMA, ENGD

**COLOPHON**
Prof. dr. ir. G. Maarten Bonnema, EngD



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Geachte Rector, Dear colleagues, students, friends and relatives, welcome to my Inaugural Lecture for the chair of Systems Engineering and Multidisciplinary Design – or SEMD for short. It is my aim to tell you about how I got here, what my plans are, and also entertain you in the process. And after all of that, we will have a few drinks and bites to eat together.

## INTRODUCTION

The title that I chose is from inside one of the pylons of Sydney's Harbour Bridge. I saw and photographed it during the IDE study tour last June. The bridge is a feast of engineering, and the materialization of an optimistic vision. It was designed and built in the 1920s and finished in the early 1930s. It then already had six (!) lanes of traffic, two tram lines, two train lines, a foot- and cycle path. The construction of the bridge with its main span of just over 500 meters was adventurous as during that construction the two half arches were kept in position with cables tied to anchor points. The example is a clear sign of a complex task, in particular if you take the planning, logistics, material selection, construction detailing and all other aspects into account. At that time, about a century ago, there were only – what we call now – simple tools available: drawings, hand-written calculations and the like. Yet, the people involved made it work! Both from an engineering and from an esthetical perspective it is a great success. It even has become a symbol for the city of Sydney and entire Australia. In the present day and age we face many complex tasks, as expressed by the UN Sustainable Development Goals, see Figure 1


*Figure 1: The United Nations Sustainable Development Goals (source: https://sdgs.un.org/2030agenda, retrieved 20230630).*

No, I do not have the illusion that we can find a solution for all of these in the remaining 45 minutes of this talk. However, we might find some inspiration in tools (yes, Simple Tools) that can be of help in addressing these tasks.

# COMPLEXITY

Let us first dive into what complex and complexity mean. In everyday speech, some people use the word "complex" as a synonym for difficult. Others say that complexity has to deal with numbers; or variety; or: the more connected the parts inside a system are, the more complex it is perceived (McDermid 2000, Manson 2001, Axelsson 2002). These are all more or less correct interpretations, but they do not help so much in *dealing* with complexity in the engineering domain.

(Suh 2005) gave an in my view refreshing idea of what complexity is. I will only take one quote: "Imaginary complexity is defined as uncertainty that is not real uncertainty, but arises because of the designer's lack of knowledge and understanding of a specific design itself." So, complexity partly expresses that we simply do not know enough! The question is then how to quickly and effectively remove that lack.

Gisela Garza Morales, Kostas Nizamis and myself recently published two papers on complexity (Morales, Nizamis, and Bonnema 2023, Garza Morales, Nizamis, and Bonnema 2023). In the one in Research in Engineering Design, we step out of the often employed solution domain, to the problem domain. Where does complexity originate from? Gisela found there are three plus one viewpoints to use, see Figure 2: The Social, the System and the Process viewpoints, plus the Tooling viewpoint. Interestingly, many of the reviewed papers go into the tooling viewpoint.

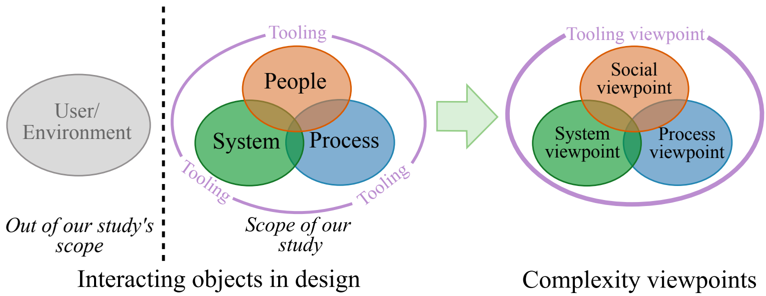



*Figure 2: Complexity Viewpoints from (Garza Morales, Nizamis, and Bonnema 2023).*

And also interesting is that the system and process viewpoints are often treated in (too much) isolation. This is where Gisela's PhD seeks a contribution.

When we thus talk about a complex problem, we need to use these 3+1 viewpoints to explore what is complex about it; and is it real or imaginary complexity?

# COMPLEX QUESTIONS

Let us now look at two complex questions that exist today.

## CLIMATE CHANGE DUE TO HUMAN INDUCED EMISSIONS.

From the series of IPCC reports (https://www.ipcc.ch/reports/), there is no doubt that mankind has had (and still has) a significant impact on the climate. We must put a lot of effort into reducing our emissions fast.

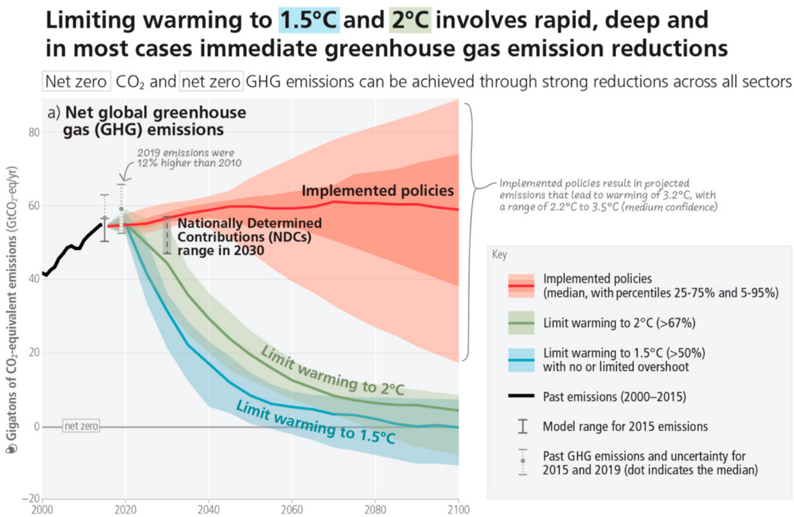



*Figure 3: Past and future scenarios for global warming (taken from the synthesis report of the IPCC sixth assessment report AR6).*

We see here already the three viewpoints mentioned earlier: The system is the climate and how human activities have affected that. The process viewpoint has not fully materialized, but the bottom line is that by reducing emissions, we can avoid too much global heating. Unfortunately if we would  stop emitting now, we will still experience global heating for some time. Finally, the social viewpoint tells that society, including each and every person and organization has to stand together to make this work.

Land transport is a large $CO_2$ emitter. When preparing this oratie in Nelson, New Zealand, the diesel busses of Nelson were being replaced by fully electric ones. And that is something we are seeing in many places. But why is electrification of transport a good idea?


*Figure 4: Nelson's new electric busses.*

Since the new buses (Figure 4) have been put in use on 1st of August (https://our.nelson.govt.nz/media-releases-2/nelson-tasmans-new-buses-are-delayed-but-its-a-service-worth-waiting-for/, retrieved 20230627):

- Prices reduced to a $2 flat fare
- Urban buses every half hour, 7am to 7pm, 7 days a week
- Simplified routes – less changing bus
- New routes
- A regular airport bus service

And all that with reduced greenhouse gas emissions, and a battery technology that does not use (as much) cobalt, nickel or magnesium (https://our.nelson.govt.nz/media-releases-2/bus-batteries-next-stop-sustainability/, retrieved 20230627). Sounds like more than enough reasons to electrify city bus fleets. Yes, I know this is just one case, so does not really count as evidence. But that electrification is a good way out is well enough described in literature (Hoekstra 2019, Nealer, Reichmuth, and Anair 2017).

My chair has a history in this field with students Lisette and Noortje and the University of Southeastern Norway. Also with FIER Automotive and Steven, Roberto and Marlise.

## FUNCTIONALITY AND PERFORMANCE INCREASE

Many systems and products today offer way more functionality and performance than comparable systems and products of one, two or three decades ago. Let's look for instance at the total available computing power on the planet:

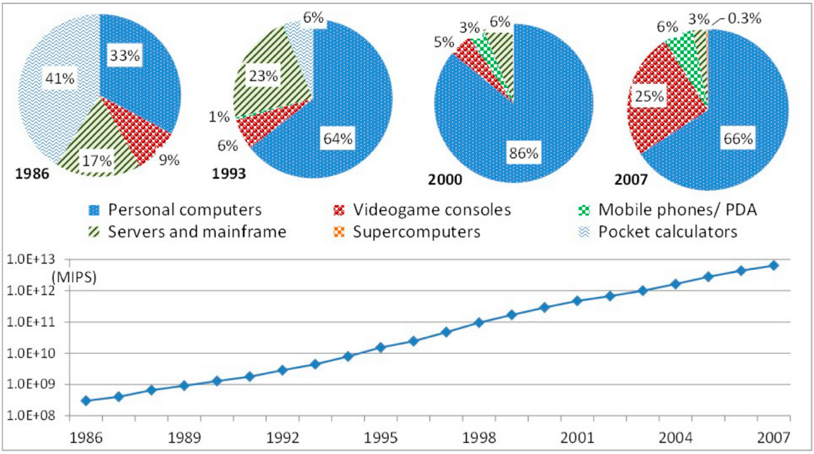



*Figure 5: Development of global computing power 1986-2007 on a vertical logarithmic scale. (source (Hilbert and López 2011)).*

In a period of 20 years, the total global computing power has increased 10 000 times. That's almost 60% increase per year! Also note the distribution: in 1986 (the year I graduated from high-school) 41% of the global computing power was in *pocket calculators*! I guess nowadays smartphones by their sheer number make up the lion share of computing power in the world. We see here the effect of Gordon Moore's observation: "the number of transistors in an integrated circuit (IC) doubles about every two years." (https://en.wikipedia.org/wiki/Moore%27s_law, retrieved 20230626). He based this observation on only a few data points in 1965; it still holds today!

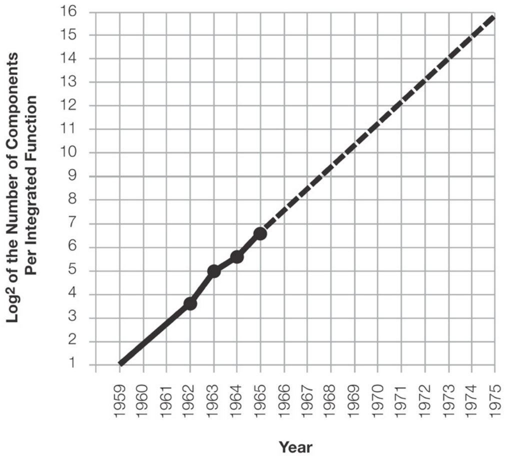



*Figure 6: Gordon Moore's famous prediction of number of transistors on an Integrated Circuit - from (Moore 1965).*

When "cramming more components on an IC", these components become smaller. Smaller components mean smaller features, and thus we need more accurate machines. The more accurate a machine has to be, the more phenomena one needs to control.

How is that possible for 6 decades? My former boss, supervisor and great example of a Professor, Fred van Houten said: "The smaller the features in a product, the bigger the machines needed to manufacture them."
Thé critical step in manufacturing integrated circuits is the lithography step. As you all know, the Netherlands are home to the champion of semiconductor lithography: ASML. It's also my former employer. If we list their machines over time, Fred's observation is quite well supported. The current EUV machines are so large, that they require 40 shipping containers and 3 Boeing 747s to ship (https://www.nytimes.com/2021/07/04/technology/tech-cold-war-chips.html, retrieved 20230626), all to "cram more components on an IC".

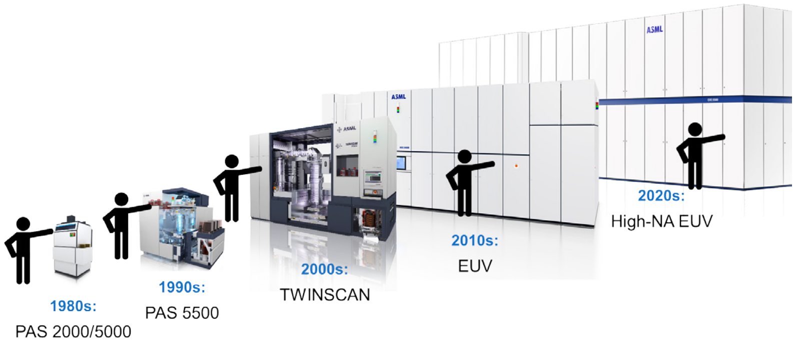



*Figure 7: Development of ASML's wafer scanners 1980s-2020s. (Pictures courtesy of ASML).*

ASML has been successful in developing and producing these machines with ever more precision and productivity for almost 40 years now. What is the secret of their success? Even if you are able to manufacture all the parts, you may not be able to make it work as a system, as known from a story by Jos Benschop. In China they got hold of the documents of a scanner. They were able to manufacture the parts. But when they tried to make it work together, it didn't work. This hints to what systems engineering entails: it is about making the whole more than just the sum of the parts. When talking about a *complex system*, there are many parts and even more interactions between the parts. Intended and unintended interactions. Failing to identify and understand one of these interactions may result in overall system failure.

Note that these interactions are often only found by personal contact between engineers, the humans that make the systems work!

Similar argumentations and observations can be made for developing printers by Canon Production Printing, Magnetic Resonance or X-Ray Imaging systems by Philips, Tyre making machines from VMI, Radar and Combat systems by Thales and more.

# SYSTEMS ENGINEERING – THE SECRET SAUCE?

The chair is called "Systems Engineering and Multidisciplinary Design". So far we have mostly talked about complexity and systems. So what is this Systems Engineering (I'll come to Multidisciplinary Design later)?

## HISTORY OF SYSTEMS ENGINEERING

Aqueducts and the road system in the Roman empire can be considered early examples of SE in the civil engineering discipline.

Early mentions of the *term* Systems Engineering come from the 1950s in Bell Labs and the Radio Corporation of America (RCA). In 1967 Bode wrote in a report for the US House of Representatives "…the systems engineer resembles an architect, …. Like architecture, systems engineering is in some ways an art as well as a branch of engineering. Thus, aesthetic criteria are appropriate … ideas as balance, proportion, proper relation of means to ends, and economy of means are all relevant in a systems-engineering discussion." (SEBoK Editorial Board 2023) A very true statement, still today!

In the 1970s the field grew, although "Many managers … viewed SE as straightforward common sense, believing that any good project would use the same principles." (Honour 2018). Among other things this resulted in limited academic interest in the field.

The National Council on Systems Engineering was established in 1990, to be renamed to the International Council on Systems Engineering – INCOSE – in 1995. Noteworthy is that CNN Money called Systems Engineer "the best job in the world" in 2009.

In Academia the field has had less interest. In Software Engineering on the other hand, several of the SE concepts were adopted and further developed. Software engineering requires rigour and ways to deal with complexity. Eric Honour states that SE principles underpin software engineering approaches (Honour 2018).

MIT's Engineering Space Laboratory; Stevens Institute's schools for systems science and engineering; Loughborough University in the UK and the University of Southeastern Norway today have a long history of Systems Engineering Education on Academic level.

## WHAT IS SYSTEMS ENGINEERING?

INCOSE has defined SE as "a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods." (https://www.incose.org/about-systems-engineering/system-and-se-definition/systems-engineering-definition, retrieved 20230626). As with all (academic) definitions: they are quite correct, but often not so informative. If I explain what the core of SE is, I usually use these aspects:

- The system perspective;
- Separate the *what* and *how* much, from the *how*;
- Focus on the interfaces (instead of on the components);
- Uncertain and incomplete information in taking far-reaching decisions;
- Relying on Communication in a context of Multi-disciplinarity.

If you like to know more about this, you can watch a recording of "SE in 45 minutes" made together with Saxion University of Applied Sciences (https://tinyurl.com/SEin45min). But a few words about these aspects are fitting here.

### *The System Perspective*

The system perspective is about zooming in to the relevant details and zooming out to the context and keeping the big picture, and seeing that your system can be my subsystem or the other way around. A great (and simple!) tool to do this, is the 9-window diagram from TRIZ. It helps one to think about parts, but also about context, environment and time. Many engineers automatically dive into the details/parts, but this tool helps to see the bigger picture.

Temporal

Hierarchical

| | Past | Now | Future |
|---|---|---|---|
| Supersystem | Cities with noise and pollution | Quiet and clean cities | Car-free urban landscapes |
| System | Diesel bus services, cars | Electric bus service, electric cars | Individual ride service (MaaS) |
| Subsystem(s) | Internal combustion engines, fuel services, parking spaces | Electric motors, charging infrastructure, parking spaces | Electric motors, charging infrastructure, app |

*Figure 8: A 9-window diagram for public transport in cities.*

### *Separate the what and how much, from the how*

This is probably most fundamental to SE. Engineers (including me), love to think in solutions, constructions, devices. When we are thinking about a solution, we want to make it better, more accurate, faster. A Systems Engineer needs to separate what has to be done, from how to do it.
So, talking about transporting a person without immediately thinking about a car. Because: do we need to transport one person or a family? Does it have to happen every day, or only occasionally? What may it cost? It might be that a recumbent bicycle is a way better solution for going to work, than a convertible car or a bus. And for holiday it may be completely different, or not.

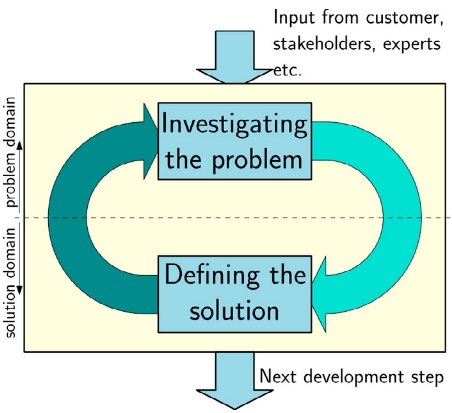



*Figure 9: The problem and solution domains, and the cyclic nature of problem exploration and solution definition (Bonnema, Veenvliet, and Broenink 2016).*

In academic terms, this relates to the problem domain versus the solution domain that I mentioned earlier. I believe designers work more cyclical than classical design methods suggest (Pahl and Beitz 1996): while investigating the problem, they use concept solutions. It is a good habit of a systems engineer to frequently hop between the solution and problem domains! By exploring the fit between problem and solution, or lack thereof, they learn more about both, so that knowledge can be increased; reducing Suh's imaginary complexity.

*Focus on the interfaces (instead of on the components)*
This is best summarized by the quote from Robert Halligan: "There are two kinds of Systems Engineers: those that look at the interfaces and amateurs". When things go wrong, it is often at the point of interaction (interface) between parts, subsystems and systems.

*Uncertain and incomplete information in taking far-reaching decisions*

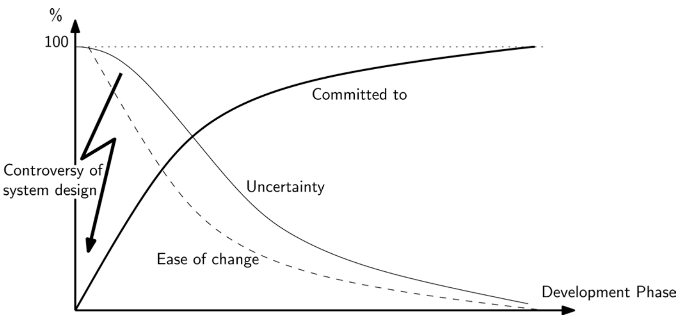



*Figure 10: Inherent controversy in system design (Bonnema, Veenvliet, and Broenink 2016).*

This picture – that exists in many variants – tells a lot: In the early phase of systems design, the designer has to take many decisions that cannot be easily modified later on, but that do determine the final system to a large extent. I see people that become very unhappy about the uncertainty and lacking information while others can handle this situation quite fine. The latter group has good prospects for becoming a systems engineer.

*Relying on communication in a context of multi-disciplinarity*
Finally, a good systems engineer has to be able to communicate with many

different types of people, in all kind of roles, see the picture below. This does mean the Systems Engineer has to be able to express a design (often quite a complex one) into formats that are understood by very different types of people.

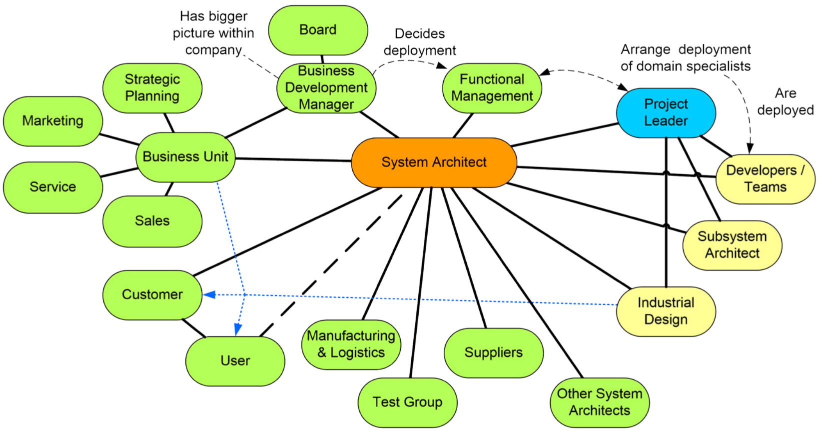



*Figure 11: Communication partners for a System Architect (Haveman 2009).*

In that regard, I remember a colleague at ASML, Erik Loopstra, who was able to draw on the whiteboard a really simple picture of the complex dynamic architecture of the new TwinScan wafer scanner. What Erik did was leaving out many details so that the picture expressed the core of the idea, understandable by many. It was an illustration of Albert Einstein's quote that "Any intelligent fool can make things bigger and more complex... It takes a touch of genius - and a lot of courage to move in the opposite direction." – in fact my favourite Einstein quote!

## CURRENT POSITION OF SE

Industry is seeing the need for Systems Engineers more and more, as for instance expressed in the NXTGEN Hightech agenda (https://nxtgenhightech.nl, retrieved 20230627), and the increase in course participants at MikroCentrum. Also in academia there is more interest, as seen in my appointment, and in the Sectorplan techniek.

A remark about the Sectorplan is that Systems Engineering is mentioned as the binding element. Strangely enough, there are no positions defined to bring the SE discipline further. Yet there is, as I see as a practitioner and a researcher, still so much to research in the SE field, to help engineers develop integrated and balanced systems designs. We will see more about that later on…

## SYSTEMS THINKING

When talking about Systems Engineering, one should address Systems Thinking. Although there are a lot of books and publications about SE that focus on the process and the tools (Honour 2018), if one doesn't *think in systems*, these become mere tricks and checklists.

Defining Systems Thinking is not easy, see (Cabrera 2006). Moti Frank (Frank 2006) describes what the abilities and competences are of a systems thinker. Boardman and Sauser have published a readable book about Systems Thinking, where many examples and cases are treated (Boardman and Sauser 2008). All of these mostly describe what they see in experienced Systems Thinkers, not how to become one.

Systems Thinking connects explicit and accurate information from the engineering world to imagination and reasoning along time and space. By daring to go beyond what the exact data tells, we acquire more understanding of what the system is and how it will impact the future. Tools like System Dynamics and Causal Loop Diagrams are very helpful in this.

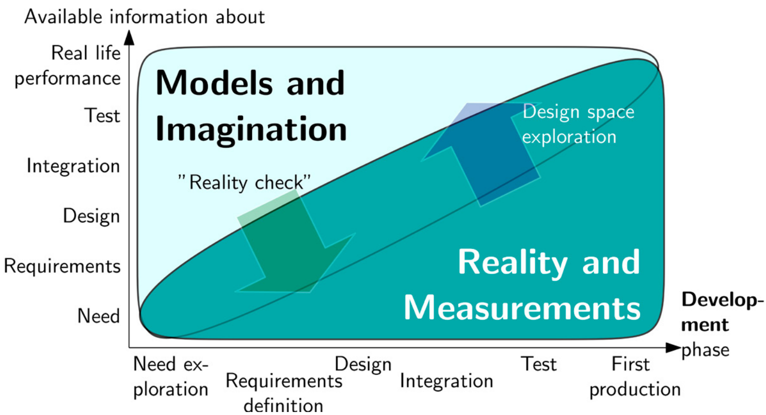



*Figure 12: In system design reality and measurements are important, as well as models and imagination (Bonnema, Veenvliet, and Broenink 2016).*

A contribution that my chair has made here are the 12 Thinking Tracks to help a novice systems thinker, and supporting the experienced systems thinker  (Bonnema and Broenink 2016, Bonnema 2012). They base on experience and academic systems thinking literature. My hypothesis is that an experienced systems thinker implicitly uses these ways of thinking. It’s only very hard to verify this hypothesis.

The 12 Thinking Tracks (Bonnema and Broenink 2016, Bonnema, Veenvliet, and Broenink 2016, Bonnema 2012):

| | |
|---|---|
| Dynamic Thinking | Decomposition-Composition Thinking |
| Feedback Thinking | Hierarchical Thinking |
| Specific-Generic Thinking | Organizational Thinking |
| Operational Thinking | Life-Cycle Thinking |
| Scales Thinking | Safety Thinking |
| Scientific Thinking | Risk Thinking |

# SIMPLE TOOLS

The earlier remark about communication hints towards the simple tools in the title. Before showing you some of those, we need to have a short intermezzo on *complex tools*.

## COMPLEX TOOLS

In contrast to the times of designing and building the Sydney Harbour Bridge, we have – as seen earlier – almost infinite computing power to support the design process that is widely used to support engineers via tools like:

- Finite Element Modelling (Ansys and the like)
- Mechanical Computer Aided Design
- Electronic Circuit simulation (pSpice)
- Computational Fluid Dynamics
- Dynamic simulation (spacar, matlab)
- Product Data Management and Product LifeCycle Management
- Etc.

With these tools, we can for instance optimize a design to an input load case to save weight.

In Systems Engineering though, we are faced with multidisciplinary problems: ensuring sub-nanometer accuracy in a wafer stepper is a combination of mechanics, control engineering, heat and flow, environmental control etc. If we tried to make the stepper work based on, let's say, mechanical CAD models alone, how would all these other disciplines stay connected?

Hence we need tools that are usable and understood by all disciplines involved and that support making *trade-offs*. Trade-offs between apples and oranges, that is! Like cost against ease of use; weight against environmental impact; time to market against accuracy. Even more so, systems design is not only about engineering, but also involves marketing, usability, safety, and economic aspects. Resulting in even more difficult (or should I say "complex") trade-offs requiring insight in the systems and the problem to be solved.

So, let's take a look at a few (not all) of the simple tools used in Systems Engineering to deal with this. The tools tend to have the form of some sort of diagram. As students shared among each other: "When you make a lot of diagrams, Mr. Bonnema is happy." And yes that is true! … as long you actually use the diagrams to understand your system better.

### 9-WINDOW DIAGRAM

We already saw the 9-window diagram: it puts the system in perspective of hierarchy and time.

### CONTEXT DIAGRAM

An overview of the people, organisations and other systems that our *system under design* relates to. The people and organisations are called the stakeholders of the system under design.

### SYSTEM BUDGETS

We're all familiar with financial budgets when planning for a vacation: how much to spend on transportation, accommodation, food, fun activities. The same principle can be used for positioning errors when designing an accurate machine, or energy use of an electric city bus and much more.

### N2 DIAGRAM

Yet another simple but oh so powerful tool. This one is to investigate the *interfaces* in a system. And as quoted, if you're not looking at the interfaces, you are an amateur Systems Engineer.

| | | | | | | |
|---|---|---|---|---|---|---|
| **Pass-enger** | Mass | Mass | | | | Senses |
| Force | **Propel Bus** | | | P, v, a values | | Heat, Noise |
| Force | | **Brake Bus** | Power | P, v, a values | | Heat, Noise |
| | Power, Mass | Mass | **Store Energy** | SoC | | |
| Inform | Accele-rator | Brake pedal | | **Control Bus** | | Indicators, Lights |
| | | | | | ... | |
| Weather[1] | Road | Road | Power[2] | Roads, Signs, Stops | | **Envi-ronment** |

*Figure 13: Part of an N2 diagram for a city-bus. 1: requires minimizing weather influences on the passenger while travelling. 2: Implies recharging or refuelling at bus stops.*

## FUNKEY ARCHITECTING

This one is a bit less simple, although the result still fits on one page. It was my own PhD research. FunKey shows how the system under design is valuable for the different stakeholders, via the use of *key drivers*. These are high level aspects that express the value of a system. The other view is on the *functions*: what does the system need to do? Then we show which functions contribute to which key drivers.

A reviewer of an article (Bonnema 2011) about it mentioned that this might very well show the internal reasoning of a system architect. I consider that a compliment, as this tool thus makes this *internal* reasoning of an architect *explicit*, and discussable among peers.

## A3 ARCHITECTURE OVERVIEW

This is a communication medium developed by Daniel Borches, the first PhD student that I supervised, together with Gerrit Muller. He worked at Philips MRI to support evolvability of the MRI scanners. A turning point in his research was when he realized that the problem is not so much the difficulty to analyse the impact of changes, but the fact that the architecture of the system was not well known by the engineers.

He then created a way to describe an existing system architecture on a piece of A3 paper: the A3AO. It shows the functional, the physical and the quantification views on a system. One view alone does not give enough information (Rozanski and Woods 2012), but together and interlinked they do. The touch of genius that Daniel had was that if you cannot put it on (two sides of) an A3AO, you probably have added too much distracting information – see again Albert Einstein's quote! A few years later, Daniel 't Hooft modified the A3AO so that it can also be used while developing a new system architecture (Hooft et al. 2020).

Today, the A3AOs have been used in various companies with quite some positive feedback (Singh and Muller 2013, Wiulsrød, Muller, and Pennotti 2011, Kooistra, Bonnema, and Skowronek 2012). An issue still to be tackled is how to connect the A3AOs to underlying more formal models. Bridging this gap between understandability and formality is a grand challenge for my chair.

## THE COFFEE CUP

And let's not forget one of the simplest tools ever: the coffee cup. Grab one and walk around in the engineering department and other places in the company to ask *constructive critical* questions that go beyond: "are you still on track?". The coffee cup is a great way to keep yourself up to date to the challenges and achievements of the engineers, and to identify the crucial trade-offs in a system under design!

All these tools are really simple. This has as great advantage that it doesn't take a lot of brainpower to deal with them. Thus, the engineers have more brainpower left to think about the real systems challenges. Using the tools, the systems engineers can uncover, describe and share knowledge and understanding that is complex, intricate and essential for development of successful systems!

## OVERALL SYSTEMS DESIGN METHODOLOGY

Having listed these tools is like having a full toolbox. You may not know which tool to use when. There is the danger of picking one tool, and using it even if it is not fit for the job at hand. So, we also need a manual, a methodology. Now that is tricky, because in academia "method" and "methodology" are sensitive words. Also, no two system design projects are the same, and neither are two systems engineers. As a starting point, I've seen quite good results with the following 7-step process:

1. Context diagram and 9-window diagram to get an understanding of what the role of the system under design is
2. Stakeholders analysis
3. Define the Key-drivers (prominent on system level) and requirements (prominent on lower levels)
4. Functions to be performed, plus the functional interface (functional N2)
5. FunKey to understand the value of the system for stakeholders, draft first System Budgets for the main key drivers
6. Create and compare architectures using modular N2 diagrams, and select the preferred one.
7. Put the chosen architecture in a communicatable form like the A3AO

This is a **way** too organized list. In practice, the architect jumps back and forth. And also, while this process runs on the system level, similar activities are carried out on the supersystem and subsystem levels.

Also, this process only makes sense when you actually think in systems as we saw earlier; frequent application of the 12 Thinking Tracks is advised!

# SEMD FOCUS

Now we've explored the field, what is the SEMD chair planning to do? If industry is in need for more Systems Engineers and Engineering, we need to work on three fronts:

1. Make existing Systems Engineers more productive,
2. Make Systems Engineers productive faster, and
3. *Produce* more Systems Engineers.

And those translate to work for the SEMD group:

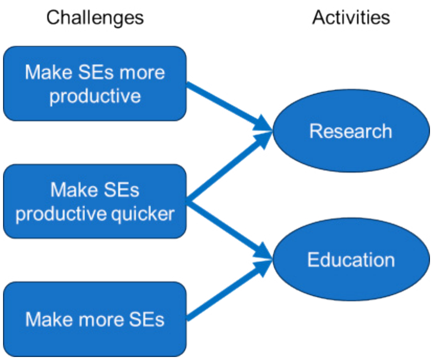



*Figure 14: SEMD's challenges in Research and Education.*

## EDUCATION

Let's start with looking at education. We have, like most chairs in the Department of Design, Production and Management, a heart for education. While I think just like CNN Money, that being a systems engineer is the best job in the world, introducing young people to this fantastic job is for me even slightly better than doing it myself.

The picture below shows how to teach SE. *Inform* the students about the field in the Bachelor, Involve them in the Master, and coach them to *Execute* the SE job in postmaster education. Inform also includes teaching them general design principles and approaches. Every engineer should be familiar with Requirements, Concept generation and selection, Detail design and Test & Evaluation! These should be part of the first year education of all engineering bachelor programs. Winnie Dankers, Hiske Schuurman and Roberto Reyes Garcia from SEMD and others are working hard on this for IDE and ME.

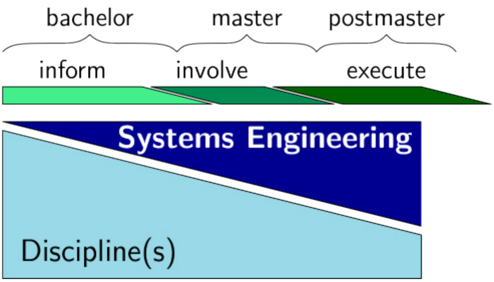



*Figure 15: Relation between education, home discipline and systems engineering.*

The involve part means that we involve students in SE type projects and courses. Example is the Master Insert module "Systems Thinking". Partly set up by Steven Haveman while he was working as a post-doc in the group. Now Kostas Nizamis and Brendan Sullivan coordinate this. Another example is the multidisciplinary course Electric Vehicle System Design where students from various backgrounds have to develop a concept for an electric vehicle.

In particular for the execute part of SE education, one needs 5-10 years of relevant job experience. In the Dutch system students tend to do their master directly after completing the bachelor. So, there is no chance to acquire relevant industry experience.

SE master programs in the US, like the Systems Design and Management program offered by MIT, do have participants with several years of industry experience (https://sdm.mit.edu, 20230627).

The industry master in Systems Engineering offered by the University of Southeastern Norway (USN) takes this one step further: not only do most of the candidates already have industry experience before entering, the program itself involves working in industry (https://www.usn.no/english/academics/find-programmes/master-of-science-in-systems-engineering/, 20230627).

How can we translate this to the Dutch situation? We have two excellent opportunities:
1. Engineering Doctorate, and
2. Lifelong Learning.

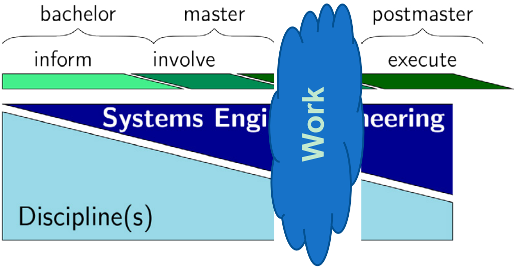



*Figure 16: Relation between education and work experience.*

### *Engineering Doctorate*
(formerly Professional Doctorate in Engineering, and before that simply called TwAIO or Ontwerpersopleiding).

At present, at the UT all Engineering Doctorate students follow a course "Systems Design and Engineering" that gives an introduction to systems engineering, value engineering, societal embedding and more. Marc van Buiten and myself with Robin de Graaf, Roberto Reyes Garcia, Klaas-Jan Visscher and Mohammad Rajabali Nejad run this.

On top of that, a goal for the chair in the near future is to develop an Engineering Doctorate in Systems Engineering and Architecting; at first as part of the existing EngD in Robotics. A course preliminarily called "Advanced Architecting" will form a centrepiece.

### *Lifelong Learning*
Over five years ago, Frank de Lange of ASML and myself started working on a program to educate the increasing numbers of Systems Engineers and Function Architects at ASML. While there was already training for attitude and soft skills, the trade of SE with its tools and approaches had to be learned on the job. We developed the Systems Engineering and Systems Architecting Master class (SESAM) to give that trade information. Since 2018 we have run about two SESAMs a year. The feedbacks from

participants are almost always positive. Berry Ouwehand, Frank de Lange, Roelie Joekema, Michael Kubis and others are working hard in ASML to make SESAM a centerpiece training. On UT side, with the increasing numbers of candidates at ASML, Kostas Nizamis and Jakup Ratkoceri are getting up to steam to deliver SESAM too.

The University of Twente now has the vision to become an important player in Lifelong Learning. Partly because present society requires professionals that constantly update their knowledge, competences and skills. We love to be part of that with our SESAM experience.

### *Other Education-related Openings*

With group member Marcus Pereira Pessoa also being part-time head of Educational Innovation at CELT, we seek as group to have a UT-wide impact on education.

## RESEARCH

### *Research Topics*

As you saw from the earlier picture, SEMD research is directed at making already experienced Systems Engineers more productive, and helping new Systems Engineers to become productive faster; reducing the learning curve. In order to do so, we focus on the following research topics (RTs):

1. Communication in Multidisciplinary Development, a.o. expanding on the A3 Architecture Overviews.
2. Methods and Tools for connecting and integrating (systems) engineering tools: The EPLM2 project of Gisela with Thales is a nice example that incorporates project management.
3. Systems Architecting: Supporting the system architects of today, and of tomorrow. By the way, we also look at Model Based SE here.
4. Systems Thinking: a.o. Building on the list of “12 Thinking Tracks” (Bonnema and Broenink 2016), that help to create a common frame of reference for people with very different background and expertise.
5. Systems of Systems Engineering: What happens if we combine systems with very different lifecycles and owners into one system of systems (Boardman and Sauser 2006)?

### *Research Methodology*

The approach to SE research that I promote, is to closely involve industry from begin to end in a research project. Gerrit Muller, basing on Colin Potts (Potts 1993), put this "Industry as Laboratory" setting in a nice picture:

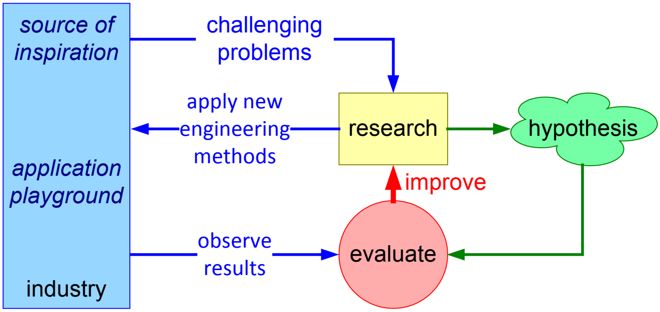



*Figure 17: Industry as Laboratory (Source: Gerrit Muller's gaudisite.nl, https://gaudisite.nl/figures/IALAindustryAsLaboratory.html)*

Industry acts as source of inspiration (what works already?), testing grounds (what can we make work, what not?) and as client. The usual goal is to create a support in the form of an approach/tool/method for systems engineers, that is useful and is founded in science.

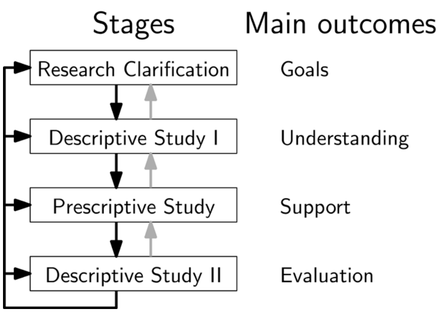



*Figure 18: The basic structure of the Design Research Methodology (Picture based on(Blessing and Chakrabarti 2009)).*

Basing on the Design Research Methodology by Blessing and Chakrabarti (Blessing and Chakrabarti 2009) and inspired by ideas from the Agile

Software domain, in particular Barry Boehm's Spiral approach for SW development (Boehm 1988), Kostas, Marcus and myself, with the SEMD PhD candidates, developed the Spiral Approach to Systems Engineering Research, or simply SASER (Bonnema, Pereira Pessoa, and Nizamis 2022). Basic concept is to go through the DRM stages a number of times with increasingly more depth and detail. We call these "loops", and simply depicted it looks like this:

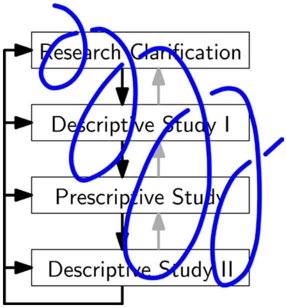



*Figure 19: Visualization of the Spiral Approach to Systems Engineering Research - SASER. From (Bonnema, Pereira Pessoa, and Nizamis 2022).*

With this, already in the second loop the researcher can create for instance a mock-up of the support to get a first evaluation within the company. This way analysis lock-in by the researcher is avoided or at least reduced, and the company remains closely connected throughout the research project. In a typical 4-year PhD project, we expect 4-6 loops (Ahmed et al. 2023). When I presented SASER at the CSDM conference in Paris last December, Prof. Jean-Michel Bruel  (Professor at IRIT) asked "why SE in the name, it looks like it can be applied to much more types of research …."

### *Industries and Application Areas*

It is my conviction that Systems Engineering is a very broadly applicable discipline. If you look beyond the many books and papers on Systems Engineering Processes, you will find approaches like ours that help to create deep understanding of the value of a system under design, and decide how to increase that value and at the same time minimise the negative impact.

My chair decided to focus on a limited number of application areas:
• Electric Mobility and the Energy Transition
• Equipment (often called high-tech industry)
• Medical Systems
• Consumer Products.

These may change in the future, depending on development of the industry contacts and how the team will evolve!

Note that we do not only look at highly complex systems: footwear and consumer products are generally less complex. The reason for having “Multidisciplinary Design” as second part of the chair’s name is that the SE body of knowledge may also be applied to such less complex products. We research which elements of the SE Body of Knowledge can be used – and how – in such settings.

A special mention goes to the Twente Battery Centre, where we collaborate with for instance Sebastian Thiede within our department, Mark Huijben from the Science faculty, and Prasanth Venugopal and Tiego Batista from the Electrical Engineering, Math and Computer Science faculty. I believe my chair’s systems perspective is an added value.

# CONNECTIONS

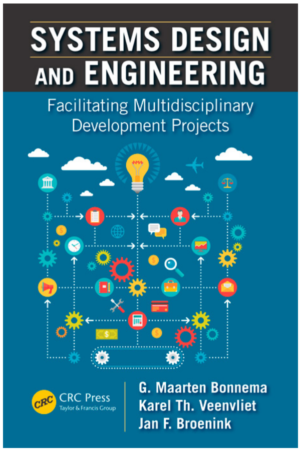
While SEMD is probably the most dedicated chair to Systems Engineering in the Netherlands, we are fortunately not alone. We already have good contacts with other groups and institutes in the Netherlands, Europe and beyond. It is something that we like to develop further. A few examples…

## ENGINEERING TECHNOLOGY FACULTY

In the Engineering Technology faculty, good connections and possibilities exist within DPM, with Civil Engineering, and in the Sustainable Engineering Technology Master program.

## UNIVERSITY OF TWENTE

In the UT, we already work together with RAMS of EEMCS: Jan Broenink and myself are working on a new version of the Systems Design and Engineering book that we originally wrote together with Karel Veenvliet (of Civil Engineering) in 2016 (Bonnema, Veenvliet, and Broenink 2016).
In the field of electric mobility, collaboration with the power electronics and EMC group of EEMCS will be strengthened.




## THE NETHERLANDS

The NXTGEN high-tech project on Comprehensive SE education is a national undertaking of UT-SEMD, TUDelft Space Systems Engineering, TU Eindhoven High Tech systems Center, Fontys, TNO Embedded Systems Institute, Holland Innovative and supported by industries like VDL, Thales and ASML.

The background is that in the Netherlands we are able to develop highly complex equipment successfully. In this project we want to make this Dutch Approach to Systems Engineering explicit and shareable.

## EUROPE

In Europe, the first to mention is the University of Southeastern Norway in Kongsberg. Gerrit Muller and others have put Kongsberg on the SE map. It is at the heart of a region that can compare in high-techness with the Eindhoven region.

In Paderborn the group of Roman Dumitrescu does interesting work on Model Based SE, in particular in the German industry context. We might revive the International Spring School on Systems Engineering, don't you think?

## GLOBAL

INCOSE is thé place to collaborate in Systems Engineering globally. Several SEMDers are member, and I have been a long time member.

Through the Lockheed Martin MIT-Netherlands seedfund we established good contacts with the Systems Design and Management group and the Engineering Space Laboratory of Prof. Oli de Weck. I expect that this will lead to future collaborations on the foundations of SE, the fundamental laws of SE and technology planning (de Weck 2022) in combination with Systems Thinking.

## SEKCT

In this part on collaborations, I like to mention the Systems Engineering Knowledge Center Twente that Robin de Graaf and myself have set up. Before this lecture, we had a kick-off symposium that has been (too) long in the making. Covid and other life-related matters kept intervening.

SEKCT aims to be a *lean* central point of access on Systems Engineering connecting industry and the UT. We join forces from different groups and faculties, so that industry questions and UT expertise can be quickly matched and lead to projects and trainings for example.

# ACKNOWLEDGMENTS & WOORDEN VAN DANK

We are getting closer to the borrel. Before we go there, I like to thank the Dean Bart Koopman, the Rector, the Executive Board, and the Benoemingsadviescommissie for advising and deciding to appoint me as Full Professor in Systems Engineering and Multidisciplinary Design, and the expression of trust that this appointment shows.

The Department of Design, Production and Management, including its past and present chairmen, Leo van Dongen and Sebastian Thiede and colleague professors, have played an important role in creating the chair. Thank you for that!

All colleagues at DPM, and there are many of you: it has been great working with all of you in the past almost 25 years. I'm looking forward to continue and hope you do too.

Group Members of SEMD: in the last few years we have built a nice group of people with good chemistry where we support and challenge each other to reach new levels in research and education. We're no longer a small group, and can have, in size, enthusiasm, drive and ideas, quite an impact in the Department, the Faculty, the University and beyond!

A big thank you to past and present PhD candidates: "My" first PhD to supervise, Daniel Borches will always remain special. Also Jeroen, Krijn, Steven, Vera and Katja that all graduated successfully. Today we have a group of five PhDs: Gisela (in the final stages), Sherly Denis and Jan Lenssen in the SPLASH project with ASML, Youn Choi as PhD from Twente in the enormous NEON research project with the HCD chair, and Usama Ahmed on a prestigious Pakistani government scholarship. And past and current EngD candidates Pieter, Rien, Marieke and Roy. You all mean a lot to me!

There is a long list of Master and Bachelor students that I had the privilege to supervise. Some of you went through a rollercoaster, others coasted along nicely. Some caused me to learn new things.

What would an academic do without the support of a good secretary team:

Inge dos Santos already from day one. Also Saskia Groenendijk, Bianca Dibbelink, Tamara Jansen and formerly Inge Hurenkamp and Annemarie Bos-Lubbers: Thanks for all your input and work! Your dedication has been amazing.

I also like to thank the companies that I have been working at or with in the past, and the companies that we have projects with or are planning to do so:
- ASML of course. A champion in the field of SE
- VDL, part of the ASML ecosystem. Ton Peijnenburg as a great advocate of SE and Matthijs Neut as VDL-UT fellow in the SEMD group.
- Thales: the high-tech company in the region. Gisela is now ready, shall we look at new projects in addition to the ongoing stream of Master projects?
- Philips, the company where Daniel Borches and Steven Haveman did their PhDs.
- Canon PP, Long term contact. New ideas for cooperation!
- VMI, trained quite some SEs via MikroCentrum. What’s next?
- Demcon: we worked closely together in Jeroen Ruiter’s Teleflex project, the Litter collection robot, and with MAPPER. Revive our cooperation?

A special mention goes to ASML. They are a champion of SE. They have been a great partner to work with in composing the SEMD approach to SE, and supporting the chair’s research. For the coming years we will keep on cooperating in training the company’s systems engineers and function architects.

Now to three important men in my life. I could call them my three fathers.

My dad Tom Bonnema.  We share the same fundamentals in Electrical Engineering. He worked on computer architectures, I work on systems architectures. He used to work at the UT after a few years in industry, I do so too. I’m sad he passed away before my PhD defense. He would have loved that, and this oratie probably even more.

Gerrit Muller, you are my father in Systems Engineering. When I worked at ASML as a systems engineer, you became my manager. The discussions we had about SE made me curious on how to improve the field. When you became a professor in SE in Norway, I never expected that one day we would both be professors in this fantastic field.

Fred van Houten is my academic father; he brought me to the University of Twente in 1999. His constant trust resulted in a lot of freedom to shape my own research. I'm grateful also for his support when things didn't go smoothly. I think he would have smiled all afternoon today, like on the photo of him during my PhD defence.

Family and Friends: I enjoy and very much appreciate your presence. You may now have a better idea of what I'm doing here. Hopefully you enjoyed it. If not, maybe a drink in a few minutes can turn your opinion around.

Then to the inner circle: my beautiful sons Joris and Casper. Joris is the third generation Electrical Engineer in the family. You've chosen a great discipline. Now working on Nuclear Fusion and Power Electronics. You have a great future ahead of you. You form a great couple with Sanne! Casper, you chose my other home discipline: Mechanical Engineering, and you're really good at it. You developed an omnidirectional robot in your Bachelor project. Now you're also diving into the energy transition and sustainability via the energy and flow master. Both of you are not only smart, but also very nice, friendly, gezellig and caring. You make me a very proud father!

And Lilian: my support, lifeline and anchor point. I would have never made it to this event without you. Almost three decades together have brought us to many places and situations. Through all this, the love and dedication between us is still going strong! Let's go for new adventures!

Dank u voor de aandacht!

***Ik heb gesproken.***

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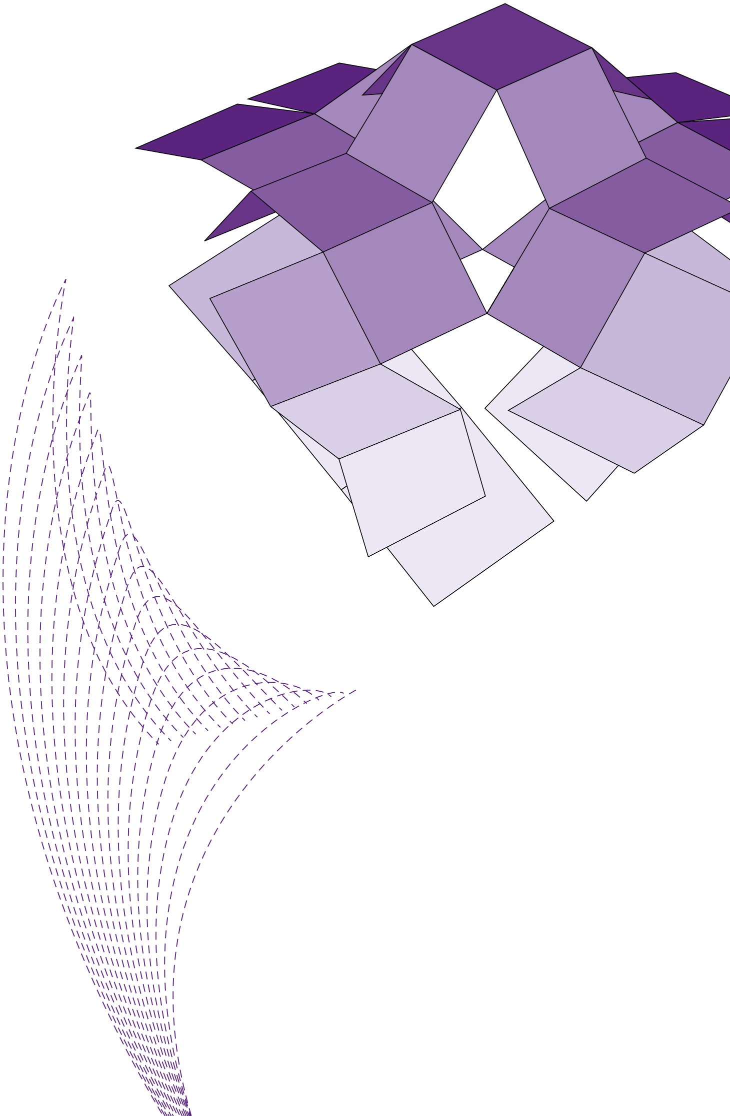

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