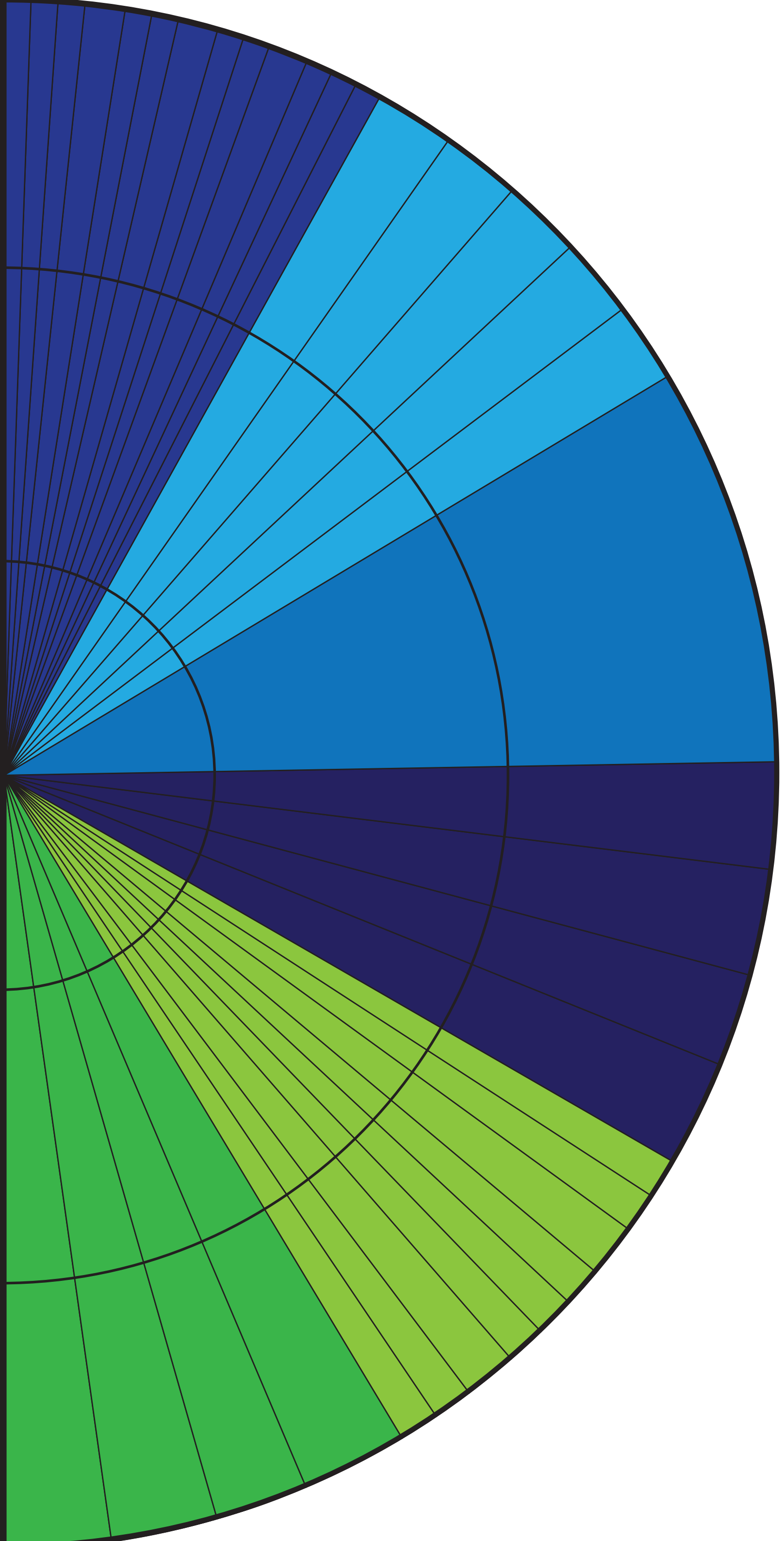

Development of a Framework for the design for maintenance solutions based on a biomimicry methodology

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Development of a Framework for the design for maintenance solutions based on a biomimicry methodology

Master thesis

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Abstract

Maintenance is all around us. In small things, as: doing the dishes or servicing a car, but also in larger assets: think of trains, machinery at a production plant, buildings or infrastructure. The maintenance of these large or complicated structures can be very costly over their whole lifecycle. To make assets more cost effective we can design them to be more resilient, effective, efficient and sustainable. Nature has been found to be very effective, efficient and resilient. Organisms have evolved and have adjusted to their environments for 3.8 billion years, finding solutions to survive. As humans, we can learn from that library full of knowledge by looking at nature and finding out how it is done. Getting inspiration from nature and applying the solutions in technology is called biomimicry.

In this research design for maintenance is combined with biomimicry in a framework, to include biomimicry based design in the field of maintenance.

This thesis provides a literature review of existing design processes, maintenance / system engineering methodology and especially the biomimicry methodology. Interviews with employees from Arcadis provide insight in the work processes in practice and how design for maintenance is handled.

Based on the literature review and interviews a framework is created that guides the design process to improve design for maintenance and to incorporate nature-inspired solutions. The framework is based on general system engineering and design processes and it is filled with categorized tools which come from maintenance engineering and the biomimicry methodology. This combination could provide more resilient, efficient, effective and sustainable designs. Resulting in benefits as less maintenance, longer asset lifetime and less lifecycle costs.

After the creation of the framework, it is tested by application in a workshop at Arcadis. During the workshop, an existing case on renovation opportunities for a block of flats is re-executed to find nature-inspired solutions for insulation and ventilation problems. The feedback of the case is used for further development of the framework.

Samenvatting

Onderhoud is overal om ons heen. In kleine taken zoals: afwassen of onderhoud aan een auto, maar ook in grotere systemen: denk aan treinen, machines in een fabriek, gebouwen of infrastructuur. Het onderhoud van deze grotere of gecompliceerde systemen kan heel kostbaar zijn over de gehele levensduur. Om systemen kosten effectiever te maken kan een ontwerp gemaakt worden dat robuuster, effectiever, efficiënter en duurzamer is. De natuur heeft deze kwaliteiten. Organismen zijn over 3.8 miljard jaar geëvolueerd en hebben zich aangepast aan hun leefomgeving en hebben oplossingen gevonden om te overleven. Als mens kunnen wij leren van die verzameling aan kennis door de natuur te ontdekken en uit te vinden hoe de natuur het doet. Inspiratie halen uit de natuur en het toepassen in de techniek is een gebied dat biomimicry heet. In dit onderzoek is ontwerp voor onderhoud gecombineerd met biomimicry in een framework. Hiermee wordt ontwerp met behulp van biomimicry toegepast in het gebied van onderhoud.

Deze thesis presenteert een literatuuronderzoek over bestaande ontwerpprocessen, een onderhoud/system engineering methodologieën en de biomimicry methodologie. Interviews met werknemers van Arcadis geven inzicht in de praktijk van ontwerpen voor onderhoud en de werkprocessen die daarbij komen kijken.

Gebaseerd op het literatuuronderzoek en de interviews wordt een framework ontworpen dat het ontwerpproces begeleid. Daarmee wordt het ontwerpen voor onderhoud verbeterd en oplossingen geïnspireerd door de natuur worden meegenomen in het ontwerpproces. Het framework is gebaseerd op algemene system engineering en ontwerpprocessen en is gevuld met gecategoriseerde tools. Deze tools zijn verzameld uit het gebied van onderhoud en de biomimicry methodologie. Deze combinatie zou robuustere, efficiëntere, effectievere en duurzamere ontwerpen kunnen opleveren. Resulterende voordelen zijn dan: minder onderhoud, langere levensduur en minder kosten over de gehele levensduur.

Na het ontwerp van het framework wordt het getest in een workshop bij Arcadis. Tijdens de workshop is een bestaande casus over de renovatiemogelijkheden van flats opnieuw uitgevoerd. Met als doel om op de natuur geïnspireerde oplossingen voor isolatie- en ventilatieproblemen te bedenken. De resultaten en terugkoppeling van de casus worden gebruikt voor het verder ontwikkelen van het framework.

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Nomenclature and Definitions

- BID - Bio-inspired Design
- Bio-assisted - “involves domesticating an organism to accomplish a function” [1]
- Bio-utilization - “entails harvesting a product or producer from nature” [1]
- Bioinspiration - ‘Creative approach based on the observation of biological systems’.[2,3]
- Biomimetics- - ‘Interdisciplinary cooperation of biology and technology or other fields of innovation with the goal of solving practical problems through the function analysis of biological systems, their abstraction into models and the transfer into and application of these models to the solution’.[2,3]
- Biomimicry - ‘Philosophy and interdisciplinary design approaches taking nature as a model to meet the challenges of sustainable development (social, environmental, and economic)’.[2,3]
- Bionics - ‘Technical discipline that seeks to replicate, increase, or replace biological functions by their electronic and/or mechanical equivalents’.” [2]
- Design for Maintenance - “Design for maintainability is concerned with achieving good designs that consider the general care and maintenance of equipment and the repair actions that follow a failure.” [4]
- Maintenance - “combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function” [5]
- Methodology - In product design: ‘‘a collection of procedures, tools and techniques for designers to use when designing.’’[6]
- Technique - A specific way of performing or using a tool.
- Technique and technique - ‘‘In product design, the combination of tools and techniques is a means to apply and exploit the skill and craftsmanship [] in order to examine a solution path (or alternative) while pursuing a specified aim in the context of a chosen or enforced design method or approach.’’ [6]
- Tool - “instruments or certain tangible aids in performing a task”[6]
- TS - Technical System

Chapter 1: Introduction

This thesis starts with an explanation of the motivation, the research challenge and the research questions. The introduction lays the foundation of a useful project and structured approach towards the research problem.

Motivation

This graduation project is started in the end of February 2017 in consultation with Alberto Martinetti. The initial combination of topics of biomimicry and design for maintenance is brought together by Alberto in the assignment description. This is developed into a more specific research approach where both interests were satisfied. My attention was attracted by the combination of different fields and the possibilities to add value with design. Biomimicry and design for maintenance are relatively new and interesting subjects for me, giving opportunities to learn about different fields. I am interested in design processes and combining two completely different fields in a design methodology is a challenge that I was curious for. In addition, the research could support the improving field of design for maintenance and a sustainable practice of biomimicry.

Problem/opportunity statement

Design for maintenance is a developing practice. Companies are more and more interested in reducing maintenance and the related costs. Maintenance can be planned efficiently, however, reducing or avoiding maintenance at all is more effective. Therefore, it is interesting to look at the design phase of the assets to improve maintenance performance. What is recognized in systems is that they are often not efficient and inflexible when it comes to changes. They cannot adapt to changes in their environment - adapting to future needs. Including sustainable, environmentally friendly and circular economy requirements.
To improve the designs of systems it is necessary to design in a way that supports all these requirements. Since nature is very efficient, sustainable and can adapt to changing conditions it[7] is interesting to use a nature-based design approach. Biomimicry is such an approach. Creating ideas and solutions through a methodology that involves nature in the design process as inspirational input. Therefore, biomimicry is an interesting approach that can improve the created designs.
Approaching together - design for maintenance and biomimicry can offer an opportunity to radically improve design and solutions creating resilient, agile and efficient solutions to improve the field of maintenance by the design of new systems.

Aim of the research

The aim of the project is crystal and clear: codifying and creating a tool/methodology to help engineers and designers in creating bio-inspired winning solutions in the field of maintenance operations and maintainable and sustainable products. By codifying and creating is meant that a new system is made where things can be arranged in. [8] [9]. In the study case, this will help to re-think a particular activity or a system of ways of doing. [10] [11]. Thus, a new system to arrange how engineers and designers create solutions should be made. Additionally, it should be a structured tool/methodology that could help to consider the usefulness of biomimicry solutions early in the process of a design task without demanding extensive resources. This sets a requirement that the process should give as an option for choosing biomimicry, based on a checkpoint that evaluates the feasibility of the bio-inspired solution.

A discussion set the direction to apply the full biomimicry idea where not just copying nature is applied, but also other tools and the idea that the solutions should be ‘fitting in on earth’. This is explained in the biomimicry chapter. Expectations are that implementing biomimicry in full will provide more sustainable maintenance solutions when using the methodology.
The usefulness of applying psychological principles in design for maintenance is recognized. E.g. improvement of maintenance work itself by employees and the ‘maintenance’ of employees during work or recovery (breaks). Setting the goal of consideration of psychological principles in the design process for maintenance.

In a nutshell: the aim is to create a methodology that structures the design for maintenance process. This methodology should include the principles of biomimicry. A toolbox of or multiple methods will be created to guide the practical process of a design task. However, a check must be in place to use biomimicry only if it is advantageous. The psychological principles influencing maintenance will be considered during the process of solution design.

Scope of research

As stated in the section Biomimicry - Definitions; biomimicry is not biomimetics, albeit they lie close together in meaning. Biomimicry adds a philosophy to the interdisciplinary design approaches. The basis of biomimicry and biomimetics is a design process of transferring biological solutions to technology. The process in short is: abstracting the problem for research in biology world, abstracting the found solution from biology and implement it as a technological solution. Biomimicry includes the encouragement to explore nature and the idea to develop sustainable solutions. Therefore, biomimicry is chosen over biomimetics. However, the main input for this research will be the design process to generate nature-inspired solutions.

Since the application of biomimicry is a new approach within the field of maintenance engineering and operations a well fitted process does still not exist. Therefore, this research follows a top down process, starting with a methodology that structures the general design process of maintenance engineering, followed by the categorisation of tools and finally by a guidance in using them. This approach allows matching biomimicry on the same strategic level. To achieve practical applicability for companies, practice will be considered in the research. The creation of products and technologies itself is not considered, but the design process is structured to provide guidance to designers and engineers.

Requirements

To have a starting point for initial reflections, a small list of requirements is set up. This list also provides a sort of “menu” of the project. It does exist besides the research questions.

Requirements for the methodology:

- Structuring the design process of maintenance, including biomimicry.
- Focussed on use within companies: must apply to a large variety of companies and must fit in the work process.
- Robust: must be flexible to variation on a tool level.
- The methodology must be a framework for lower level activities.
- Must be understandable and usable with poor knowledge on the field maintenance, nor biomimicry.
- Visual representation and ‘how to use’ appendix are required.
- Forms basis for translation to other fields of science.
- Gives a direction for sustainable innovation.
- Supports integration of other fields (such as psychology).
- Guiding the design process by helping with a tool selection and with a design process route.
- Giving enough freedom on the tools to use and being open to various ways of designing. Every company can choose the tools to use throughout the design process.
- Supports the use of biomimicry/bio-inspired tools and sustainable innovation.
- The framework improves design thinking for new innovative solutions in the maintenance field, by input of biomimicry knowledge.
- The tools can already be used within companies, in order to achieve easier implementation.

Significance of the research

As mentioned, this research is focussed on the creation of a design methodology for the design process of maintenance solutions. The addition of the biomimicry approach in the design process for maintenance is new and should offer a way to design more robust, agile, efficient and sustainable solutions. Moreover, these solutions create, in the end, the possibility of cost reductions, less maintenance, more effective and efficient systems and solutions that could be much more sustainable in their lifecycle on earth.
The framework is thus a first starting point for combining the field of maintenance with nature-inspired methods. Maybe a further step to develop more tools that find itself on the edge between different fields of research and another opportunity to bridge biomimicry to practice.

Research questions

Based on the previous sections, four main research questions (with consequent sub questions) are formulated. These questions will be answered through this research and in the conclusions the answers will be summarized. The questions are the following:

- Does a design for maintenance methodology or model exist?
  - If not, a new design methodology for maintenance will be created, what elements does such methodology exist of?
  - If it does exist, can the methodology be used in combination with biomimicry?
- What would the unified problem-driven process of biomimicry for maintenance be?
  - What a biomimicry methodology is?
  - How does a new methodology looks like, combining design for maintenance and biomimicry?
- What tools would support the combined biomimicry – design for maintenance process and in which stages are these applicable?
  - Which tools does the field biomimicry have?
  - Which tools does the field design for maintenance have?
  - How are these tools combined in a methodology?
- How can the methodology be used in practice?

Company introduction: Arcadis

Arcadis is a multinational company, with 27.000 people active in over 70 countries. Arcadis provides services in design and consultancy for natural and built assets, which includes activities as: Business Advisory, Program Management, Cost management, Engineering and Master Planning and Sustainable Urban Development. Arcadis is active in many sectors, for example: Cities, Financial Institutions, Industrials, Natural Resources, Public Sector, Retail, and Water and Utilities. Arcadis develops complex solutions for assets by combining technical, consulting and management skills.
For this research, contact is made with Arcadis to get insight in practice. The first step is to find out what the current practice is around maintenance and design for maintenance. The findings will be used in the research to improve the methodology. With the assistance of Bianca Nijhof this resulted in several interviews with employees of Arcadis. After the creation of the methodology, a workshop is organized to get feedback for improvement. Verali von Meijenfeldt assisted in the project and supported the organization of the workshop. The workshop also showed interested employees the general idea and possibilities of biomimicry. Further information can be found in the sections of the interviews and workshop.

Chapter 2: State of the art

To create a design methodology for use in a design for maintenance process, it is necessary to find the border of current research progresses. The aimed for design methodology would have several subjects that are reviewed in this chapter. Design processes are described to create a basis for the design methodology. This will consist of a review of system engineering processes and (product) design processes. The following subject is the biomimicry methodology. This methodology is aimed for bringing the innovative ideas and solutions to the design. At last, maintenance processes are reviewed. Maintenance is the field that is aimed for to improve using biomimicry in a design process for maintenance.

Design models

Design models guide the activities to create new artefacts or ideas. Because of the changing nature of design, it is not possible to capture a design process that will be useful in every occasion. During projects, between projects and as well between field of operation can design activities change. [6] This change is often created by the process itself, creating a requirement for iteration. Otherwise the change can be induced by the context of the design process. Example given: change in organisation/ management, change in project team, change stakeholders, resulting in a change of requirements and solution scope. Therefore, design models can only be a tool of guidance. They help structuring an extensive process to achieve the goals of creating something. By this structure they can help to control quality and induce new ways of thinking and development. Tools and techniques fill the project phases with guided activities for one smaller step in the process. A couple together can fulfil the requirement imposed by the project phase. The selection of tools and techniques to be used during a project therefore highly depends on the goal to achieve. Not only in the project phase, but as well during the entire project itself. Thus, project phases create an outline which guide a design process within a scope that is specific for the subject, the chosen process and stakeholders. Within these phases of the selected design model there must be freedom to operate, to allow multiple projects and flexible projects to be developed. The selection of tools and techniques to be used for a project, must be based on the requirements and goals of that project. In this way give tools and techniques the opportunity to work on different projects within a framework that is the same every time.

One of the most known systematic design processes is developed by Pahl and Beitz. [12] They developed a linear design process with the following phases: Planning and Task clarification: specification of information, Conceptual design: specification of principle solution (concept), Embodiment design: specification of layout (construction), and Detail design: specification of production. These phases can be found in the model; Figure 1. The model of Pahl and Beitz is a sufficient base to start development of the framework.

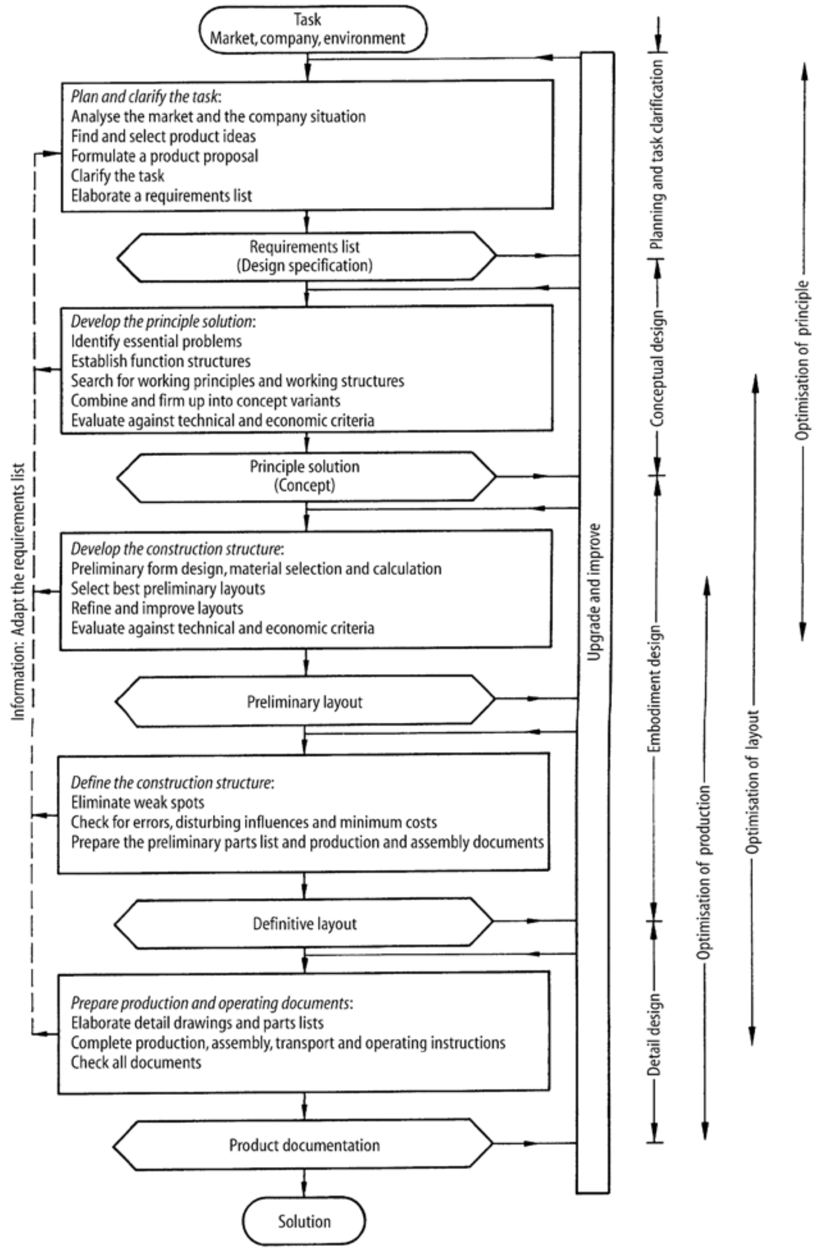


Figure 1. Design model by Pahl and Beitz [12]

The advantages are the following:

- Linear
- Common, often taught
- General
- Concrete

Linearity of a model simplifies the process, which is ideal for presenting a model to non-designers. This also explains the commonality; this model is used on many universities to teach design engineering. Furthermore, generality creates applicability to a wide range of products. The prescriptive nature of this model[13] makes it very concrete and clear for users. However, a prescriptive methodology does not allow much flexibility. Therefore, this also appears in the list of disadvantages. Another disadvantage is the lack of efficiency principles during the design, such as concurrent engineering. For many companies, this is a crucial for their time to market. The disadvantages are the following:

- Prescriptive
- Lacking efficiency principles

However, each design process described in literature may focus on different aspects and therefore look and feel different. For example, the importance of feedback, communication, deadlines and decision moments, iteration or field specific steps to take. However, they all describe a process of creating an artefact, physical or virtual.
The following phases represent the basis of the new framework: Analysis, Concept generation, Detail design and construction/implementation. Feedback, iteration processes, ease of use, clarity and descriptions of input and results will be considered for the development of the framework.

Design for Maintenance

In this research for a design approach the term maintenance is best applicable to capital goods as machinery, rolling stock or buildings, amongst others. The design approach is all-embracing and focussed on everything that has an industrial or technological materialisation.
Maintenance is defined as: *“the process of making sure that something continues in the same way or at the same level”* [5] [14]. Thus, the technological ‘things’ should be working at a certain level and when this level is not achieved, it should be adjusted (repaired) to be able to continue to work at this level.
Maintenance activities can be grouped in three levels, also shown in figure ...:

- *Maintenance Action - Basic maintenance intervention, elementary task carried out by a technician (What to do?)*
- *Maintenance Policy - Rule or set of rules describing the triggering mechanism for the different maintenance actions (How is it triggered?)*
- *Maintenance Concept - Set of maintenance policies and actions of various types and the general decision structure in which these are planned and supported. (The logic and maintenance recipe used?)* [15]

Maintenance actions can be divided over the categories Corrective Maintenance and Precautionary maintenance. Corrective maintenance actions repair or restore functions after a breakdown or loss of function has happened. It is reactive of nature. An important factor is the unpredictability of these failures. Precautionary maintenance is focussed on anticipating on or avoiding failures or its consequences. These actions can be: preventive, predictive, proactive or

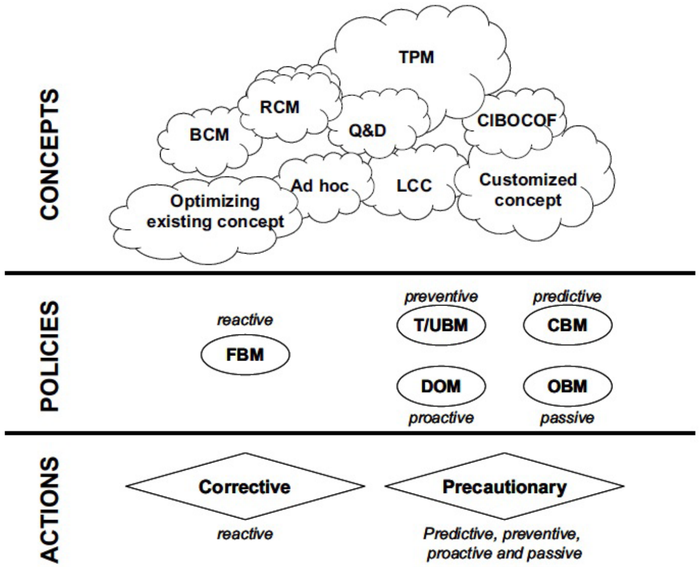


Figure 2. Actions, policies and concepts in maintenance [15]

passive in nature. These actions often require failure rate and moment predictions. [15]
Maintenance policies can also be categorised under corrective maintenance and precautionary maintenance, as they drive the maintenance activities. Policies are chosen on their economic impact. They determine expenses by triggering an amount of maintenance activities.
The following maintenance policies are most generic: Failure-Based Maintenance (FBM), Time/Used-Based Maintenance (TBM/UBM), Condition-Based Maintenance (CBM), Opportunity-Based Maintenance (OBM) Design-Out Maintenance (DOM), and e-maintenance. [15]
To optimise the combination of activities and policies for a certain system companies create maintenance concepts.

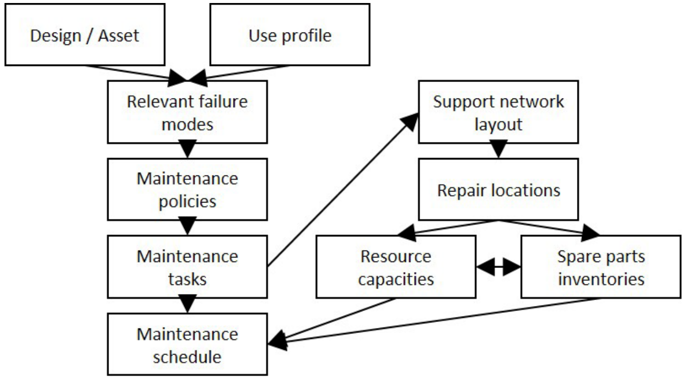


Figure 3. Maintenance plan development process [18]

Maintenance concepts are holistic views on the system and include the context of the system. Resulting in maintenance approaches that include strategies and even mindsets. Examples and maybe the most influential concepts are: Reliability Centred Maintenance (RCM)[16], Total Productive Maintenance (TPM) or Life Cycle Costing (LCC) approaches. [17] [15].
These activities, policies and concepts play a role in a maintenance plan. The maintenance plan describes the approach of a company towards maintenance. These plans can be developed according to the model presented in Figure 3 [18]

Performance measures are a must to control a system and develop a maintenance plan. Apart from that do performance measures give input to design for new developments. For evaluation of performance of assets, the concept of RAMSSHEEP is used. RAMSSHEEP has clear definitions of the most important maintenance characteristics and how these can be measured. The first four are already recognized by most companies, these are: Reliability, Availability, Maintainability and Supportability. However, secondary context influences: Safety, Health, Environment, Economics and Politics, give the possibility to design, plan, realise, use and dispose and asset with increasing efficiency, reducing costs and environmental impacts. [19] See Table 1.

Table 1. Elements of RAMSSHEEP [19]

Element	Definition	Contextualization
Reliability	"The probability that an asset can perform a required function under given conditions for a given time interval"	The reliability of a train is for example 90 %. This means that there is a certainty of 90 % that the train could travel.
Availability	"The ability of an asset to be in a state to perform a required function under given conditions at a given instant of time assuming that the required external resources are provided"	The availability of a train is for example 85%. This means that the train should be operational circa 310 days/year.
Maintainability	"The probability that following the occurrence of a failure of an asset will once again be operational within a specific time".	The maintainability of a train is for example 90 %. This means that there is a certainty of 90 % that the train will be put in service on time after a maintenance action. (To note that, in addition to the stochastic definition, the Maintainability could also represent the level of easiness to maintain an asset/product/component. In other words, how quickly maintenance activities can be performed reaching the required level of quality.)
Supportability	"The characteristic of an asset to influence the easiness with which logistic resources can be available at the right time at the right place".	The supportability of an asset can heavily affect the logistic organization causing delays (waiting for spare parts, technicians, equipment available) during the maintenance operations and influencing the Mean Time To Maintain (MTTM).
Safety	"A state in which or a place where you are safe and not in danger or at risk"; "Freedom from unacceptable risks of harm".	The Safety has to be included to ensure a safe asset for the final users and safe working places for the personnel involved in the production and in the maintenance operations. To note, how the absence of safety could change the cost-effectiveness of an asset.
Health	"Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity".	Health has to be included to ensure that an asset does not cause diseases for the final users and for the personnel involved in the production and in the maintenance operations.
Environment	"The environment represents the earth, including rocks, soils, water, air, atmosphere and living things".	The asset should reduce as much as possible, for example by using the Best Available Techniques (BAT) the impact on the Environment during the entire life-cycle. Here lies the difference between environmental compatibility and environmental sustainability.
Economics	"The economic perspective is concerned with the financial aspects of the asset and its operation."	The economic factors often drive the main direction and the investment from the design phase to the decommission phase of a product/asset.
Politics	"The first definition of politics was used in the Aristotle's book Πολιτικά, Politika, referring to the affairs of the cities".	The politic decisions should affect the main direction of a capital assets investment pinpointing and underlining the needs of the community.

Design for Maintenance

The following definition shows what design for maintenance is about:

> *"Design for maintainability is concerned with achieving good designs that consider the general care and maintenance of equipment and the repair actions that follow a failure." [4]*

Design for maintenance is already applied in various forms. Designers of assets think about accessibility, modularity and the many other possibilities presented in guidelines [20] or by personal experience. A special kind of design for maintenance is: Design-out maintenance, where a part of maintenance is made obsolete by designing an asset to not require maintenance or less maintenance.
Thompson wrote the book: Improving Maintainability and Reliability through Design. Design for reliability considers just a different subject that is not discussed in this research. Defined as:

> *"Design for reliability is concerned with achieving good designs that will perform a specified duty without failure." [4]*

The book is one of the few resources that specifically connects design processes and skills with maintenance. Thompson describes the main design process, how it is learned by design scholars, refer to section Design Process. The main phases of design for maintenance or systems are discussed, which will be discussed in the following section. The main part of the book considers various tools and how to apply them regarding maintenance, these are collected and listed in appendix A, for use in the developed framework. The book finalizes with creative skills and tools for the design practice, which is kept out of scope of this research.

Design phases of equipment design

Thompson describes three phases in design for equipment: Specification, Concept design and Detail design. Shown in Figure 4. This is based on the Pahl and Beitz design process. The Specification phase handles the definition of requirements in a specification. In concept design, various ideas are generated and feasible concepts are selected. Specific analyses, detail drawings and selection of components are made in detail design. This process could be extended for systems of a larger scale. Shown in Figure 5. Client requirements are first documented in the tender document. Followed by system design, where sub-systems and functional units are defined. After which the Equipment design model is used for every functional unit. [4] This more elaborate model seems to involve more system engineering principles. Specification and definitions are made on multiple system levels and possibilities are shown to create multiple subsystems that can be developed apart from each other. This can be shown by the analysis and requirement definition phases that are specified in the model by Blanchard; Figure 6. [21]

In the book: Maintenance engineering and management from K. Smit [22] is a more elaborate project plan and design process provided. This model starts with a feasibility study before the concept design phase. The feasibility study is alike the (market)analysis phase in other models. Business and commercial objectives, planning, market expectations and product portfolio are examples of the variables that are considered. Where Thompson's model is limited to detail design and component selection, does Smit add three additional phases: Construction & Commissioning, Operation & Maintenance and Life Extension & Reuse, based on Blanchard's model. These phases represent the

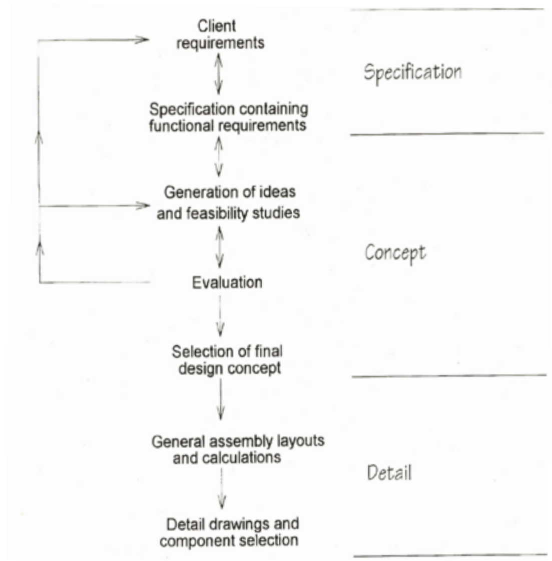


Figure 4. Equipment design model

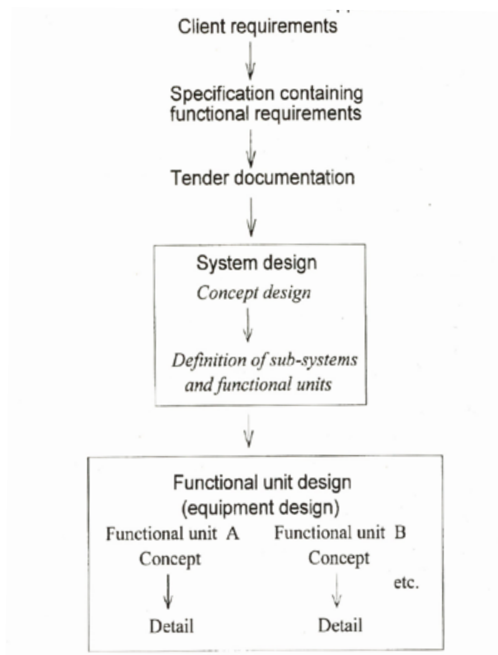


Figure 5. Design model for systems of equipment

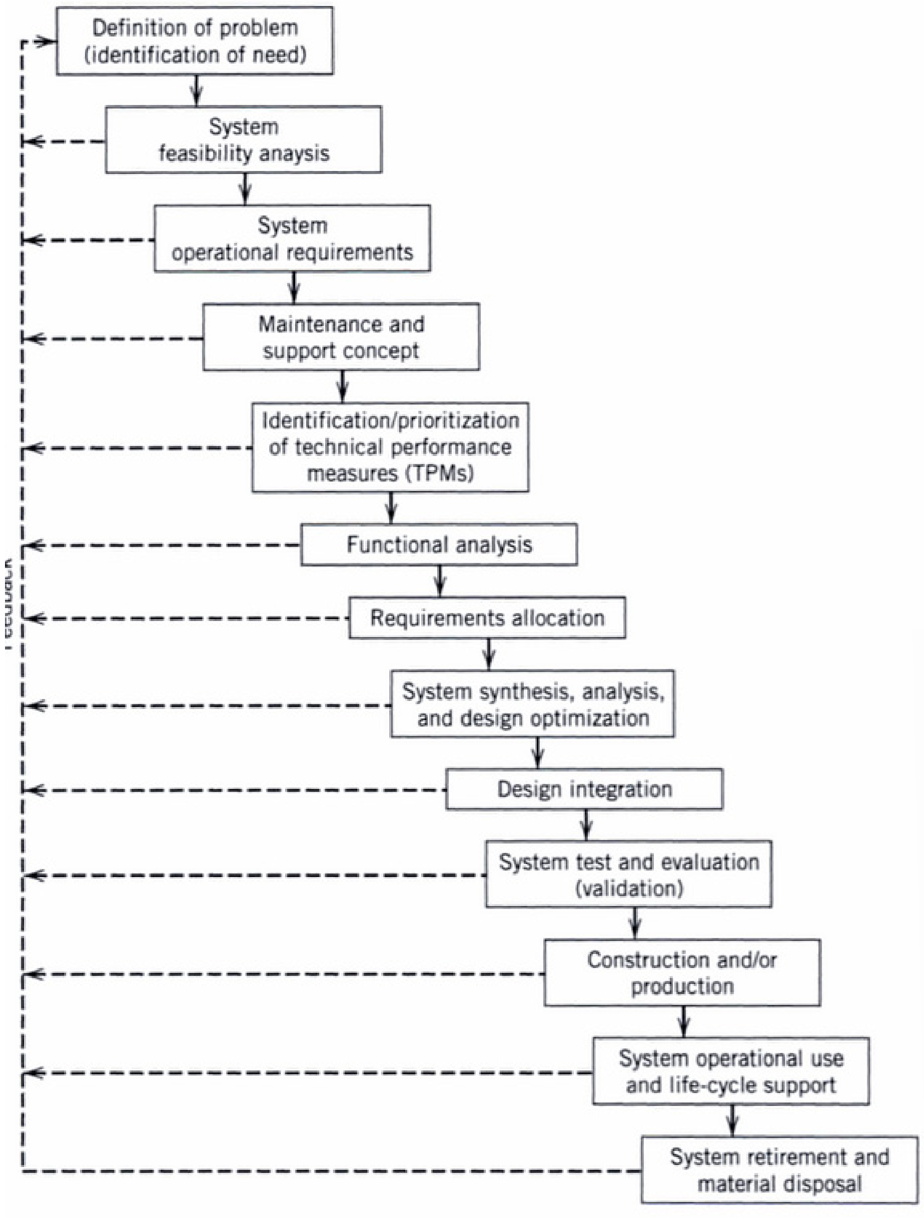


Figure 6. The system engineering process in the life cycle [21]

technical realisation of the system, its operational phase with maintenance and the end of life decisions of life extension, reuse or demolition of the system. Shown in Figure 6.

Smit also presents a maintenance design process consisting of the following phases: specifying maintenance behaviour, design for RAMS, development of the maintenance concept and lifecycle costs. Remarkable is the reoccurrence of maintenance concepts of RAMS and LCC. See figure XXX. The design for maintenance process is a sub-process of the technical system design process. However, it is applied as an integral part of each phase of the design process. Thus, the four design for maintenance phases are applied in every system design phase. For every combination of these phases there are specific tools that can be applied. These tools are listed for each phase in table XXXXXX. The phases recognized by Thompson are combined and added to that framework. For the framework to be developed this design for maintenance process forms a basis.

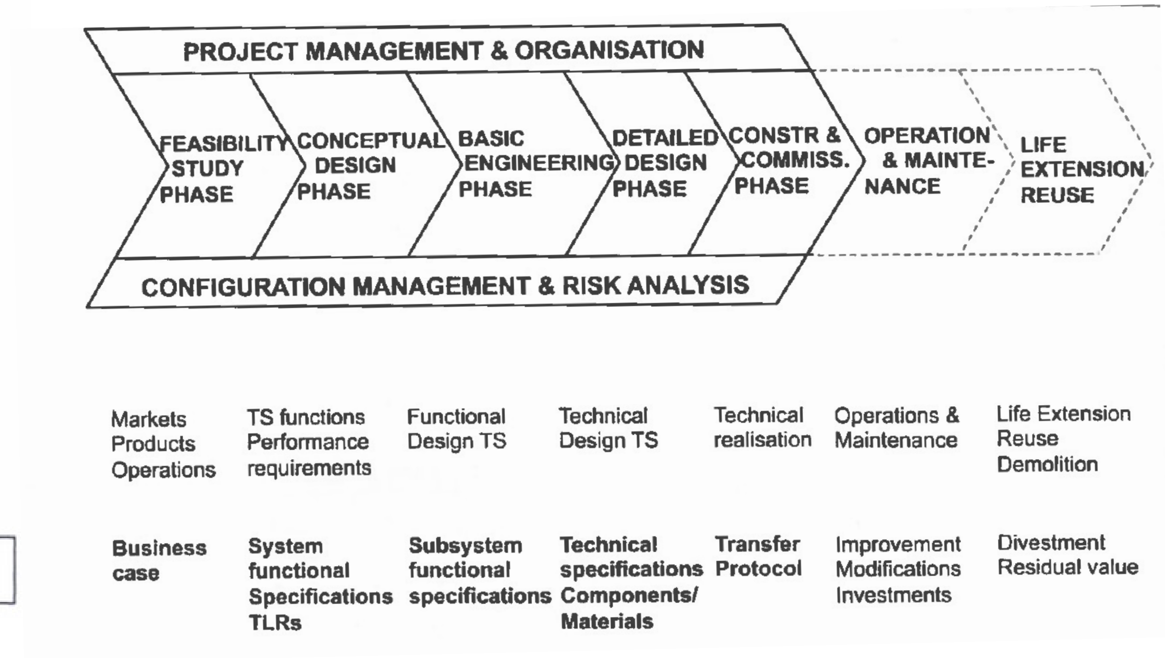


Figure 7. Phases and phase products of investment projects [22]

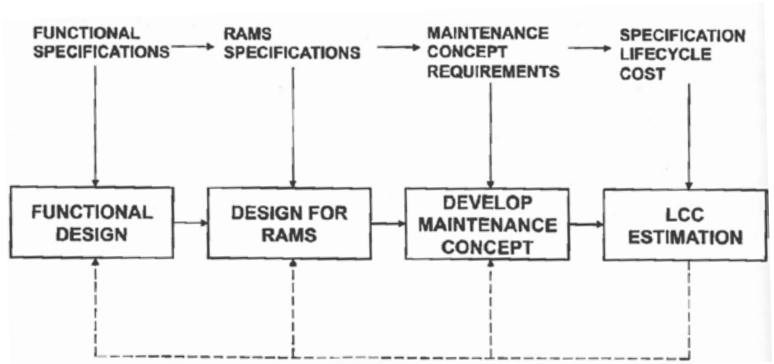
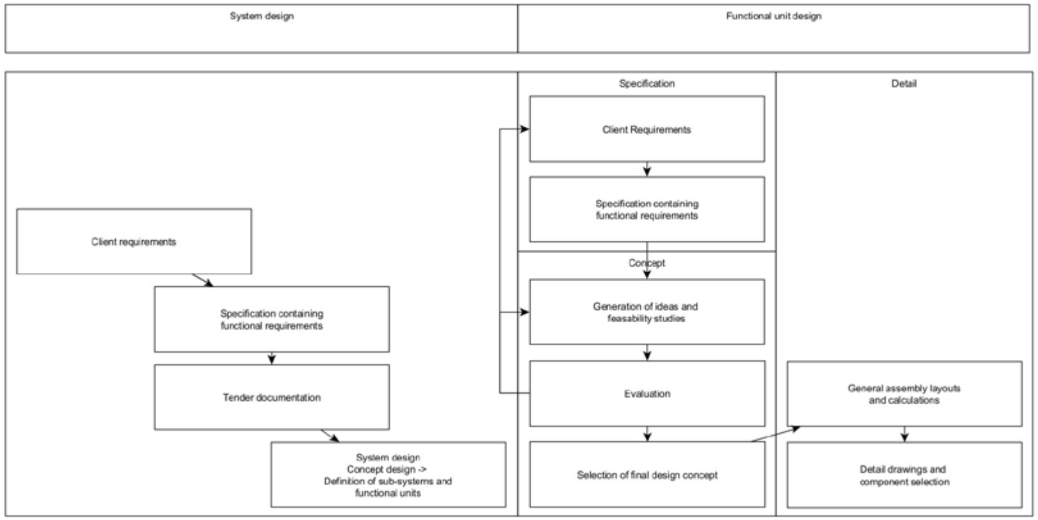


Figure 8. Design for Maintenance model [22]



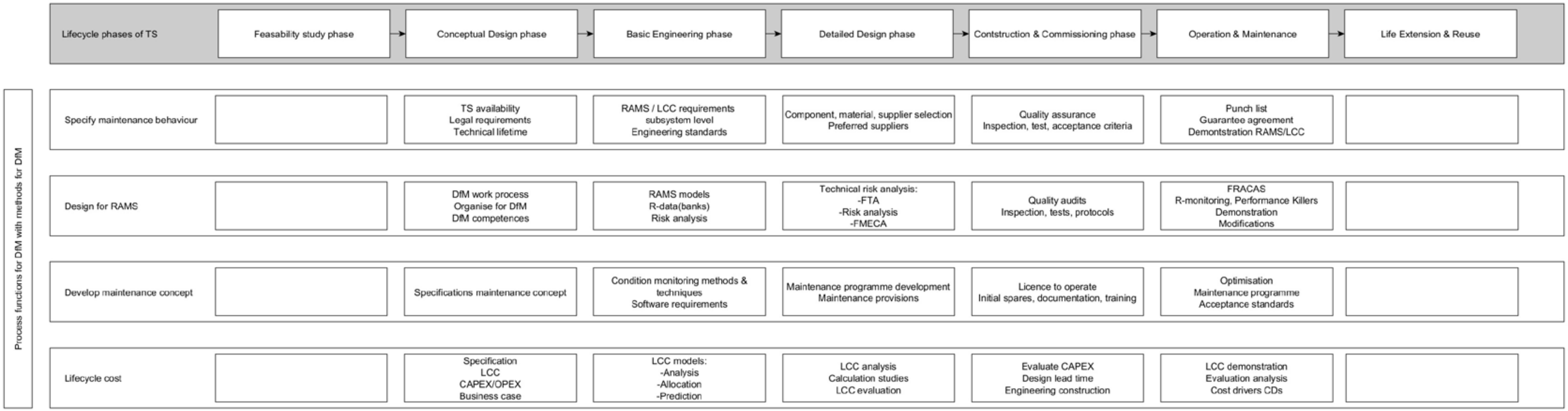


Figure 9. Aligned design and development models. Top: Equipment design process by Thompson. Bottom: Lifecycle phases of a TS and Design for Maintenance model by Smit. Adapted from Thompson [4] and Smit [22].

Biomimicry

In this research biomimicry will act as resource for a sustainable approach to design for maintenance. In this chapter, the biomimicry methodology will be introduced, including its philosophy and the tool Life's Principles.

Definitions

As stated in the definition section, biomimicry is very closely related to other nature-inspired methods and for clarity it is important to follow a standardized terminology. As presented by Fayemi [2], and defined by ISO/TC266 2015[3], the following definitions are adhered to:

- *"Bioinspiration: Creative approach based on the observation of biological systems.*
- *Biomimicry: Philosophy and interdisciplinary design approaches taking nature as a model to meet the challenges of sustainable development (social, environmental, and economic).*
- *Biomimetics: Interdisciplinary cooperation of biology and technology or other fields of innovation with the goal of solving practical problems through the function analysis of biological systems, their abstraction into models and the transfer into and application of these models to the solution.*
- *Bionics: Technical discipline that seeks to replicate, increase, or replace biological functions by their electronic and/or mechanical equivalents."*

Additionally, the definition of biomimicry by the Biomimicry Handbook is the following: Biomimicry is learning from and then emulating natural forms, processes, ecosystems to create more sustainable designs. [1] This definition is more specific than the ISO standard and influenced by the methodology created by the organisation Biomimicry 3.8. However, it does fit within the definition of ISO and therefore the latter is used in this research.

Biomimicry line of thought

Biomimicry is a methodology that influences in two ways; as an idea, it covers the direction and mindset of people and its tools create the pragmatic application of this idea. This is brought together in three elements of biomimicry, which are: Ethos, (Re)Connect and Emulate. Shown in Figure 10.

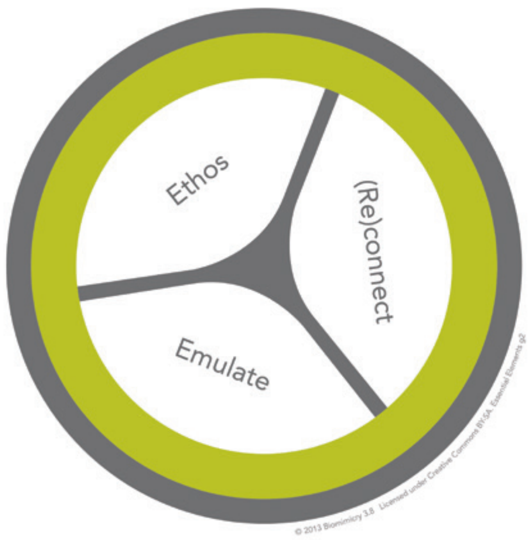


Figure 10. Biomimicry Essential Elements [1]

The idea behind biomimicry is called the Ethos. It is about fitting in on earth as human species. We separated us from nature by trying to control it; we build and invent things that make use of nature and deplete its resources. The practice of biomimicry should create conditions conducive to life. The second element of biomimicry is (Re)Connect. This is about reconnecting with nature, as in discovering what it is, what it does and how it does live. It is possible to find principles and patterns in nature of organisms that solve problems in the same way. Often a method to survive. These ideas can be used in the third element of biomimicry: Emulate. Emulation is the part that will be built on in this research. To achieve the goals of biomimicry it proposes a method to create solutions that would 'fit in on earth'. These solutions are emulated from nature and therefore follow the principles and advantages of nature. Including the efficiency, effectivity and resiliency that organism have developed to survive. In this way it can be seen as a way to view and value nature, as a problem-solving method and as a branch of science. [1]

As the definition of biomimicry by the Biomimicry Handbook indicates; the main goal is to learn from nature and use this knowledge to create a sustainable way of living with nature. This is done through emulating or being inspired by natural solutions to fit our way of living. This is not copying, but reapplication of nature's designs.
The conscious intent to look for nature's solutions forms the basis of the design processes by Biomimicry 3.8. These Biomimicry Thinking processes, formerly known as the Design Spirals[23], have a workflow that is either solution-based or problem-based. The problem-based process, follows the following process: define the problem, transfer problem to biology, look for solutions, transfer solution

back to engineering and develop and evaluate the result. The steps of the design processes are the second basis for the phases of the framework to be developed. For the application in engineering fields it is more useful to follow a problem-based design process. That would help in creating new products, which are mostly designed to solve a specific problem. Thus, the challenge-to-biology approach, which is the same as problem-based[2], will be used in the framework. See Figure 11.

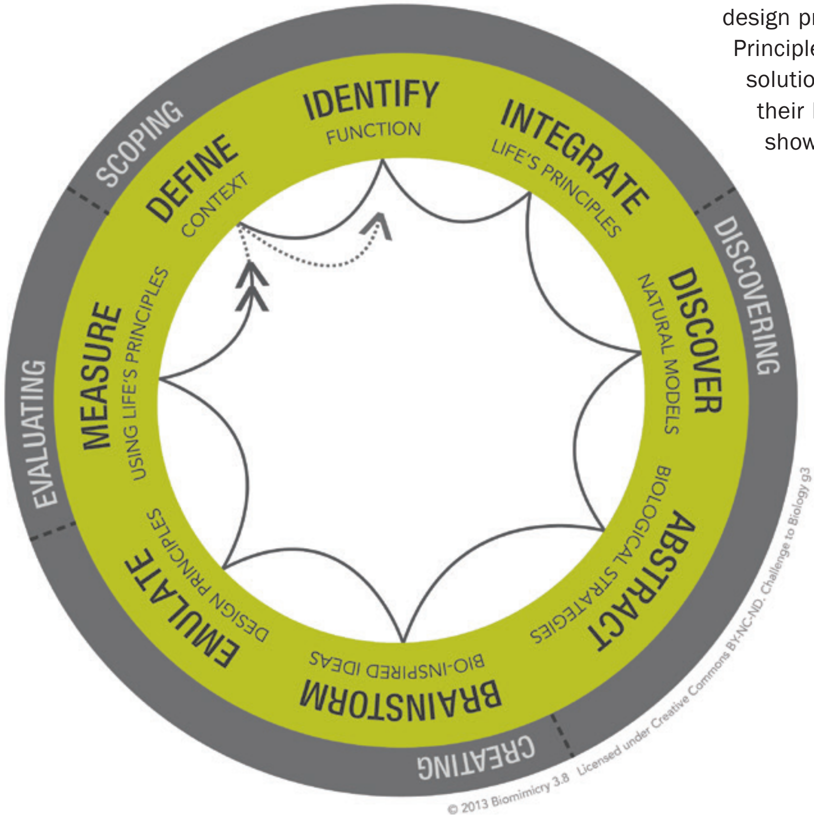


Figure 11. Biomimicry design process: Challenge to Biology [1]

Next to the general design process of biomimicry there are many tools available to support each part of it[24]. One essential tool for biomimicry is Life's Principles. Biomimicry 3.8 developed the Life's Principles based on Janine Benyus work[25]. The resulting designs created with the biomimicry design process should be in conformity with the Life's Principles, which form an assessment to ensure that the solutions fit within the larger natural system ensuring their long-term sustainability. [1] The principles, also shown in Figure 12 are:

1. Adapt to changing conditions
2. Be locally attuned and responsive
3. Use life-friendly chemistry
4. Be resource efficient (material and energy)
5. Integrate development with growth
6. Evolve to survive [26]

All organisms on the planet follow some of these 'requirements'. With these principles, it is possible to survive the conditions of earth. And since those conditions can be very hard to survive in, the principles promote efficiency and responsiveness of the organisms to the environment. This efficiency and sustainability applied by nature is exactly what could improve our technological solutions. The Life's Principles is only one tool, in literature many other tools are explained and developed to guide the biomimicry design process in more detail.

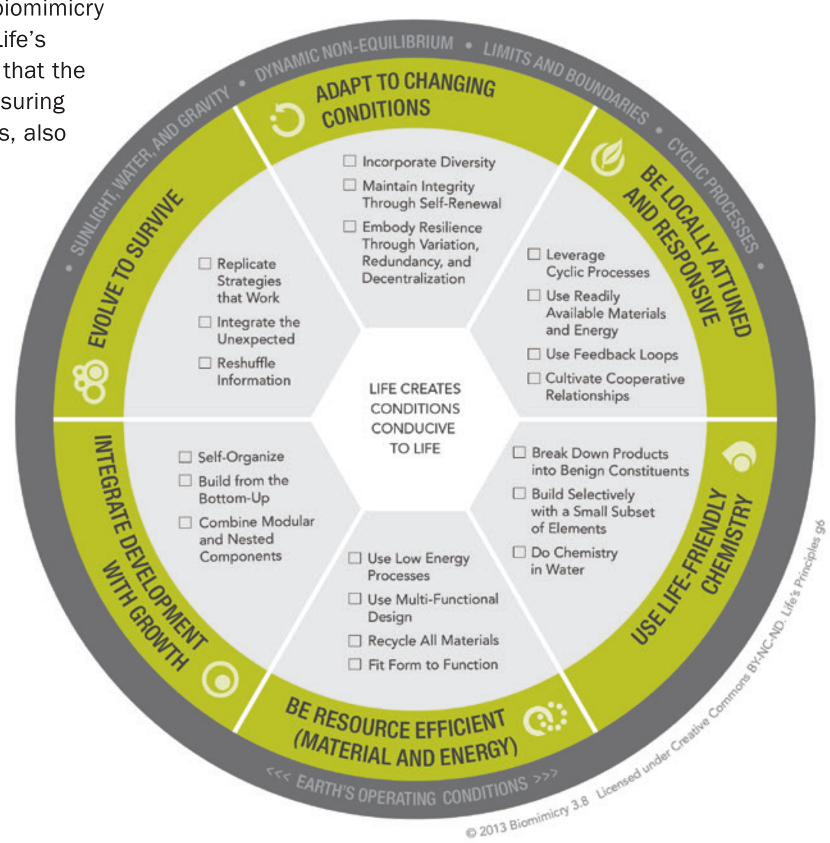


Figure 12. Biomimicry Life's Principles [1]

As explained before; biomimicry includes the same design process as biomimetics. Therefore, biomimetic methods and tools can also be used in the design process to be developed. The design process by Fayemi [2] presents an overall project flow of biomimetic design. See Figure 13. The biomimicry (challenge to biology) design process is remodelled over two axes. On the y-axis, it shows the abstractness of the material that is worked with. In the phases on top are the problem and solutions described in their most abstract form. This abstraction creates the possibility to transfer a concept between fields of study. In this case; biology and engineering. The flow through the lemniscus shows the phases to follow within the project.

The flow is straightened and shown on the left side in the decision tree, Figure 15, page 23. The phases are related to engineering and biology, shown by the gears and cord of DNA. This clearly shows the previously mentioned steps between engineering and biology. One starts in engineering, transposing the problem to biology and after finding ideas or principles, then these are transposed back to engineering. These project phases are a basis to classify and divide tools.
Fayemi [2] presents a classification of tools based on the project phases. The tools are divided over four categories: Analysis, Abstraction, Transfer and Application. Thus, tools within the same category end up in the same project phase. To choose between the tools during a phase, a decision diagram is made. This helps users to select the tools by asking questions that will sort out tools on their characteristics. Many TRIZ tools are included next to biomimetic tools. TRIZ is a known tool for solution finding and has a variant for bio-inspired solution finding as well [27].

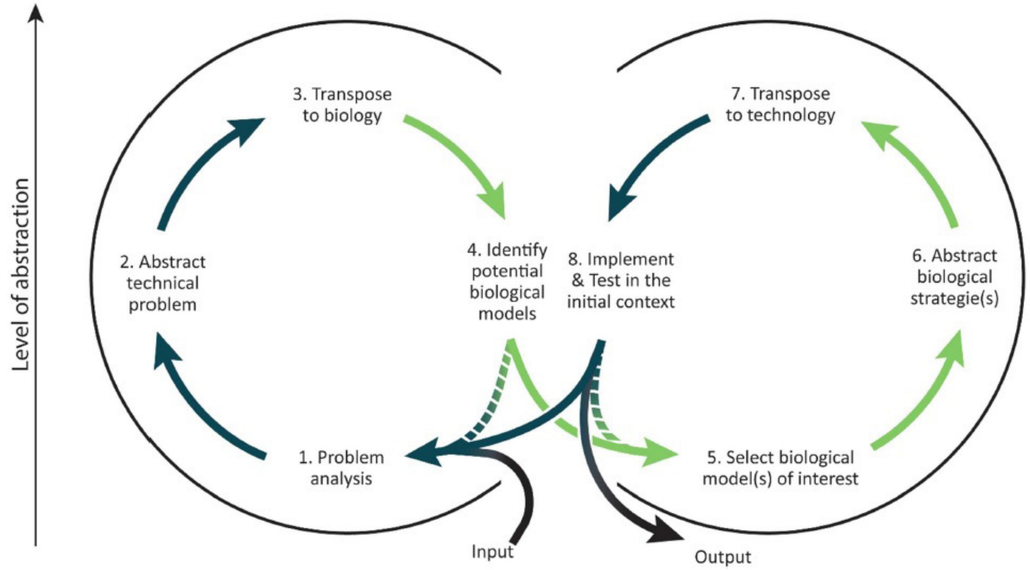


Figure 13. The unified problem-driven process of biomimetics [2]

Developing tools to work within a design process is important to overcome gaps during this process. [24] The gaps recognized are shown in Figure 14. In their research, a list has been compiled and a comparison is made on biomimicry, biomimetic or bionic tools. The list is added in appendix B.

The list of tools presented is currently one of the most complete and therefore it is used as main input of tools in the framework to be developed. A comparison showed that it covered all tools (except for some the TRIZ tools) mentioned by Fayemi.

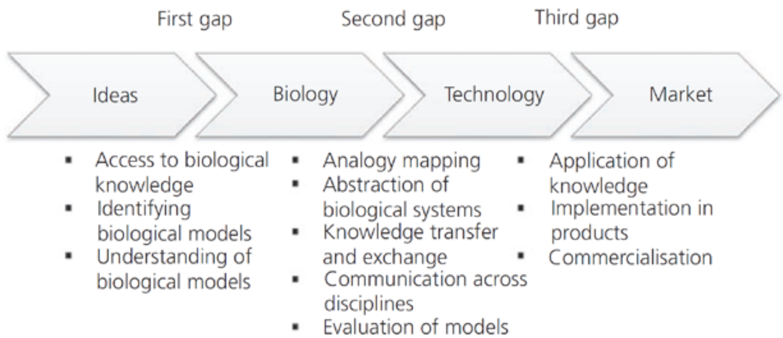


Figure 14. Gaps between fields in the biomimetic design process [2]

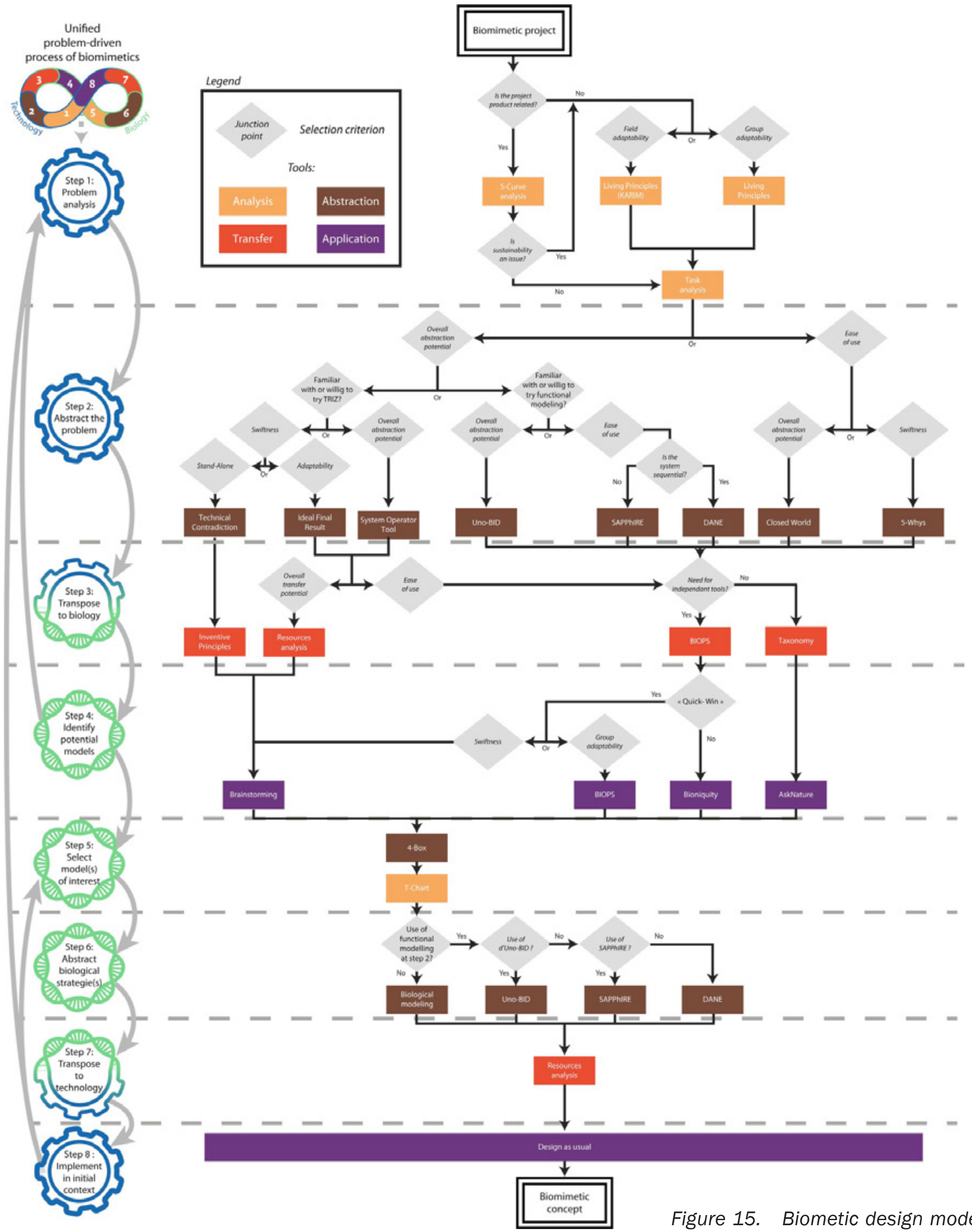


Figure 15. Biometic design model desicion tree [2]

The current efforts on enabling a systematic bio-inspired design (BID): “a) focus on different aspects of the process, b) do not yet interface together, and c) are not openly accessible to practitioners.” [28] These statements are partially solved by Fayemi [2]. The unified biomimetic design process systemizes the biomimetic process, including all development phases of the design process and an overview on which tools to apply in each phase. Which is a starting point for connecting the different tools together. The tools themselves, however, are not accessible enough to be instantly applicable for practitioners. This is substantiated by Fayemi [2] and Volstad [29] as in that the practical implementation is not sufficiently evolved to be applicable in companies. Probably due to the large process change and the investment costs to modify the development cycle. This would support a remark of [28]: “Industry as a whole has been generally slow to adopt BID approaches likely due to resource and organizational constraints.”

On the other hand, Nagel [28] expresses the potential impact of BID on society. It underlines the potential of systematic BID in three points:

- *“Alleviate the knowledge gap, assist with transferring valuable biological knowledge to the field of engineering.*
- *Remove the element of chance, and/or reduce the amount of time and effort required to developing bio-inspired solutions.*
- *Bridge the seemingly immense disconnect between the engineering and biological domains.”*

These points strengthen the case for bio-inspired design and its new application in domains as maintenance engineering.

Biomimicry is a method of approaching a design problem. Just like any other tools and methods it adds more working time and costs to a project. However, the tools and methods are systemizing the process, which creates advantages as reliability, reducing risk and better results. In addition, it is important to recognize the following statement: “How companies implement the design phase is varying between all companies. An inflexible, prescriptive approach will be difficult to put in practice.” [4]

Chapter 3: Current design practice

Practice and research often do not adopt new ideas and methodologies at the same time. Research often recognizes added value of new developments long before businesses do. Businesses, of course, work in a market environment. It is important to create value for customers and new developments must add values recognized by the company. Therefore, it is logical that new developments must prove its value before they are picked up by the market.
To develop a methodology that is as close as possible to a useful product for business, it must be adjusted for being used in a business environment. By having interviews with employees of Arcadis about maintenance, management and implementation of new methodologies, interesting information is gathered to consider practice during the development of the framework. In the following section, the conclusions of these interviews will be described. The summaries of the interviews are available in appendix C.

Interviews with Arcadis

Implementing new methodologies

Experience during a thesis showed that Rijkswaterstaat is more progressive in maintenance management and asset management than water boards. In these traditional and smaller management organisations, a fixed style of working dominates. The style of working consists of unformalized coordination, standardised work, working a lot from experience, the idea that if something works no change is needed and a limited view for the future. Therefore, it can be difficult to implement innovative methodologies.

Application of (design for) maintenance

Maintenance and design for maintenance are not used extensively in design or building projects. It seems to be more important for bigger organisations and larger, often more complicated, projects. Smaller organisations and projects often do not have the amount of management, structure, knowledge and the large costs of failure, required to consider or implement maintenance as a structured approach. What counts for any size of organisation is the fact that lots of work is based on standards and guidelines and the experience of the designer. Large and important subjects are discussed within the teams. In projects where the problem and risk have developed and time pressure is high, quick and dirty solutions are applied. These insights give that solutions are not created in a structured way and problems can be solved in many, inconsistent, ways. The importance of maintenance is also often neglected.

It is stated that tools and approaches as: LCC, RAMS(SHEEP), Failure Mode Effect and Criticality Analysis (FMECA), and RCM depending on the field, are generally known. However, the application of methods heavily relies on the size of the project (complexity), the time available and the amount of funds available. Maintenance is often only considered as part of these methods. Within the domain of asset management condition and risk based management is a relevant often applied methodology, combining FMECA and condition measurements.

Moreover, during the investments and tender processes maintenance can only have a dedicated project phase if it yields more profit than invested efforts, which is currently difficult to support. Maintenance could also be not remarkably considered in the RAMSSHEEP and risk analysis, stressing more safety and availability aspects. Unfortunately, the added value of maintenance appears not to be sufficient or is not recognized to be sufficient to commit more attention to it.
However, maintenance is more and more considered and used. The traditional idea of design, which resulted in over-the-wall engineering, is slowly being renounced. Previous results of flawed design acknowledge the need for an integral design and management approach, in order to improve efficiency, safety and reducing cost.
In relation to that, the Dutch water boards (waterschappen) are an example, they involve people responsible for the maintenance solutions in a project team. Bringing maintenance knowledge for improvement and representing these interests. Generally speaking, in specialty and bigger projects there is often more time and funds available to consider maintenance properly.

Rijkswaterstaat is improving to work with an optimisation triangle of costs, performance and risk. Nevertheless, this is not fully implemented yet since the current methods still

do not allow this way of working. This culture change is difficult to put in place and always needs the full support of the clients (in this specific case Rijkswaterstaat) and of the contractors since they deliver the essential work for the organisation.
In increasing extent, a RAMS analysis is made from the first design on, this is also standard in projects for Rijkswaterstaat. Then the failure rates are added to the components, which can be used to question the constructor. Between each phase there are validation moments, to check if delivered work is as it should be.

One of the most important concerns is the difference of interests from stakeholders, which holds back (design for) maintenance development. As a company, it could be a goal to satisfy the client with as little investment as possible. If maintenance is not important or not requested by the client it can be neglected. Design can be optimised to deliver satisfying RAMS values. Managers request maximum availability and availability, which is not possible from a design perspective. This difference in view can result in oversized designs. Only calculated proposals show that chances of failure do not outweigh the costs.
An indicated problem with recognition of the importance of maintenance is that the maintaining party is different from the party that designs and builds the asset. The latter does not concern itself with the care during the lifetime of the asset. If this party is related to lifetime expenses or profits, then they will also see the value of better design. For the field of the national road network, the revenue model of Rijkswaterstaat and incentive of the contract do not allow much room for innovation. Rijkswaterstaat is the ideal organisation to take a lead in design for maintenance during investments.

A short-term view is also seen by boards of companies. Resulting in quick prestige projects with little thought into future maintenance.

Feedback for design teams is available in a moderate level. The designing team or organisation is obligated to be replaced for the building phase of the project. Adjustments initiated by the subcontractor are discussed directly. But notes taken by the design team during building is presented to the client, who decides to make use of that information. Within the design team there is often room for iterations and redesigns of parts of the project.

The Netherlands is a kind of finalized, importance will transfer from building new things to repurposing existing assets (buildings and infrastructure). Therefore, it is very interesting to apply new maintenance methodologies to existing assets (areaal). Which could be a developing market with opportunities.

Tools for the framework

'Duurzaam GWW' (Sustainable Land-, Road, and Water construction) is a cooperation between organisations to work on long term sustainable developments, to achieve the climate targets. It involves agreements on targets to achieve, example given: CO_2-reduction of 20% between 1990 and 2020.Such guidelines and rules made by the governments and related organisations can be useful tools to set advanced requirements and project goals. Such agreements can be used for input in requirement setting or evaluation.

Cost estimations become more specific during a project, starting with a margin of +-50 percent. If a project is considered too expensive after the design phase, it could be stopped despite the possibility that the whole project could fit within the budget. This is partially a result of different project managers. A tool, which is out of the scope for this research project, could improve the communication on budget estimations and budget spending during a project.

Innovation in a company

The amount of innovation that companies incorporate is influenced by the type of company, its vision or approach and the discussions with clients. Generally, solutions are developed beforehand and implemented many times in an optimised form for clients. Clients are often attracted trough these developed solutions. Only on client request are brainstorms and specific new solutions developed during a project. This process of creating specialised solutions sometimes triggers innovations. The ideas can come from anyone within and outside the company or consortium, everyone has its own field of expertise.
It is recognized that for new developments, you need

the people in the tactical layer, are often engineers and technology-driven and able to think out-of-the-box about new technologies and maintenance engineering from a process and business perspective. In contrast to the old guard and operational level who are more specialists, task-oriented and activity guided. People between the tactical and operational levels (thinking about the system/planning (thus operation planners) should watch the developments in the tactical layer and try to implement it in the operational layer. The organisational layers can be recognized in Figure 16.

Further innovation can be recognized in the development of combinations of existing solutions. It has been said that education (research) has the time and money available to study and design new developments.
Types of innovation that are growing in popularity are innovation for sustainability and social innovation (which includes working together with stakeholders). Lessening costs is always a reason for development.
As is recognized on a maintenance specific level, innovation is initiated by boards of an organisation. They are an internal employer and should ask for development of low life cycle costs, sustainability and maintainability. This can be complicated in a political organisation where focus lies on goals to be achieved in the term of the then current board. The incentive to structurally change work flows lacks in some organisations. Therefore, money should be reserved and business cases should be made to sell it to the management. Innovations must be proven to get accepted. This could be difficult when only soft data is available. Solutions created in the tactical level should therefore also be presented in a proper way (including advantages) to the operational level. They will be working with it and will be affected. Developing innovation through an already existing, sustainability, program, could quicken the implementation on the work floor.
In fields where standardization is common, innovation is inhibited by the rules and predefined properties.

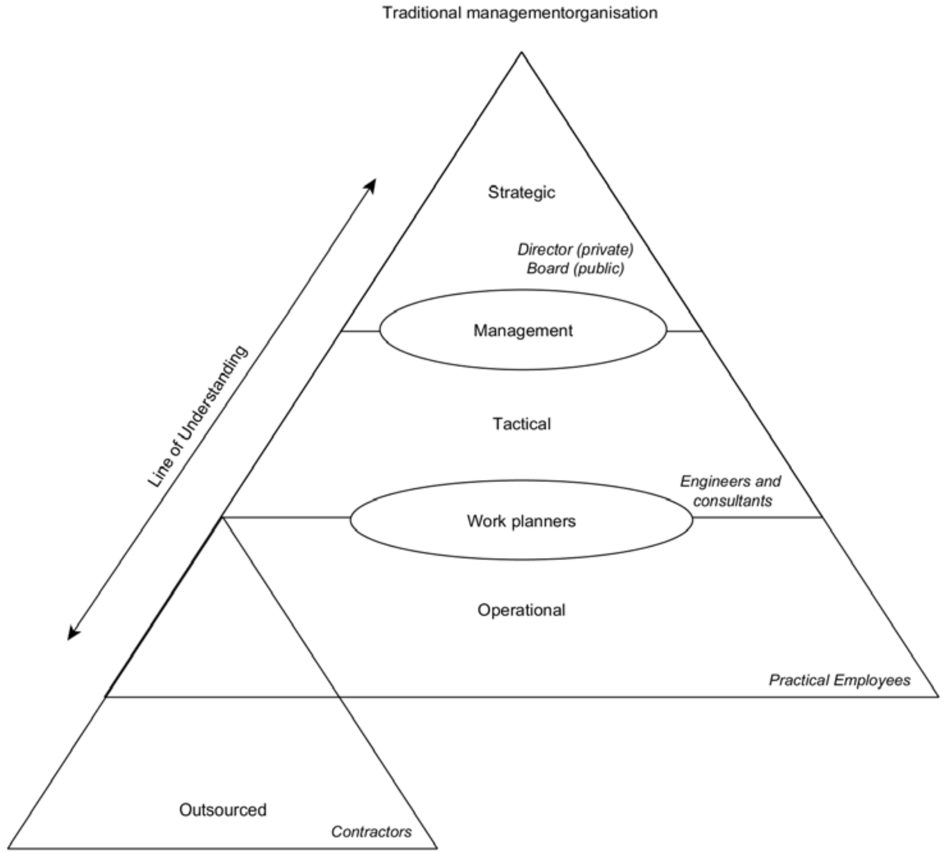


Figure 16. Organisational structure.

Development of biomimicry in a company

Biomimicry is a sustainable concept that is still in development. Another sustainable concept that already is implemented is Natural Capital. “Natural capital can be defined as the world’s stocks of natural assets which include geology, soil, air, water and all living things.” [30] Humans can derive a wide set of services from natural capital, example given: natural flood defences provided by forests or pollination of crops by insects. Contributing to a company is not only done through generating money, but also through added environmental value. This idea came together with university concepts that evolved to Natural Capital. Biomimicry is coming up via the same steps and given the sustainability aspect and being relatively new, natural capital is comparable with biomimicry. However, Natural Capital is already further implemented than biomimicry and therefore it is possible to learn and follow the successful path of natural capital for the implementation of biomimicry.

Biomimicry and Natural Capital are only implemented by leading companies and often only picked up by some individuals in those companies. However, Natural Capital is already having a larger support base, creating a platform for projects as the Natural Capital Protocol, which provides companies with a universal standard to measure and value natural capital.[31] Since the business case, which is the value of nature, behind biomimicry is less visible than with Natural Capital and should therefore be communicated clearly.

Such as Natural Capital, Biomimicry is a way of thinking and it does not bring ready-to-use solutions. A company should be open for that and its use is dependent on people who want to pick it up. To sell a concept as Biomimicry in a company, everything from concepts to operation plans should be ready. A sales person could start to pose the body of thoughts, present a business case and show concrete examples. It is important to show the advantages for the company, in euro’s, less risk or distinctiveness. The advantages of a new concept should be followed by ideas to implement and execute the concept in the companies’ processes and in the products.

Changes in the way of working will get resistance from employees. Therefore, people that are open to new ideas and have the ability to influence should lay the foundation of a concept within a company.
In the end, and as said before, companies will only use a new development if they are able to create added value with it. Therefore, their caution should be refuted by examples and cases to show their ability to profit with a new concept.

At the moment, Arcadis does not have a structured approach for implementing biomimicry in its business. A structured protocol or framework could help develop a more consistent approach within the boundaries of biomimicry. Especially, when useful and applicable solutions are proposed. Next to a structured approach for biomimicry, a framework could also improve the approach for maintenance. Maintenance does receive some attention, however there is not structured approach available that supports design for maintenance or the development of new maintenance practices. This can be addressed in the framework. At last, the framework could also be a platform that initiates the development of innovative solutions. Unfortunately, two main problems that fall out of the scope of the framework are over-the-wall engineering between companies -not thinking about the future use and maintenance of assets- and the fact that maintenance is valued low in RAMSSHEEP criteria.

Chapter 4: Framework

In this chapter, the creation of the new framework will be discussed. The aim of the framework is to implement biomimicry in the development cycle for design for maintenance and categorise tools to support the development process by making them accessible for designers and engineers. One by one, every component of the framework will be explained.
The framework is mainly based on the literature review, further inspiration comes from the interviews and personal experience with design methods. Discussions contributed to incremental improvements.
First, the project phases are discussed, followed by the tools and the representation of the framework.

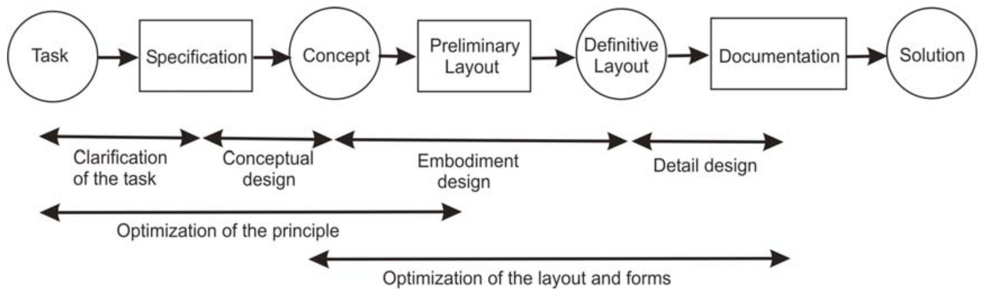


Figure 17. Simplified design model of Pahl and Beitz. [12]

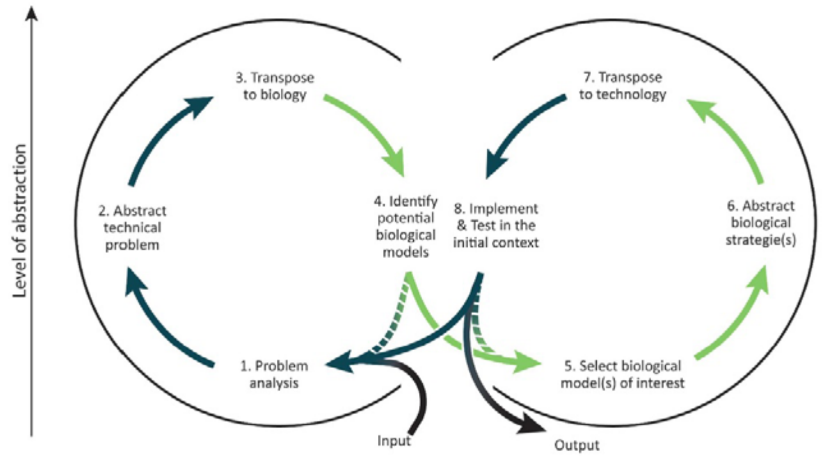


Figure 19. The unified problem-driven process of biomimetics [2]

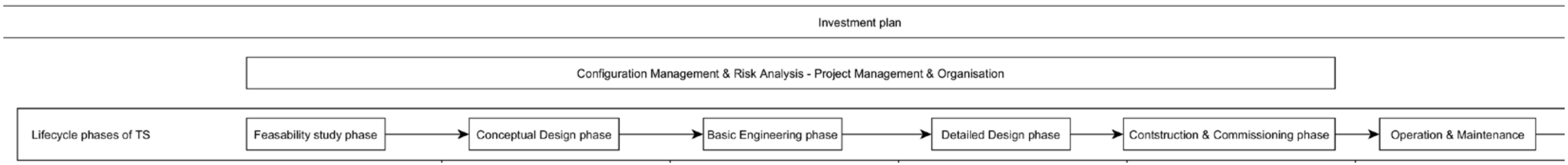


Figure 18. System engineering design model [22]

The project phases

The project phases are designed from a combination of systems engineering, biomimicry and industrial design methodologies. The systems engineering process developed by Blanchard and Smit[22], shown in Figure 18, is the basis for the projects phases. It is chosen to keep the process linear. This creates simpler feel, people can get an idea on how far they are in the process and it is easier to learn. This is recognized from the fact that the linear design model of Pahl and Beitz[12], shown in Figure 17, is often used as the first design process to learn.

The biomimicry process is compared with the system engineering process to find similar phases. These phases are merged to prevent duplicates and over-complicated process schemes. The leftover biomimicry phases are fitted in the system engineering process. Since the biomimicry process is almost completely consistent of phases that support idea generation and early solution development this has replaced the idea phase of industrial design processes. The used biomimetics model is from Fayemi[2]; see Figure 19. The framework is shown in Figure 20, the entire poster with examples is available in Appendix D.

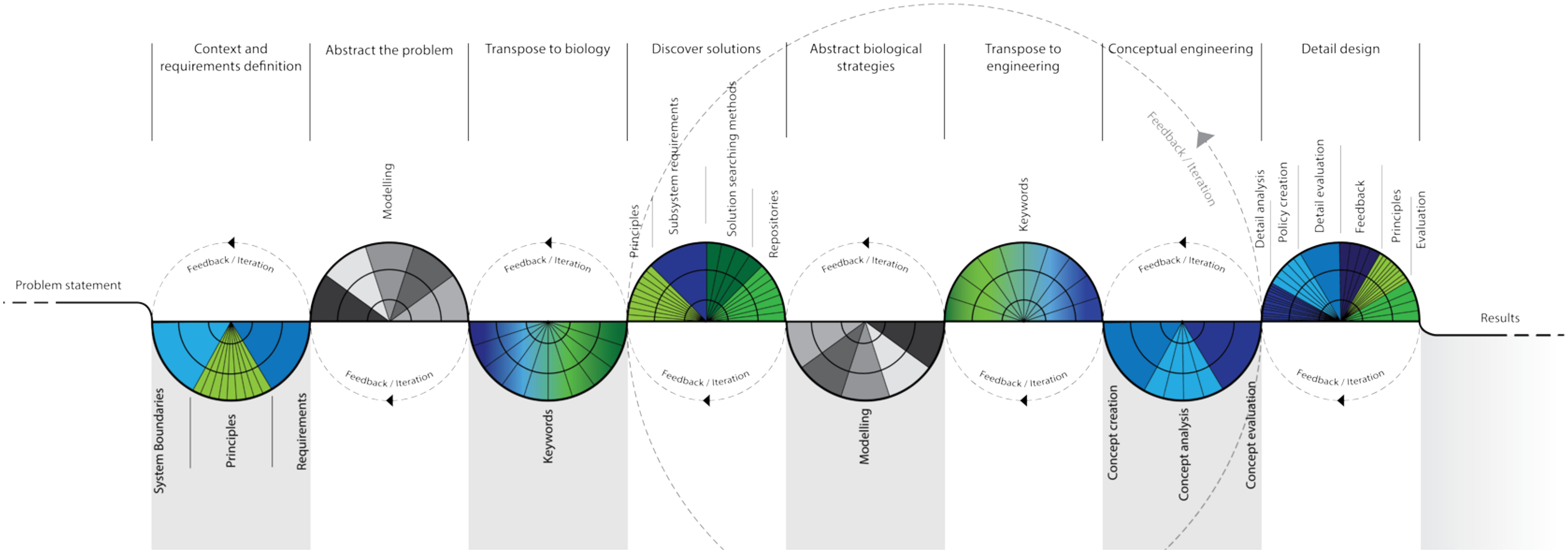


Figure 20. The framework for the design for maintenance solutions based on a biomimicry methodology.

Context and requirement analysis
This results in an analysis and defining phase as the first phase of the framework. In this phase are all the inputs from the clients and stakeholders gathered and analysed. With additional analysis the context and requirements are defined. This phase creates the basis, ground layer, of the project by creating the reference documents with all information to refer to when required during the further project.
The second phase to sixth phases are biomimicry phases, of which the goal is to find the ideas and solutions to the problems defined in the Context and requirements definition phase. The naming and process used for these phases have the models of Fayemi[2] as basis. This model is more abstract and direct than the biomimicry process terms of Biomimicry 3.8.

Discover solutions
The steps for identifying and selecting biological models are merged into the phase Discover solutions. This decision is made based on a project management and industrial design experience. In some models, it is common to end every phase with a reflection moment, considering feedback and iteration. In this case it is important to check the solutions through the set requirements and use iterations to make sure the right solution is developed within this phase. The Discover solutions phase is about the exploration of nature and its principles to find ideas and solutions. Following the idea of biomimicry, the database of nature can give us inspiration to solve our technology based problems.

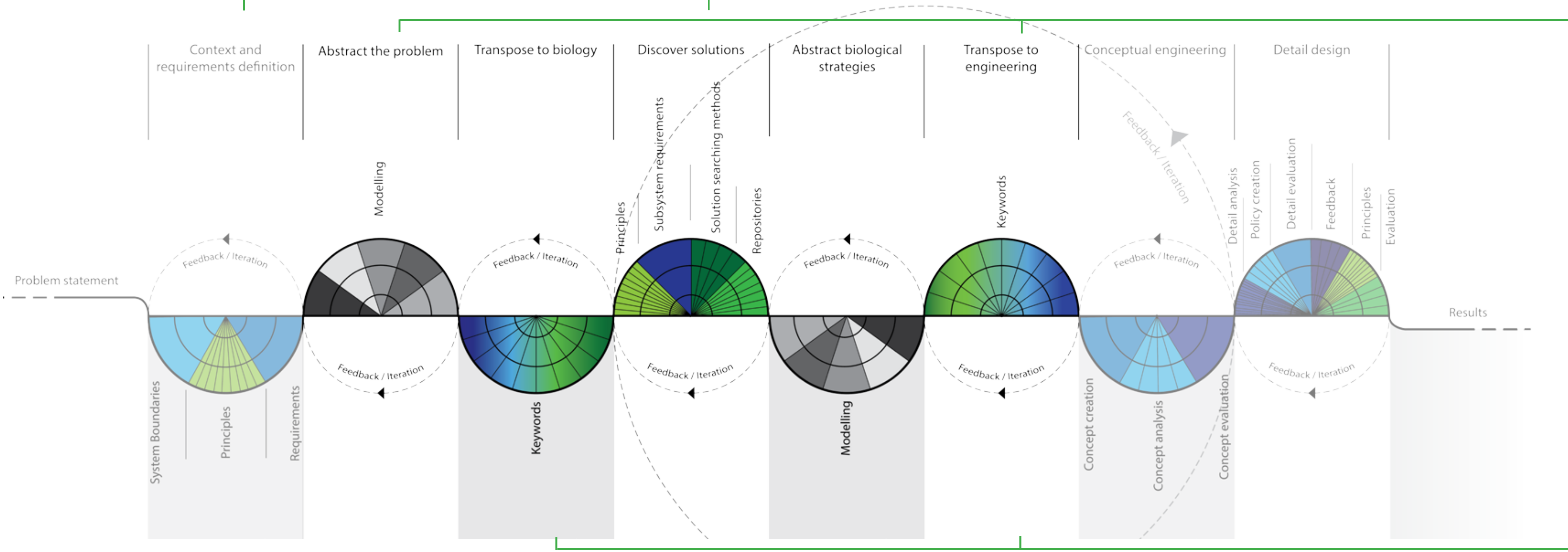


Figure 21. Framework with highlighted biomimicry phases

Abstract the problem and Abstract biological strategies
In the abstraction phases the problem and the found solutions are abstracted. The abstraction is used to disconnect the problem or idea from its field, engineering or biology. In the abstraction, an analytical model is made, which creates a view that focusses on the essential parts of the problem or idea. This abstraction is very useful to find the keywords or functions in the following phases.

Transpose to biology and Transpose to engineering
In these phases is a bridge formed from the engineering field to the biology and the other way around. The keywords or functions are used in the presented tools to connect these fields. They are words that can be used in both fields or can help to translate specific engineering terms to biology terms. When the translation is done, it is possible to work further within the other field, finding solutions or developing the ideas.

Conceptual engineering and Detail Design
Following the biomimicry phases and the translation back to engineering the last two phases are well known in design: Conceptual Engineering and Detail design. During these phases, the found ideas and principles are developed further into implementable solutions. Starting with Conceptual engineering the basic characteristics are defined and the general outline of the solutions is known. The concepts are analysed for expected performance and evaluated to see if iterations can be made or if iteration is necessary.
During the detail design phase, the designs are developed in full. The following phases, which are not considered in this research, will be construction, implementation and use. The solution is therefore optimised for its use and maintenance properties are developed in detail. In this phase are reflection, evaluation and iteration again very important. The function of the system must be working, the solutions must fulfil the set requirements and feedback for the project team and for future projects must be gathered and communicated.

The tools

For each phase implemented in practice, it is necessary to show how this could be done. Therefore, an extensive list of tools to be used during the design process is compiled. The tools are then divided over the design phases to show the possibilities for each design phase. It must be said that a list of tools is always incomplete. Current developments, fields not reviewed and design decisions contribute to that fact. The list of tools is a compilation of biomimicry tools presented by Wanieck[24], more information in literature [1,33–81], and Fayemi[2], shown in Figure 22. The maintenance tools are collected from the books of Thompson[4] and Smit[22]. Available in appendices A and B. TRIZ tools presented by Fayemi, which did not appear on the list of Wanieck, are not included. These tools are general design tools and fall out of the focus on biomimicry and maintenance tools.

Step 1	S-Curve, Domino, LP, KLP
Step 2	MSD, Uno-BID, TC, IFR, CW, DANE, SAPPhIRE, 4-Box, 5-Whys
Step 3	IP, Resources, Taxonomy, BIOPS
Step 4	BIOPS, Bioniquity, AskNature, Brainstorming
Step 5	T-chart
Step 6	Uno-BID, DANE, SAPPhIRE, BioM, 4-Box
Step 7	IP, Resources
Step 8	—

Figure 22. Tools considered by Fayemi, divided over the unified problem-driven process of biomimetics [2]

The tools had to be divided over the design phases. To sort the list of tools, new categories are created to divide the tools in groups of similar function or goal. The categories are fit to the design phases of biomimicry and engineering. In this way tools with the right function are available in the right design phase. All tools currently gathered are shown in Figure 23 and Figure 24. In appendix E is a premature version of the framework added, in which the in- and outputs for every category and phase described. The tools can be found underneath the examples in the framework poster. The explanation of tool categories follows here.

The System boundaries category presents tools that help defining the scope of the problem, setting the boundaries for the system to be designed. This is a maintenance category.

The Principles category presents tools that include biological principles and patterns that nature follows. Most of them are lists. Principles are represented in three phases, showing the ability for use as requirement setting standards or evaluation criteria. This is a biomimicry category. Requirements, a separate category, which shows the importance of requirement setting. This category is specified again for subsystems as subsystem requirements. Strengthening the importance of proper requirement setting on multiple levels of the system. This is generally an engineering category.

The category Modelling holds tools that have a way of modelling systems. These can be natural and technical based. Some also include additional functions, such as a digital library search function. Modelling is used twice in the framework, for technical problems and biological solutions. Since modelling is analytical, it is an engineering category. Keywords are the bridge between engineering and biology. This category has tools that help translating field specific terms and many tools that help working with functions to bridge fields of study. The keywords are used twice, both in the Transpose phases. Since keywords are bridging two fields of study it cannot be said if it is engineering or a biomimicry category.

Solution searching methods are tools or even methods that guide solution searching in, amongst others, collections listed under Repositories. This is a biomimicry category. The Repositories are the libraries of ideas and solutions already found in nature. They often already include a way to search them, however, Solution searching methods can be used in some cases.

Concept Creation, tools that help the development of new concepts. This is a biomimicry category.

Concept analysis tools help to analyse the performance of the concepts created. Results can be used for iterations and evaluations. During concept design, it is not possible or not expected to do a complete analysis. The large analyses for this phase are marked as: light. The purpose is to make people aware that a quick version (more generic) is possible and in most cases sufficient. This is an engineering category.

Concept evaluation is required to check if performance is expected to be sufficient and this can indicate the need for iteration of solutions. Possibly starting from Discover solutions phase. This is an engineering category. Detail evaluation during detail design is more specific than during conceptual design. Often there is little room for improvement, thus system should perform according to the requirements. This is an engineering category.

Evaluation during detail design, holds the biomimicry related evaluation tools. This is a biomimicry category. Category Feedback presents tools that reviews design proposals and design processes, and tools that help establishing a feedback loop to previous phases or other people. This is an engineering category.

The Policy creation category holds methods to develop maintenance related policies. From maintenance tasks to support structure planning. This is a maintenance engineering category.

The category of Detail analysis builds on the Concept analysis. It presents all tools that help analysis performance of systems. This is an engineering category.

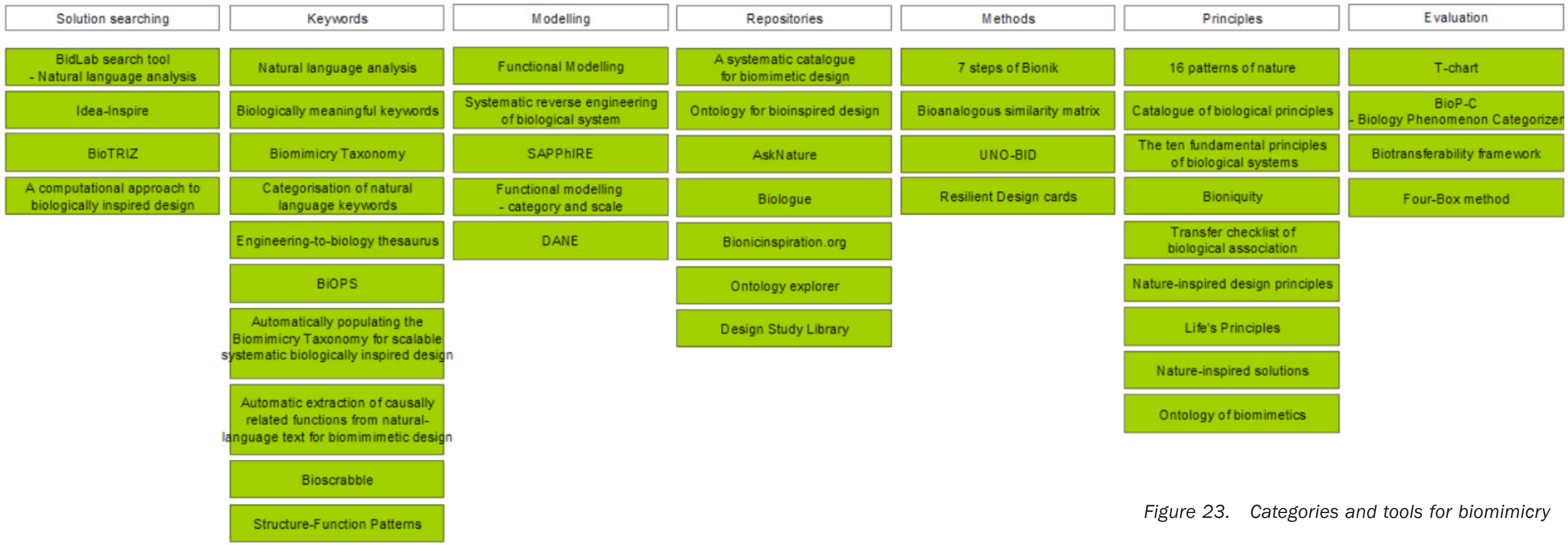


Figure 23. Categories and tools for biomimicry

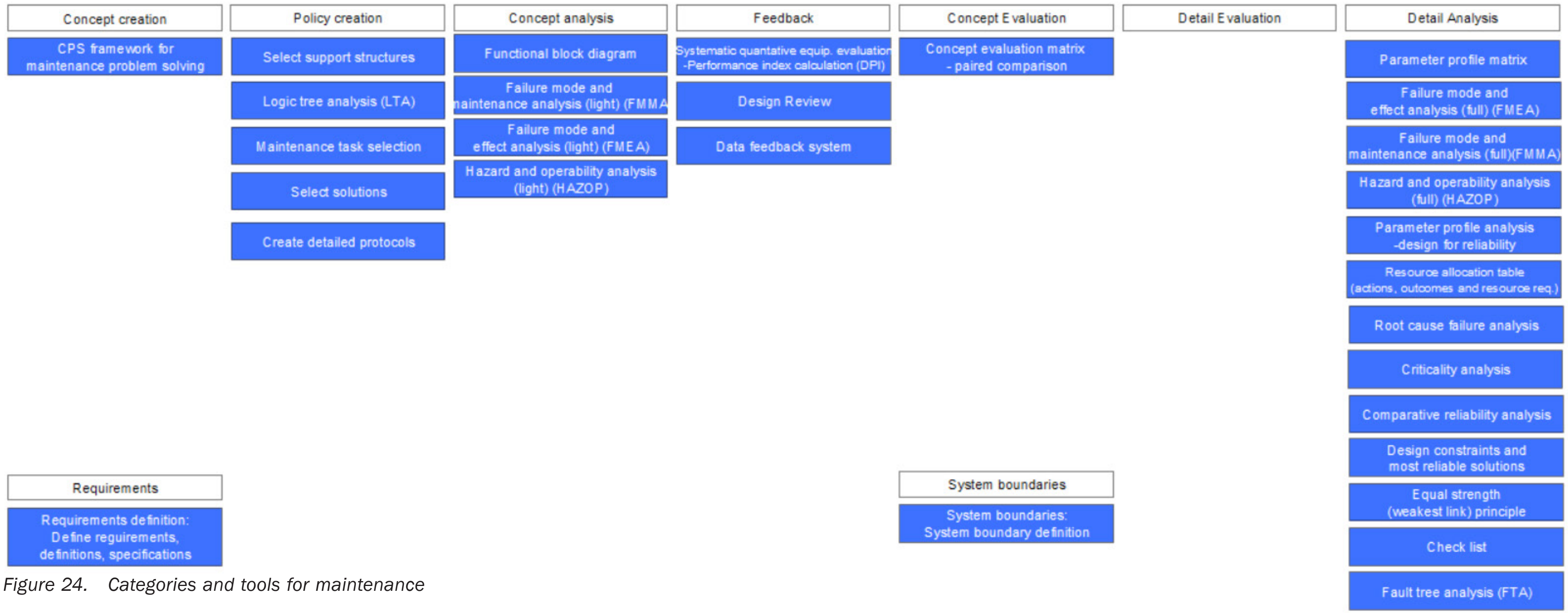


Figure 24. Categories and tools for maintenance

Visual aid

The created framework is not only developed content-wise, visually it has several cues to support the understanding and an ease of use. In this section, the framework as visual aid will be explained.

Starting on top of the framework, the project phases are dividing the process in eight steps. The timeline through the phases consists of eight circles, one for each phase. On the left side, the problem statement is marked as the input for the design process. This includes all information that is given before any work is done on the project. On the right side of the timeline the results of the process should be documented completely. See Figure 25.

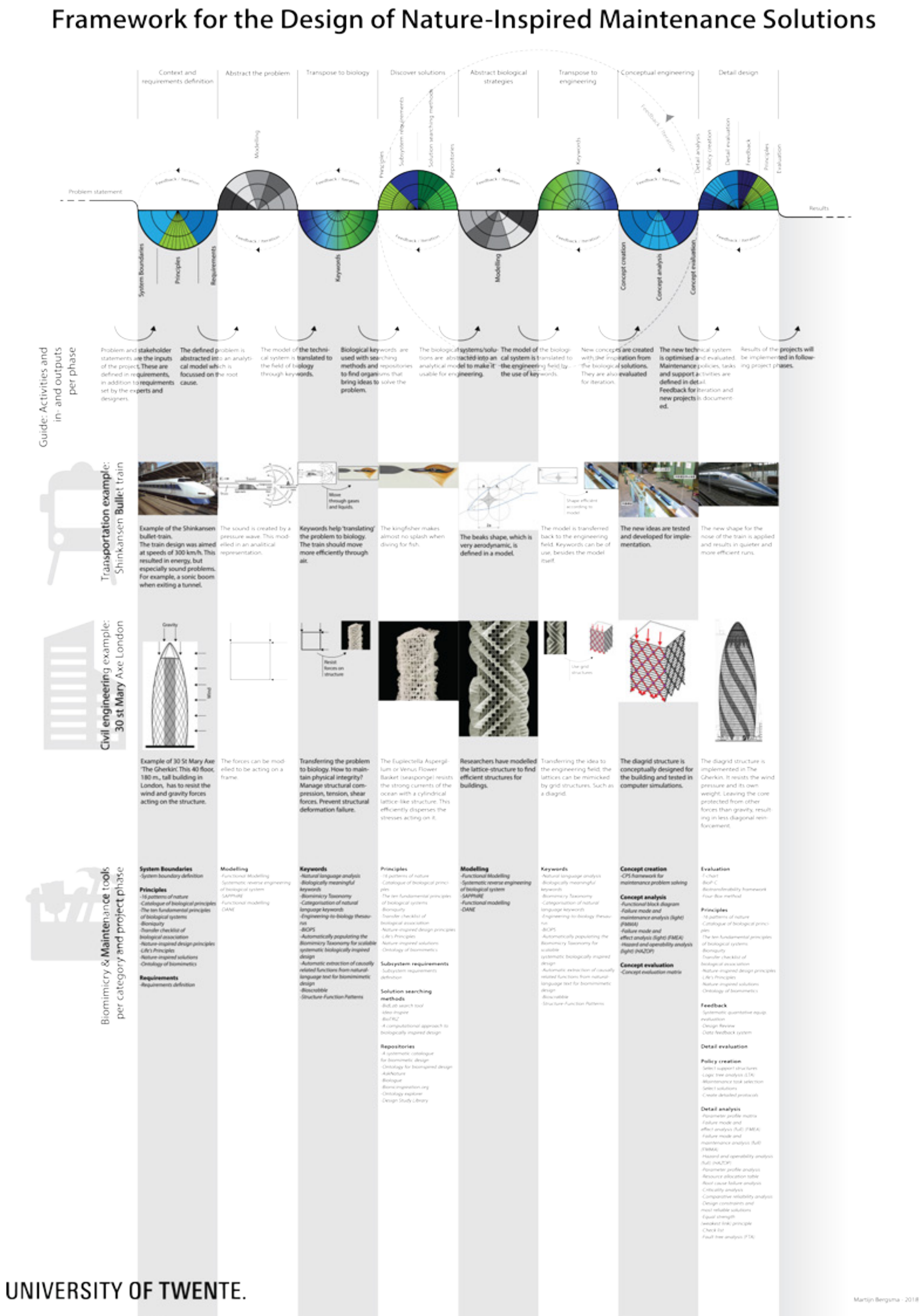


Figure 25. Framework poster, including: design phases and timeline, short explanations of in- and outputs per phase, two examples and the categorised tools divided over the design phases.

Zooming on one circle a couple characteristics can be recognized. See Figure 26. There is no difference in the use of the top half or the bottom half of the circle, this is a design choice to connect the timeline neatly and form a flow through the project phases. The circles are segmented. The number of small segments in a semi-circle is the same as the number of tools currently available for that phase. All segments with the same colour represent tools that fall within the same category. This category is written just outside the circle next to the related segments. The blue-coloured segments/categories are maintenance or engineering related. Green-coloured segments/categories are biomimicry related. There are four semi-circles coloured differently. Since Modelling is analytical, engineering related, but purposed to abstract both engineering problems and bio-inspired solutions, it is chosen to not apply a field of study for it. The Keyword category is the bridge between biology and engineering. Therefore, these tools fall in the middle of both fields and is chosen for a gradient to represent the change of field within these phases. See Figure 25, page 34 or Figure 20, page 29.

Two semi-circles places over the segments create three ‘levels’. This related on one hand to the depth of the development, the amount of detail of the project phase. Projects start abstract and with a broad view and generally end in the detail design phase with specifics. On the other hand it represents the levels of biomimicry: form, process and ecosystem [1].
A practical experience has shown, a design process always includes iterations and feedback to improve designs. This process plays on multiple levels of detail, from rethinking a part of a solution to the redesign of a whole methodology. Therefore, is in every phase the feedback circle present.

During idea generation and concept design is the number of iterations especially high. Logically resulting from the creative and free design phases. Therefore, is for these phases an additional feedback circle present.

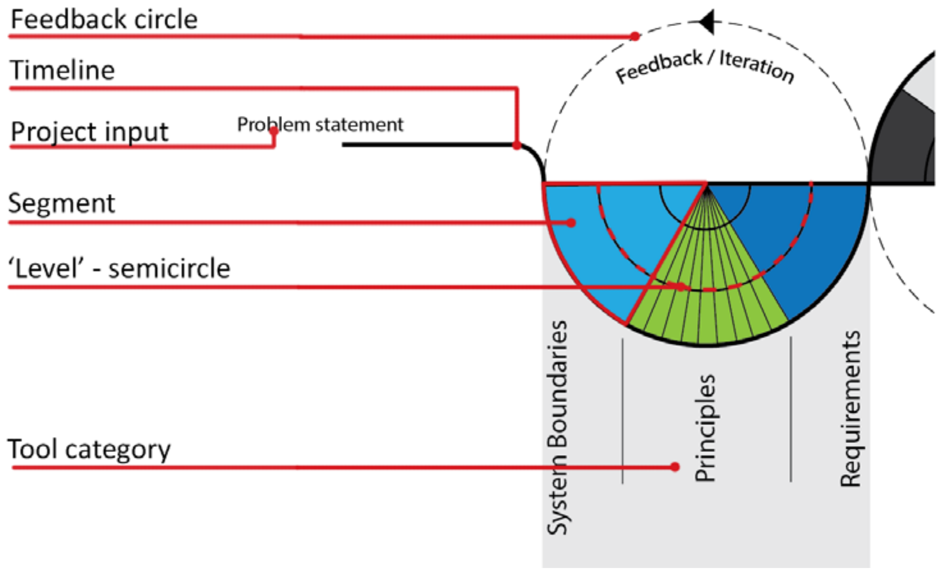


Figure 26. Visual elements of a design phase circle

Just underneath the timeline a short description explains the activities that should be done and the in- and outputs of each phase. See Figure 27.

In the middle are two examples presented. Shown in Figure 28. The examples follow the design process and describe the basic idea or activity for each phase. The images are supported with explanatory text. One example presents the case of the Shinkansen bullet train from Japan. Which is an example related to transportation. The second example presents the case of 30 st Mary Axe, a tall building in London. This is a civil engineering example.

As said before, the tool categories are written next to the circles. These categories, and the tools they contain, are listed at the bottom of the framework. See Figure 29. All tool categories possibly required within a phase, are presented in the column of that phase. Thus, it is not needed to gather tools from other columns. This does, however, result in categories that are listed double. For example; the category of Principles.

At last, the framework fades on the right side. If projects are successful, implementation will follow the design process. Thus, this design process is a beginning and is followed up by additional phases. Those were out of scope of this research.

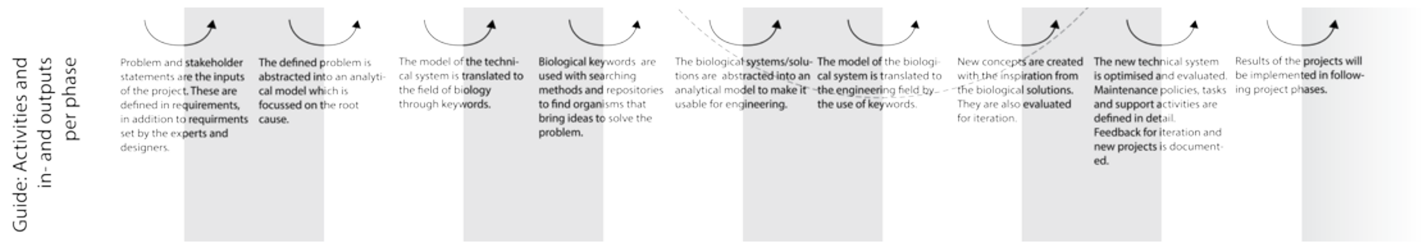


Figure 27. Framework poster: Activities and in- and outputs per phase.

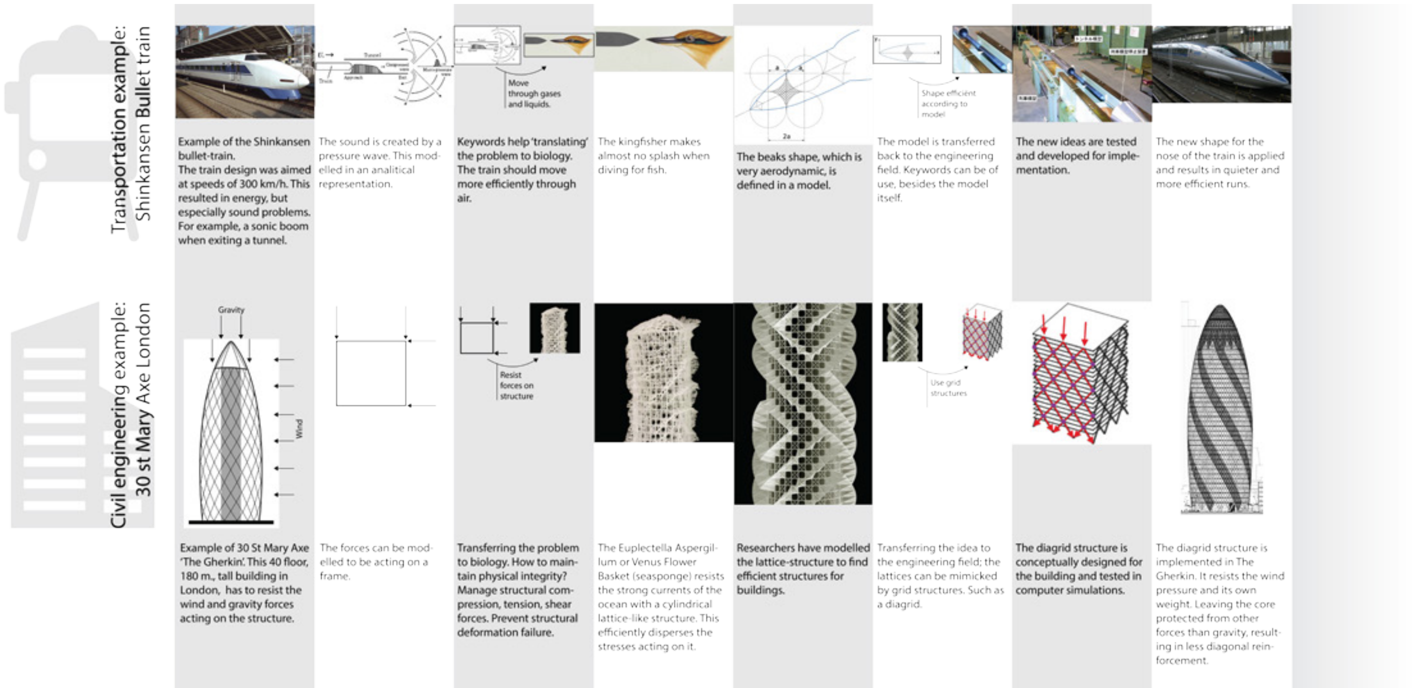


Figure 28. Framework poster: Examples of biomimicry projects related to the framework.

Biomimicry & Maintenance tools per category and project phase

System Boundaries
-System boundary definition

Principles
-16 patterns of nature
-Catalogue of biological principles
-The ten fundamental principles of biological systems
-Bioniquity
-Transfer checklist of biological association
-Nature-inspired design principles
-Life's Principles
-Nature-inspired solutions
-Ontology of biomimetics

Requirements
-Requirements definition

Modelling
-Functional Modelling
-Systematic reverse engineering of biological system
-SAPPhIRE
-Functional modelling
-DANE

Keywords
-Natural language analysis
-Biologically meaningful keywords
-Biomimicry Taxonomy
-Categorisation of natural language keywords
-Engineering-to-biology thesaurus
-BiOPS
-Automatically populating the Biomimicry Taxonomy for scalable systematic biologically inspired design
-Automatic extraction of causally related functions from natural-language text for biomimimetic design
-Bioscrabble
-Structure-Function Patterns

Principles
-16 patterns of nature
-Catalogue of biological principles
-The ten fundamental principles of biological systems
-Bioniquity
-Transfer checklist of biological association
-Nature-inspired design principles
-Life's Principles
-Nature-inspired solutions
-Ontology of biomimetics

Subsystem requirements
-Subsystem requirements definition

Solution searching methods
-BidLab search tool
-Idea-Inspire
-BioTRIZ
-A computational approach to biologically inspired design

Repositories
-A systematic catalogue for biomimetic design
-Ontology for bioinspired design
-AskNature
-Biologue
-Bionicinspiration.org
-Ontology explorer
-Design Study Library

Modelling
-Functional Modelling
-Systematic reverse engineering of biological system
-SAPPhIRE
-Functional modelling
-DANE

Keywords
-Natural language analysis
-Biologically meaningful keywords
-Biomimicry Taxonomy
-Categorisation of natural language keywords
-Engineering-to-biology thesaurus
-BiOPS
-Automatically populating the Biomimicry Taxonomy for scalable systematic biologically inspired design
-Automatic extraction of causally related functions from natural-language text for biomimimetic design
-Bioscrabble
-Structure-Function Patterns

Concept creation
-CPS framework for maintenance problem solving

Concept analysis
-Functional block diagram
-Failure mode and maintenance analysis (light) (FMMA)
-Failure mode and effect analysis (light) (FMEA)
-Hazard and operability analysis (light) (HAZOP)

Concept evaluation
-Concept evaluation matrix

Evaluation
-T-chart
-BioP-C
-Biotransferability framework
-Four-Box method

Principles
-16 patterns of nature
-Catalogue of biological principles
-The ten fundamental principles of biological systems
-Bioniquity
-Transfer checklist of biological association
-Nature-inspired design principles
-Life's Principles
-Nature-inspired solutions
-Ontology of biomimetics

Feedback
-Systematic quantative equip. evaluation
-Design Review
-Data feedback system

Detail evaluation

Policy creation
-Select support structures
-Logic tree analysis (LTA)
-Maintenance task selection
-Select solutions
-Create detailed protocols

Detail analysis
-Parameter profile matrix
-Failure mode and effect analysis (full) (FMEA)
-Failure mode and maintenance analysis (full) (FMMA)
-Hazard and operability analysis (full) (HAZOP)
-Parameter profile analysis
-Resource allocation table
-Root cause failure analysis
-Criticality analysis
-Comparative reliability analysis
-Design constraints and most reliable solutions
-Equal strength (weakest link) principle
-Check list
-Fault tree analysis (FTA)

Figure 29. Framework poster: Biomimicry and maintenance tools categorised and divided over the design phases.

Chapter 5: Case

To test the value of the framework explained in the previous chapter a comparison must be made. The comparison includes the results of a real case project and the results of the same project at which the framework is applied. The comparison will show if working with biomimicry and a structured guide is beneficial for design for maintenance projects.

The comparison

To test the value of the framework a comparison is made between the results of a case executed by Arcadis as a regular project and the results of the same case with the application of the framework. See Figure 30. The case is a research project of Arcadis on the investment opportunities of old buildings. The project is a construction technical research to the current state of the buildings. The maintenance-requiring interior and exterior parts of the building and mechanical and electrical installations have been reviewed. In the resulting report written by Arcadis, the results of this condition measurement are presented and translated to improvement measures. This research is slimmed down and is used to create a case. This case is used in the workshop where the framework is applied. During the workshop, new improvement measures are developed. These are compared with the measures developed by Arcadis, showing the difference in results. The report written by Arcadis is confidential and cannot be added to this thesis report. However, the details are discussed in the following sections and the case presentation is available in appendix F.

The case

The case revolves about renovative investment possibilities of a housing corporation for 8 apartment buildings. Shown in Figure 32. The complexes are built just after 1950. The housing corporation has asked Arcadis to do research on the building quality of these flats. In this research, the buildings are assessed on structural quality, comfort for inhabitants and sustainability and several other points of interest. The results are input for a proposal of investment measures. Four scenarios were created to propose measures for short and long-term situations. The measures incorporate the building quality, budget of the housing corporation, sustainability, quality of life and return on investment terms. An example of an investment measure is the replacement of central heating systems. The costs of each scenario are calculated and presented in the report.

As mentioned, the workshop a slimmed down version of the case is discussed. This consideration is made since the workshop could only last for 2,5 hours. This has been decided based on the availability of participants that would join the workshop.
The original case discussed three types of buildings, which are reduced to one. This simplification reduced the amount

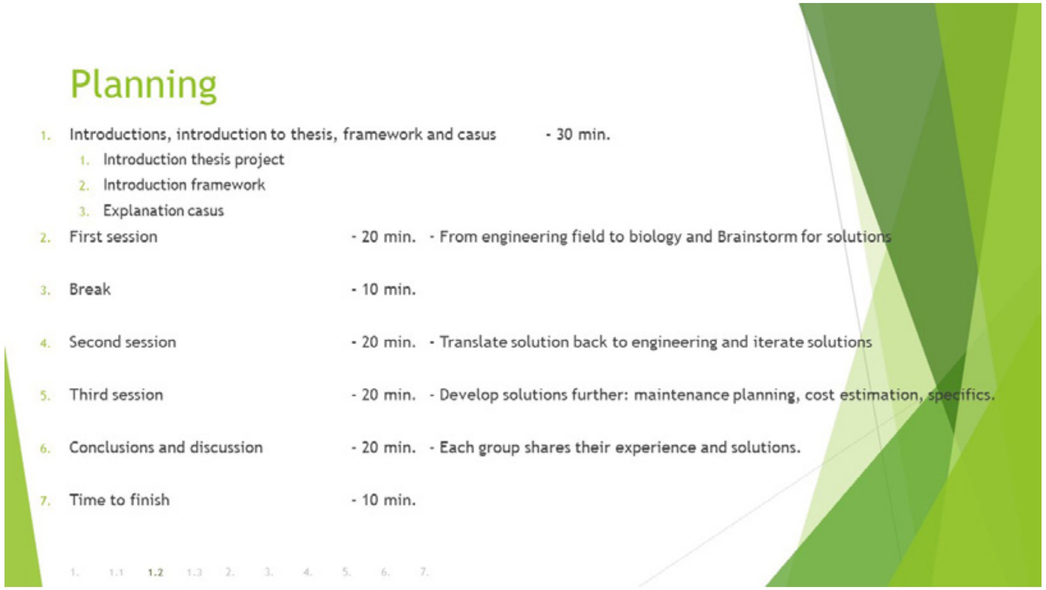


Figure 31. Planning of the workshop

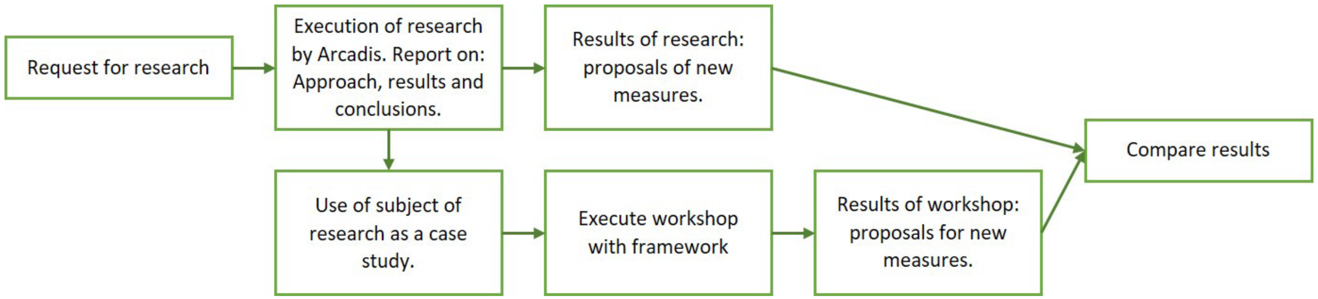


Figure 30. Information flow of the case; comparing results of a regular project with the results of the workshop

of details and explanation, without affecting the goal of the case. The results and problems found in the research by Arcadis are consequently reduced. Only ventilation and insulation are indicated as major problems, which should be discussed in the workshop. Other problems, such as polluted waste systems, are neglected to reduce the time needed to come up with solutions. Finally, to reduce the time needed for explanation even more, the results of the research and characteristics of the buildings are summarized and presented as a list of statements.

The workshop

The workshop is guided by a presentation; it consists of all steps to take throughout the workshop. The presentation, including all information presented during the workshop can be found in appendix F. The planning of the workshop is shown in Figure 31. The thesis project is explained after the introductions of the participants. Followed by an introduction on the framework and the explanation of the case itself. After these introductory parts, the workshop is set up to have three sessions, explained and guided by the presentation. In the first session, the project phases of: Transpose to biology and Discover solutions, are worked on. In the second session the phases of: Abstract biological strategies and Transpose to engineering, are worked on. As third session, the phases Conceptual engineering and Detail engineering are planned. The phases of: Context and requirements definition and Abstract the problem are already prepared in advance and presented in the presentation. During the sessions, the participants are split in two groups, one of three and one of four persons with various fields of knowledge. Each group discussed one problem; either ventilation or insulation.

Figure 32. Apartment buildings, subject of the case.

Execution of the workshop

Since the workshop did not progress as planned, the differences with the planning will be discussed here.
The workshop was planned to start with half an hour of introductions followed by three sessions of twenty minutes. As a result of intermediate question rounds and ensuring the case was clear for all participants, the introductory part of the presentation took one hour. By the start of the first session it appeared that the premade models of the problems were not sufficient in detail. Therefore, it was agreed upon that the models would be reconsidered by each group during the first session. Since there was some time pressure and the groups were in a flow it was decided to let the sessions go and explain personally what the next steps were. The framework and especially the presentation in the background provided information on what these steps included. This resulted in a long brainstorm session of one hour. As expected the results of the brainstorm were not as detailed as aimed for, however, this was also not to be expected because of the time constraint. The final half hour of the workshop was used for feedback on the framework, reaction on the workshop and presentations of the new ideas of the groups. This is all presented in the following section.

Results of the workshop

During the workshop, each group is working on flip overs to write down and track their ideas. The sheets are shown in Figure 33 and Figure 34. These results are also aligned with the framework, shown in Figure 35. Both groups first redefine the problem. Followed by the search for solutions in a quick brainstorm with the help of biology books and the internet. Then the solutions are modelled and some are even transposed to engineering.

The ventilation group tried to find the essential function that the solution must perform. They do that by drawing up questions to nature with different levels of detail. The insulation group puts their main question in front, but they also define more detailed functions.

Both groups are enthusiastic during solution discovery and multiple ideas are coming up.

Some ideas are then abstracted to be used in the following phases. However, in the drawings nature still seems to play a role. The abstraction is not yet analytical and therefore difficult to imagine engineering solutions without thinking about the biological manner of implementation.

The Transpose to engineering phase was not entirely executed as prescribed. This is assumed to be a result of time pressure. However, a couple solution proposals are made. They are described as an answer to a 'how to' question. The proposed solutions are the shown underneath the flipover sheets.

To be able to compare these solutions with the solutions from the project that Arcadis executed, the solutions are developed towards an engineering concept. Then the concepts are compared with the measures that Arcadis proposed in their project report.

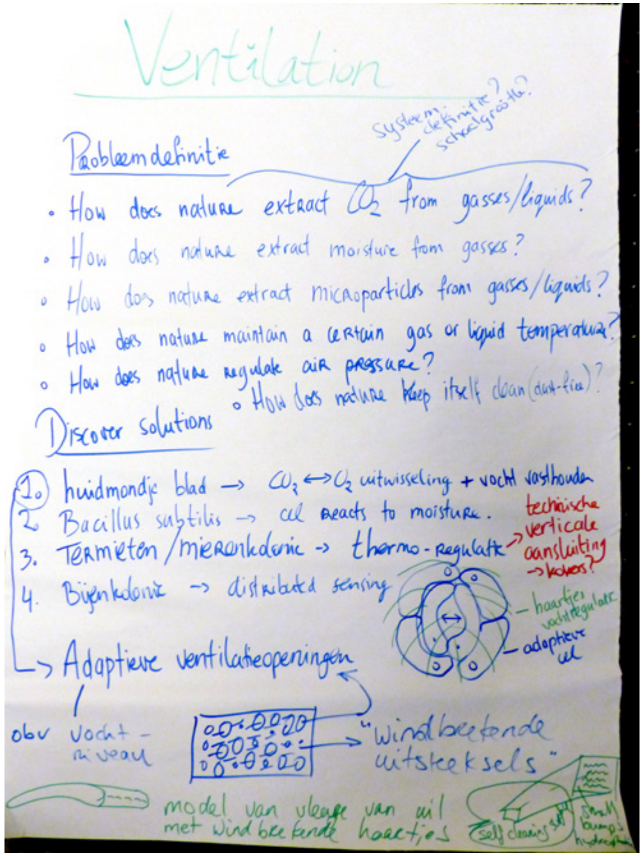


Figure 33. Flipover of team ventilation.

For ventilation:

1. Adaptive ventilation openings based on moisture level
2. Airflow breaking projections
3. Hydrophobic self-cleaning bumps
4. Distributed airflow mechanism.

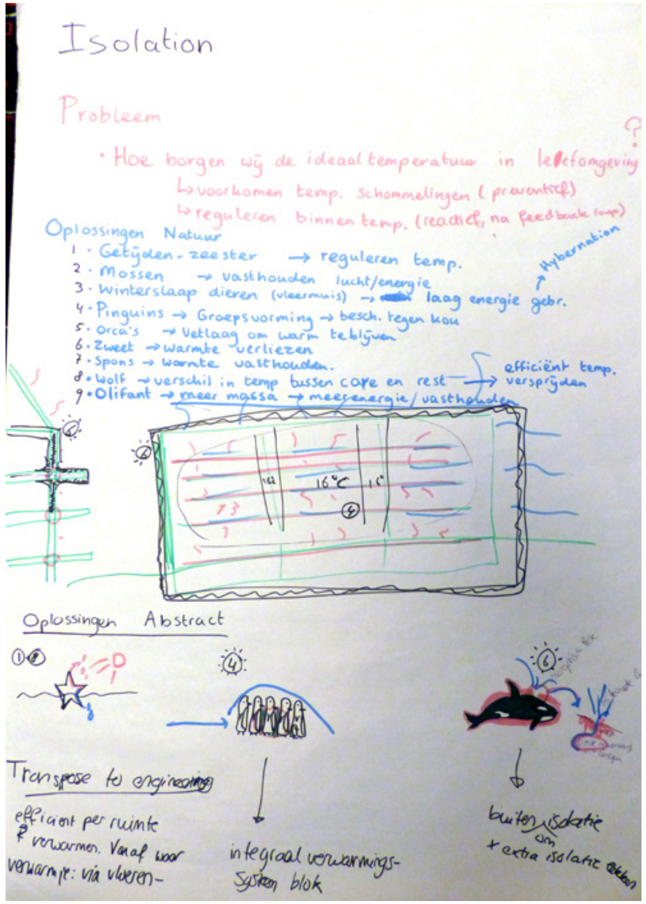
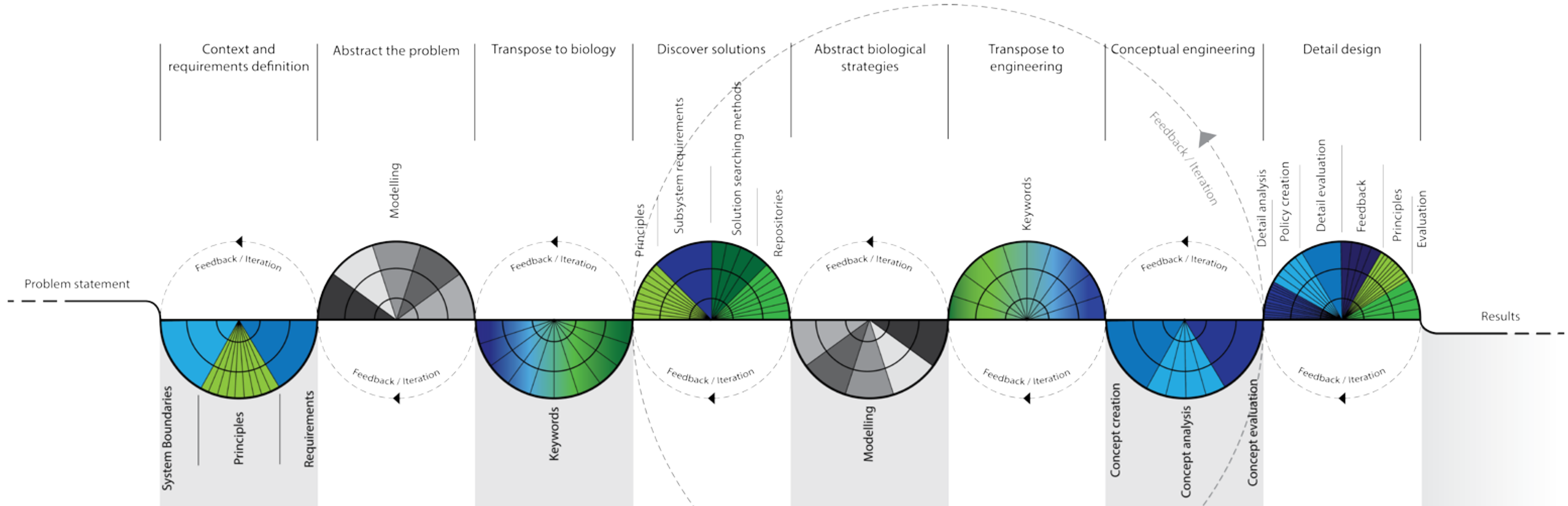


Figure 34. Flipover sheet of team insulation.

For insulation:

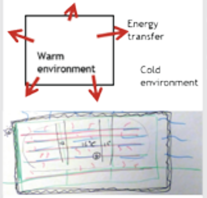
5. Efficient per space heating, consider heating location, e.g. in rooms via underfloor heating (warm air rises)
6. Integral heating system block
7. Outside insulation + additional insulation for energy leaks.



Case progress: Insulation

Redefined problem
- How do we secure the ideal temperature in living spaces?

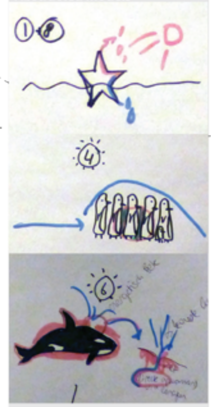
Model of problem



Functions
- Prevent temp. fluctuations (preventive).
- Regulate inside temp. (reactive, after feedback loop).

Solutions from nature
1. Tides-starfish -> regulate temp.
2. Moss -> hold air/energy
3. Hibernating animals (bats) -> low energy use.
4. Pinguins -> forming groups -> shield against cold.
5. Killer whale -> Layer of fat to stay warm.
6. Sweat -> lose heat.
7. Sponge -> hold heat.
8. Wolf -> difference in temp. between core and rest -> efficient temp. use.
9. Elephant -> more mass -> hold more energy.

Abstracted models



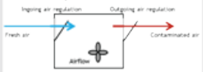
Transpose to engineering
- Efficient heating per room, heat source location.
- Integral heating system block.
- Insulation around the outside.
- Insulate more around energy leaks.

Concepts
-Insulate entire building with ISPO, and the roof.
- Insulate walls against storage rooms.
- Floor heating in balcony segment inside the house.
- Heating systems on lower floors.
- Concentrate heated rooms together.
- Heated inflow ventilation ports.

Case progress: Ventilation

Problem
- How do we secure the ideal temperature in living spaces?

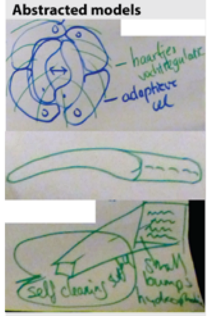
Model of problem



Functions
How does nature:
-extract CO2 from gasses/liquids?
- extract moisture from gasses?
-extract microparticles from gasses/liquids?
-maintain a certain gas or liquid temperature?
-regulate air pressure?
-keep itself clean (dust-free)?

Solutions from nature
1. Leaf stoma -> CO2-O2 exchange + hold moisture.
2. Bacillus subtilis ->cel reacts to moisture.
3. Termite/ant colonies -> thermo regulation.
4. Bee colony ->distributed sensing
5. Owl feathers -> silent airflow.
6. Lotus leaf -> self cleaning hydrophobic surface

Abstracted models



Transpose to engineering
- Adaptive ventilation opening.
- Smaill 'hairs' that break wind to keep ventilation silent.
- Self cleaning surface with smaill hydrophobic bumps.
- Integrated system through distributed sensing.

Concepts
- (Moisture) adaptive, self-cleaning, noise reductive ventilation ports, working as a distributed ventilation system.

Figure 35. Case results aligned to the frameworks' design phases

Further development of solutions

The presentation of the case study included the first two phases of the framework; Context and requirements definition and Abstract the problem. During the case, the definition and abstracted model were reconsidered and developed in the further phases: Transpose to biology, Discover solutions, Abstract biological strategies and Transpose to engineering. To be able to compare solutions the ideas that are transposed to engineering should be developed to concepts. The ideas created by transposing to engineering and the discussions during the workshop are input for the development of the concepts. These concepts are created through a short personal brainstorm, predicting implementations of the ideas. Essentially, performing the Conceptual engineering phase.

Ventilation

The ideas from the ventilation group are all focused on a new ventilation port; which should improve the airflow through a house by an adaptive ventilation system while keeping a high level of comfort. The system consists of ventilation ports that connect each room to create sufficient airflow. However, each port will adapt to environmental conditions to prevent uncomfortable airflow speeds and improve ventilation when needed, e.g. while showering.
Each ventilation port would react differently dependent on the place it is installed in. For example, the bathroom port will open when a high moisture level is achieved, but the window port will close if strong winds create an uncomfortable airflow in the house. Materials that react to their environment are already around, e.g. thermobimetals [82] [83] and moisture reactive material [84] [83].
To rule out draught it is necessary to have a connected system, a distributed airflow mechanism. All ventilation ports communicate with each other to prevent draught by a situation that they are all open. Current home automation systems already apply such ideas.
Projections to break airflow would attract more dirt and will have to be developed together with a hydrophobic self-cleaning material. Both ideas have already existing examples; self-cleaning paint [85] and silencing owl-feathers [86]. If these could be combined a self-cleaning and silent ventilation port can be made.
By reengineering all ideas to fit in one solution a new generation of ventilation ports could be created and refitted to housing complexes.

Insulation

The group working on insulation presents three strategies to work with. The first idea, efficient per space heating, considering heating location; focusses on the right placement of heating systems. Since warm air will rise, use heating systems in the floors instead of ceilings. When this is applied to the housing complex, it could be said that the heating systems should be on the lowest floors. Heating the upper floors by convection.
An integral heating block could be created by concentrating the separate heated parts into one block. One could say this idea has already been implemented by concentrating multiple houses into one large complex, where rooms and houses are minimized of external surface area, reducing heat loss. Within an apartment or groups of apartments it is possible to concentrate heated rooms near each other.
The third idea proposes a layer of insulation on the outside edges of a structure. Such application can already be recognized in the applied ISPO insulation system at the west-side of the buildings. Insulated balconies, to prevent a thermal bridge through the concrete, are currently implemented in many forms. However, to close the insulation barrier around the building it is necessary to insulate the roof and outside walls. The roof could be done from the inside between the wooden structure. The other three outside walls can be insulated from the outside with the ISPO system.
Lastly, energy leaks should be dealt with on the spot. E.g.: ventilation leaks, fresh cold air should be warmed up while entering the building. Heated inflow ventilation ports. Floor heating to stop the thermal bridge of balconies. Or walls between living rooms and storage rooms can be insulated preventing energy leakage through rooms that are kept cold.

Comparison of new measures with measures from the regular process

The regular project presents solutions for four scenarios: Preservation; preservation and improving sustainability; light renovation; and high-quality renovations. For each is an investment term considered, respectively: 3, 10, 25 and 25+ years.
The ventilation and insulation solutions require an investment in new installations or insulation systems (in this case: a system is a complete solution, which could exist of multiple elements) and in working hours for the implementation. These solutions require applications in scenarios where only improvement of sustainability and disturbance of occupants are allowed. This would not fit in short term scenario's and therefore only applied for the scenarios of 10, 25 and 25+ years.
Table 2 and Table 3 present the measures from the regular process next to the new solutions. The measures from the regular process are selected to be related to insulation and ventilation and they are summarized to show the

improvement for each scenario. The new solutions are put next to the regular measures that are most alike.
For the ventilation system it can be said that the new solution is an upgraded natural ventilation system. It can be implemented by replacing all existing ventilation grates. This amount of work is comparable to the regular 25-year scenario. The most straightforward new solution for the insulation case is to insulate the entire building. This is also given as one of the first solutions through the regular process. More rigorous and precise insulation, thus insulating more and more detailed, is done in the 25-year investment term. The insulation of storage rooms is therefore considered a solution for the 25-year scenario. For more extensive renovations it is possible to add floor heating, as stated in the research report of Arcadis. This is also an idea from the workshop, with the specific idea to stop the thermal bridge of the balcony. Therefore, this solution is placed in the 25+-year investment term. The 25+-year investment term gives also the possibility for more elaborate and rigorous solutions. Such as replacing heating systems and restructuring the houses, which is required for the other new solutions found.
The new solutions found during the workshop are related to 'standard' measures. In such a way that they are not completely new approaches to ventilation or insulation. They also propose the 'standard' insulation and ventilation improvements; insulate all outside walls and improve airflow by a new ventilation system. However, in addition to the 'standard' contribution of the workshop ideas, they do present some out-of-the-box ideas (self-cleaning, noise reductive ventilation ports). These ideas seem to go into a bit more detail and present new functions that can be applied. On the other hand, some solutions resulted from a view that the whole complex is a system, where individual elements (houses) can work together in a solution, e.g. heating systems on lower floors and concentrate heated rooms together.

Ventilation		
Investment term	*Measure from regular process*	*New idea*
10 yr	Add fixed ventilation by air intake grates in window frames and air outtake by mechanical extraction.	
25 yr	Window frames are replaced with windows with more ventilation grates. Add fixed ventilation by air intake grates in window frames and air outtake by mechanical extraction.	Adaptive, self-cleaning, noise reductive ventilation ports, working as a distributed ventilation system.
25+ yr	Window frames are replaced with windows with more ventilation grates. Add fixed ventilation by air intake grates in window frames and air outtake by mechanical extraction. In the bathroom can be chosen to add mechanical intake as well.	

Table 2. Ventilation: results comparison between regular process and workshop.

Insulation		
Investment term	*Measure from regular process*	*New idea*
10 yr	The flats, which are not insulated yet, will be insulated on the outside with the ISPO system. The inside can be insulated with panels. The roof should be insulated at the same time. This is done from the inside with panels.	Insulate the entire building (ISPO) and roof.
25 yr	The flats, which are not insulated yet, will be insulated on the outside with the ISPO system. The inside can be insulated with panels. The roof should be insulated at the same time. This is done by stripping the roof to the roof purlins, where new insulated roof panels are placed. The windows will be replaced with HR++ glass.	Insulate walls against storage rooms.
25+ yr	The ground and upper floors are renovated including insulation and possible floor heating. All facades will be insulated, either from the outside or inside. All windows are replaced with HR++ glass. The whole roof will be renewed with an insulated roof. The thermal bridge of the balcony must be insulated.	Floor heating in balcony-segment inside the house. Heating systems on lower floors. Concentrate heated rooms together. Heated inflow ventilation ports.

Table 3. Insulation: results comparison between regular process and workshop.

Feedback on the workshop and framework

At the end of the workshop participants could discuss the framework and the results of the workshop. Some small remarks are written down on the print-outs of the framework. The feedback covers some subjects around the framework which are discussed in this section.

The first remark is focussed on the activities that are performed during the workshop and the importance of proper execution of each phase. It should be mentioned that throughout the process a holistic view should be kept, while certain parts must be defined in detail. Specifically, during the phases of problem statement and analysis, which should result in the requirements for the solution. Analysis should involve defined physical, economical and time characteristics. This is essential for and influences the choices that will be made and the different ideas that will be identified during the process. In the Transpose phases is it important to define the functions as specific as possible. This may require multiple iterations.
It must also be recognized that time is important. To properly execute each phase enough time should be planned for it. Focussing on the problem definition, researching the organism and abstracting, an extensive analysis will eventually this will pay off in solution finding and save costly time during that process. As well a better modelled problem will make the essence clear and therefore the solutions that are searched for will better fit to this problem.

The second point is the question of who will work with the framework? Is the framework useful for people from the biomimicry field or the maintenance field? The consensus was that the framework would be most useful for people from the field of maintenance or engineering. It will add biomimicry to their solution sources. In the case of the workshop the process was very close to the biomimicry methodology. Besides basic engineering tools used in biomimicry, specific maintenance tools did not play a part in the workshop. The workshop was therefore an application of biomimicry to a case. To include the engineering side of the framework, a case must be executed in more detail where there is time to use maintenance tools next to the biomimicry methodology.
To make the new combination of maintenance with biomimicry it is necessary to merge the fields in a certain method that is accessible to both fields. An improvement upon the framework could be tools that integrate both fields as well. Then a combination is made on different levels of organisation.

A third point is the added value of the framework when applied in a business environment. The research project, where the case is based on, is assumed to follow a generic design process. Essentially performing a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis with problem statement and solution process. The results are based on expert judgement with consultation of a standard list of measures. With the goal to solve problems on the short term and secure it for the long term.
With the framework (or biomimicry), the problem is being looked at in a different way, through a different process. This will result in different solutions. If a solution is developed, then the next step is for an expert to define what is required to implement the new measures in a building. Thus, also with the framework, expert judgement is still required to apply the solutions. The framework or biomimicry are therefore additions to the current design tools, and experts with experience are still required.
The framework and the process of biomimicry require people of different fields together to work on the same project. Not only engineering and biology, but also people who are involved in the field of the problem should have a place at the table to bring their knowledge.
Since the framework can be used flexible, many fields could benefit from it. Example given: civil engineering, mechanical engineering, maintenance engineering, industrial design engineering, system engineering, biology and ecology. However, a minimum would be experts related to the fields of ecology, maintenance, design and someone related to the domain of the project.

The last remark revolves around the implementation and use of new perspectives or process sequences. It is important to let people use their current working process and pull them out sometimes to add new things, instead of teaching them a complete new process. People can stay in their natural workflow, while getting extra input from other methods. For the framework would it be beneficial if it is an addition to current work processes. Building upon a maintenance oriented process, where biomimicry can be applied during that process.

Conclusions of the workshop

Since the workshop was mainly based on a biomimicry methodology makes that the results generated during the workshop only reflect on the application of biomimicry and not the combination of maintenance and biomimicry or the framework itself.
The diversity of solutions found during the workshop implies that the biomimicry methodology delivers the regular ideas and innovative, alternative ideas as well. It could be said that the biomimicry methodology would be an addition to the regular method of working. The timeframe of the workshop was too small to apply as an implemented procedure. It is expected that the application of proposed tools with a suitable timeframe would generate more applicable results as well as a more thorough analysis.

The application of biomimicry has showed to spark enthusiasm by the exploration of the natural world and discovery of possible ideas to work with. This helps with finding many ideas and may be an alternative to regular brainstorm sessions.
Because biomimicry and the framework work on the edge of field of knowledge it is a must to have knowledge of different fields available during the workshops. This includes, of course, biological/ecological knowledge and knowledge of engineering fields, but also specific knowledge related to the subjects that is worked on. For example, in the case of the workshop in this research, knowledge on buildings, constructions and thermodynamics is essential information to create valid solutions.
The feedback gathered during the workshop proposes some improvements for the framework. The importance of analysis and feedback during the process is not emphasized in the framework. It could be improved by the creation of two phases dedicated to these activities. This also applies to the amount of detail or holistic view required during the process.
The framework is targeted for use by people from an engineering field, as an addition to their current solutions sources. However, it is still necessary to involve experts from all fields involved in a problem case.
The added value from the framework for Arcadis is another way of looking at a problem. A different tool to be used by experts next to their standard list of measures.
At last, the framework should add new possibilities to a current work process. Preferably by pulling people out of their regular work process for short moments. Therefore, it is best to view the framework as engineering workflow with the addition of biomimicry.

Discussion

The results of this research will be reflected on in this discussion. The field of design for maintenance is in an early development phase. Only few design for maintenance processes available in literature. Most of these processes or methodologies are based on system engineering and include only little of industrial design models and practices. Example given: iterations. On the tool level, most tools brought in relation with design for maintenance are coming from other maintenance related fields, lacking tools that improve design principles and skills, for example: creativity.

The biomimicry methodology can be adopted to fit within the maintenance field. However, to not lose its functionality the translation steps, that are essential for a biomimicry process, must be included. The framework created in this research is largely based on the biomimicry or biomimetic design models. To fit better in the field of maintenance engineering, the framework could support the development of essential maintenance specific processes by incorporating those in the framework. Example given: development of maintenance policies or concepts or include more specific maintenance performance parameters throughout the framework. On the other hand, does a framework as presented in this research allow for differentiation in projects and the freedom to choose an individual way through the design process. The selected tools form the foundation of the process and the framework guides the user through the steps.

The workshop showed that the phases of problem definition and feedback are important and could receive more attention by improving the framework. The results of the workshop also suggest that the framework mainly based on the biomimicry process and the maintenance engineering influence is only available through the tools used. The workshop also shows that the framework, or biomimicry approach, could be introduced as an addition to the regular way of working based on experience and standardized lists; new design methods could structurally add creativity to the current design process.

The interviews suggest that biomimicry is currently only used by very few people within the company. An example for the creation of support for implementation of biomimicry is Natural Capital. The Natural Capital method sets an example to follow and shows that developments as frameworks and exemplary cases are helping the improvement of the method. To achieve success in implementing biomimicry make the start by creating examples and business cases that show the functionality of the methodology.

Conclusions

The conclusions of this research project will be linked to on the research aim and the research questions that were posed at the start of this project. Starting with the research aim.

The research aim was to design a new system to help early in the process of a design task engineers and designers in creating bio-inspired solutions without demanding extensive resources.
This research aim has been partially fulfilled, the developed framework has shown in the workshop some potential in guiding the design process. It set the general approach for a design project and it therefore arranged how engineers and designers create solutions. However, it cannot be said that the framework is an entirely new system. Reactions during the workshop pointed out that it still follows the biomimicry design process. Its added value, however, comes from the categorisation of the tools. The categorisation of tools, the division over the project phases and coupling of the project phases seem to be helpful, but this value is still not fully proven by the workshop. It has incorporated the biomimicry process, but there is no check if this will be fruitful. In practice, the process could be executed in a very quick manner, probing the usability of the model. It can be concluded that this process would require a relatively substantial amount of resources. The 2,5-hour workshop was enough to go through only four phases with the use of a minimal number of tools in minimal detail. In practice, this could be applicable in large projects, but there is room for a more condensed approach.

Continuing with the conclusions on the research questions. Through the approach of this research, with limited maintenance resources reviewed, no existing design for maintenance model was available in literature that could be applied as a design model. Most importantly, because they did not follow typical design process phases. However, two remarkable design models (Thompson and Smit) for maintenance engineering have been discussed. These design models could not directly be matched with biomimicry or design processes; therefore, they were included as tools in the new framework.
The biomimicry methodology is built on three pillars: ethos, reconnection and emulation. The emulation part is the ‘useful’ part, considering the goal is to find solutions to problems. As already mentioned, emulation consists of three essential steps:

1. Modelling and translating the problem to the field of biology.
2. Discovering nature to find solutions.
3. Modelling and transferring the solution back to engineering.

The biomimicry or relatable biomimetic process is combined with the system engineering process to form a biomimicry and design-for-engineering process. This process is the basis of the framework and has the following phases:

- Context and requirements definition
- Abstract the problem
- Transpose to biology
- Discover solutions
- Abstract biological strategies
- Transpose to engineering
- Conceptual engineering
- Detail design.

The addition of maintenance is represented in the maintenance tools that are categorised and divided over the design phases.

The biomimicry tools proposed to use in the framework come from an extensive literature research, which is compared with tools from other studies to check for its completeness. The tools mentioned in the framework encompass the most relevant tools available now. However, due to new developments a list of tools could never be complete. The biomimicry tools cover a whole range of functions, example given; requirement setting, develop a repository of solutions, help transposing by creating models and finding its functions.
All design for maintenance tools are gathered from articles and the books of Thompson and Smit. The tools functions are, amongst others: performance analysis, evaluations, requirements setting and maintenance policy development. Also, these tools are categorised and divided over the project phases.
The framework can be used in practice during projects that require new solutions to be developed. It can be a standalone methodology, but it is also useful as extension of existing practice. For implementation of new ways of working the latter is even preferred. Specific use of the methodology is dependent on the project. The framework guides the general process and proposes tools that can be used during a design phase. The tools itself are the content, through them the targeted results of the project are achieved and they can be chosen to suit the project as best as possible. It is shown that the biomimicry process that is followed during execution of this framework creates enthusiasm during the Solution finding phase.

Recommendations

Recommendations for Arcadis can be derived from this research to improve implementation of the framework in practice.
There is a basis of support available within Arcadis for implementation of the framework and the practice of biomimicry. These people are working at different levels in the company, e.g.: designer, consultant, program manager and business development. This group has the power to influence and create a course for the implementation of biomimicry practice. As individuals, it is possible to create awareness of the subject and projects can be steered towards the use of biomimicry. To establish biomimicry within Arcadis cases should be developed to show the value of biomimicry. Moreover, the creation of a workflow, e.g. the framework, that is easily incorporated in current practice will help. The last important part of the foundation is gathering available information to create one knowledge base. These developments are only achievable with people from different fields. Therefore, it is recommended to collaborate with organisations as BiomimicryNL and educational institutes.

When using the framework people with related knowledge should be available. For use of biomimicry it is required to have someone that knows the process and is able to guide the sessions. Furthermore, a biologist or ecologist are essential for the ideas and the right engineers are required for development.
Use the phases of the framework to guide the design process. However, select the tools that suit the project and the processes of Arcadis, the collection presented can be extended with tools from other fields of engineering. The value of the framework and the tools is the addition of a new point of view towards a design project. The tools support the development of new ideas, help to analyse and evaluate. Consider the framework as an extra tool for innovative ideas that can be extended in the future towards a methodology for sustainable design on a day-to-day basis.

Recommendations for Arcadis

The research topics to address in the future for improving the developed methodology are discussed here.
The proposed framework is only tested through a qualitative experiment; using a workshop for analysing its readiness level to propose innovative solution adopting biomimicry approaches. Thus, the feedback and other results gathered during this research suggest considering it obviously not as an arrival point, but rather as a starting point for combining two very different domains. It is therefore recommended that in further researches the scope is limited to create a study with higher level of detail in a longer time span.
To more tightly integrate design for maintenance with biomimicry the current framework can be improved by adding maintenance specific phases. The biomimicry phases will then be surrounded by phases that specifically contribute to maintenance work. Moreover, a clear choice must be made to develop a new phase or a new tool that can be used. Examples of maintenance related design and management: designing the policies, planning, actions, spare parts logistics structure and concepts. As mentioned, tools can be developed to be flexible blocks that can be chosen to use in a design project. New tools that further integrate design for maintenance and biomimicry, for example in specific problems, could be useful for merging the design practice with the maintenance engineering practice.
A subject that has been excluded from the research, because of narrowing the scope, is the development of design for maintenance solutions with biomimicry focussed on improving the wellness of people. The use of natural solutions and effects of natural environment in workplaces could improve the efficiency of employees. In combination with psychology studies this is an interesting subject to develop further.

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List of Figures

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List of Tables

Appendix A

Tool nr:	1
Tool:	Design Review
Design Phase:	Several – See report
Level of Design:	Several – See report
Description:	The design review may be defined as: *the quantitative and qualitative examination of a proposed design to ensure that it is safe and has optimum performance with respect to maintainability, reliability and those performance variables needed to specify the equipment.* Try to incorporate all factors, however, some are not known yet, therefore, the focus is on reliability and maintainability. Variables that specify equipment and performance are different for every product or system. The role of the design review with respect to safety should be to formally record the fact that the appropriate internal and external authorities have been satisfied, that environmental impact factors have been considered and that the necessary safety standards have been adhered to
Source:	Book; Improving maintainability and reliability through design; Graham Thompson; [13]

Tool nr:	2
Tool:	Check list
Design Phase:	Equipment evaluation. Detailed checklist not suitable for concept design evaluation.
Level of Design:	Equipment evaluation
Description:	– Simple: Yes/no – Rated: 1-5
Source:	Book; Improving maintainability and reliability through design; Graham Thompson

Tool nr:	3
Tool:	Comparative reliability analysis
Design Phase:	Equipment evaluation
Level of Design:	Equipment evaluation
Description:	Reliability modelling may be used to compare two or more items of equipment.
Source:	Book; Improving maintainability and reliability through design; Graham Thompson

Tool nr:	4
Tool:	Concept evaluation matrix – Paired comparison
Design Phase:	Concept evaluation
Level of Design:	Equipment evaluation
Description:	Comparison matrix with +, - and S ratings, which are counted for every concept.
Source:	Book; Improving maintainability and reliability through design; Graham Thompson

Tool nr:	5
Tool:	Systematic quantitative equipment evaluation - Performance index calculation - DPI
Design Phase:	Not for Concept evaluation, thus detailed evaluation.
Level of Design:	Equipment evaluation
Description:	Assessment criteria, measurement and value. Define assessment criteria. Set value judgements. Determine the relative importance of criteria Performance prediction Convert the performances to value scores. Overall value. Additional stuff for equipment handling fluids.

Source:	Book; Improving maintainability and reliability through design; Graham Thompson

Tool nr:	6
Tool:	Parameter profile matrix
Design Phase:	Detail evaluation – intended for use in schematic design when systems are synthesized using propriety equipment.
Level of Design:	System evaluation (Equipment evaluation, minisystem)
Description:	Identifies potential causes of poor reliability - …can be used effectively to collate and analyse system data to reveal the weak areas of design proposals where problems may be found in service.
Source:	Book; Improving maintainability and reliability through design; Graham Thompson

Tool nr:	7
Tool:	Failure mode and maintenance analysis (FMMA)
Design Phase:	Concept design, detail design and condition monitoring
Level of Design:	Evaluate design proposals or proprietary items of equipment.
Description:	Is used to identify the principal areas for which the required maintenance and repair actions should be especially considered and evaluated.
Source:	Book; Improving maintainability and reliability through design; Graham Thompson

Tool nr:	8
Tool:	Failure mode and effect analysis (FMEA)
Design Phase:	Begins at the most detailed level that is practicable. However, the outline procedure can be used as quick assessment as the principal failure modes are known.
Level of Design:	Machines or systems, thus equipment
Description:	It is used as a review of failure modes and their effect on the production availability of equipment. It is an analysis method that complements reliability studies. The fmea can be used to evaluate the seriousness of the consequences of the fialures. Comprehensive fmea studies are used extensively to evaluate the safety of equipment and systems.
Source:	Book; Improving maintainability and reliability through design; Graham Thompson

Tool nr:	9
Tool:	Fault tree analysis (FTA)
Design Phase:	Detailed analysis method
Level of Design:	Systems evaluation
Description:	FTA can be used to identify critical areas in a design review.
Source:	Book; Improving maintainability and reliability through design; Graham Thompson

Tool nr:	10
Tool:	Hazard and operability (HAZOP)
Design Phase:	Post-design. Analysis of systems before design of functional units. After design of equipment, comprehensive analysis. Thinking about hazards is useful for designers in concept and detail design phases as well.
Level of Design:	Faults in systems, maloperation of equipment and systems
Description:	Is used to identify the principal areas for which the required maintenance and repair actions should be especially considered and evaluated.
Source:	Book; Improving maintainability and reliability through design; Graham Thompson

Tool nr:	11

Tool:	Equal strength (weakest link) principle
Design Phase:	(Detail design)
Level of Design:	Component level
Description:	A common-sense approach to design for reliability is to create a set of components that are equally strong so that an assembly has no ‘weak links’.
Source:	Book; Improving maintainability and reliability through design; Graham Thompson

Tool nr:	12
Tool:	Design constraints and most reliable solutions
Design Phase:	(Detail design)
Level of Design:	Component level (but can vary)
Description:	The most reliable solution is the solution that is the farthest away from all the constraints.
Source:	Book; Improving maintainability and reliability through design; Graham Thompson

Tool nr:	13 (6b)
Tool:	Parameter profile analysis – design for reliability
Design Phase:	Review and analysis of reliability of components and systems during detail design
Level of Design:	Component – equipment evaluation
Description:	Adopted parameter profile analysis for the use and a quantified optimization method for reliability during design. Based on design constraints and weakest link principles.
Source:	Book; Improving maintainability and reliability through design; Graham Thompson

Tool nr:	14
Tool:	Resource allocation table (actions, outcomes and resource requirements)
Design Phase:	Redesign of equipment after identification of maintenance problems
Level of Design:	Detail design (generally)
Description:	Adopted parameter profile analysis for the use and a quantified optimization method for reliability during design. Based on design constraints and weakest link principles.
Source:	Book; Improving maintainability and reliability through design; Graham Thompson

Tool nr:	15
Tool:	CPS framework for maintenance problems solving
Design Phase:	Redesign of equipment after identification of maintenance problems
Level of Design:	Detail design (generally)
Description:	Creative problem solving approach, with additional tool. See book appendix 2. Quicker than full blown FMEA analysis.
Source:	Book; Improving maintainability and reliability through design; Graham Thompson

Tool nr:	16
Tool:	Data feedback system
Design Phase:	Redesign of equipment after identification of maintenance problems
Level of Design:	Detail design (generally)
Description:	Data feedback system comprises of: a design reference with expected performance, data collection, active element (analysis) and output reports with regular reports about maintainability, reliability and performance data and special reports comparing actual performance with the design reference expectation. See fig. 13.2
Source:	Book; Improving maintainability and reliability through design; Graham Thompson

Tool nr:	17

Tool:	Logic Tree Analysis (LTA)
Design Phase:	Maintenance policy decisions (RCM step)
Level of Design:	-
Description:	RCM tool that helps deciding the maintenance policy for each failure mode.
Source:	Article; Reliability Centered Maintenance Methodology and Application: A case study; Islam H. Afefy; [28]

Tool nr:	18
Tool:	System Boundary definition
Design Phase:	Problem/solution area selection (RCM step)
Level of Design:	-
Description:	RCM tool that helps deciding what the scope of the problem is and where to apply the solutions.
Source:	Article; Reliability Centered Maintenance Methodology and Application: A case study; Islam H. Afefy

Tool nr:	19
Tool:	Functional block diagram
Design Phase:	Input resource and output definition of system components (RCM step)
Level of Design:	-
Description:	RCM tool that helps defining the inputs and outputs of system blocks. *Information to select the type of maintenance for a certain substance?*
Source:	Article; Reliability Centered Maintenance Methodology and Application: A case study; Islam H. Afefy

Tool nr:	20
Tool:	Root Cause Failure Analysis
Design Phase:	Root cause finding of failure modes (RCM step)
Level of Design:	-
Description:	RCM tool that helps finding the cause of failure modes in three steps: failure mode, reason and root cause. Used for most critical equipment.
Source:	Article; Reliability Centered Maintenance Methodology and Application: A case study; Islam H. Afefy

Tool nr:	21
Tool:	Criticality Analysis (RCM step)
Design Phase:	Categorising failure modes on criticality (RCM step)
Level of Design:	-
Description:	RCM tool that categorises failure modes on criticality, to define which is most critical. Often part of FMEA.
Source:	Article; Reliability Centered Maintenance Methodology and Application: A case study; Islam H. Afefy

Tool nr:	22
Tool:	Maintenance task selection (RCM step)
Design Phase:	Maintenance policy selection (RCM step)
Level of Design:	-
Description:	RCM tool that helps the selection of maintenance policies and frequencies, often within the FMEA. And extended with labour cost calculations.
Source:	Article; Reliability Centered Maintenance Methodology and Application: A case study; Islam H. Afefy

Appendix B

	Name	Year	Description	References
1	The seven steps of Bionik (Die sieben Denkschritte der Bionik)[32]	1987	Methodology, comparison of biological and technological function, constraints and performance criteria to compare solutions and to measure applicability	Zerbst[32]
2	16 patterns of nature[33]	1995	Classification of biological systems, general overview	Hoagland and Dodson[33]
3	Catalogue of biological principles (Katalog biologischer Konstruktionen)[34]	1998	Static list, biological principles for giving insight on biological construction	Hill[34]
4	Bioanalogous similarity matrix (Bioanaloge Ähnlichkeitsmatrix)[35]	2002	Methodology, comparison of biological and technological system to measure applicability	Küppers and Tributsch[35]
5	The ten fundamental principles of biological systems (Die zehn Grundprinzipien biologischer Systeme)[36]	2002	Static list of ten characteristics of biological systems for a deeper understanding of biology; enables to compare biology and technology and to transpose principles to technology	Nachtigall[36]
6	BidLab search tool – natural language analysis for biomimetic design[37]	2004	Computational tool based on WordNet for searching texts from the biology literature to identify biological analogies	Chiu and Shu[37]
7	Idea-Inspire[38,39]	2005	Software for browsing a database of biological and artificial systems for inspiration and problem-solving	Chakrabarti *et al.*[38,39]
8	A systematic catalogue for biomimetic design (Systematischer Katalog für bionisches Gestalten)[40]	2005	Catalogue of biological systems for a deeper understanding of biological systems and the transfer to technology	Nachtigall and Wisser[40]
9	Bioniquity (Biology – Technology – Creativity)[41]	2005	42 abstracted principles of biological models which can be used for idea generation on the meta level	BMVIT[41]
10	Transfer checklist of biological association (Assoziationsliste)[42,43]	2006	Functional principles of technology which are mapped to selected examples from biology; serves for association	Gramann,[42] Lindemann and Gramann[43]
11	BioTriz[4]	2006	Matrix for the resolution of conflicts derived from biological solutions, refers to the 40 inventive principles of the theory of inventive problem-solving (TRIZ)	Vincent *et al.*[4]
12	Functional modelling[44]	2008	Method for modelling biological systems functionally, aims towards a function-based biomimetic design repository	Nagel *et al.*[44]
13	Systematic reverse engineering of biological systems[45]	2007	Systematic method for reverse engineering of biological systems, assists designers in identifying biological models	Wilson and Rosen[45]
14	Natural language analysis[46,47]	2007	Method for generation and ranking of biologically meaningful keywords to bridge biology and engineering	Chiu and Shu[46,47]
15	Biologically meaningful keywords[48,49]	2008	Defining biologically meaningful keywords referring to the terms of the functional basis	Cheong *et al.*[48,49]
16	Ontology for bioinspired design[50]	2008	Ontology for capturing, retrieving and reusing bioinspired design solutions based on associated physical architectures, behaviours, functions and strategies; aims towards internal repository	Yim *et al.*[50]
17	AskNature[19,20]	2008	Publicly available database of biological information classified by functions	Deldin and Schuknecht[19]
18	Biomimicry Taxonomy[19,51]	2008	Static list organising biology by function and abstracted functional principles	Deldin and Schuknecht[19]
19	SAPPhIRE (State change–Action–Part–Phenomenon–Input–oRgan–Effect) model[39,52]	2005	Model used to represent biological or artificial systems	Chakrabarti *et al.*,[39] Chakrabarti[52]
20	Categorisation of natural language keywords[53]	2010	Method for categorisation of keywords to improve effectivity of identifying biological phenomena	Ke *et al.*[53]
21	Functional modelling – category and scale[54]	2010	Method for modelling biology	Nagel *et al.*[54]
22	Engineering-to-biology thesaurus[55]	2010	Thesaurus correlating biological terms to engineering based on the functional basis lexicon	Nagel *et al.*[55]
23	Nature-inspired design principles[56]	2010	Natural principles based on Biomimicry 3.8's life's principles and cradle-to-cradle principles	Delft University of Technology[56]
24	BiOPS[28]	2010	Thesaurus and dictionary for bridging technology to biology, for identification of biological models; link to patent database	Fraunhofer IAO[28]
25	DANE (Design by Analogy to Nature Engine)[57,58]	2010	Computational tool, database of biological Structure-Behavior-Function (SBF) models	Vattam *et al.*,[57] Design Intelligence Lab[58]
26	Automatically populating the Biomimicry Taxonomy for scalable systematic biologically inspired design[59]	2012	Method for supporting structuring and selection of biological designs and classifying biological analogies into the Biomimicry Taxonomy	Vandevenne *et al.*[59]

Figure 36. List of biomimicry tools [24] *(continued on page 61)*

Name	Year	Description	References
27 Automatic extraction of causally related functions from natural-language text for biomimetic design[60]	2012	Tool for identifying relevant linguistic patterns in biological text	Cheong and Shu[60]
28 A computational approach to biologically inspired design[8,61]	2012	Algorithm for biologically inspired concept generation	Nagel and Stone,[8] Design Engineering Lab[62]
29 Life's principles[11,63]	2008	26 fundamental principles of biology, refers to sustainability	Baumeister *et al.*,[11] Benyus[63]
30 Biologue[64,65]	2013	Interactive online information system for collaborative semantic annotation of biology articles, leading to internal repository; search engine for semantically annotated biology articles	Vattam and Goel,[64] Design & Intelligence Laboratory[65]
31 Ontology of biomimetics[66]	2014	Ontology of biological functions, refers to the 40 innovative principles of TRIZ	Vincent[66]
32 bionicinspiration.org[67]	2014	Website offering bionic categories and case studies	bionicinspiration.org[67]
33 Ontology Explorer[68,69]	2014	Web tool for identification of biological models and exploring biomimetics database	Kozaki *et al.*,[68] Kozaki[69]
34 Unified ontology for causal-function modeling in biologically inspired design (UNO-BID)[70]	2014	Process description, including biomimetic tools	Rosa *et al.*[70]
35 Four-Box method[9]	2014	Problem formulation and analogy evaluation; describes function, operational environment, specifications and performance criteria of systems	Helms and Goel[9]
36 T-chart[9]	2014	Analogy evaluation, comparison of biological and technological systems	Helms and Goel[9]
37 Bioscrabble[71]	2014	Software supporting search term-based extraction of biological analogies out of large text sources, supports managing results	Kaiser *et al.*[71]
38 BioP-C: the Biology Phenomenon Categorizer[72]	2014	Computation game; collects computable knowledge about biological phenomena and assesses their quality; benchmarks are AskNature, Dane, Idea-Inspire and natural-language search tools	Arlitt *et al.*[72]
39 Biotransferability framework[73]	2014	Combination of stochastic multicriteria acceptability analysis with criteria from biologically-inspired design (BID) to evaluate the utility of biological analogies and the biology-to-engineering risk	Williams *et al.*[73]
40 Structure–Function Patterns[74]	2014	Table of biological structure–function patterns, provides keywords for searching biological databases, helps to abstract biological texts, for identifying biological models, useful for idea generation	Helfman Cohen *et al.*[74]
41 Design Study Library[75]	2015	Web tool, searches case studies of a digital library, supports analogical learning	Goel *et al.*[75]
42 Nature-inspired solutions[76,77]	2015	Design principles and methodology, biological principles for sustainable innovation	Karim Network[76]
43 Resilient Design cards[78]	2015	Based on design principles found in nature, methodology for sustainable innovation	ResilieNtWeb[78]

Appendix C

Interview 1

She works as Global Sustainability Program Manager at Arcadis. Natural capital, the value of natural environment for people is one part of her job. The other half is coordinating the membership of two business networks where Arcadis is a member of, where one is a sustainability network. These networks help finding the ideas of the customers on the topic of sustainability, and find the opportunities for Arcadis to help.
Generally, she has many customers conversations and coordinates tasks. She gets many requests for tenders or customer requests or coordination requests on sustainability in general. But also capital specific requests. She also helps colleagues during design trajectories with a broad sustainability point of view.
To support the customer, customer analysis is done to know what they actually want, what their position is on the market and find together the value of the added piece of sustainability. Besides, Arcadis can find points to differentiate from competitors.
She mostly uses her way of thinking as a skill to find solutions. Seeing the connections between things to support creating win-win situations as in for the company as for the natural environment. This broader, integral view is the core of her thinking. Combining the fields and find a way to achieve added value.
Biomimicry stands for learning from nature. With 3.8 billion years of evolution, nature has things that we as humans can learn from. It has invented things that we didn't think about. That's where there is a large value for us.
Biomimicry and sustainability are two different things, however, biomimicry fits under the umbrella of sustainability. Most of the companies are doing something with sustainability, but sustainability is often simplistically seen as CO2 and energy. Often it is thought it is expensive. Concepts as biomimicry and natural capital is only implemented by leading companies. Often only picked up by individuals within those companies. For natural capital there is already a broader support, but one or two years ago that was limited to some individuals.
Natural Capital has surfaced three years ago from broader sustainability thinking as People Planet Profit. Contributing to a company is not only done through generating money, but also through added environmental value. This idea came together with university concepts evolved to Natural Capital. The Natural Capital Protocol, developed in July 2016 has improved its publicity, implementation, strengthened by the coverage about that.
In comparison to biomimicry, biomimicry has some coverage: biomimicry.nl, biomimicrytradepoint amongst others. The concept is coming up, but the business case behind is less visible than with Natural Capital. Putting biomimicry under Natural Capital has added value. It is one of the ways to profit from nature. The value of nature.
The origin of many concepts is nature, but that is not communicated, which makes that people aren't aware of this value. Communicating these examples will help the familiarity with biomimicry. Companies will be more susceptible for that nowadays. E.g. from the natural capital concept: We see nature in this way, we get value from nature in this way.
Companies don't go further than getting CO2 neutral. Only leading companies see the broader picture, initiated by the sustainable development goals they set.
For companies the first thing to do about sustainability is separating waste. Companies as Philips or Interface look at the design of their products and the use of materials, for e.g. a circular economy goal. Companies work on it in different ways, not only on CO2. The concept of biomimicry will play a role for some companies. Such as Natural Capital, biomimicry is a way of thinking, it is unknown, there are no ready-to-use solutions and it stands away from our current financial system. Biomimicry's way of thinking, its concept, is new and a company should be willing to be open for that. You are dependent on people who want to pick it up, such as innovation directors or sustainability directors.
So, it's the kind of company, there focus area, a fitting method and a person that founds the concept in a company.
To sell a concept as biomimicry in a company, you need everything from concepts to operation plan. Think broader than energy and sustainability. Start with and position the body of thoughts, present a business case and show concrete examples. The salesman within the company knows how to sell it and make a business case for it. Only a body of thoughts won't make it. Show the advantages for the company, in euro's, less risk or distinctiveness (important for biomimicry). Followed by ideas to implement and execution of it in the companies' process and in the products. (E.g. Interface) Eventually the point is that the company is improving; financially, in risks, differentiation or in any other way. One of the most important motivations for a company to introduce sustainability is differentiation from competitors. This can evolve in ESG, Environmental, Sustainable and Governance Criteria or for use in the operation plant. Businesses are looking for concepts where they can differentiate with.
Changes in the way of working, like with the biomimicry concept, will get resistance from employees. E.g. engineers are not flexible and think in a certain way and like to keep it that way. Therefore, you need people and colleagues that are open to new ideas, concepts and approaches. When the concept is viable those people will help to spread to

word. As can be seen with sustainability and Natural Capital that mostly individuals with some influence and interest in the concept will lay the foundation within a company, only sometimes it's an initiative from the employees.
The Natural Capital Protocol is a framework, it is supplemented with the Natural Capital Toolkit which provides concrete tools to work with natural capital. The protocol developed from a need of companies to standardize the methods and point of view to get to work with natural capital and from organizations (as: TEEB or Natural Capital Coalition) that were looking for ways to support businesses in working with natural capital. Eventually, these parties found each other.
She was in the strategic management. Other people executed the project.
The Protocol brings all methods together and points in the direction to go. This makes that companies are comparable, directions can be determined and companies know which direction to go. It is all about creating a standard.
Executing the protocol can be done on many levels. First companies need to know what business decision they want to influence with natural capital. E.g. strategy adjustment, site extension, site change, product development, relationship with natural capital as company. The next step is a focus on business decisions and business units. Followed by decisions as: qualitative or quantitative, and monetizing. All these different steps are being measured and valued.
Each of those steps is supported by the toolbox with an overview of the methods and tools to answer this question. And for companies to know where the tools fit in the protocol and what they do with this toolkit and how this relates. The tools are applied in their own way, but following the protocol.

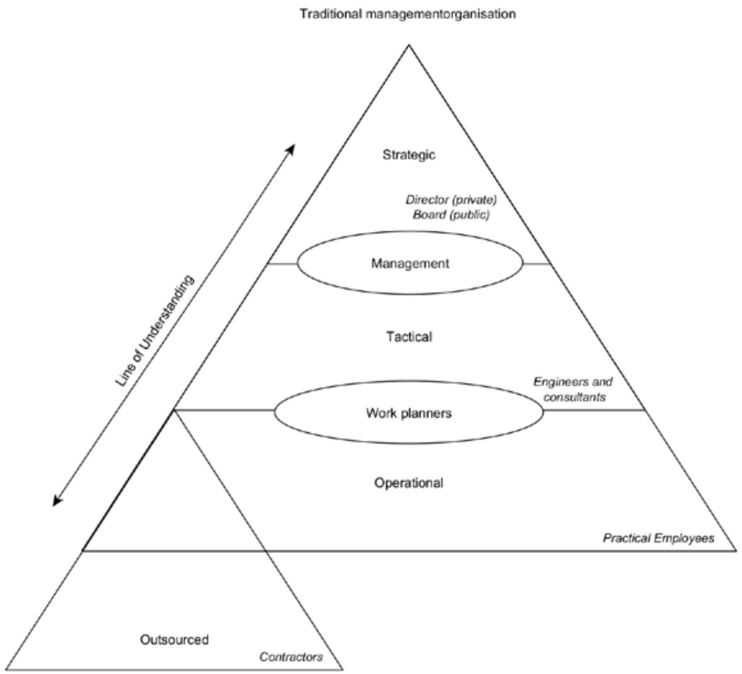
The toolkit and the protocol are used moderately, it is certainly not mainstream yet. Companies use it and communicate about it and the amount of case studies is growing. Keep in mind; the toolkit is launched recently the protocol is only one year old.
On the other hand companies find it too complex and costly in energy in comparison to its results.
The balance for using it is mostly on that they are sure that they can win something with it, if that is not the case they wait for a moment. Only by executing it once, they can see the advantages they can make. E.g. sharpening the view on risks.
Within Arcadis; sustainability is important in the Netherlands and more and more worldwide. In the Netherlands, it started gaining familiarity because of the CO2 performance ladder as a financial incentive. This helped with CO2 and energy levels. But sustainability in a broader sense was a bit harder for Arcadis as engineering company.
Natural Capital had an introductory period, but is now gaining awareness. It is a holistic point of view with incorporating the whole chain, which makes it a black box for some people. Its support is marginal and therefore requires more explanation and concrete examples. The Netherlands is leading in that.
Biomimicry is only know by a couple of people within Arcadis. Except for Mark and this thesis, no concrete action has been done on this topic. There are individuals who are interested, but it is no more than that.
A structured approach is missing for implementation and use of biomimicry. For natural capital it helps to refer to the Protocol which suits that need. To start with biomimicry in Arcadis the development of such a protocol, including the tools, would help a lot. Especially when you show concrete examples.

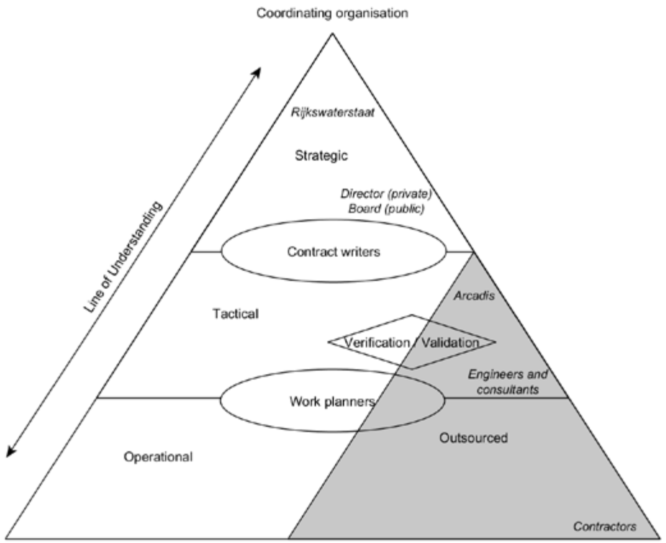
To compare the thesis results, a casus on the design of The Beacon in Amsterdam would suffice. The design should be finished, however, to check the biomimicry method the results of the regular design team can be compared to the results of the casus with the biomimicry method.

Interview 2

She works at Arcadis as asset management consultant. She is stationed in Amsterdam, but works sometimes at clients' offices. She advises clients on issues of management (beheer) and maintenance, asset management. Thus, how to do technology differently or improve it or how to improve or change things from a management perspective. This all comes together in costs, performance and risks. I help them in technology or approach to work more efficient. E.g. the translation from easiest, efficient and reliable assets to costs, performances and risks for the employer. How to cover risk with my management and maintenance. I think about these ways of working, which is partly information management. That is about: people, SMART criteria, culture, competences and technology or maintenance techniques. This all belongs to this advice.
She works for the water board throughout the Netherlands, did a project on a new risk management methodology at Rijkswaterstaat, for a contractor she does asset management within a performance contract for Rijkswaterstaat and sometimes she gets questions from the chemical technology industry. A lot of projects are with water, but she can easily help with roads, only with a colleague that has more knowledge in that field.
She deals with management (beheer) of an organisation, as in the organisation pyramid. On top is the board, at the bottom are the operational services and in between the management system. This system translates the targets of the board to operational tasks. The actual technical knowledge is kept with the specialists, however the benchmark and the steps towards the main targets are an asset manager's work (Her work).
However, it doesn't work that way right now, but it should, from a point of costs effectiveness. E.g. an inspection methodology is made by the asset manager and the inspections itself are for the specialists. The methodologies should make sure the higher targets are achieved.
One big methodology within the field of asset management is condition and risk based management. Which is a combination of FMECA and checks on the condition of technical systems.
Some board groups are struggling with risk. There can be other incentives than risk, such as image and RAMSSHEEP. RAMSSHEEP are the aspects to satisfy and there are agreements with the board on the requirements. Dependent on the company and within industries the 'multiplier' for each RAMSSHEEP criteria is different.
Managers (asset) (beheerders) should stay critical about the added value of maintenance.
She has guided students during practical assignments and exams on physical maintenance work.
During design of capital intensive, technical installations many things for management and maintenance are already implemented in the design without our awareness.
The process of Rick de Boer is specific for Rijkswaterstaat for dry contracts (droge contracten). The process is the same for a wet contract (nat contract) for Amsterdam Rijnkanaal (which She is working on).
Rijkswaterstaat delivers everything including RAMSSHEEP, then the control measures (beheersmaatregelen) and planning are based on that. In the future, the contractors of Rijkswaterstaat will optimise on the triangle of costs, performance and risk. This is currently not possible since the methods nowadays do not allow this way of working. However, they are presented as leading in asset management. But they aren't there yet, they miss the risk and condition based management. To change that requires lots of effort from the internal organisation. This culture change needs the support of the people internally at Rijkswaterstaat and the contractors since they deliver essential work for the organisation.
These are performance contracts at coordinating organisations (regieorganisaties), these are different than management organisations (beheerorganisaties).
Outsourcing in a traditional way is an extension of the abilities of the company and takeover of operational activities. However, at coordinating organisations outsourcing involves their own tasks and knowledge. Which currently bounces back in that they lost the knowledge to create integral solutions, due to ageing and replacement of employees the Line of Understanding (Lijn van Inzicht) has been lost. This problem makes them already setting up new engineering groups.
The verification-validation activities are happening between the contractors and the employing company. Arcadis is set as a managing agent in the tactical outsourced area.
For new developments, you need the people in the tactical layer, those can think out-of-the-box about new technologies and maintenance engineering. Maintenance management is a grey old man's business, which are from the practical side. Therefore, the other side is not quickly linked to management and maintenance.
The scheme is good for Rijkswaterstaat and maybe for water boards with a little change.
The scheme is focussed on planning and a level higher, in tactics, you should make some analyses about the costs and benefits of the maintenance to be done. Then you can decide how to maintain and apply (technical) innovations. By combining the knowledge of the maintenance engineer, universities and parties on the market. This point of view, of innovation in maintenance, is never happening with performance contracts at Rijkswaterstaat, the incentive isn't

there either. At both the employer and contractor's side. At this level, plan do act is more about analysis and how to maintain, then only adjusting the planning.
Implementing innovative technologies doesn't happen much in maintenance. In management (beheer) there are some examples and there is thus a tactical layer that promotes the use of new technologies and development. This difference comes maybe from the kind of people; at the tactical layer, there are more engineers and technology-driven people working from a process and business perspective, where at the operational level these people are specialists, task-oriented and activity guided. People in companies, between the tactical and operational levels (thinking about the system/planning (thus operation planners) should watch the developments in the tactical layer and try to implement it in the operational layer. That is only little happening right now. The only things happening are coating and changing to LED bulbs. Rijkswaterstaat has a certain revenue model, the incentive of the contract, which doesn't allow much room for innovation.
The innovations are there, however they aren't always implemented and used. This is possibly a result of the kind of people, the operational people are not the early adaptors.
Also for the innovations; money should be reserved and business cases should be made to sell it to the management.
And the incentive to innovate lacks in many organisations, to structurally change you own work.
And something must prove itself before it will get accepted commonly.
Solutions at the tactical level should be presented in a clear and especially understandable way with additional advantages, to the operational level. It should affect the person who executes the maintenance. The sustainability programs within management organisations could also quicken the implementation on the work floor. The added value of sustainability, CO2 or cradle to cradle principles is a hot topic there.
Additionally, creating sound and comprehensible business cases would help as well. However, it is hard to create those from the soft data, the added value of management (beheer).
The strategic management sets the targets in time, capacity and requirements (vraagspecificatie). Then it will often go to an internal projects department who will put it on the market with additional requirements, which could be on usability and maintainability. The design will stay with the contractor.
To implement these technologies it is possible to look for a combination with parties on the market. It is possible to stimulate clients with propositions of possibilities, with a clear and practical business case of the revenue financially or in image. With larger improvements and innovations, it is maybe possible to just launch this idea with clients, onto the market or building it yourself.
It is an interesting idea; that management is busy with developments in the





Netherlands, however, maintenance with technology and in combination with the practical side (or level) is lacking.
Thinking about maintenance for new assets is done in the following way: First there is the decomposition of the asset. The used materials are listed (automatically). Then, per component, will be defined what the technical lifespan is and how it will deteriorate during that lifespan. The first estimation is based on empirical numbers. Those will determine the maintenance checks and planning. During that time additional adjustments, planning and maintenance will be done based on inspections. This comes back to the types of maintenance: preventive and corrective. Preventive is done to take away the big risks (based on RAMSSHEEP) and corrective is also based on RAMSSHEEP but way less important to plan preventively. Additional methods and policies are used as well, such as; RCM, which is a form of risk and condition based maintenance.
The failure rates come from books with many types of systems, calculations of the company and scientific research, studies and analyses.
In increasing extent, we see that a RAMS analysis is made from the first design on, this is also standard in projects for Rijkswaterstaat. Then the failure rates are added to the components, which can be used to question the constructor. Between each phase there are validation moments, to check if delivered work is as it should be.
The V-model with RAMS, as shown in Leidraad RAMS, is the lifecycle model accompanied by RAMS. This is followed by Rijkswaterstaat and uses RAMS to state the top-level requirements.
The Technical System lifecycle chart is the V-model in a different form (platgeslagen).
Rijkswaterstaat uses the V-model for design and contract drafting. However, every process phase could use it: management, maintenance, design.
The life cycle as shown here is recognizable, however, it doesn't go that way right now, but it should be. The world is not ready yet. This is risk management 2 or 3.0. People struggle with the idea of risk, costs and performance, the contract drafting doesn't even cover that completely. The new method from Rijkswaterstaat is coming up and field services are now informed to create commitment. After that they are ready for the next step. This is asking a lot from people.
It is the same as the operational layer only thinking about maintenance for a little bit, though the work is done there. Coming up exciting new things, doesn't work in practice if it is not matched to the work floor.
Still it is often that the work is left unorganised for the next party (over de schutting). Such as the transfer from projects to management is in every organisation a mess. E.g. without explanation what to do, so the manager will do and plan what he has learned before.
There are examples of companies that implemented a whole asset management system including commitment building and still at the operational level everyone works the same as before. Just like this it is an ideal idea, but in practice it doesn't work like that.
Interesting about this question is that it shows that there is a mind shift within the Netherlands. From the thought that asset management, management and maintenance is not elegant and intellectual, towards the fact that those people are not dogs-bodies.
There is a gap between in and outside companies, but also between university level people and the people outside doing the work. This is where the returns are made. And that develops a culture shift since everyone should work together.
These things could land quickly by following the line of sustainability, circularity, amongst others, ignited by the crisis and governmental stimulation.
In the latest years there was a shift at Arcadis from technology/engineers in management and maintenance towards a process point of view in management and maintenance, and Operate and Maintain became a global strategy.

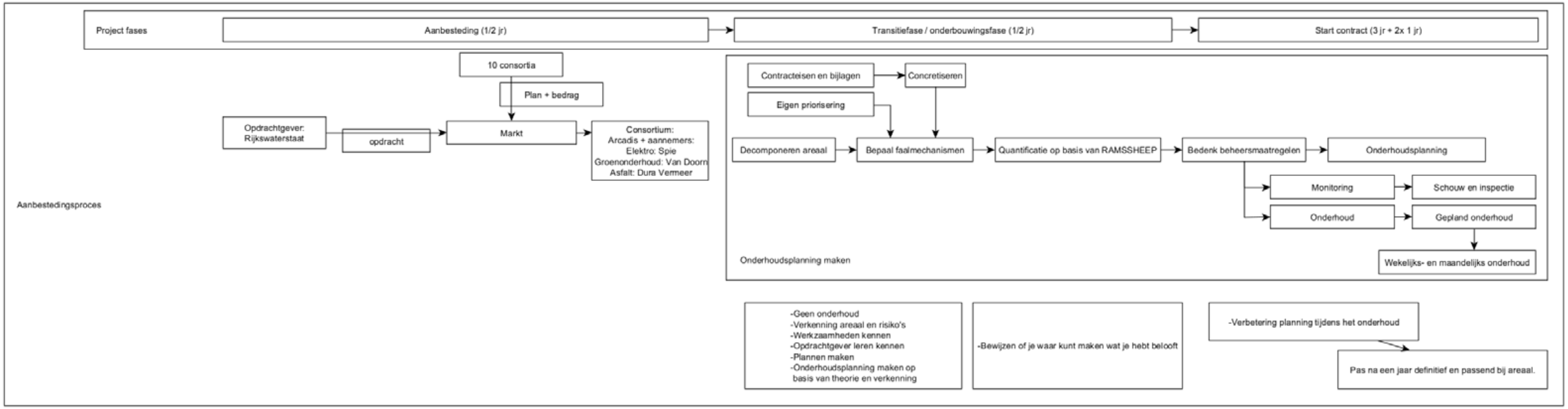
Interview 3

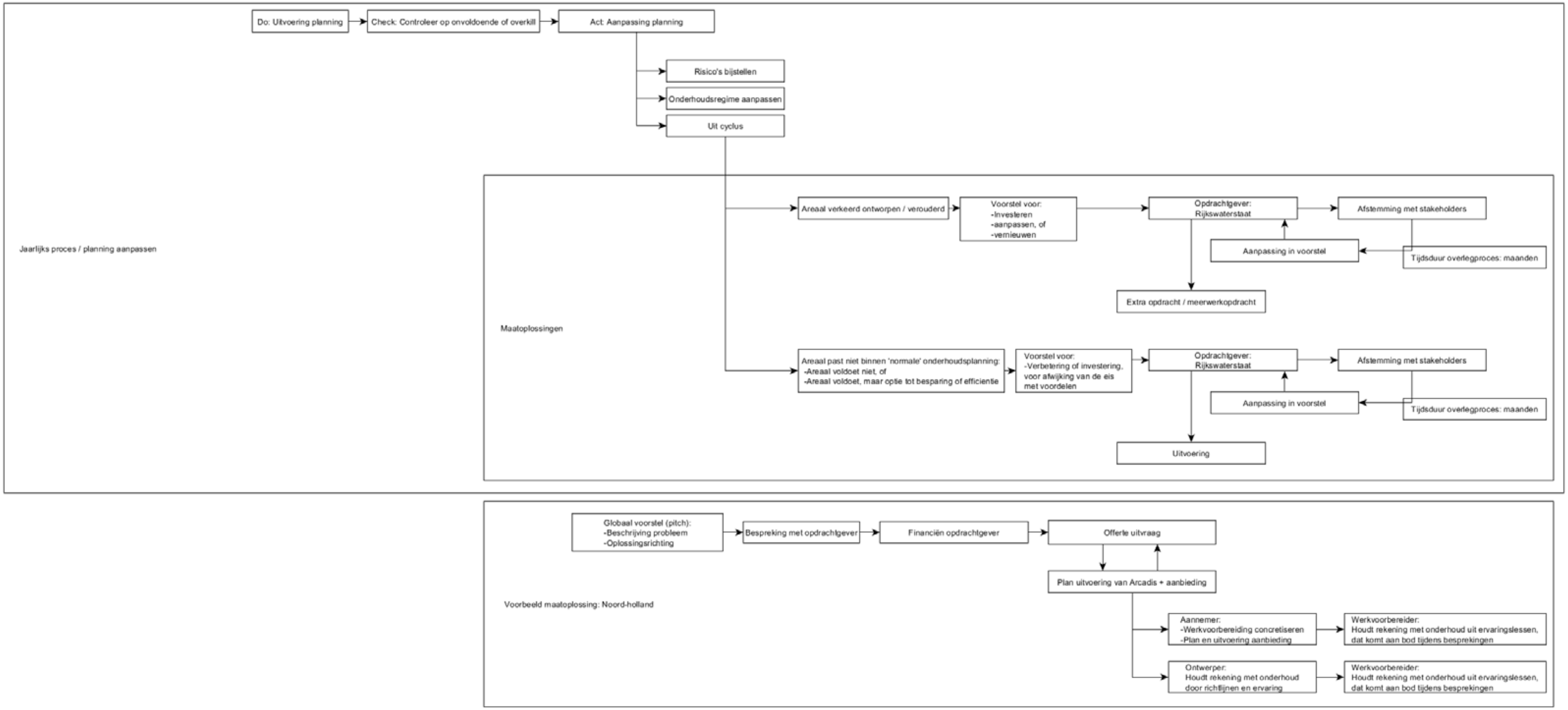
He is a project leader at the maintenance-side of Infrastructure department of Arcadis. He writes plans and is concerned with tenders. Daily activities are talking with people, making plans, check if everyone follows the planning and analysing data for trends to create improvement plans. He works now a lot with performance contracts. He is not or hardly concerned with the design process.
Managing assets, infrastructure or something else, is about optimising the triangle of resources, risks and targets. Asset management is applicable on buildings, public spaces, etc.
He is mostly working in the phases: Operation & Maintenance and Life extension & Reuse.
Within the maintenance contracts Arcadis works together with contractors in a consortium of specialised parties. This consortium, (consisting of Arcadis for managing, analyses and brainwork, Spie for electro, Van Doorn for green-maintenance, Dura Vermeer for asphalt) works for a client (Rijkswaterstaat).
Arcadis advises contractors by calculating risks, writing the plans and writing the contracts.
The contractors execute the operational activities.
The contractor creates the planning/schedule (werkvoorbereiding).
All national highways are managed by Rijkswaterstaat; however, Arcadis Infrastructure manages the availability, condition and maintenance. Also, provinces and municipalities.
The area (areaal) is everything this consortium is responsible for. The borders are defined in the contract. Sometimes there are additional sub-agreements with specific parties. In performance contracts, the area (areaal) must perform to certain requirements.
The phases of a certain maintenance contract are: tender phase (aanbestedingsfase), Transition phase (transitiefase) or foundation phase (onderbouwingsfase), contract phase (contractfase). This and its sub-processes are depicted in the flowchart.
During the contract phase, there is no standard process for recognition of problems and proposing solutions. Per contract this is different depending on the people working for Rijkswaterstaat on that topic. Example for Noord-Holland in the flowchart.
The project leader initiates the solution process, raising the matter and helps looking for solutions. The contractor will then concretize and execute the project, including planning (werkvoorbereiding).
This process of creating specialised solutions sometimes triggers innovations. The ideas can come from anyone within and outside the company or consortium, everyone has its own field of expertise.
The process for specialised solutions always consists of lots of conversations with stakeholders. E.g. planning with other maintenance activities and opinions of people living in the neighbourhood.
In case of a project, e.g. sound wall or hard shoulder (vluchthaven), after the approval the project is transferred from the project leader at Arcadis to the designer and construction supervisor (uitvoerder). They will check the regulations and create the design. The designer will use regulations and experience and the supervisor will use experience to reckon with future maintenance, especially in performance contracts it is based on experience. Lots is already assured through regulations and standards, e.g. from Rijkswaterstaat, NEN, ROW, amongst others. However, there is no person responsible for the maintainability of a design. There is no separate design phase for maintainability. Often, quick and dirty solutions are applied for current problems, since there is already a risk and thus time pressure. With on the other hand thinking about the future 20 years; what are the life cycle costs and what are the consequences for daily maintenance. Possibly this is better with big new projects.
Sometimes maintenance is not important, or rated very low in RAMSSHEEP by Rijkswaterstaat since safety and availability are much more important. Examples enough for that case.
There is no extensive use of tools or methods or of a single method. There is more and more use of Life Cycle Costs calculations for a tender. Therefore, there is a moment to think about maintenance in a quick analysis, to define the consequences for Life Cycle Costs. However, no effect is expected for design for maintainability.
In the short and busy time of a tender process, maintainability being a separate project phase is only feasible if it yields more than effort it costs. This is still hard to underpin.
For standard solutions, where norm and regulations are sufficient, it is not necessary to have a certain project phase. For complicated designs, where norms and regulations are not sufficient and many disciplines come together, it would be useful to have a separate maintainability phase. In this case it is already considered in an implicit manner.
When finding solutions to a problem, currently a little more thought is going into making maintenance faster in the future, it’s sometimes a little extra step in thinking. It is not a fixed step or phase in the process.
Maintenance is considered though RAMSSHEEP. However, the added value is not yet big enough to give more attention to it.
The biggest problem is that the maintaining party is

different from the one that designs or builds it. The designing party doesn't care about the maintenance (rest of lifetime). If that party profits itself from how it is designed, build and maintained, then they'll see the added value. Rijkswaterstaat could be a leading party, however. The ones determining the projects and budgets are too far away from the operations. They do have technical advisors that know, but they are not calling the shots. Thus, right now Rijkswaterstaat does not take the role of thinking about maintenance during investments.
On both sides things are missing. If contracts are longer you'll think automatically about maintenance since it provides revenue. Then it would be a self-solving problem. Rijkswaterstaat is asset manager and responsible for the road network and it should be valuable if they would think along.
Tools known are: LCC, RAMS, FMECA and FTA. Tools under 'specify maintenance behaviour and conceptual design phase doesn't say much and FRACAS is not known. LCC is more and more important, FMECA are we doing a bit, inspections, maintenance concepts and condition monitoring/measurements are the methods/tools we use. Per piece of maintenance documents are available for operations to check for requirements, how to do maintenance and how to verify their maintenance.
FMECA is probably not made in the detailed design phase. And only used for large projects, e.g. national highway, and not for smaller projects, e.g. mooring construction (aanleginrichting) or bumpers (wrijfschorten).
With LCC you need to know the global maintenance measures, costs for maintenance and the lifespan of the design. Comparing those facts through the LCC for several alternatives is useful, and it helps thinking about maintenance.
Maintenance concepts are used, in the transition phase are the made and they are adjusted.
RCM is not used within the road area of Arcadis. But probably for lock throughs and waterways, since RCM is going deeper and better applicable on complicated projects.
The maintenance process (of Tinga) is recognizable, but just different. The area (areaal) and use profile are already defined when Arcadis will get it. (Design/Asset and Use profile phase). The failure modes are clarified, the maintenance organization (onderhoudsregime) is made up by Arcadis to control the risks of the failure modes. The tasks and planning are the result for the maintenance crew.
For some contracts it is mandatory to have a list of critical components (for availability and safety in the area) that should be on stock.
The maintenance planning coming from the FMECA is put in the maintenance system (onderhoudssysteem). The teams of workmen are coupled to this planning. The planner (werkvoorbereider) can upload pictures, registration, work orders, (werkbonnen), or make a report of executed maintenance, also to verify its execution. And the inspector (schouwer) can report needed maintenance for the workmen. This system is essential.
Thinking, in advance, about how assets are used in a natural way is hard and not done in cases like bins at parking spots or drains at bridges.
The water lily example, with the dirt repellent coating, triggers enthusiasm for solutions for during the maintenance during the life cycle of assets. It is expected that there is potential for such solutions. Construction projects (aanlegprojecten) could be very different than maintenance projects, so there may be a different kind and maybe more or less value for this idea.
Eventually, if money or safety are improved then companies, e.g. Rijkwaterstaat, will be interested. For most, certainly the contractor, the most attractive option is more profit.
The Netherlands is a kind of finalized, therefore is optimal management and optimal maintenance more likely than there will be many more construction works. Not counting some exceptions of new highways, detours, new tunnels. Therefore, it is interesting to use it in new designs, however, it could be even more useful if applied in existing assets (areaal). There is more money to make.
Theory is always conveniently arranged, better than practice. However, that doesn't have to be problem, it gives grip as well.


Asset management = Optimalisatie van:
Geld
Risiko's
Doelen


Tijdens contract:
Do
Act
Check


Project fases
Aanbesteding (1/2 jr)
Transitiefase / onderbouwingsfase (1/2 jr)
Start contract (3 jr + 2x 1 jr)
10 consortia
Plan + bedrag
Opdrachtgever: Rijkswaterstaat
opdracht
Markt
Consortium: Arcadis + aannemers: Elektro: Spie Groenonderhoud: Van Doorn Asfalt: Dura Vermeer
Aanbestedingsproces
Contracteisen en bijlagen
Concretiseren
Eigen priorisering
Decomponeren areaal
Bepaal faalmechanismen
Quantificatie op basis van RAMSSHEEP
Bedenk beheersmaatregelen
Onderhoudsplanning
Monitoring
Schouw en inspectie
Onderhoud
Gepland onderhoud
Wekelijks- en maandelijks onderhoud
Onderhoudsplanning maken
-Geen onderhoud
-Verkenning areaal en risiko's
-Werkzaamheden kennen
-Opdrachtgever leren kennen
-Plannen maken
-Onderhoudsplanning maken op basis van theorie en verkenning
-Bewijzen of je waar kunt maken wat je hebt belooft
-Verbetering planning tijdens het onderhoud
Pas na een jaar definitief en passend bij areaal.


Do: Uitvoering planning
Check: Controleer op onvoldoende of overkill
Act: Aanpassing planning
Risico's bijstellen
Onderhoudsregime aanpassen
Uit cyclus
Jaarlijks proces / planning aanpassen
Maatoplossingen
Areaal verkeerd ontworpen / verouderd
Voorstel voor:
-Investeren
-aanpassen, of
-vernieuwen
Opdrachtgever:
Rijkswaterstaat
Afstemming met stakeholders
Aanpassing in voorstel
Tijdsduur overlegproces: maanden
Extra opdracht / meerwerkopdracht
Areaal past niet binnen 'normale' onderhoudsplanning:
-Areaal voldoet niet, of
-Areaal voldoet, maar optie tot besparing of efficientie
Voorstel voor:
-Verbetering of investering,
voor afwijking van de eis
met voordelen
Opdrachtgever:
Rijkswaterstaat
Afstemming met stakeholders
Aanpassing in voorstel
Tijdsduur overlegproces: maanden
Uitvoering
Voorbeeld maatoplossing: Noord-holland
Globaal voorstel (pitch):
-Beschrijving probleem
-Oplossingsrichting
Bespreking met opdrachtgever
Financiën opdrachtgever
Offerte uitvraag
Plan uitvoering van Arcadis + aanbieding
Aannemer:
-Werkvoorbereiding concretiseren
-Plan en uitvoering aanbieding
Werkvoorbereider:
Houdt rekening met onderhoud uit ervaringslessen,
dat komt aan bod tijdens besprekingen
Ontwerper:
Houdt rekening met onderhoud
door richtlijnen en ervaring
Werkvoorbereider:
Houdt rekening met onderhoud uit ervaringslessen,
dat komt aan bod tijdens besprekingen

Interview 4

He has studied water management in Enschede and focusses on all aspects of that in his work. In his half year traineeship within Arcadis focusses He on domestic water defence (binnenlands waterweer) and sustainability. Currently he is studying business administration with a focus on asset management, for which he has worked at two water boards (waterschappen). He is concerned with strategic issues, organisation management and change management. Operational and design aren't his work areas. He knows a little bit about design for maintenance, but is unknown with biomimicry.
As a trainee in a project organisation as Arcadis the daily activities change quickly. You can be seconded at clients, with projects that differ in workload. As trainee, it is often small and more things to do at the same time. And you have the billable eu and tender projects. Currently he is working on a management plan (beheerplan) for the river the Vecht, next to sustainability studies with costs and benefits and exploration studies. Management (beheer) and maintenance planning for water boards are typical projects for him, converting the management decisions to tactical planning. Arcadis does projects for water boards, Rijkswaterstaat, municipalities; government mostly. These projects can be: design projects, management plans, policy studies, visual plans (beeldbestekken).
In his thesis assignment, He works on organisation management, asset management, how to take maintenance as early as possible into account during the design process. Especially for water boards (waterschappen). Rijkswaterstaat is more progressive in maintenance management and asset management than the water boards. The latter are smaller, more traditional and management organisations which have existed and functioned well for hundreds of years and therefore it is hard to change the way of working. This comes forth from the idea that everything works fine and the money flows in and small improvements are made in effectiveness and efficiency, and thus no change or improvement is needed.
Innovation for sustainability is growing. Innovation to suppress costs is getting more and more important. Innovation is also social innovation, working together with all stakeholders. E.g. give the farmer the competence to maintain the ditch next to his field, including compensation. Water system (watersysteem) and water chain (waterketen), are differentiated parts of the water flow. Water chain: generally, from the place where it enters the pipe system or human-built structures to discharge in the water system (nature), e.g. pressure pipes, water collection basin, sewage plant. Which includes requirements as capacity and quality. Therefore, this part is already managed, by optimisations in cost and efficiency. Water system: Natural and human built waterworks in natural environments. As dikes, rivers and lakes. Which are used by multiple groups as recreation, transport and nature. This involves requirements as water safety, quantity. Arcadis has an additional differentiation within water system, rural and urban.
The management plan (beheerplan) is the framework for maintenance. Management plan describes what to achieve, how to check it and measure it. The maintenance follows from that plan. This is written down in the yearly maintenance plans (onderhoudsbestekken).
Example, management plan de Vecht. A water board can put a project out to tender, this can be done is several ways: privately or multiple privately if the amount is low enough. If it is higher, then it should be done publicly. Then first there will be a communication plan, which states how is communicated with the stakeholders. This includes; what will be happening with the environment, what are you going to do with the plans, which stakeholders are important, what are the concerns of the stakeholders and how to all achieve our targets. Then the management plan follows the communication plan and states how to manage the Vecht and the surrounding area. It is the framework for the management, who bear in mind, which rules to reckon with and which circumstances need to be considered. A small chapter is about maintenance. This is written in cooperation with the stakeholders to merge targets of all parties. Natural targets are considered more and more as well. Following the management plan the maintenance plan is created, this is needed when maintenance is outsourced. It states who does what and when.
The concept Building with Nature, related to Natural Capital, is the smart use of nature for different targets. As mangroves help dim the force of tsunamis and prevent flooding. This is a current topic within the water-field, such as use in the water system and coastal waters.
In the recent years there is interest in fighting urban water problems such as: heat, water and dryness, with natural means.
Sustainable civil engineering (Duurzaam GWW) is a guideline for bringing sustainability in project. It is the result from the climate agreement in Paris and the Green Deal. It should be implemented in 2020 in standardised ways. It forces everyone to think about sustainability when they are working on projects.
Projects are unique, there are policy studies, policy writing and design projects. Arcadis does a bit of contracts.
DBFM – Design Build Finance and Maintain is an all-in-one contract variant. If e.g. Arcadis accepts this contract, one price is set for the whole thing, this is a risk for Arcadis. If the requirements are not met a penalty must be paid.

Instead of steps of five years, one company does the thing integrally.
When working on specific parts, the contract should be defined very well. This brings risk analysis into account and there are specific people that write the contracts.
Project leaders have a step-by-step guide to follow during a project, which is called the Arcadis Way.
It is hard for a water system manager to determine the function of a part of the system. Just because they have a lot of assets (and functions) or sometimes it is hard to explain or sometimes it is not known how the system works. And the function should be written in SMART criteria. For road network management and the water chain (waterketen) the line of thoughts and reasoning is further, more managerial, resulting from the higher costs of failures. RAMS and LCC fall within this field of asset management.
At Arcadis there are ambassadors, experts in a field, that join different projects. These persons bring people in on the subject and activates them, next to thinking out of the box or bringing substantive knowledge. This is also happening for the sustainable 'GWW'.
Currently every project is somewhat related to climate change, thus considering lots of precipitation in short time and dry periods. We design these solutions to help survive climate change.
Sometimes will the client ask for specific solutions, then the team will design it. Sometimes we execute the phase before that: we think of the solutions for their projects. The ideas then come from the project team. Brainstorms are generally not done, only if the client asks for it. The project team has already made those solutions many times.
Arcadis is not spontaneous with innovation. The client often comes to us because we already designed the innovation. Instant ideas or innovation are not made, only combinations of already existing solutions can be found and called innovations. Education takes the times and has the money to study and design these things.
Maintenance is more and more used in the design phase; however, it is certainly not common yet. Arcadis does what the client asks and that can also be just one phase of a project. To make profit as engineering firm, you can smartly say: 'take this and this into account so you can adjust your design n it'. One of the challenges for He is implement asset management, the life cycle thinking, more in the organisation.
The traditional idea, of several separated steps, is being renounced, since the next person or water board then found out that the design is flawed. The water boards are now asking to make things more integral for cost efficiency and solving internal issues. However, this requires a whole development process and organisation change, since they work in the same system for decades. A lot is done from experience, unformalized coordination or standardised work.
The water boards of Vechtstromen and Zuiderzeeland are working on a more efficient and effective water system and water chain, to e.g. safe money. Before there were some buildings that did not fit the bill in hindsight. E.g. maybe the building looks nice, but for maintenance it is not efficient or safe.
There is more and more structure in thinking about maintenance. Water boards involve for maintenance responsible people in a project team. They should be able to represent their interests, think about how to improve maintenance and bring knowledge to the project. Mostly they are not only responsible for the maintenance.
At the water boards there are several teams: technical and maintenance, responsible for maintenance; management team; responsible for management, projects team; with project leaders and sometimes teams of experts with knowledge about ecology, policy or environmental management, amongst others. Then in a project joins a person from each relevant team.
The change is that before you did not have a management and maintenance person at all, which is now the case.
And next to that there is the board (bestuur), which is an internal employer, who should ask the right questions; e.g. low life cycle costs and maintainability. This is sometimes complicated in such a political organisation where they are focussed on the short term. In a term, the board wants to realise a goal and then what lies behind their term is not that important in that situation. This is noticeable by the whole organisation.
It is unknown if such a maintenance person in a project works in a structured way. Probably this is dependent on the level of education, which differs a lot within a water board.
There is a lot of knowledge inside people's heads, this means that everyone can solve problems differently.
Therefore, the water boards are working on developing the organisation, improve professionalism and standardisation.
Lots of knowledge about the water system and procedures or smart solutions are not in the system, standard or guidelines defined. The water boards also work together and exchange knowledge.
Arcadis is very diverse, there are designers, He is more an advisor, working at the broad side with specialists, contract writers, and others. And in as many life phases of an asset of a project that it is hard to define his work.

Interview 5

Opleiding en werk
Hij heeft een HBO opleiding Industrieel Product Ontwerpen gedaan. Als 'WB'er' aangenomen. Hij is nu Adviseur Duurzaamheid en heeft daarvoor gewerkt als Ontwerper Bovenleiding.

Bovenleidingsystemen, standaardisatie en vernieuwing
Voor bovenleidingen bestaan er acht verschillende systemen. Daarbij komen de Specials, de custom-made onderdelen. De regelgeving is opgesteld door ProRail, dit zijn de eisen aan het systeem. Er is een vrij verre standaardisatie doorgevoerd. Maar door herontwerp worden marges geoptimaliseerd en worden besparingen gecreëerd. Dit gaat stroef doordat men wantrouwend is tegenover vernieuwingen, ivm. Kosten en veiligheid.

Ontwerpproces
Het ontwerpproces gaat als volgt.
Eerst wordt door Prorail of een andere vervoerder een opdracht opgesteld, inclusief een begroting. Vervolgens wordt het spoor eerst ontworpen en vervolgens de bovenleiding. De AutoCAD tekeningen van het spoor worden als basis genomen en daarop wordt ook de soort bovenleiding gekozen. Vervolgens komen de knelpunten (wissels, viaducten, stations en overwegen) aan bod. Waarna de tussenstukken opgevuld worden. Dit wordt gedaan door middel van een 1:1000 tekening bovenaanzicht. Vervolgens worden ook dwars profielen gemaakt en evt. langsprofielen. Voor specials worden ook constructietekeningen gemaakt. Als het ontwerp klaar is worden de plannen goedgekeurd door Prorail en worden aannemers en andere ingenieursbureaus ingeschakeld voor de uitvoering. Elke partij geeft aan waar een ontwerp; schets, definitief, uitvoering of opdracht aan moet voldoen. (Voordat zij er aan beginnen.) Zie tijdlijn.

Onderzoek en analyses
Er wordt geen onderzoek gedaan naar het meest geschikte systeem voor een project. Losse onderzoeksprojecten worden wel uitgevoerd; zoals: kunnen de voltages van de bovenleiding omhoog?
Feasability onderzoek doet prorail vaak zelf Als de rails er al ligt is dat al gedaan, voordat de ontwerpers bij het project betrokken worden. Het team doet ook wel planstudies, die duren lang en dan gaat het eerst langs prorail voordat er verder mee wordt gewerkt.

Ontwerpen voor onderhoud
Er wordt gedacht aan onderhoud: Waar plaats je je bovenleiding, waar plaats je je kastjes die op de bovenleidingmasten komen? -> Monteur kijkt naar rijrichting van de trein, mast tussen twee sporen – kast aan de buitenkant.
Secties in de bovenleiding, de rest van NL niet uitschakelen en of treinen er omheen kunnen rijden als de stroom van een deel wordt gehaald.
De sectie indeling worden in het begin van het ontwerpproces bepaald (rekening houden met de bovenleiding velden). Waar kastjes worden geplaatst en waar dat het meest gunstig is komt later in het proces.

Gebruik van tools bij het ontwerpen
De ontwerpers gebruiken een tool; de zichtlijn tool. Om te

bepalen of de machinist voldoende kan zien.
Alleen bij Specials wordt een Brainstormsessie gedaan. Verder worden er geen specifieke tools gebruikt. Wel worden er risicosessies gehouden. In het begin van het ontwerpproces. Bijvoorbeeld een vrachtwagen die een lightrail bovenleiding meeneemt. Daarvoor wordt de bovenleiding zelf niet vaak aangepast. Eerder de omgeving zoals een extra bord, hoogtebalk, extra rand of lichten.

Innovatie
Er ligt al snel heel veel vast, dus nieuwe dingen kunnen niet snel geïmplementeerd worden.
NL-markt is te klein om onderzoekskosten te compenseren. Buitenland geeft meer mogelijkheden.
Prorail heeft een tabel met verdiensten per stuk spoor, daarmee is uit te rekenen hoeveel een verbetering oplevert en of het terugverdient kan worden.

Kosten levenscyclus en efficiëntie van reparaties
De kostendeskundige neemt de kosten voor de hele levenscyclus mee. (Niet alleen de bouw, maar ook het onderhoud). Veel te winnen op kostengebied is de fasering, namelijk 's nachts werken, of de gehele dag en in het weekend of doordeweeks. Wordt er de gehele dag gewerkt, dan is er een buitendienststelling en worden bussen ingezet. 's Nachts is niet efficiënt, want men moet vaker terugkomen en elke keer moet er afgesloten, gecontroleerd dat er echt geen trein komt, met verkeersleiding bellen, en veiligheidsmaatregelen getroffen worden. Werk is ook 's nachts in het donker minder efficiënt. De aannemer vindt het fijn om overdag te werken, krijgt klachten over te veel werk 's nachts. Prorail en vooral NS hebben voorkeur voor s nachts i.v.m. met treinen die niet rijden en daardoor overlast veroorzaken.
Combinaties van werkzaamheden worden geprobeerd te maken, zoals een bovenleiding vervangen en tegelijk een wissel een kilometer verderop. Prorail doet het wel, maar is soms moeilijk met de vele aannemers. Zelf kan het voorkomen dat te veel tegelijk op een spoordeel gebeurd waardoor elkaar in de weg gezeten wordt en minder efficiënt wordt.
De kostenramingen worden door het project heen steeds specifieker. In het begin met een marge van +-50 procent. Als een project in de ontwerpfase te duur uitvalt kan het project gestopt worden, terwijl het volledige project binnen de begroting zou passen. Lastig met wisselende projectmanagers.

Gebruik van RAMS waarden
Standaard getallen (RAMS waarden) worden wel uitgerekend. Risico's en storingsaantallen zijn bekend. Managers willen deze getallen graag optimaal, maar de ontwerpers weten dat dit niet kan. Vooral bij safety en verstoringen wil men 0. Dit veroorzaakt overdimensionering. Het gevoel hierbij is maar langzaam groeiende. De voorstellen die voorgerekend en voorgelegd worden, laten zien dat de kosten niet opwegen tegen de kans dat er iets gebeurd. Dit soort problemen lopen tijdens het gehele project. Safety is vooral een spanningsveld. Een voorbeeld hiervan is overdimensionering van de treinbeveiliging.

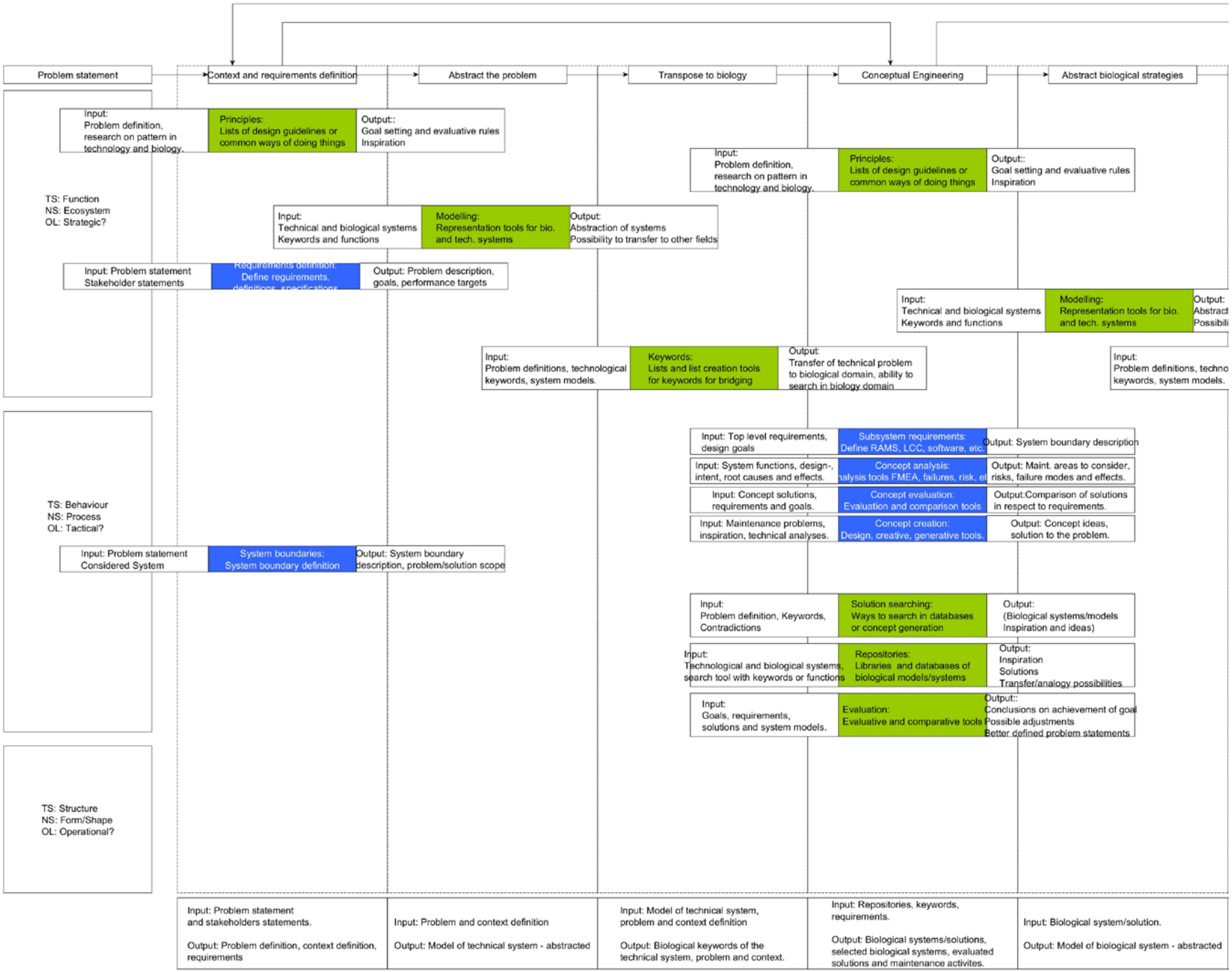
Meest voorkomende problemen met bovenleidingen en spoor
De meest voorkomende oorzaken van problemen zijn: Vrachtwagens die bovenleiding meeneemt en bomen die omvallen. Verder valt t mee. Verder is voor de bovenleiding standaard onderhoud nodig voor de slijtage. Dit is ingepland en wordt rekening mee gehouden. Andere veelvoorkomende problemen zijn ijsbrokken tussen de wissels en blaadjes op het spoor, dit veroorzaakt inslijten van spoorstaven en vierkante wielen. Daarnaast zijn blaadjes op het spoor vaak lokaal, maar wordt voor een groot spoorstuk aangegeven dat treinen verder uit elkaar moeten rijden.
Feedback naar ontwerper
De uitvoering van het project door de aannemer. Je mag als ontwerpbureau dan niet opnieuw daar onderdeel van uitmaken. Dus een ander ingenieursbureau wordt dan aangenomen als partner. Of de aannemer doet het project zelf. Het is aan de aannemer om aan te tonen of het gebouwde voldoet aan de eisen. Het ontwerpteam mag meekijken en schrijft de opmerkingen op, die worden naar Prorail gegeven en verder wordt er geen controle uitgevoerd vanuit de ontwerpers. Er is wel terugkoppeling, als een aannemer een probleem of nieuwe/betere oplossing wil bespreken wordt dat gedaan met het ontwerpteam. Ook binnen de fases van het ontwerpteam wordt weleens terug gestapt naar een eerdere fase om een specifiek probleem anders aan te pakken.

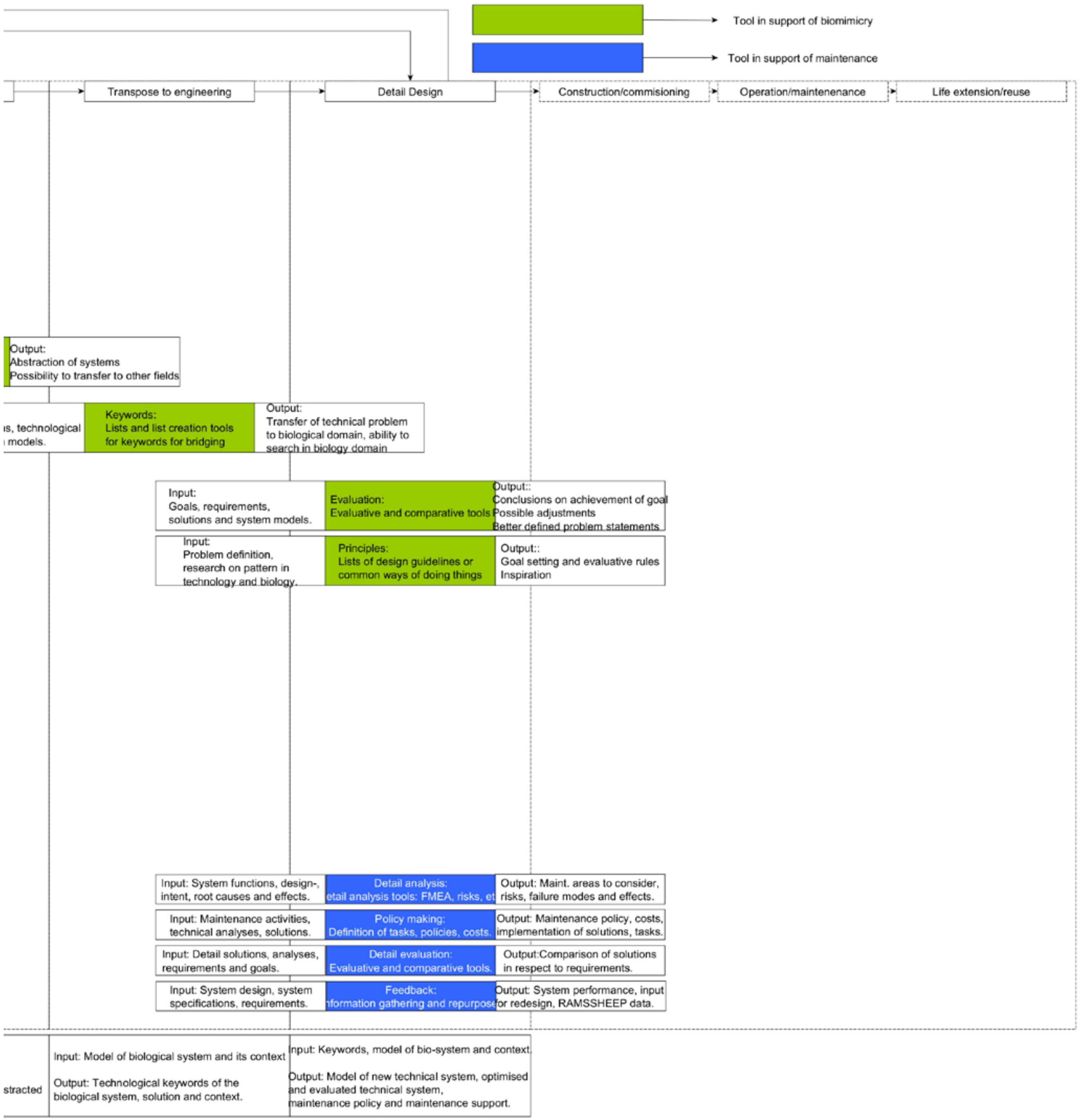
Toegevoegde discussie en conclusies:
Het ontwerpproces dat gevolgd wordt heeft de structuur van een productontwerp proces of systeemontwerp proces. De fases zijn ingericht naar een structuur van schetsontwerp, detail ontwerp en uitvoeringsontwerp.
Er is aangegeven dat er weinig specifieke tools worden gebruikt (alleen Zichtlijn tool voor de machinist) en dat er weinig analyse, onderzoek en vernieuwing voor de projecten wordt gedaan. Echter, worden 'onbewust' een aantal belangrijke analyses meegenomen in het ontwerpproces. Zoals: Een brainstormsessie bij de Specials, een risicoanalyse, levenscyclus kostenanalyse, RAMS-waarden zijn beschikbaar en extern door Prorail een feasability

onderzoek. Daarnaast wordt specifiek voor onderhoud wel nagedacht over de secties in de bovenleiding (afschakelen voor onderhoud). En over de veiligheid van de monteurs (monteur kijkt naar richting waaruit de trein komt tijdens het werk bij elektriciteitskastjes).
Ontwerpen voor maintenance wordt niet expliciet en gestructureerd gedaan bij het ontwerpen van een bovenleiding. Het lijkt erop dat dit voornamelijk automatisch/inherent wordt meegenomen door het volgen van de vele standaarden en richtlijnen die al vastliggen en vanuit de ervaring van de ontwerper. Echter, worden er wel belangrijke onderwerpen behandeld in het proces.
Door ontwerpen voor onderhoud structureel te benaderen en de juiste tools combineren met de huidige manier van werken zijn er waarschijnlijk verbeteringen mogelijk. Een structuur geeft de zekerheid dat bepaalde onderwerpen behandeld zijn en tools en methodes kunnen helpen om het inhoudelijke resultaat te optimaliseren.

Appendix D

Appendix E


Problem statement
Context and requirements definition
Abstract the problem
Transpose to biology
Conceptual Engineering
Abstract biological strategies
Input: Problem definition, research on pattern in technology and biology.
Principles: Lists of design guidelines or common ways of doing things
Output:: Goal setting and evaluative rules Inspiration
TS: Function NS: Ecosystem OL: Strategic?
Input: Technical and biological systems Keywords and functions
Modelling: Representation tools for bio. and tech. systems
Output: Abstraction of systems Possibility to transfer to other fields
Input: Problem statement Stakeholder statements
Requirements definition: Define requirements, definitions, specifications
Output: Problem description, goals, performance targets
Input: Problem definitions, technological keywords, system models.
Keywords: Lists and list creation tools for keywords for bridging
Output: Transfer of technical problem to biological domain, ability to search in biology domain
Input: Top level requirements, design goals
Subsystem requirements: Define RAMS, LCC, software, etc
Output: System boundary description
Input: System functions, design-, intent, root causes and effects.
Concept analysis: Analysis tools FMEA, failures, risk, etc
Output: Maint. areas to consider, risks, failure modes and effects.
Input: Concept solutions, requirements and goals.
Concept evaluation: Evaluation and comparison tools
Output:Comparison of solutions in respect to requirements.
Input: Maintenance problems, inspiration, technical analyses.
Concept creation: Design, creative, generative tools.
Output: Concept ideas, solution to the problem.
TS: Behaviour NS: Process OL: Tactical?
Input: Problem statement Considered System
System boundaries: System boundary definition
Output: System boundary description, problem/solution scope
Input: Problem definition, Keywords, Contradictions
Solution searching: Ways to search in databases or concept generation
Output: (Biological systems/models Inspiration and ideas)
Input: Technological and biological systems, search tool with keywords or functions
Repositories: Libraries and databases of biological models/systems
Output: Inspiration Solutions Transfer/analogy possibilities
Input: Goals, requirements, solutions and system models.
Evaluation: Evaluative and comparative tools
Output:: Conclusions on achievement of goal Possible adjustments Better defined problem statements
TS: Structure NS: Form/Shape OL: Operational?
Input: Problem statement and stakeholders statements.
Output: Problem definition, context definition, requirements
Input: Problem and context definition
Output: Model of technical system - abstracted
Input: Model of technical system, problem and context definition
Output: Biological keywords of the technical system, problem and context.
Input: Repositories, keywords, requirements.
Output: Biological systems/solutions, selected biological systems, evaluated solutions and maintenance activites.
Input: Biological system/solution.
Output: Model of biological system - abstracted



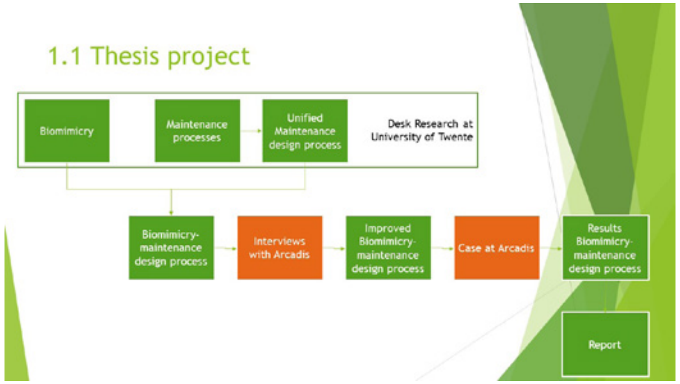
Tool in support of biomimicry
Tool in support of maintenance
Transpose to engineering
Detail Design
Construction/commisioning
Operation/maintenenance
Life extension/reuse
Output:
Abstraction of systems
Possibility to transfer to other fields
Keywords:
Lists and list creation tools
for keywords for bridging
Output:
Transfer of technical problem
to biological domain, ability to
search in biology domain
Input:
Goals, requirements,
solutions and system models.
Evaluation:
Evaluative and comparative tools
Output::
Conclusions on achievement of goal
Possible adjustments
Better defined problem statements
Input:
Problem definition,
research on pattern in
technology and biology.
Principles:
Lists of design guidelines or
common ways of doing things
Output::
Goal setting and evaluative rules
Inspiration
Input: System functions, design-, intent, root causes and effects.
Detail analysis:
etail analysis tools: FMEA, risks, et
Output: Maint. areas to consider, risks, failure modes and effects.
Input: Maintenance activities, technical analyses, solutions.
Policy making:
Definition of tasks, policies, costs.
Output: Maintenance policy, costs, implementation of solutions, tasks.
Input: Detail solutions, analyses, requirements and goals.
Detail evaluation:
Evaluative and comparative tools.
Output:Comparison of solutions in respect to requirements.
Input: System design, system specifications, requirements.
Feedback:
nformation gathering and repurpose
Output: System performance, input for redesign, RAMSSHEEP data.
Input: Model of biological system and its context
Output: Technological keywords of the biological system, solution and context.
Input: Keywords, model of bio-system and context.
Output: Model of new technical system, optimised and evaluated technical system, maintenance policy and maintenance support.

Appendix F

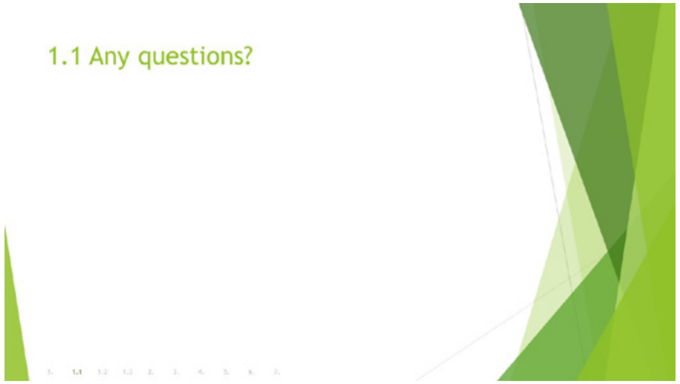

Workshop: Finding nature-inspired solutions for building renovations
Part of research: Development of a Framework for the design of nature-inspired maintenance solutions based on a biomimicry methodology.
UNIVERSITY OF TWENTE.
ARCADIS
Martijn Bergsma - 21-12-17

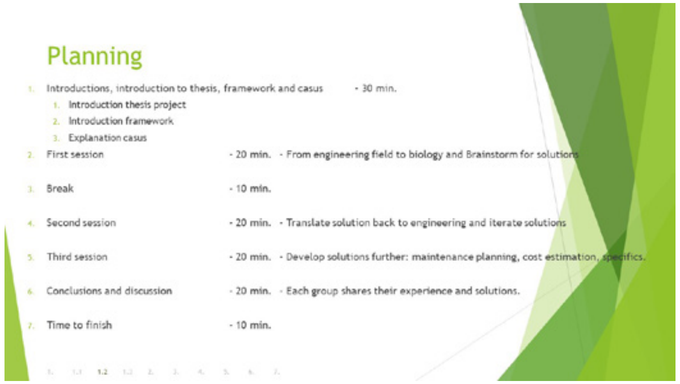

Introductions
Name and field of work.

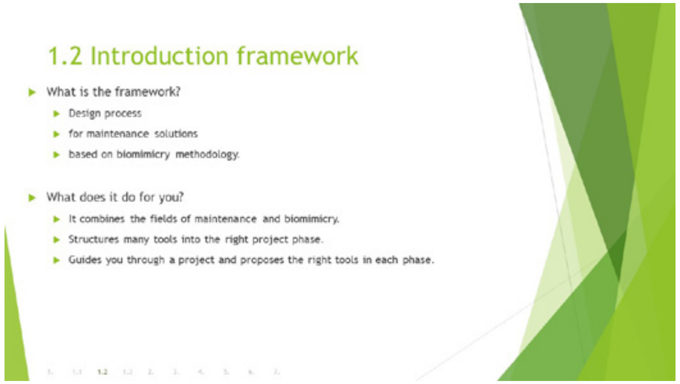

1.1 Thesis project
Universiteit Twente, Industrial Design Engineering, Martijn Bergsma.
Maintenance engineering, Alberto Martinetti.
Use biomimicry to develop better solutions for maintenance (design for maintenance).
Maintenance is needed for infrastructure, machines, buildings, etc.
What if?: Create assets with less maintenance, less maintenance costs and lifecycle costs.
Nature and organisms survive in very specific environments.
By adaptations to the environment organisms are very resilient and efficient with their resources.
Learn from nature by using their solutions to solve our technical problems -> Biomimicry

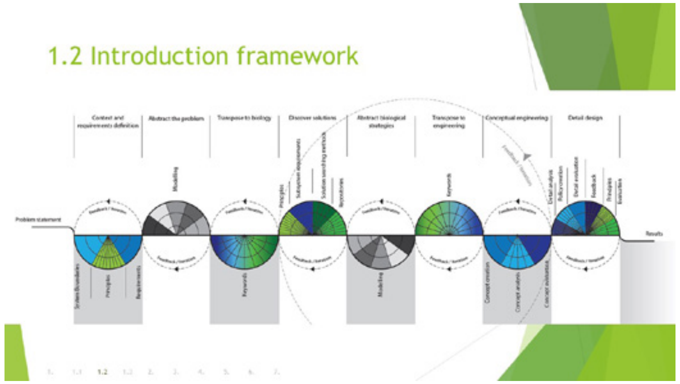

1.1 Thesis project
Biomimicry
Maintenance processes
Unified Maintenance design process
Desk Research at University of Twente
Biomimicry-maintenance design process
Interviews with Arcadis
Improved Biomimicry-maintenance design process
Case at Arcadis
Results Biomimicry-maintenance design process
Report

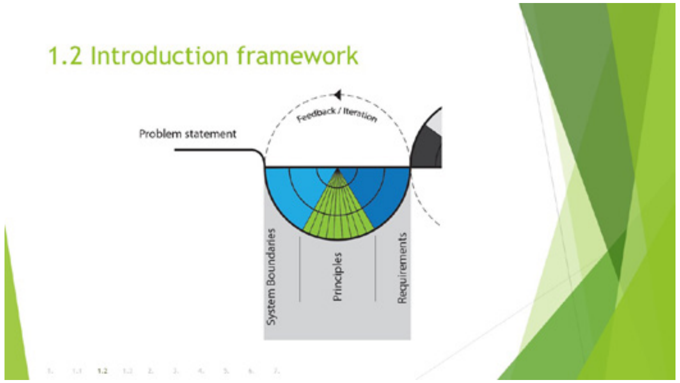

1.1 Goal of the workshop
Get feedback on the framework
Please write down any comment.
Find solutions to compare with real case result
Framework guides the workshop (and future design processes)

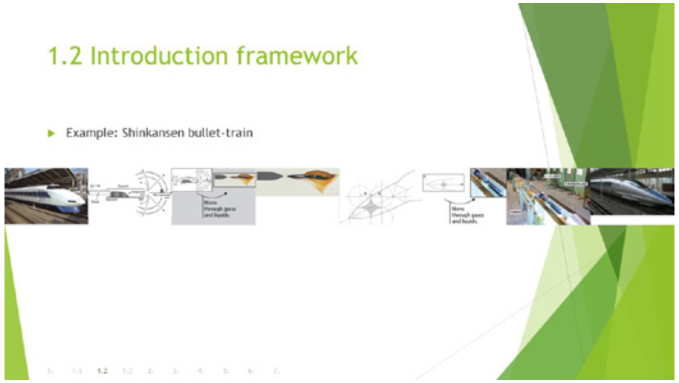

1.1 Any questions?

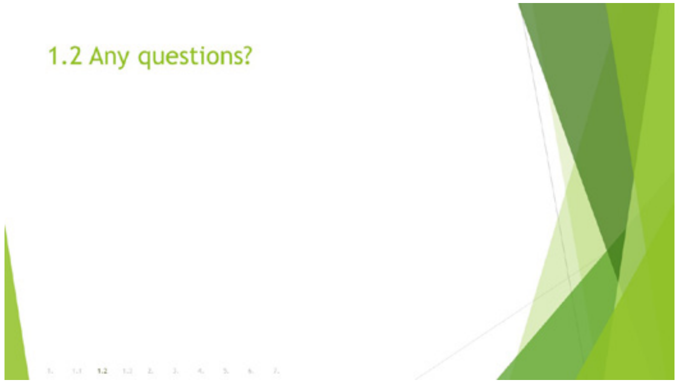

Planning
1. Introductions, introduction to thesis, framework and casus - 30 min.
1. Introduction thesis project
2. Introduction framework
3. Explanation casus
2. First session - 20 min. - From engineering field to biology and Brainstorm for solutions
3. Break - 10 min.
4. Second session - 20 min. - Translate solution back to engineering and iterate solutions
5. Third session - 20 min. - Develop solutions further: maintenance planning, cost estimation, specifics.
6. Conclusions and discussion - 20 min. - Each group shares their experience and solutions.
7. Time to finish - 10 min.


1.2 Introduction framework
What is the framework?
Design process
for maintenance solutions
based on biomimicry methodology.
What does it do for you?
It combines the fields of maintenance and biomimicry.
Structures many tools into the right project phase.
Guides you through a project and proposes the right tools in each phase.

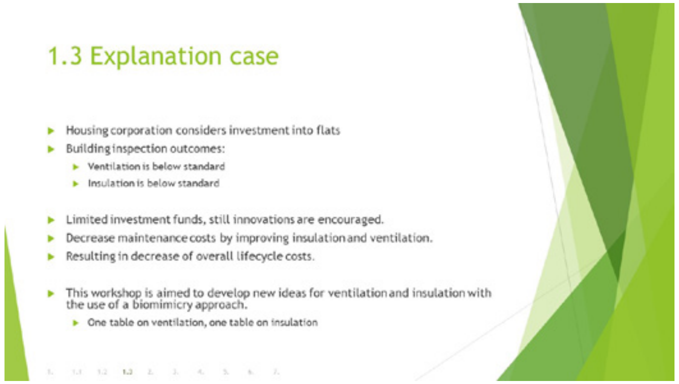

1.2 Introduction framework


1.2 Introduction framework
Problem statement
Feedback / Iteration
System Boundaries
Principles
Requirements


1.2 Introduction framework
Example: Shinkansen bullet-train

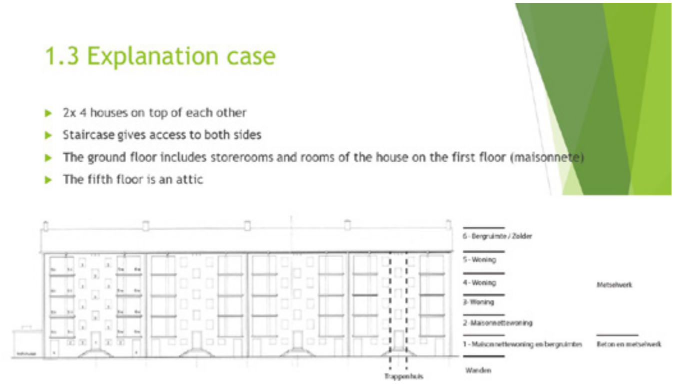

1.2 Any questions?


1.3 Explanation case


1.3 Explanation case
Housing corporation considers investment into flats
Building inspection outcomes:
Ventilation is below standard
Insulation is below standard
Limited investment funds, still innovations are encouraged.
Decrease maintenance costs by improving insulation and ventilation.
Resulting in decrease of overall lifecycle costs.
This workshop is aimed to develop new ideas for ventilation and insulation with the use of a biomimicry approach.
One table on ventilation, one table on insulation

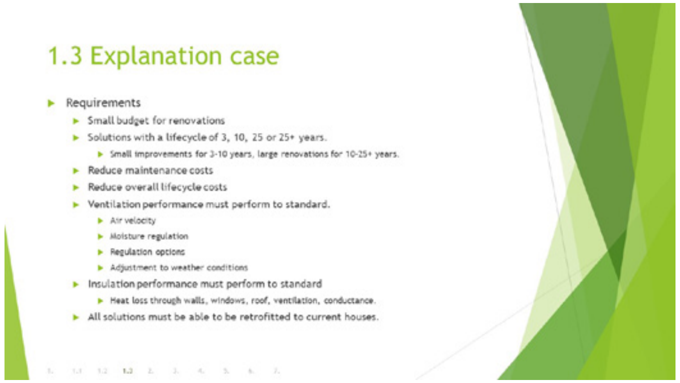

1.3 Explanation case
Information on the tables
Case information
Views of the buildings
Maps
Research results
Inspiration sources
Biology related books
Framework
Writing and Feedback material
Pens and paper


1.3 Explanation case
6 complexes
208 houses
Built around 1950
Renovated around 1985

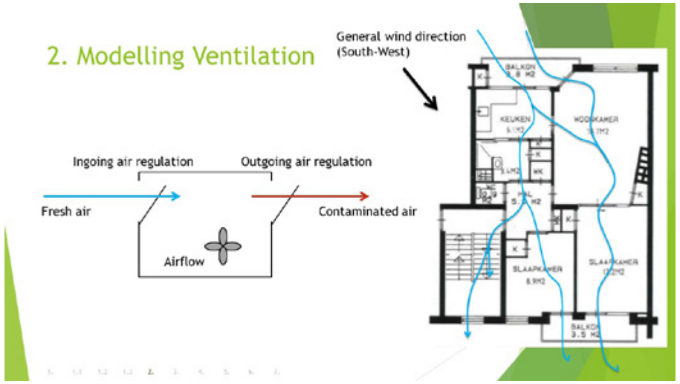

1.3 Explanation case
2x 4 houses on top of each other
Staircase gives access to both sides
The ground floor includes storerooms and rooms of the house on the first floor (maisonnete)
The fifth floor is an attic
6 - Bergruimte / Zolder
5 - Woning
4 - Woning
3 - Woning
2 - Maisonnettewoning
1 - Maisonnettewoning en bergruimtes
Wanden
Trappenhuis
Metselwerk
Beton en metselwerk

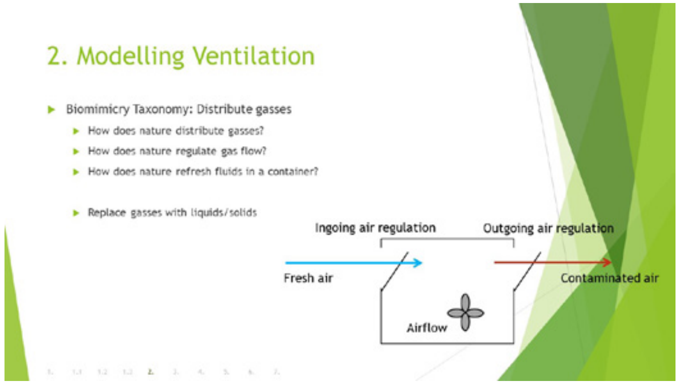

1.3 Explanation case
Insulation
All walls are made of bricks.
Kopgevels hebben een spouw, langsgevels niet.
1 kopgevel is insulated on the outside (ISPO system).
Window frames are partially wood, and partially plastic.
Most plastic window frames have double-glass windows. (Not HR++)
Roof is not insulated.
Concrete balconies form cold-bridges (koudebruggen).
Houten kozijnen: algemene ruimtes en bergingen
Kunststof kozijnen met dubbelglas: woningen

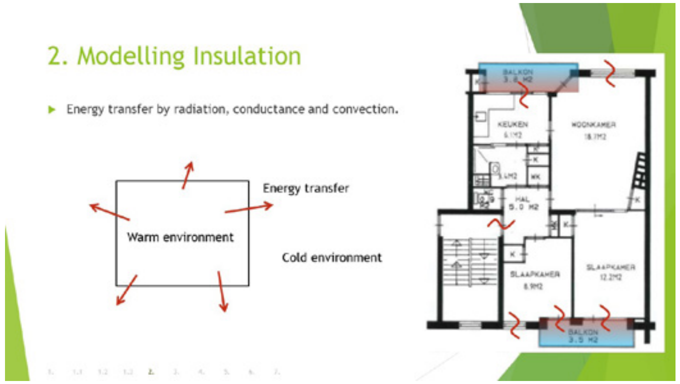

1.3 Explanation case
Ventilation
Based on natural ventilation, no dynamic regulation.
Registers (ventilatieroosters) often dirty and closed.
Old doors and windows do not close properly, induces draught.
Kitchens and bathrooms have problems with moulds and moisture.
Ventilatieroosters
l:Back - r:Front

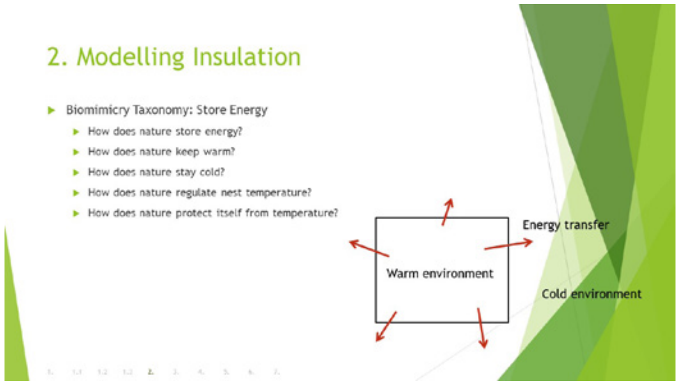

1.3 Explanation case
Requirements
Small budget for renovations
Solutions with a lifecycle of 3, 10, 25 or 25+ years.
Small improvements for 3-10 years, large renovations for 10-25+ years.
Reduce maintenance costs
Reduce overall lifecycle costs
Ventilation performance must perform to standard.
Air velocity
Moisture regulation
Regulation options
Adjustment to weather conditions
Insulation performance must perform to standard
Heat loss through walls, windows, roof, ventilation, conductance.
All solutions must be able to be retrofitted to current houses.


1.3 Any questions?


2. Modelling Ventilation
General wind direction
(South-West)
Ingoing air regulation
Outgoing air regulation
Fresh air
Contaminated air
Airflow
BALKON
KEUKEN
WOONKAMER
SLAAPKAMER
SLAAPKAMER
BALKON


2. Modelling Ventilation
Biomimicry Taxonomy: Distribute gasses
How does nature distribute gasses?
How does nature regulate gas flow?
How does nature refresh fluids in a container?
Replace gasses with liquids/solids
Ingoing air regulation
Outgoing air regulation
Fresh air
Contaminated air
Airflow


2. Modelling Insulation
Energy transfer by radiation, conductance and convection.
Energy transfer
Warm environment
Cold environment
BALKON
KEUKEN
WOONKAMER
SLAAPKAMER
SLAAPKAMER
BALKON


2. Modelling Insulation
Biomimicry Taxonomy: Store Energy
How does nature store energy?
How does nature keep warm?
How does nature stay cold?
How does nature regulate nest temperature?
How does nature protect itself from temperature?
Energy transfer
Warm environment
Cold environment


2. Session 1: Discover solutions
Now it is up to you!
Find organisms that answer the questions.
Resources: Biology books, asknature.org, bionikinspiration.org, favourite movie/show/animal, plant from your garden, imagine walk in the woods.
Brainstorm: Draw, list ideas, share ideas, mindmap, iteration.
How does nature distribute gasses?
How does nature regulate gas flow?
How does nature refresh fluids in a container?
How does nature store energy?
How does nature keep warm?
How does nature stay cold?
How does nature regulate nest temperature?
How does nature protect itself from temperature?

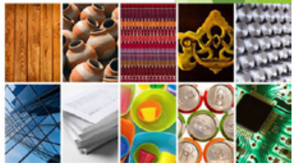

2. Session 1: Share
Each group pitches their ideas
Quick reactions from each group

3. Break!

- Get a cup of coffee!
- And meanwhile; write down what you think of: the framework
- the application of the framework
- the biomimicry steps
- the workshop

4. Session 2: Transfer and iteration

- Make an analytical model of your biology idea
- Describe an engineering solution that uses the principles of your idea
  - Think of materials, how it works, resources, in- and outputs.
- Got another idea; model and describe it as well!
- Try to change, improve, develop your idea.



4. Session 2: Share

- Each group pitches their technical solutions
- Quick reactions from each group

5. Session 3: Detail design

- Choose one idea/solution/adjustments/system.
- Define kind of solution: Short term 3-10 years (improvements) or long term 10-25+ years (renovations).
- Divide the system in main logical parts.
- Describe for each part: materials needed.
- activities to implement the part.
- main regular maintenance activities for that part.
- Try to estimate costs per house for each described subject.
- Describe why your solution is better than current situation.
- Anything else to describe, specialties?

6. Conclusions and discussions

- Each group presents their final solution
- Reactions on any of the ideas
- What do you think about the framework? - Please, write down your reactions!
  - Does each step contribute/fit in this order?
  - Do you think the framework guides on what to do during a project / or on using certain tools?
  - Do you see value in using the framework in projects at Arcadis?
  - Do you think the framework combines maintenance and biomimicry?
  - Do you see a future (use) for the framework?
- What do you think about this workshop and your experience today?

7. Finalizing

- Thank you!!