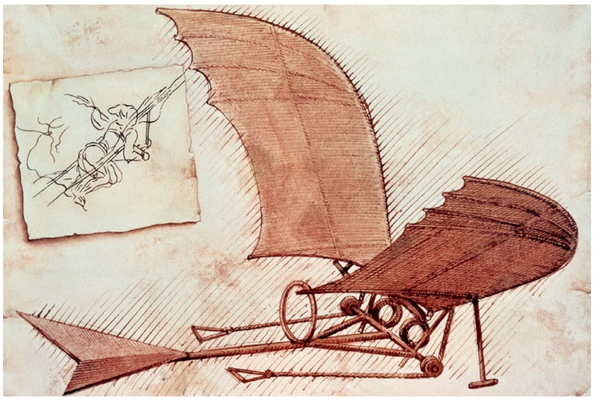
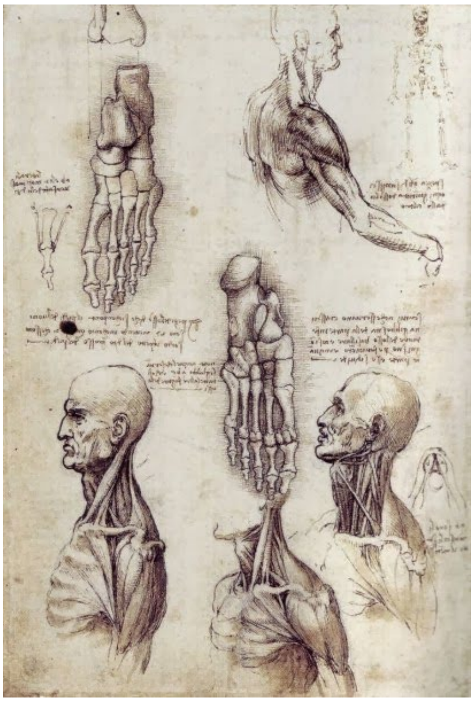
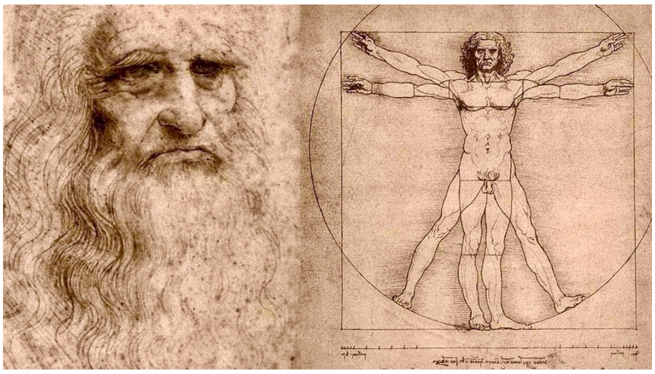
SYLLABUS – CME5030
R&D METHODOLOGY & MANAGEMENT FOR E&S







STUDY LOAD	5 ECTS
EDUCATION PERIOD	Q4 Start: May 2023
CONSTRUCTORS	Prof. Dr. Ir. A.R.M. Wolfert Dr. Ir. R. Binnekamp

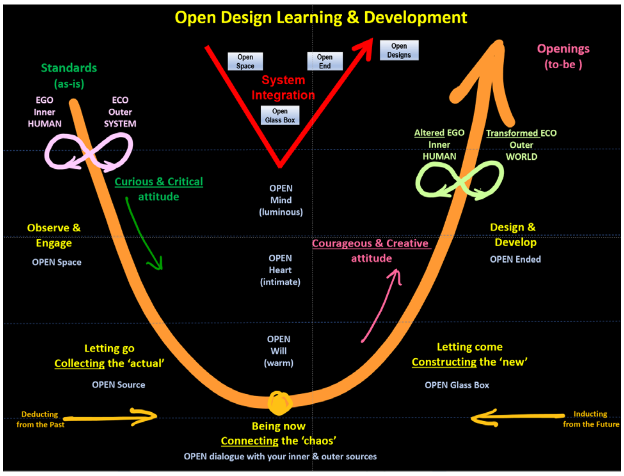
Version April 2022

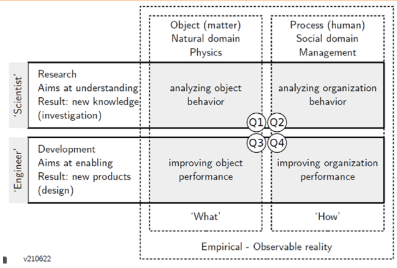
1 GENERAL INFORMATION

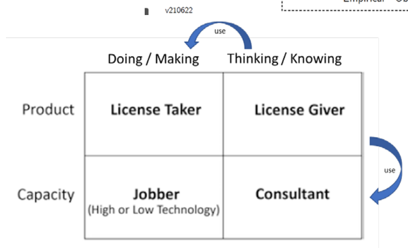
This course is intended to prepare students for their final MSc thesis project either with a research or with a development flavor (conjecture thinking vs. design thinking). The 4 types of problem (dis)solving will be discussed. The students will get experience with these two main research (hypotheses) and development (prototypes) approaches and associated typical Research and Development (R&D) methodologies and management. The ‘contradictio in terminis’ of the term R&D management will be handled : organic leadership vs. bureaucratic management. The two conditions for successful socio-technological innovation (R&D), excellence and intrinsic motivation to a common purpose, constitute the basis for the classification of business identities in the strategic business concept of License Giver, License Taker, Jobber, Consultant, briefly referred to as the License Giver business concept.
The concept of open idealized design learning & development connected with the intuitive thinking U-model is introduced (and it’s theory: open heart, open will and open mind). The process of developing from an idealized design (imagination, inspiration and intuition) towards best fit for common socio-eco purpose (integrating common ground, common sense, common interest:) will be incited. The concept of and thinking fast and slow (SI and SII) will be introduced.
Different organizational development phases and/or maturity levels (emerge, develop and mature) and it’s innovative potential are discussed: (1) Pioneer- (birth and first expansion) (2) Differentiated- (on-going expansion and isolated maturity) (3) Integrated (connective maturity)- (4) Associative phase (purpose maturity). The cooperation/partnering evolution can be distinguished by ‘management’ approaches and their particular partner features: 1) vertical alignment, 2) horizontal alignment.
Finally different organizational embedding organizational systems dimensions will be evaluated: (1) governmental innovation interference (2) the freedom to excel (3) the power game (4) intercultural dimensions

The general concepts of this course read as:

1. Scientific research Question vs. Engineering development Statement (4Q-model).
2. The license giver business concept (License giver/taker and Jobber/Consultant).
3. Open idealized design for common purpose and the will to lead
4. The living enterprise for the future – rise and decline of innovative capabilities
5. Governmental interference & embedding innovation dimensions
6. The Game of Excellence – freedom to excel
7. Special R&D organizational concepts – (1) the power game (2) intercultural dimensions







1.1 Teaching concept: Open Design Learning (ODL)

The Open Design Learning concept (ODLc) is an innovative educational concept for higher education. It is a reflective, creative and engaged learning approach that opens human development and unlocks new knowledge and solutions. ODLc stimulates students' curiosity, clarity and creativity. ODLc teachers and students are working in an open spirit levelling relation.
The ODL approach connects the inner personal learning ego and the outer real world eco. ODL integrates the student's learning and development via the U-model with the engineering system development via the V-model. Here the U-model constitutes experiential learning with an open mind, open heart, and open will design approach. The V-model represents an engineering system development process from an open-source, open-ended, and open glass-box modeling design approach. So in other words, the ODL teaching concepts integrates experiential and design based learning.
The students and the teachers cooperate in a living dialogue in- and on-action. This co-reflective dialogue creates an open space where alternative views can co-exist and new insights can be conceived. Students learn via a self-chosen system of interest arriving at an original response demonstrating their individual learning achievements. The ODLc forms the fundamental basis for creating 'open, integrative and persistent learners' concerned about solving future world problems. For more information on Open Design Learning (ODL) and it's concepts, see: www.open-design.school.

For this course the ODLc is implemented as follows. Every week students are asked to study specific concepts and apply these to their self-chosen R&D organization of interest (OoI) by means of a self-created response / logical diagrams The teachers incite the course concepts as a reflective practitioner using both reference books and dialogue questions from the students. The students have 2 hours of these concept and dialogue sessions and 4 hours of reflective work sessions. During the first 2 weeks the concepts will be introduced. During the remaining weeks the students work in translating concepts to their OoI. During the work sessions, students can work on their ODL response under supervision of the teacher/constructor. On top of this, a masterclass is used where students and constructors co-reflect on a student's concept translation.

In this course, the 'deep' U-approach will be based on front-loading the incitements and concepts over 1st half of the course, the first 5 weeks (including the self-chosen choice of a CoI) and construction and co-transforming during practical works and masterclass sessions over the remaining 3-5 weeks (2nd half of the 10 weeks period).

After this course students should be able to:

- Be familiarized with and understand Research and Development (R&D) concepts, principles and practices, by (i) dialoguing these with the constructors, (ii) navigating through the R&D reference documents and (iii) engaging to a self-chosen real-life R&D organization of interest (OoI).
- Form an individual judgement and appraise academic R&D output on whether this (i) is part of the body of knowledge (researcher- new scientific theory) or body of products (developer - new engineering system) and (ii) makes properly use of research questions, hypotheses, development statements, prototypes, including their respective R&D methods, within both the natural sciences and social sciences context.
- Examine and relate these abstract R&D concepts, by (i) constructing OoI specific models, (ii) dialoguing with these models and (iii) experiencing these with the OoI and its reflective practice.
- Rework and transform the OoI specific R&D concepts observations, by (i) transforming and linking the dialogues and experiences into new insights and (ii) developing improvement results where applicable.
- Form an individual judgement and appraise these new insights/results by means of a conspection between these and the original concepts within the specific context of the OoI.
- Create an original Open Design Learning (ODL) response that (i) integrates all concepts, (computer) models, new insights and developed results and (ii) demonstrates the internalization process of the aforementioned learning goals and conveys the ODL achievements. Reflection(1) & introduction: Concept sessions.

1.2 Concept & introduction: Incitement sessions

The concept sessions start with a brief dialogue part where the teachers go over the different dialogue questions that emerged during the practical meeting of the previous week. Dialogue questions are questions that are general and of interest for all students (not necessarily linked to an individual OoI). The second part of these sessions are about introducing the new concepts. Each new concept needs to be translated and transformed towards the OoI. These concept sessions are being organized by the constructors (overall responsible teachers).

This year's course is structured as follows:

- Week 1 and 2 are devoted to introducing all course concepts. Each student also has to start searching for their OoI. This search should be finalized at the end of week 2.
- The remaining weeks are devoted to practical work sessions. These sessions allow students to work on their ODL response under supervision of the teacher/constructor.
- At the end of the course a masterclass is scheduled which is meant for feedback from the teachers/constructors on the work of selected students.

1.3 Transformation: Practical work sessions

The practical work sessions are scheduled from week 3 onward. These are sessions where you can get feedback from your teachers. These are on campus work sessions.

1.4 Reflection (2): Masterclass sessions

A masterclass is a short event in which one or more students share their **work in progress** followed by feedback from the teachers. There is no formal evaluation. The goal of a masterclass is to identify a student's issues, problems, ideas and opportunities that mostly also apply to other students.
We have experienced masterclasses to be very useful, both by the students who share their work and by the attending students. For this course 1 masterclass is planned in week 7.

1.5 Learning vehicle: the Organization of Interest

At the start of this course groups of 2 must be formed and each group must choose an Organization of Interest (OoI) from the Architecture, Engineering and Construction (AEC) industrial domain. In order to be able to convert all course concepts, it is important that the OoI meets the following criteria:

- has an R&D and/or innovation and/or business development entity;
- its the turnover exceeds 5 mio EUR.
- you are able to get in touch with an innovation/development manager within the OoI;
- you are able to organize an interview with a board of management director of the OoI.

The OoI must be approved by the lecturers. The first few practical sessions allow you to discuss the candidate OoI with your teachers. The OoI must be approved by the lecturers. Approval is based on a short document that you send **latest 29 April**. This proposal contains a short description of your OoI, how you are connected and how you plan to obtain the required information.

1.6 Deliverable: the ODL response

All of these should be presented in a self-chosen format such as report/ elaborative presentation/ digital audio or video files/ animation/ website…. The ODL response illustrates how the general concepts have been linked and evaluated to the self-chosen OoI using a: 1) logical review and/or 2) model(s).

Some hints for finalizing your response:

- Start your response with a management summary that already catches the imagination of its 'beholder'.

- Take care of your response's signal to noise ratio. For each piece of information, ask yourself: would it hurt the line of reasoning if I left it out? Usually less is more. Note: the response is not a day to day report of what you have done.
- Don't assume that the number of pages correlates with the final grade. In our experience usually the opposite holds as it takes much time to end with the most agile line of reasoning.
- Your final response can be achieved by backwards engineering. After you have translated all concepts you will have enough of an overview to put all parts together into a coherent and well-structured response.
- Do not repeat what is in the reference material. Your text will be unique because you used reference material to link it to your OoI.
- Only use references that support your line of reasoning.

Students should demonstrate how and/or if these concepts are being utilized and the rationale behind its specific use(fullness). **The final ODL response needs to be handed in no later than 24 June 2022.**

1.7 Judgment: the ODL commendation

The Open Design Learning commendation principle will be applied as a grading rubric for the ODL response. Both the OoI content characteristics, and the student's learning process are integrated within these commendation principles.
We call it 'commendation' because when we grade your response, we start from a grade of 10 and only deduct points if aspects are missing/only partially worked out.

Commendation Categories	**Relates to:**	**Expressed in (the making of) the ODL response:**
Connect	Learning process	Showing courage, being curious, being a creative problem solver. Engagement factor.
Construct	Model / concept transformation, improvement proposals and verification	Showing proper concept conversion, conceptions for improvements, correctness in modeling. Going the extra mile in concept conversion. Content factor.
Conclude& Conspect	Developed results, validation and reflection	Showing a cyclical approach, dealing with completeness, conspection of own work. Overview factor.
Convey	Reporting and presenting the response	Showing a clear line of reasoning. Being concise (signal to noise ratio). Not copying reference material. Straightforward factor.
Convince	Response speaking to / arousing the imagination	Being cogent and demonstrating a critical attitude. Compelling factor.

After handing in the ODL response your will receive your grade. To pass the course your ODL commendation grade should be higher than or equal to 6. After commending your ODL response **one plenary open dialogue session** (max. 3 hours, somewhere between **week 12 and 14** to be announced) with one of the constructors will be scheduled. Only during this session(s) we can reflect on your ODL response: bear in mind, the outcome of this reflection can result in a lower/equal/higher grade.

- If your grade is higher than or equal to 6 you can learn the rationale behind this commendation. This does not mean that you can use the provided feedback to improve your response and re-upload to get a higher grade.
- If your grade is below a 6 your will receive (prior to the session) a constructive and written proposal for improving your ODL response with a specific deadline. During the aforementioned session you can discuss this proposal in more detail on how to update your ODL response which will be commended with a maximum grade of 6.

2 WEEKLY COURSE CONTENT: THE ODL CONCEPTS

The course consists of two types of meetings: 1) a dialogue and concept introduction session (IS) and 2) a reflection and practical work session (PW). The dialogue and concept introduction sessions are scheduled in week 1 and 2, the reflection and practical work sessions are scheduled in the remaining weeks.

Week	Session	Concept	Topic	Constructor	ODL activity / product
1	IS WED 20 April 13:45 – 15:30	Scientific research Question vs. Engineering development Statement within both the natural & social sciences – C#1	• Science • Technology • Research • Development • Natural sciences • Social sciences • Management • Science is never settled • Falsifiability (Popper) • Reproducibility • Ockam's razor • Value free / Value driven	RW, RB ❶	• Search for suitable OoI within AEC industry. • Study related material.
	IS THU 21 April 8:45 – 10:30	The license giver business concept – C#2	• Business identity • License giver • License taker • Jobber • Consultant • Engineering design • Fitness for purpose • Technological balance • State of the art technology • Design quality • Innovation • Renewal	RW, RB ❷	• Search for a suitable OoI. • Study related material.
2*	IS MON 25 April 10:45 – 12:30	The intrinsically motivated crowd – the Idealized design & The rise and decline of innovative capability – C#3 , C#4	• Common purpose • Innovation endeavors • Technological progress • Work culture • Organizational development phases • Organizational structures • Transitioning	RW, RB ❸	• Search for a suitable OoI. • Study related material.
	IS THU 28 April 8:45 – 10:30	The license giver business concept in the evolution of industries & Governmental interference & Excellence through competence – keywords – C#5 , C#6 , C#7	• Development stages • Industry evolution • Outsourcing and subcontracting • OEMs • Horizontal vs vertical alignment • Industry platforms • Rational view of innovation • Failure and incompetence • Technological progress	RW, RB ❹	• Upload OoI proposal.* • Study related material.
3*	**PW** MON 2 May 10:45 – 12:30			LvG, RB ①	Integrating concepts in your ODL response.
4	**PW** MON 9 May 10:45 – 12:30			LvG, RB ②	Integrating concepts in your ODL response.
5	**MC** MON 16 May 10:45 – 12:30	ODL response development		LvG, RB ①	Presenting ODL response WIP
6	- MON 23 May 10:45 – 12:30	ODL response development	No practical.	-	
7	**PW** MON 30 May 10:45 – 12:30	ODL response development		LvG, RB ③	Integrating concepts in your ODL response.
8	**MC** MON 16 May 10:45 – 12:30	ODL response development		LvG, RB ②	Presenting ODL response WIP
10	FRI 24 June				• Upload your final response.

* This proposal contains a short description of your OoI, how you are connected and how you plan to obtain the required information.

In the following sections practical guidelines (sessions, practical work, literature, etc.) are given for each weekly concept mentioned in section 1.1 and the lecture schedule.

Concept 1: Scientific research vs. Engineering development (4Q model)

It is important to make a distinction between scientific research and engineering development because the line of reasoning and end result that scientists aim for is fundamentally different from that of engineers. Where scientists strive for knowledge acquisition, engineers strive for technical action. This closely relates to the two domains that humans function in: the domain of the material reality and the domain of the mind. Given these two domains we can distinguish two directions: 1) a process from the outside to the inside (from the material reality to the domain of the mind) - a process that we call knowledge acquisition - and, 2) a process from the inside to the outside (from the domain of the mind to the domain of the material reality), we call technical action.

CEG students, concerned with civil engineering objects, mainly operate within the natural sciences, more specifically, physics. Physics is a natural science that involves the study of matter and its motion through space-time, along with related concepts such as energy and force. CME students, concerned with organizing or managing the design, realization, and operating process of these objects, mainly operate within the social sciences. The social sciences are the fields of scholarship that study society. Management can be defined as the organization and coordination of the (human) activities of business organizations in order to achieve defined objectives.

ODL building block: find a project within your OoI and for each of the 4 quadrants do the following:

1. Describe the context of the problem that needs to be addressed.
2. Describe the gap: what is unknown yet (Q1/Q2) or cannot be done yet (Q3/Q4).
3. Determine the research question (Q1/Q2) or development statement (Q3/Q4).
4. Describe how data will be collected (Q1/Q2) or requirements will be determined (Q3/Q4).
5. Describe what research methods (Q1/Q2) or design methods (Q3/Q4) are likely to be used.
6. Describe the expected end result and how it will be evaluated (Q1/Q2) or validated (Q3/Q4).

Reference material:

- Roozenburg and Eekels, Product Design: Fundamentals and Methods, Wiley, 1995. Sections 3.1 to 3.4, section 4.4, sections 5.1, 5.2 and 5.5.

Concept 2: The license giver's business concept

The two conditions for successful socio-technological innovation, excellence and intrinsic commitment to a common purpose, constitute the basis for the classification of business identities in the strategic business concept of License Giver, License Taker, Jobber, Consultant, briefly referred to as the License Giver business concept. The concept is extended here by including design quality as a guiding principle in the License Giver's strategic decision making.

ODL building block: Determine and appraise the identity of your OoI.

Reference material:

- Van Gunsteren and Vlas, The Licence Giver Business Concept of Technological Innovation. Springer, 2022. Chapter 1 and 2.

Students can use the following link:

https://link.springer.com/book/10.1007/978-3-030-91123-2

Concept 3: Open idealized design for common purpose and the will to lead

The common goal of innovating endeavors to create new products that significantly contribute to socio-technological progress inspires everyone involved. The mindset of an intrinsically motivated crowd is a characteristic feature of the innovative organization and its work culture. The concept of open idealized design learning & development connected with the U-model is introduced (and it's theory: open heart, open will and open mind). The process of developing from an idealized design (imagination, inspiration and intuition) towards best fit for common socio-eco purpose (integrating common ground, common sense, common interest) will be incited. The concept of intuitive thinking and thinking fast and slow (SI and SII) will be introduced. The 4 types of problem (dis)solving will be discussed. The 'contradictio in terminis' of the term R&D management will be handled: organic leadership vs. bureaucratic management.

ODL building block: Determine whether OoI staff shows characteristics of an intrinsically motivated crowd. Reflect on at least the co-sensing part of the U-model within the context of the OoI development cycle. Determine the idealized design and its problem dissolution potential of the OoI according to its top management via the interview (its idealized organizational purpose). Appraise the management versus the leadership nature of you OoI.

Reference material:

- Van Gunsteren and Vlas, The Licence Giver Business Concept of Technological Innovation. Springer, 2022. Chapter 3.
- C. Otto Scharmer, Theory U: Learning from the Future as It Emerges. Berrett-Koehler Publishers, 2009. Part II (design from the future, the principles of the U model) and specifically Chapter 21 (intrinsic motivation→ co-sensing etc.).
- Russell L. Ackoff, Idealized Design, Creating an Organization's Future. Wharton School Publishing, 2006. Chapters 1-3 & chapter 7.
- Daniel Kahneman System I and II, https://www.dailymotion.com/video/x3dp8o2 BBC Documentary 2015 || How You Really Make Decisions - BBC Science Documentaries
- Marvin Bower "The Will to Lead: Running a Business With a Network of Leaders, 1997

Concept 4: The living enterprise for the future – rise and decline of innovative capabilities

We can distinguish four different phases in the history of a developing corporation, each having their typical challenges. The starting point/ organizational paradigm is here that a organization is seen as a social organic living system ('a biotope'). Different organizational development phases and/or maturity levels (emerge, develop and mature) and it's innovative potential are discussed: (1) Pioneer- (birth and first expansion) (2) Differentiated- (on-going expansion and isolated maturity) (3) Integrated (connective maturity)- (4) Associative phase (purpose maturity). In the pioneer phase, there is little room for innovating endeavors. Failure could easily draw the company into bankruptcy. In the expansion driven phases, the firm has accumulated sufficient financial buffer to afford the failures that are inherent to innovative development projects. A token that bureaucracy has sneaked in, indicating that the company has entered the maturity phases (predominantly in differentiated phase), is that discussions in the organization are predominantly about internal control processes-rules, regulations, and policies- and no longer about content and or innovations. The usual way to cope with these size-related issues is to adopt the multi-divisional structure. Unfortunately, the multi-divisional structure is not particularly conducive to state-of-the-art socio-technological innovations. In the integrated phase the organization is no longer focusing on his on process and organizational system, but is starting to cooperate within its related market place (the network organization). Finally the organization will develop into a socio-eco purpose oriented organization with associative partners (focus on tripartism including the cultural system. These co-maker organization will be resilient to the emerging future.

The cooperation/partnering evolution of an industry can be distinguished by 'management' approaches and their particular partner features: 1) vertical alignment, 2) horizontal alignment. The process of industry (partnering) restructuring over time is demonstrated for the ship, aircraft, vehicle and computer industries. In the computer industry, a further new industry and innovation dynamic emerged: the phenomenon of industry platforms. For some companies it offered the opportunity to establish themselves as platform leaders.

ODL building block: Determine and appraise what type of development phase your OoI is in and link this to their socio-technological innovative capabilities (maturity and phases). Determine to what extent the OoI is part of an industry platform. Determine to what extent the OoI adheres to Porter's cluster theory.

Reference material:

- Van Gunsteren and Vlas, The Licence Giver Business Concept of Technological Innovation. Springer, 2022. Chapter 6 and 7.
- Friedrich Glasl. The Enterprise of the Future: Moral Intuition in Leadership and Organisational Development (Social Ecology), 1997. Part I
- C. Otto Scharmer, Theory U: Learning from the Future as It Emerges. Berrett-Koehler Publishers, 2009. Chapter 4

Concept 5: Governmental interference & embedding innovation dimensions

Indirect governmental support to innovation, in particular regarding legislation and infrastructure around clusters of competence, is useful and should be welcomed. Direct governmental interference in existing (R&D) industries is always counter-productive in the long run. Direct subsidies to sunset industries provide only short-term relief. On the long run, their distortion of competitive market conditions weakens the resilience of the subsidized corporations. However, in some instances the governmental regulator can also drive innovations, as companies are 'forced' to dissolve regulatory issues by alternative product innovation (e.g RANN/Huawei combined 3G antenna, split for core network)

ODL building block: Determine and appraise governmental interference and competence of your OoI.

Reference material:

- Van Gunsteren and Vlas, The Licence Giver Business Concept of Technological Innovation. Springer, 2022. Chapter 8.

Concept 6: The Game of Excellence – freedom to excel

Innovation requires a tolerance for failure and freedom to excel. The genuine daring attempt is what counts, not the result. But failure due to incompetence of the people involved should be considered to be unacceptable. A tolerance for failure requires intolerance for incompetence. Failures can be very useful to learn from. The process of innovation is too fragile to allow incompetence of key decision makers. A strategy of becoming a License Giver organization is bound to fail if its management is reluctant to remove employees that are lacking the required competence for their job.

ODL building block: Determine and appraise how the R&DOoI deals with tolerance for failure and intolerance for incompetence.

Reference material:

- Van Gunsteren and Vlas, The Licence Giver Business Concept of Technological Innovation. Springer, 2022. Chapter 9.

Concept 7: Special R&D organizational concepts

(1) The Power Game (2) Intercultural dimensions << two topics/ chapters from Gunsteren's multi-stakeholder book>>

ODL building block: Determine and appraise how the R&DOoI deals with the power game model and with intercultural dimensions

Reference material:

- L.A. Van Gunsteren, Stakeholder-oriented Project Management: Tools and Concepts 2011.
- Hofstede

3 REFERENCE MATERIAL

The following reference books and scientific articles are recommended for this course.

General:

- Roozenburg and Eekels, Product Design: Fundamentals and Methods, Wiley, 1995.
- Van Gunsteren and Vlas, The Licence Giver Business Concept of Technological Innovation. Springer, 2022.
- C. Otto Scharmer, Theory U: Learning from the Future as It Emerges. Berrett-Koehler Publishers, 2009
- Russell L. Ackoff, Idealized Design, Creating an Organization's Future. Wharton School Publishing, 2006
- Friedrich Glasl. The Enterprise of the Future: Moral Intuition in Leadership and Organisational Development (Social Ecology), 1997. Part I

Extra:

- Dym, C. L., Little, P. and Orwin, E. J. (2014) Engineering design: a project-based introduction. 4th ed. New York: Wiley.
- Simon, Herbert, A. 1996. The Sciences of the Artificial. 3rd ed. Cambridge, MA: MIT Press.
- Kahneman Thinking Fast Slow
- Marvin Bower The will to Lead

4 ADDENDUM TO THE READER -THE 4Q R&D MODEL

This addendum applies to the first concept of the course. We will introduce a 4 Quadrant model that helps you understand why CME is different from CEG and what the difference is between science and the engineering.

Where civil engineering students mainly focus on the design of physical objects (bridges, tunnels, buildings, offshore facilities etc.), construction management students are concerned with organizing the actual design, construction and operating process and related activities (planning, budgeting, organizing, information, risk and safety etc.).

The difference between CEG and CME

This relates in essence to the branch of science that you operate within. Figure 1 shows the so-called hierarchy of the sciences taken from Wikipedia. This figure shows the different branches and we can use this to explain what makes CEG education different from CME education.

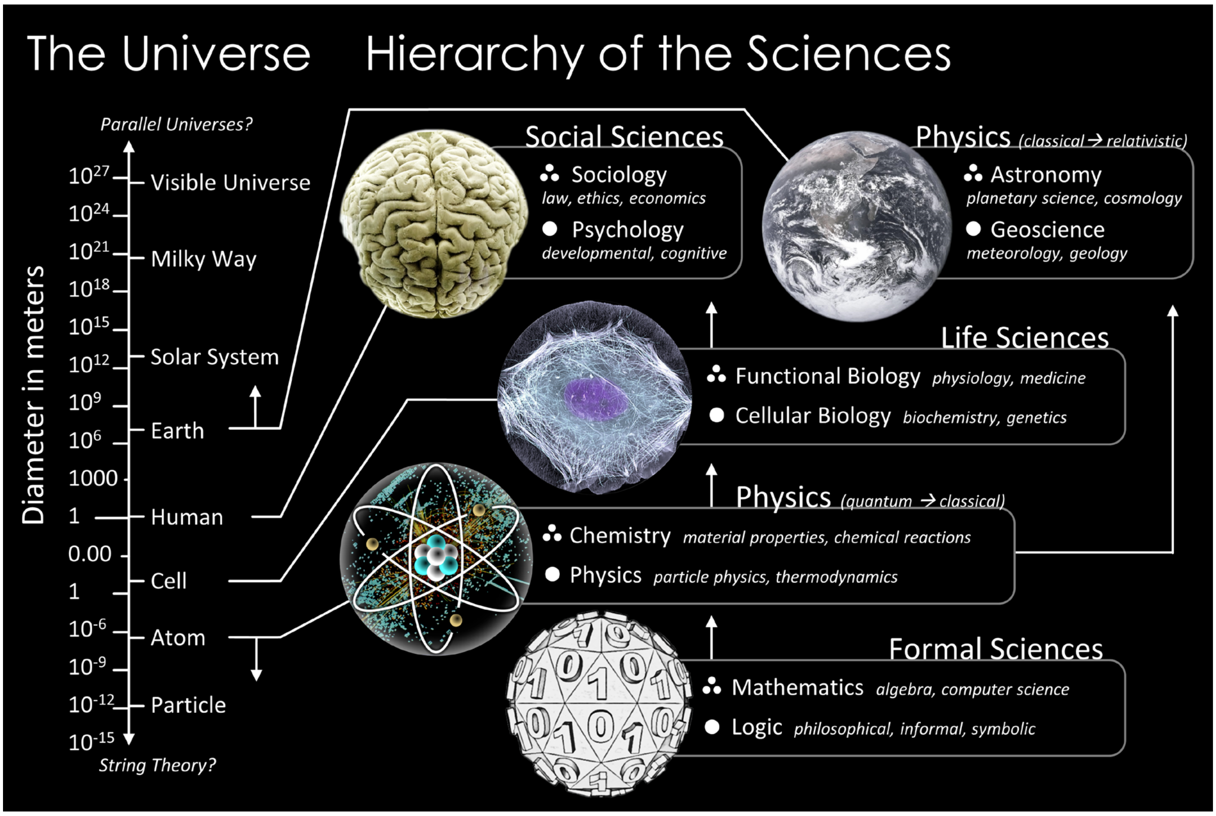


Figure 1: The scientific universe (source: wikipedia.org).

CEG students, concerned with civil engineering objects, mainly operate within the natural sciences, more specifically, physics. Physics is a natural science that involves the study of matter and its motion through space-time, along with related concepts such as energy and force.

CME students, concerned with organizing or managing the design, realization, and operating process of these objects, mainly operate within the social sciences. The social sciences are the fields of scholarship that study society. Management can be defined as the organization and coordination of the (human) activities of business organizations in order to achieve defined objectives. Management consists of the interlocking functions of organizing, planning, controlling, and directing a (human) organization's resources in order to achieve its objectives.

Note that the formal sciences operate completely in the domain of the mind.

The second topic that we address is the difference between science and technology.

The difference between scientists and engineers

We can start with examining the origin of both words and their definitions using Wikipedia. The word science is derived from the Latin word scientia, meaning ‘knowledge’. Science is defined as a systematic enterprise that builds and organizes knowledge in the form of testable explanations and predictions about the universe. The word engineer (Latin ingeniator) is derived from the Latin words ingeniare (‘to create, generate, contrive, devise’) and ingenium (‘cleverness’). Engineers are professionals who invent, design, analyze, build and test machines, complex systems, structures, gadgets and materials to fulfill functional objectives and requirements while considering the limitations imposed by practicality, regulation, safety and cost.

It is important to make this distinction because the line of reasoning and end result that scientists aim for is fundamentally different from that of engineers. Where scientists strive for knowledge acquisition, engineers strive for technical action. This closely relates to the two domains that humans function in: the domain of the material reality and the domain of the mind. Given these two domains we can distinguish two directions: 1) a process from the outside to the inside (from the material reality to the domain of the mind) - a process that we call knowledge acquisition - and, 2) a process from the inside to the outside (from the domain of the mind to the domain of the material reality), we call technical action. The process from the outside to the inside is directed towards acquiring new knowledge of the world. The process from the inside to the outside is directed towards change of the world, i.e. creating/developing new engineering solutions, see Figure 2.

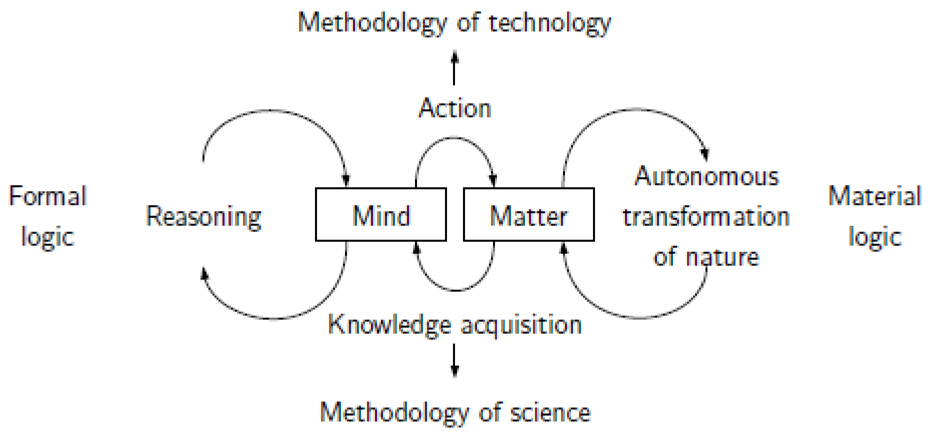


Figure 2: Methodology of science and technology (source: Eekels and Rozenburg).

Both scientists and the engineers start with a problem. This problem points to an unsatisfactory situation which one wants to change into a more satisfactory one.

For scientists the problem is that the available knowledge (a collection of factual statements about the world) is not aligned, or is insufficiently aligned, to the empirical facts. The facts are unassailable; hence the aim of scientific research is to change, respectively expand, the collection of factual statements (which appeared to be insufficiently true), in such a manner that they align better with the facts.

For engineers the problem at the onset is that the facts are not aligned with our values and preferences concerning these facts. And since (in the first instance) our values are unassailable, this discrepancy leads to us making it our aim to change the facts, i.e. changes to the material world. We want to create a material condition which does agree with our values and preferences. This requires technical action. Technical action requires technical means, and these must be engineered, i.e. designed.

Now that we have distinguished between scientists and engineers we also need to further define the related processes as they are also completely different.

The process of scientific research and engineering development

Figure 3 shows the basic cycles of scientific research and engineering development one beside the other. We shall refer to these from now on as the research and development cycle, respectively.

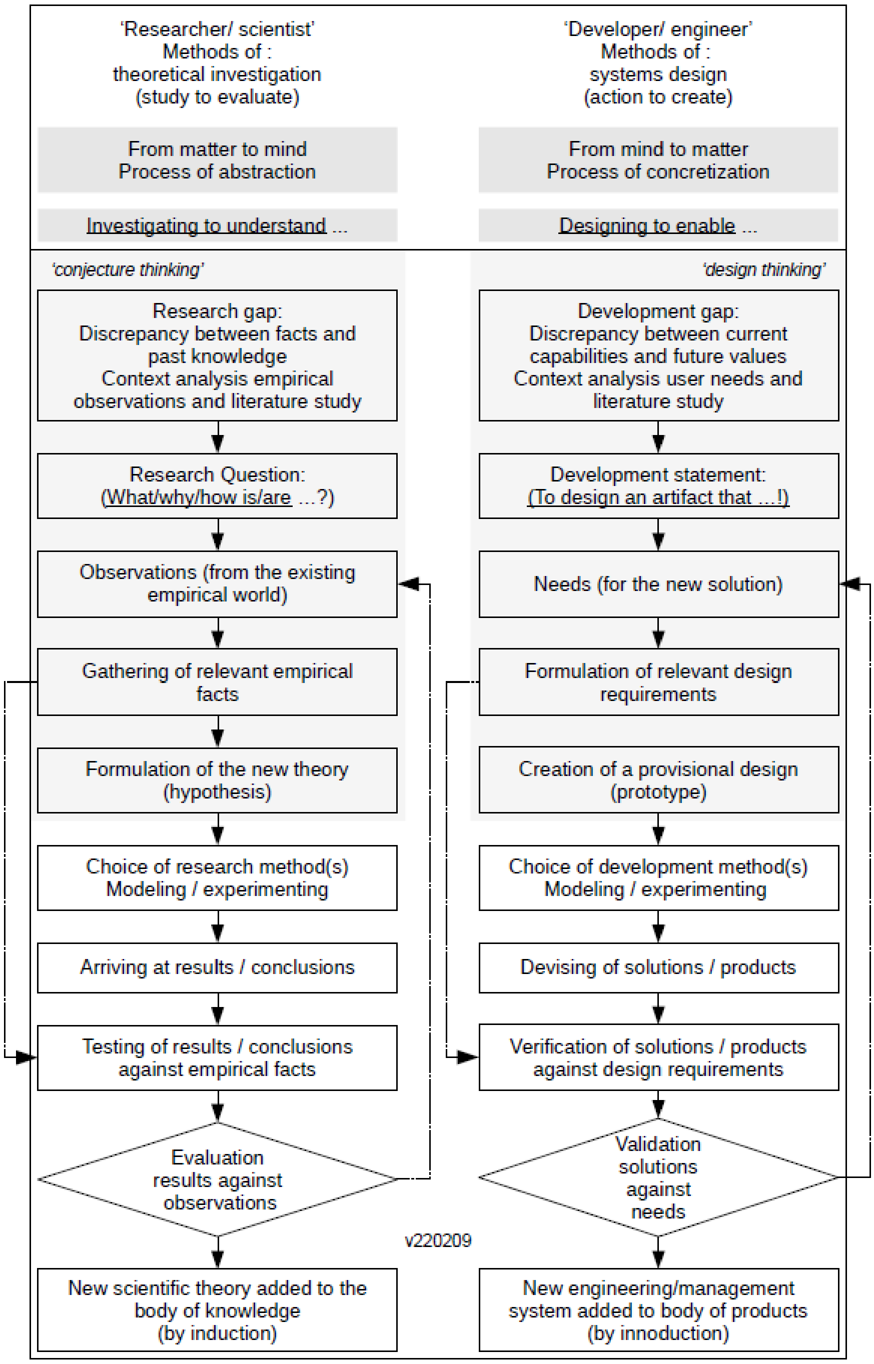


Figure 3: The research and development cycles (adapted from Eekels and Rozenburg).

It is clear that they resemble one another. They have the same number of elements which, moreover, relate to one another in the same manner. One could conclude that technology is merely a form of applied science and that, if you have scientific research, you 'automatically' have technology and engineering development. We will show, however, that this train of thought, which is indeed widely prevalent, is incorrect. In order to do so, we will explain the essential methodical differences between the two cycles.

Two types of problems
We already stated that both cycles begin with a problem. These problems appear to be different already:

- The research cycle is triggered by a discrepancy between current facts (derived from observations) and our existing knowledge. The aim of the process is adjustment of our knowledge to the facts. In other words, we want to understand something that we do not fully understand now. This is the scientific knowledge acquisition process.
- The problem at the onset in the development cycle is a discrepancy between current capabilities and our values. The aim of the process is adjustment of current capabilities (by means of the engineered system) to our values and preferences. In other words, we want to be able to do something we cannot do yet by changing the material world. This is the engineering design process.

Observation versus needs
Research occupies itself with the existing real world and with our representation thereof in factual statement. Development, on the other hand, occupies itself with a not yet existing, but (hopefully) feasible world, or worlds.

The observation phase in research originally started with the observation of facts from the empirical world that did not agree with existing theory. In order to improve the theory, we need more than the establishment of one or a few 'anomalous' instances. We therefore need purposeful observation to show that the facts indeed do not agree with existing theory. This phase leads, by means of induction, to the construction of a hypothesis.

The analysis phase in development is aimed at possible worlds guided by our needs. In this phase one can ask oneself in reasoning under what conditions a world that has been thought up will be both feasible and desirable. This phase leads, by means of deduction, to the set of requirements that the engineered system will be judged upon.

Results versus solutions
The following two parallel elements of the two cycles are 'results' and 'solutions'.

It should be possible to derive the phenomena to be explained or predicted by means of deduction, from the theoretical relationships acquired from induction. This is what one tries to do in the `deduction phase'. We can state that deduction in the research cycle leads to a categorical explanation and/or prediction of one or some aspects of reality. Arriving at results is done by means of a chosen research method, see Table 1. The results will be tested against the hypothesis. The application of development methods, see Table 1 will lead by means of 'innoduction'[1] to a provisional solution to the identified problem. This is what will be verified against the requirements.

Testing versus verification
Testing within scientific research can direct itself to the explanatory power or the predictive power of the postulated laws or theories. In view of the inductively acquired hypothesis, deductively a prediction has been made (with or without the help of an experiment) on facts to be observed in the future. In the testing procedure these facts are observed and compared with the prediction. Does it fit the observations? If not, to what extent do the observations 'support' the hypothesis, that is how 'true' is the hypothesis?

During verification in the development cycle, comparisons are made as well, albeit not between fact and theory, but between (simulated) system behavior and the desired behavior of the system to be developed. Does the engineered system meet the requirements on all system levels? If not, what adjustments need to be made to parts of the system?

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[1] See Section 4.4 of the book of Roozenburg and Eekels on Product design for further information.

Evaluation versus validation
In the research cycle 'evaluation' does not judge only on how well predictions fit observations. A decision is also taken of whether the goal laid down, (improved theory) has been sufficiently attained, or whether more observations are required. Hence, the feedback arrow which runs in Figure 3 from the element of 'evaluation' back upwards. But if the evaluation has been satisfactory, it is decided to add the knowledge which the process has yield to the acreage of knowledge in the domain of the mind. Usually this takes place more explicitly in the form of a scientific publication.

In the development cycle we encounter the element 'validation' at this level. As with research, validation does not judge only on whether or not the obtained solution meets the requirements, but also on whether the goal laid down, (improved system), has been sufficiently attained, or whether an adjustment of the needs is required. And finally, the decision can refer to choosing an attractive alternative from the collection of generated solutions. The process ends with the yield of a number of acceptable solutions, or - one decision step further - with the manufacturing or implementation of the most attractive solution, i.e. engineered system.

We have now distinguished between the physical and social sciences and also between scientific research and engineering development. This allows us to define four types of graduation domains as will be explained in the following section.

Types of research and development domains

Figure 4 shows the distinction between: 1) the research-oriented approach aimed at understanding, focusing on either physical objects or human organization processes, resulting in new knowledge and, 2) the development-oriented approach aimed at enabling, focusing on either objects or processes, resulting in new solutions.

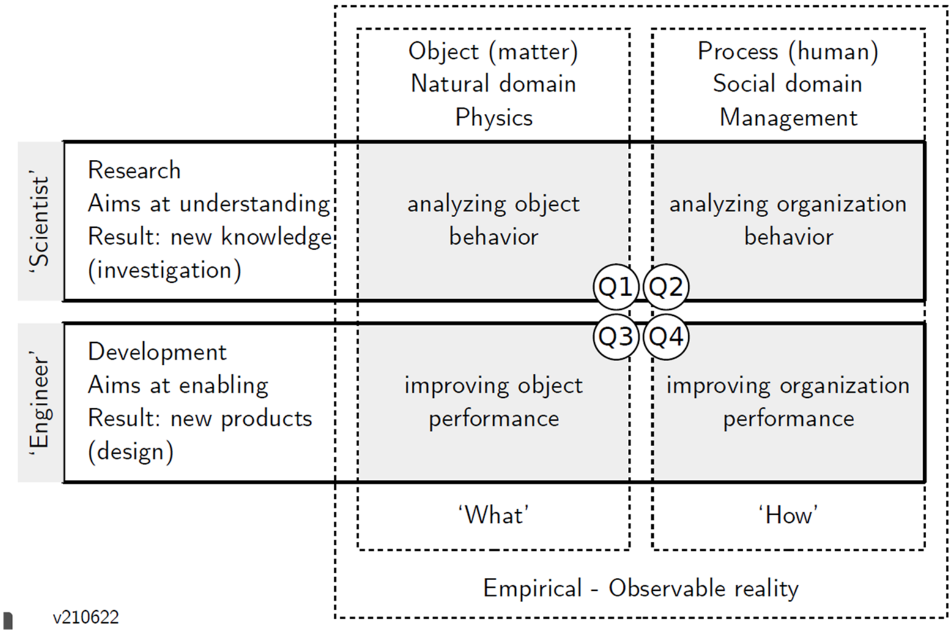

Figure 4: Four types of graduation domains.

The related questions differ according to the different quadrants. Figure 5 shows for each quadrant typical questions or statements. Questions related to scientific research normally start with `what' or 'how' as they are aimed at knowledge acquisition; we want to better understand and explain something. Statements related to the development approach normally start with 'to develop' as they are aimed at technical action; we want to be able to do something that we cannot do yet.

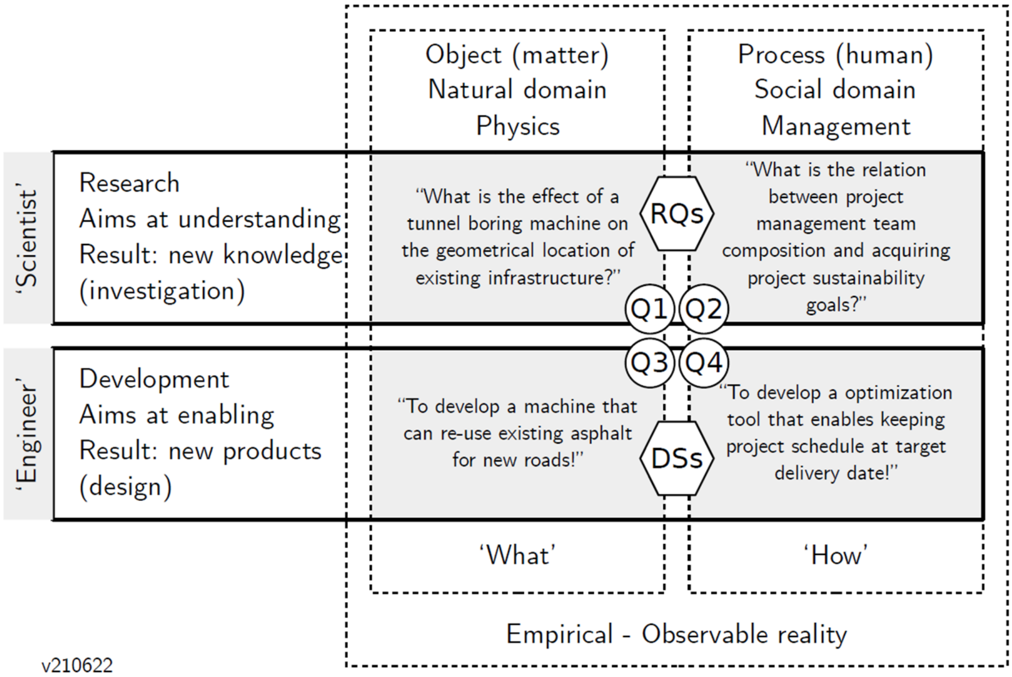

Figure 5: Four types of graduation projects and related research questions / development statements.

Depending on the quadrant also the methods used to arrive at the graduation end deliverable will differ. Figure 6 shows for each quadrant typical methods. Scientific research, when focusing on physical objects, makes use of research methods such as lab testing, statistical analysis, sensoring/monitoring, data mining, etc. Scientific research, when focusing on human organization processes, makes use of research methods such as case studies/focus groups, surveys/interviews, statistical analysis, evaluation, etc. Engineering development, when focusing on physical objects, makes use of development methods such as physical/numerical modeling, technical optimization, product lab testing, proof of concept validation, etc. Engineering development, when focusing on human organization processes, make use of development methods such as systems modeling, multi-objective optimization, simulation/programming, model testing and validation, etc. A more exhaustive list of research and development methods is provided in Table 1 at the end of this document.

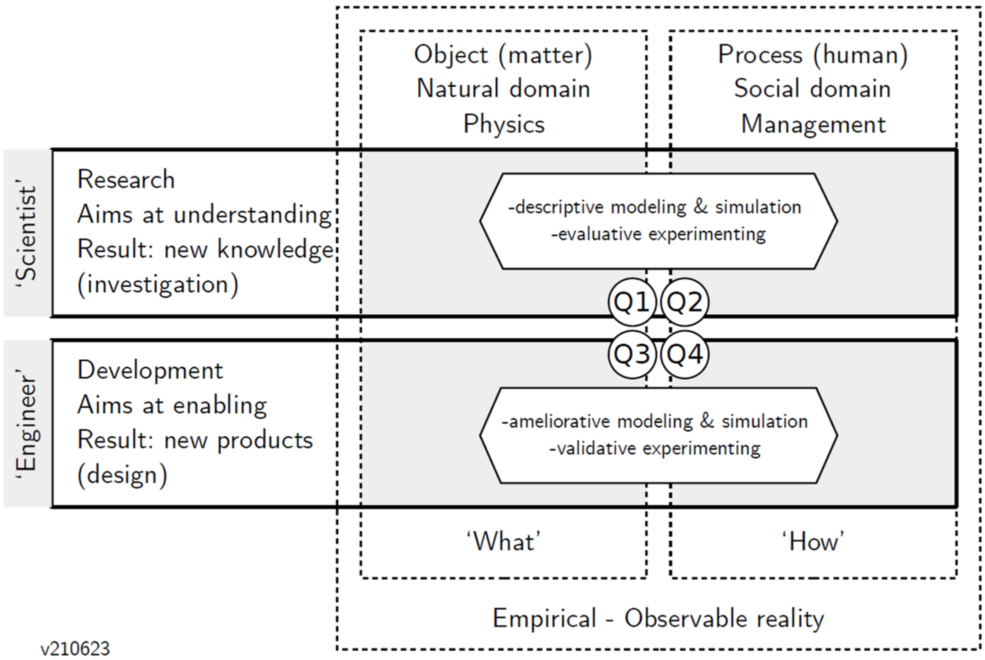

Figure 6: Four types of graduation projects and related research / development methods.

Mini example project using the 4 quadrant model

Let us consider the 'Rotterdamsebaan road project' aimed to improve the accessibility to The Hague and the region. For each quadrant we give examples of possible questions relating to this project and how they could be answered.

Q1: Research, related to physical objects

"What is the effect of the tunnel boring machine on the geometrical location of existing infrastructure?" Such a question relates to the physical effects of the tunnel boring machine on its environment such as existing real estate. It requires measuring over time the exact position of building components by means of measuring instruments. It would require lab testing of the instruments, statistical analysis of the acquired sensor and monitoring data over time, and possibly data mining. The end result would be insight into whether or not change of the position of building components can be attributed to the tunnel boring machine.

Q2: Research, related to management organizations

"What is the relation between project management team composition and acquiring project sustainability goals?" Such a question relates to gathering insight into the effect of team composition on the realization of certain project goals that determine whether or not goals with respect to sustainability have been achieved. It would require multiple case studies of which the Rotterdamsebaan road project would be just one, setting up and organizing surveys or interviews, performing statistical analysis on the results obtained. The end result would be insight into which factors in relation to team composition contribute to achieving goals that define sustainability.

Q3: Development, related to physical objects

"To develop a machine that enables the re-use of existing asphalt for new roads." Such a statement relates to the design of a crushing, filtering and mixing machine that outputs asphalt material that is of good enough quality to be used for the new roads. It will require physical and/or numerical modeling of the recycling process, possibly in combination with lab testing, optimization of the machine so that it can produce material of good enough quality. The end result would be a design of a first 'proof of concept machine'.

Q4: Development, related to management organizations

"To develop an optimization tool that enables keeping a project schedule at target delivery date." Such a statement relates to mitigating the effects of risk events so that they have minimal impact on the project delivery date. It would require modeling of the network planning, optimization of mitigation measures using simulation and finally testing and approving the created decision support model.

Table 1: Research and development methods overview.

Research and Development methods			
MODELLING & simulation (silico) [0]			
Domain	*Type*	*Orientation*	*Method/technique*
Mngt. & Phys.	Mathematical	Development validation	(Non)-linear programming [1] Dynamic programming Preference function modelling
Mngt. & Phys.	Mathematical	Research evaluation – development validation	Statistical methods [2]/ data mining Neural networking Probabilistic methods [3]/ forecasting
Mngt. & Phys.	Mathematical	Research evaluation – development validation	Analytical (PDE continuous) Numerical (finite elements) Discrete-events System dynamics Agent based Adaptive pathways
Mngt. & Phys.	Logical	Research evaluation – development validation	Diagramming [4] Functional/ OCD design Scenario validation
Mngt. & Phys.	Digital	Research evaluation	Diagramming [4] Software utilizing [5]
Mngt. & Phys.	Digital	Development validation	Software developing [5]
EXPERIMENTING & observation (vitro/vivo)			
Mngt. -vitro	true-Experimental	Research evaluation – development validation	Statistical methods [2] Serious gaming/ observational methods [8] (human process)
Mngt. -vivo	quasi [6]-true - Experimental	Research evaluation – development validation	Statistical methods [2] Observational methods [8]
Mngt. -vivo	pre-Experimental [5]	Research evaluation	Statistical methods [2] Observational methods [8]
Phys. -vitro	true-Experimental	Research evaluation – development validation	Statistical methods [2] Lab or mock-up/ observational methods [8] (physical object)
Phys. -vivo	quasi [6]-true - Experimental	Research evaluation – development validation	Statistical methods [2] Observational methods [8]
Phys. -vivo	pre -Experimental [5]	Research evaluation	Statistical methods [2] Observational methods [8]

[0] Research modelling has generally a descriptive/confirmative orientation to understand questions/hypotheses for the body of knowledge. Development has generally a ameliorative/constructive orientation to enable problems/prototypes for the body of products.

[1] using different algorithms such as genetic algorithms, simplex algorithm, negotiable constraints, etc.

[2] regression analysis, q-method, structured expert judgement, MCDA (eg. Preference Function Modelling, AHP), random forests, data and image processing, etc.

[3] such as Bayesian networks, Markov chains, stochastic processes, etc.

[4] frameworks, process flow charts, organization models, breakdown structures, swimming lanes, relation diagrams, etc.

[5] object models (e.g. UML), entity relationship models or XML schemas or other computer programming languages techniques (Python, semantic web design, JSON, etc.)

[6] could also be performed as a pre-modelling context analysis

[7] quasi is like a true experiment, a quasi-experimental design aims to establish a cause-and-effect relationship between an independent and dependent variable. However, unlike a true experiment, a quasi-experiment does not rely on random assignment. Instead, subjects are assigned to groups based on non-random criteria.

[8] active and structured data and information acquisition from a primary source (objects/human) that also involves observing behaviour in the environment in which it typically occurs (structured, controlled, naturalistic, participative): e.g. sensors, interviews, audits etc. It also contains a specific research method to observe the impact of human actions named action research: i.e., action research is a philosophy and methodology of research generally applied in the social sciences. It seeks transformative change through the simultaneous process of taking action in vivo and doing research, which are linked together by critical reflection.