DTU GLOBAL DECISION SUPPORT INITIATIVE

Risk-Related Activities at DTU

A situation assessment report of the DTU Global Decision Support Initiative

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Purpose, Scope, Intended Audience and Acknowledgements

The diversity and pervasiveness of the notion of risk is evident among practitioners (industry), regulators (government) and experts (academia). Similarly, risk research and risk education activities are undertaken across DTU departments, creating a vast body of knowledge with little or no coordination among the different departments and research areas. The present risk mapping report is envisaged as a first step toward such coordination. The report has been prepared as preliminary, horizon scanning activity of DTU's Global Decision Support Initiative (hereafter, GDSI), which was established in October 2014 as a collaborative initiative of six DTU departments (Civil Engineering, Transport, Food, Environment, Management and Compute) to provide evidence-based decision support to national and international actors with respect to risk and sustainability assessment and risk management in general. As such the report aims to map all risk-related activities (research, education and advisory) across the specified six departments in order to identify common and complementary procedural and scientific frameworks, generic and specific educational offers, national and international collaboration networks and present gaps in knowledge.

The attempt to synchronize these activities as well as arrive at more uniform principles and metrics for assessing and managing risk is in direct response to one of the major challenges in risk management in the field – the accommodation of risk perspectives of multiple stakeholders in the public and private sector alike. Most risk management strategies regardless of the hazards considered, have been designed for individual risks and for individual organizations responsible for managing them. In an increasingly inter-connected and complex society, compartmenting risks and risk ownership into narrowly defined fields and organizations can not only minimize the effects on desired outcomes but it can lead to adverse consequences and strategic surprise failures.

Building a holistic, cross-departmental risk management capability is seen as a challenging process for three inter-dependent reasons: the constantly evolving nature of the risks themselves; the complex ways even simple threats can lead to societal disruption as a result of inter-connectivity; and the synchronization of efforts of many societal stakeholders. Each of the DTU departments surveyed in this report has its own strategic and operational objectives, with each being exposed to a unique set of hazards, data constraints and resource limitations. It is hoped that the findings of the report will be utilized in the strategic planning activities of the GDSI, the participating departments as well as DTU's central administration as a possible means to forming a better informed collective judgment and approach to risk assessment and management of risks that may be of concern to more than one institution.

The intended audience for this report are thus primarily, but not exclusively, the GDSI staff and associates, the scientific staff at the surveyed departments and those members of the central administration, directly involved in coordinating risk-related studies commissioned by the Danish public sector authorities or other high level external clients. Academics specializing in one of the risk areas presented in the report will likely find the presentation of their field too general to be of practical use. It is hoped, however, that they would benefit from learning about risk research in the other fields, their specific concerns, constraints and advocated approaches.

Finally, it should be acknowledged that risk research and educational activities take place in many other DTU departments and research centers. Within the timeframe allocated for producing this report, only the six departments participating in the GDSI could be surveyed. A broader survey of all DTU scientific entities is therefore recommended as a follow-up activity.

Due acknowledgment must be given to Jørgen Schlundt of the GDSI, without whose support this report would not have been written. Additionally, thanks are given to all scientific staff who provided the author with valuable insights during a process of personal interviews: Michael Faber of DTU Civil Engineering, Kim Bang Selling of DTU Transport, Tine Hald, Flemming Bager and Anette Schnipper of DTU Food, Anders Baun of DTU Environment, Frank Markert, Igor Kozine and Josef Oehmen of DTU Management Engineering, and Elena Boriani of the GDSI. Finally, the author would like to thank Søren Salomo of DTU Management Engineering, Henrik Saxe of the GDSI and Mikkel Hougaard Orlovski of DTU HR for hosting her at DTU Management Engineering over the past six months and giving her the trust and opportunity to work on this challenging, relevant and deeply fascinating subject.

Organization, Methodology, Data

The report is organized as follows:

Section 1 describes four main trends in the field of risk as well as their drivers and offers a subjective assessment of how risk research at DTU measures up against them.

Section 2 examines the different perspectives of the concept of risk adopted by the various research groups and sections at the different departments, together with how the different interpretations impact risk management preferences and choices. Also in this section, procedural risk frameworks are discussed and differences in terminology are compared with regard to risk analysis, risk assessment and risk management. Finally, scientific risk frameworks are considered, together with underlying principles, methodologies and metrics. Several theoretical principles are highlighted as particularly suitable in the context of risk-informed decision making as they are applicable across the surveyed departments: Bayesian decision analysis, Value of Information, Bayesian Probabilistic Nets, Multi-Criteria Decision Analysis, and a number of socio-economic models and indicators for risk acceptance criteria.

Section 3 looks at existing and prospective educational offers and provides recommendations.

Section 4 summarizes findings related to academic networks and collaboration as well as advisory activities and provides recommendations.

Section 5 lists areas of risk research which are not well covered or not at all covered at DTU and provides recommendations.

The report concludes with some general considerations for reflection on the future outlook of risk-related activities at DTU.

Appendices

The six appendices are where in-depth information is presented about the individual departments risk-related activities. Each appendix follows the same organization to facilitate comparison across departments.

Section 1 in each appendix looks at the concept of risk in the particular domain as well as responses to trends in the field. Included in this section is also information on how and to what degree sustainability is taken into consideration in the respective field.

Section 2 outlines the procedural risk management framework adhered to in the field.

Section 3 outlines methods and approaches.

Section 4 lists data types and metrics.

Section 5 presents the research topics of relevance to risk covered by a given department.

Section 6 provides information on the department's research networks with relation to risk.

Section 7 elaborates on advisory activities undertaken by the department in the context of risk.

Section 8 lists all educational offers at the department, explicitly or implicitly related to risk.

Data sources and a glossary of risk-related terms specific for each field are provided at the end of each appendix.

Methodology and Data

The majority of research for this report is based on a desk-study, consisting of relevant literature review for each field, in-house publications of DTU scientific staff and information collected from the departments' websites, *DTU Portalen* and *DTU Kursusbasen*. Where possible, this information was supplemented with insights from semi-structured personal interviews with scientific staff who were recommended by the respective Heads of Departments to provide an overview of the department's risk-related activities. Regrettably, time and other constraints made it impossible to interview all relevant stakeholders, which has naturally impoverished the breadth of perspective the report was able to assume. Given the significant intra-departmental differences in conceptual outlook and methodologies with regard to risk, departments where more than one researcher could be interviewed resulted in better, i.e. more thorough representation of a particular perspective or a particular line of research. The author has tried to compensate as much as possible for this shortcoming by referring to secondary sources (DTU publications, field manuals, etc.), however, this information has not been verified by a representative of the department.

All data sources are listed at the end of each appendix as they pertain to each specific field. Information on the position and academic specialization and interests of the interviewed scientific staff is also listed there. Contact information, background and professional interests of the report's author are provided at the end of the report.

1. Introduction: Trends in the field of risk

Increasingly, all organizations, both in the public and private sectors, are being asked to show evidence of a systematic approach to the identification, assessment, analysis, treatment, and ongoing monitoring and communication of risk. Over the past decade, a fundamental shift in strategy has been observed in the context of risk evaluation and management from a compartmentalized and largely technical approach to an all encompassing, multi-sectoral, multi-disciplinary and multi-stakeholder approach. Furthermore, all risk-related activities are guided by a system theory view so that interconnection and dependencies are not neglected, with the aim of avoiding cascading effects which could result in trans-boundary, and potentially, catastrophic consequences.

It is argued in the present report that there are four major external trends driving developments in the field of risk:

(i) A demand for pragmatic evidence-based policy that legitimizes and makes transparent the decision making processes while at the same time optimizes scarce resources;
(ii) A demand for integrated, all hazard, risk-informed risk management process, which takes explicit consideration of sustainability;
(iii) A demand for pro-active mitigation risk management strategy vs. cost heavy reactive response to adverse consequences; and
(iv) A shift from MINIMAX toward PARETO-optimal and MAXIMIN risk optimization strategy.

Trend 1: Pragmatic evidence-based policy

The demand for scientific knowledge, based on objective evidence and risk assessment has been motivated by a pragmatic public policy which evokes the terms *risk-based, risk-informed, science-based, evidence-based* policy with two particular aims: legitimatization of decision making processes and optimization of scarce resources. The evidence-based movement in public policy is linked with the current emphasis on rational problem-solving, with a focus on accurate diagnosis and knowledge of causal linkages. In this sense, it is also congruent with risk analysis and risk management options and strategies. From the academic research perspective, this has implied a strong utilitarian turn whereby academic research is seen as a means to economic and social development rather than as a scientific end in itself. In addition, there has been a call to make research not only useful but usable. This has put the academic research community in direct (disadvantaged) competition with the commercial research and consultancy sector in terms of conducting and communicating research in ways that ‘users’ (e.g. public sector authorities investing in government-funded research units on specific problems) find helpful. Research is now demanded to provide *actionable knowledge*.

One possible driver for the increased interest in *evidence* among both public and private actors is their loss of public confidence; another one is an increasingly educated society which is less inclined to take professional views on trust. Society’s individuals’ *informed consent* is now needed for most intervention, which means that professionals and experts must be able to explain not just what they advise and why it is appropriate, but also what they know of its likely efficiency, what alternatives exist and what the trade-offs among them are, so that they may make *informed choices*.

Yet scientific evidence is only one type of evidence used to justify decisions and policies in both the public and private sectors. The Oxford English Dictionary defines evidence as 'the available body of facts or information indicating whether a belief or proposition is true or valid'. This definition resonates with what could be considered evidence from a scientific, academic perspective, where availability and validity are the key issues in considering evidence. When philosophers talk of evidence in an epistemological sense, they talk about justification. Evidence is the kind of thing which can make a difference to what one is justified in believing or what it is reasonable to believe. In the context of philosophy of science, evidence is relied upon in cases in which access to truth would otherwise be problematic. In this sense, evidence confirms a theory just in case that evidence makes the theory more likely to be true; evidence disconfirms a theory just in case that evidence renders the theory less likely to be true.

In the policy and executive realms, evidence can mean a number of things. Networks and partnerships bring to the negotiation table a diversity of stakeholder 'evidence', i.e. relevant information, interpretations and priorities. The argument is that addressing complex inter-linked problems requires a strong emphasis on the social relations and stakeholder perceptions. In this broader view, there is not one evidence base but several bases. These disparate bodies of knowledge become multiple sets of evidence that inform and influence policy rather than determine it. Academic researchers tend to quite easily fall into the cognitive trap of believing that only academic research counts as evidence and that somehow it is the basis for all knowledge. The prestige and utility of scientific evidence, validated by standards of scientific methodology, remains a significant input to policy. However, scientific evidence has little influence on shaping the political agenda and on framing and prioritizing various risks. Evidence, seen from the political lens, is about persuasion and support rather than objective truth. Importantly for science, the political framing of a problem is also crucial with regard to what research is commissioned and what economic resources for it are allocated. It is rare that research is commissioned without some expectation that reports may assist in upholding or denouncing a certain viewpoint.

Despite efforts of public actors to embrace evidence-based research from academia and academic institutions trying to capitalize on such efforts by adopting business models to integrate a greater share of consultancy services, mutual awareness, recognition and understanding of each other's approaches remains low, leaving the question of what might be some mutually beneficial incentives to working better together open.

Trend 2: Integrated, All hazard, Risk-informed, Sustainable Risk Management

Over the past decade, integrated risk management frameworks have been adopted across public and private sector organizations and academic fields. The term *integrated* refers to the explicit consideration of the interaction between all relevant agents, i.e. technical and structural elements, nature, humans and organizations in the assessment of the risks associated with a considered system. Integrated risk management advocates a holistic perspective to risk assessment, not only in terms of considering multiple risks through a portfolio approach, but also taking time in consideration. Thus risk assessments have been prompted to consider all phases of the life of a system from the early concept/design phase to the end of the service life, including decommissioning. In the context of environmental and sustainability assessments, this approach is referred to as the *'cradle to grave'* approach for both products and processes. In the context of food safety, both with regard to human and animal health, the approach is labeled *'farm to fork'*. In the public sector, an integrated approach to risk management is also often referred to as an *'all hazards'* approach and '*whole of government'* approach, while in industry, where the concept originated, it is termed *'enterprise risk management'*.

Trend 3: Pro-active mitigation vs reactive response

A third major trend driving developments in the field of risk is a pragmatic approach to risk treatment, where preventive, pro-active mitigation is considered the preferred approach over a cost heavy reactive response. The strategic goal of putting a priority on life safety regardless the cost is increasingly seen as an economically unsustainable risk treatment strategy. The new approach, dominant in both the public and private sectors seeks to identify the most effective risk treatment measure, based on principles of decision utility, cost-effectiveness and revealed rather than stated preferences whereby societal risk acceptance criteria prevails over individual.

The trend toward preventive and pro-active risk management is itself driven by larger trends, which are not sector specific: globalization, use of risk analysis and cost benefit analysis and (total) quality management in industry. Historically, costs for safety systems and protection measures have been formidable. Strategies to save maximum amount of lives at any cost (e.g. hazards-based approach to food safety whereby the mere presence of a hazard in a food would be considered unsafe, or building expensive structural protection measures against natural hazards in the context of civil engineering regardless of their net utility) have largely become obsolete over the past 20 years. Risk-based strategies whereby an estimate can be produced on the combination of exposure to the hazard and the impact from the hazard are at the heart of preventive intervention policies across sectors. To be economically beneficial, safety and protection measures must yield more utility than the costs associated with establishing and maintaining them.

There are significant differences among disciplines and sectors, and by extension academic departments, as to the extent to which such utility considerations are taken into account. One area where these differences become most apparent is the division between research focusing on risk from a reliability perspective and from a safety perspective; another one is based on the differences between reliability and quality assurance perspectives.

Risk can be understood both in the context of reliability engineering and safety engineering, and often these different perspectives are grouped together as the same discipline. Yet in practical terms, they diverge both in terms of principles and methods. In the context of civil engineering, in order to minimize failures in engineering systems, it is essential to understand why, how and how often failures occur. One principle difference between reliability and safety engineers is that the former deal with the failure concept, whereas the latter deal with the consequences of failure. A second important difference is that reliability engineering is ultimately concerned with cost, relating to all reliability hazards that could transform into incidents with a particular level of loss. Safety engineering, on the other hand, relates to only very specific safety hazards and it is primarily concerned with loss of life, injuries and loss or damage to equipment. It does not normally look at cost directly. DTU Civil Engineering conducts primarily risk research from a reliability perspective. Hence, economic utility models are an integral part of risk analyses produced in this department. Safety engineering in the context of civil engineering is conducted at DTU Management Engineering, and the risk-related research there does not utilize economic models in their risk analyses.

Similarly, risk research at DTU Transport is carried out in the two different domains of risk and safety. The former is organized around a research theme called Model Uncertainties and Risk Analysis (hereafter MURA) and Traffic Safety. At MURA, risk is often defined in the context of cost benefit and decision analysis. The understanding is similar to that at DTU Civil Engineering, where risk is understood as expected utility. A risk assessment for transport appraisal is therefore a product of a socio-economic model. In the context of traffic safety, risk is defined as the occurrence of an unwanted event (e.g. dying in a car crash), considered relative to the exposure to this risk. As such, a risk assessment in this domain is better thought of as a safety assessment, which as in the case of DTU Management Engineering is typically an empirical study, based on qualitative surveys, descriptive statistics and accident analysis, with basically complete absence of utility modeling.

One research area at DTU Management Engineering, where economic and utility models are applied is project risk management for large engineering projects. Project risk is a type of operational risk, where budget, schedule and process standard adherence are typical metrics. Socio-economic methods such as the risk value method, real options, cost benefit analysis and multi criteria decision analysis are typically employed.

At DTU Food economics and risk assessment are not integrated. Research in these areas is conducted by separate research entities. In the context of food safety, economics is conventionally viewed as part of risk management and isolated from risk assessment as specified by authorities such as the Codex Alimentarius Commission established by WHO and FAO for the purpose of protecting the 'scientific' analysis (i.e. the risk assessment) from political influence (i.e. the politically-driven process of risk management). DTU Food has a research section dedicated to Risk Benefit Analysis, which conducts socio-economic research on the benefits of food safety policies, typically combining cost of illness estimates (e.g. cost of treatment and loss of productivity) with disability-adjusted life years (DALYs). Past discussions about the separation between economic analysis and risk assessment have focused on the difficulties stemming from lack of communication between risk assessors and risk managers and the consequent negative implications for implementation of intervention policies. It is only recently (last 5 years) that the discussion has been expanded to include how separation of economic analysis and risk assessment weakens the actual risk assessment itself. The integration of bio/physical-economic modeling that may help improve risk assessment of food safety policy is thus one desirable outcome of DTU Food's research collaboration with the GDSI.

As at DTU Food, DTU Environment also makes a sharp distinction between 'scientifically-driven' risk assessments and 'politically-driven' risk management. As economic analyses are seen as part of the latter, they are generally not incorporated in the research conducted at the department. Some of this function (at least what concerns theoretical research) is outsourced to the Quantitative Sustainability Assessment research division of DTU Management Engineering. There have also been a number of joint PhD projects combining life cycle assessment with multi-criteria decision analysis methodologies for applied environmental problems in the area of ground/surface water contamination and flood risk, which are based at DTU Environment.

Trend 4: From MINIMAX towards PARETO-optimal and MAXIMIN

The fourth major trend discussed in this report relates to the challenge of finding a near-optimal measure mix in an effort to balance trade-offs of various risk management strategies in a sustainable and equitable way. The MINIMAX strategy, a rational strategy that promises to minimize the maximum possible losses, has historically been the dominating paradigm in most sectors and industries. Over the past decade, there have been efforts to apply and improve PARETO-optimal strategies aimed at optimizing social welfare by evaluating trade-offs between probable losses, probable benefits and probable costs such as, e.g. cost benefit and cost effectiveness analyses. Following the debate on sustainable development, a new strategy MAXIMIN, has come on the agenda, aiming to promote the principle of social equity.

With regard to the fourth trend, it could be concluded that DTU has embraced the philosophy behind PARETO-optimal strategies in most domains involving applied risk research. The areas that remain largely conservative and loyal to the MINIMAX philosophy are those areas of risk research which deal with safety, i.e. occupational health and safety at DTU Management Engineering, traffic safety at DTU transport and food safety at DTU Food, though more so in the area of chemical hazards than microbial hazards.

MAXIMIN is supported in principle by all surveyed departments in as much as they all embrace the philosophy underlying the importance of sustainability considerations, however, it could not be assessed in this report to what extent the MAXIMIN principle is actually used in applied research. In general, theoretical research in decision theory as well as applied decision analysis, where these strategies take their basis, are most rigorously conducted at DTU Civil Engineering and DTU Transport. It is assumed likely that there is strong research basis in this domain in other areas at DTU, which have not been surveyed in this report. Two such areas which would merit investigation would be DTU Mechanical Engineering and the research section for Operations Research at DTU Management Engineering (in the case of the latter, the author was unfortunately unable to establish contact with members of the research group).

2. Discussion

2.1 Risk Concepts and Perspectives

There is no agreed definition of the concept of risk – not in the field, and not at the different DTU departments surveyed in this report. There is even no agreed definition of the concept within individual fields and departments. This fact invites the thought that even though risk analysis is the underlying objective scientific component of the goal of evidence-based policy, subjective considerations of risk, including not only in the management but also in the assessment domain, cannot be eliminated from any decision making process be that risk-based (narrow and technocratic) or risk-informed (holistic and relational).

There is a general agreement across disciplines and across the six departments that risk is a function of probability and consequences, however various interpretations of probability as well as of consequences are possible. Semantically related concepts such as uncertainty and utility express different nuances in how risk is perceived and conceptualized. Classical, frequentistic and Bayesian interpretations of probability result similarly in different ways of framing risk. Finally, risk seen from a reliability, safety or quality assurance perspectives produce each in turn their specific formulations and methodologies. Comparing conceptual definitions of risk by a subject area or department is hence suggested to be less useful than a comparison based on principles, metrics and applied methodologies. In this light, four definitions of risk can be distinguished among the surveyed departments:

(i) Risk = Expected value/utility (R = E)
(ii) Risk = Probability and Scenarios/(severity of) Consequences (R =PC)
(iii) Risk = (severity of) Consequences/Damages (and Uncertainty) (R = C (+U))
(iv) Risk = the effect of uncertainty on objectives[1] (R = ISO)

Risk = Expected value/utility (R = E)

According to this view of risk, risk is the product of the probability and (dis)utility of some future events. This concept is applied at DTU Civil Engineering in the context of Structural Engineering and Risk and Decision Analysis, at DTU Transport – in the context of MURA, and at DTU Compute.

Risk = Probability and Scenarios/(severity of) Consequences (R =PC)

According to this view, risk is a function of the probability and severity of adverse effects, encompassing the questions: What can happen?; How likely is that to happen?; and If it does happen, what are the consequences? This concept is applied at DTU Management Engineering in the context of Major Accident Hazards, at DTU Food in the context of Microbial Hazards, and at DTU Environment in the contexts of Microorganisms in Water and Flood Risk.

[1] The definition of risk given in the ISO 310000 code standard

Risk = (severity of) Consequences/Damages (and Uncertainty) (R = C (+U))

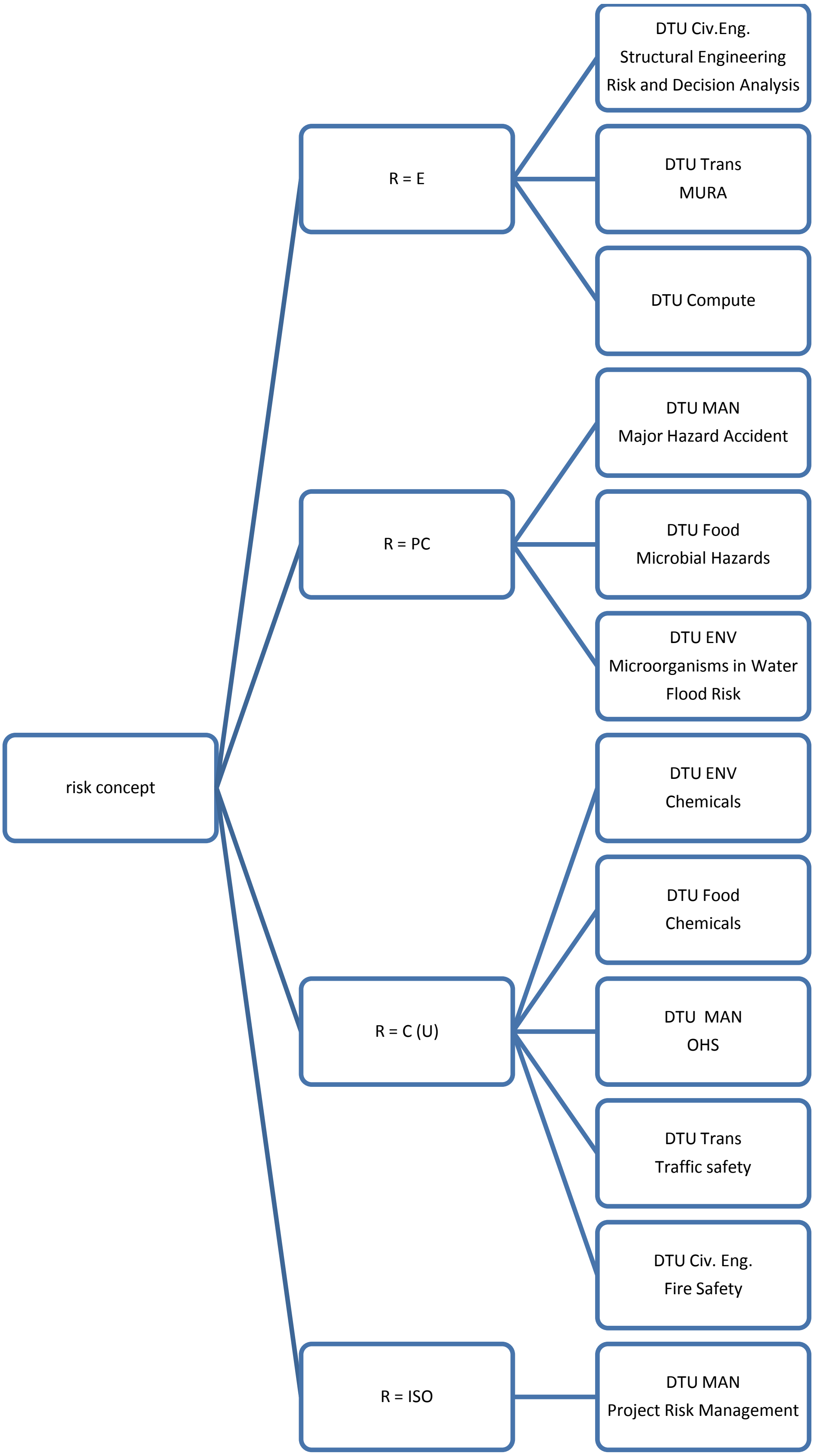
In this definition, risk is a combination of events/consequences (of an activity) and associated uncertainties (not always explicitly accounted for, e.g. environmental impact assessments, life cycle assessments). According to this definition, risk can also be seen as the deviation from a reference level (i.e. ideal states, threshold values, planned values), which explains its prevalence in areas related to chemical risk assessments with regard to both human and environmental health, which rely on threshold criteria to determine acceptable intake and adverse effect levels. At DTU, this definition is adopted by DTU Environment and DTU Food in the context of chemical hazards and DTU Management Engineering in the context of Quantitative Sustainability Assessment as well as any area, which makes methodological use of LCA methodologies.

The same concept, but not typically including the uncertainty considerations is used at DTU Management Engineering in the context of Occupational Health and Safety, at DTU Transport in the context of Traffic Safety and at DTU Civil Engineering in the context of Fire Safety.

Risk = the effect of uncertainty on objectives (R = ISO)

This definition of risk is the broadest of all. It has received much criticism in the field for being imprecise and ambiguous. At DTU, it is used in the context of DTU Management Engineering in the context of Project Risk Management. It is judged in this report to be a de facto relevant definition for the context in which it is used as it better relates risk to the concept of quality management, which is the underlying philosophy of the research done in this area.

The figure below illustrates the different concepts of risk used at DTU according to research sub-fields of the surveyed departments.


risk concept
R = E
R = PC
R = C (U)
R = ISO
DTU Civ.Eng.
Structural Engineering
Risk and Decision Analysis
DTU Trans
MURA
DTU Compute
DTU MAN
Major Hazard Accident
DTU Food
Microbial Hazards
DTU ENV
Microorganisms in Water
Flood Risk
DTU ENV
Chemicals
DTU Food
Chemicals
DTU MAN
OHS
DTU Trans
Traffic safety
DTU Civ. Eng.
Fire Safety
DTU MAN
Project Risk Management

Implications of how risk is framed as a concept have obvious philosophical and methodological repercussions for both the risk assessment and risk management phases as well as for risk communication, where the latter is considered a separate activity. These implications are discussed in greater detail in the subsequent two sub-sections. Section 2.2 outlines how conceptual differences of risk are reflected in procedural risk frameworks and how they have resulted in defining different boundary conditions for what body of knowledge should fall under the headings of risk analysis, risk assessment and risk management.

Section 2.3 discusses how conceptual differences of risk affect how the concept is measured, namely the principles, methodologies and metrics stemming from the different interpretations. In addition to this situation assessment, this section also highlights specific methodologies and metrics which could be applied generically across disciplines.

2.2 Procedural Risk Frameworks

Numerous procedural frameworks for risk-based/risk-informed decision making are available in the field, which tend to focus on the process flow for the risk assessment rather than the framework for assessment itself. A significant drawback of these frameworks is that they do not sufficiently facilitate and enhance the potential for utilizing evidence and/or indications of evidence in the assessment of risks.

The private sector typically refers to two frameworks: ISO 31000 and COSO-ERM. At DTU, occasional reference is made to the ISO standard (e.g. DTU Management Engineering in the context of Major Accident Hazard and Project Risk Management and at DTU Civil Engineering in the context of Structural Engineering, where scientific staff actually contribute to updates in the ISO code.) Enterprise risk management (ERM), which is the private sector risk management tool and philosophy is largely dismissed at DTU for two reasons: firstly because it is considered too focused on financial risk, and secondly because it is too regulatory oriented and not fit for purpose for the risk activities subject to research at DTU.

The public sector refers to a similar procedural framework as the ISO 31000, which involves risk identification, risk assessment, risk response, risk communication and risk monitoring, in the context of so-called *national/country risk assessments*, which have proliferated in the past 5 years. Typical outputs of such assessments include: comprehensive national disaster risk profiles, national risk information systems, and national disaster risk reduction priorities. Some of these assessments are coordinated through a whole of government approach (e.g. Canada, the U.S., the U.K., the Netherlands, Sweden, etc.); others are coordinated at specific agency level (e.g. Norway, Switzerland, Denmark, etc.).

Specific sector risk analyses are governed by frameworks and guidelines issued by national or international normative and pre-normative committees. For example, food safety risk is internationally guided by FAO/WHO /EFSA guidelines, the Codex Alimentarius and the WTO SPS Agreement and by national agencies, such as the Danish Veterinary and Food Administration and the Danish Environmental Protection Agency in the case of Denmark.

The type of framework that is followed at DTU departments with regard to risk assessment and/or management is largely dependent on the historical use and availability of such frameworks in the context of a given field or sector. Thus DTU Environment and DTU Food are strongly dependent upon such public sector frameworks, while DTU Transport and DTU Civil Engineering are largely independent in their choice of framework. DTU Civil Engineering refers to the framework of the Joint Committee on Structural Safety, of which it is an active participant and contributor. No framework was identified for DTU Transport. Similarly, there is no uniform framework at DTU Management Engineering. There, the ISO 31000 is sometimes used as a reference.

To the extent that applied risk research is conducted for a particular sector or industry, the framework adopted is the one of that sector, e.g. in the case of Major Accident Hazard, oil and gas, nuclear, etc. industry standards are typically used.

Research in the area of Quantitative Sustainability Assessment is guided by the LCA framework outlined in the ILCD 2010 Guidebook.

The GDSI is in the process of developing a generic framework for risk-informed decision making, whose principles will be outlined in the subsequent section.

Terminology in the context of procedural risk frameworks raises a host of challenges not only in terms of communication (i.e. the same terms are used with different meanings by different fields), but more importantly, deeper philosophical challenges with regard to whether and how different activities in the overall analytical risk management processes are separated and who has ownership, and respectively, accountability for the various phases. In the individual departments' sections of this report, detailed information is given on how each department/academic field defines these procedural steps (see section 2 in each appendix). In addition, a detailed glossary of risk-related terms is provided at the end of each appendix. The argument made in the present report is that despite the inconvenience of the mixed terminology, the basic challenge in each discipline is the same, namely to conceptualize and event or activity which in the future could lead to consequences that are in some way undesired or not planned. Thus, efforts should be expanded upon this challenge rather than the rather futile exercise of synchronizing vocabularies. Glossaries of terms are judged to be a good enough solution for that.

The relevant challenge is to find an optimal framework that is generic enough to accommodate the needs and perspectives of each discipline as well as be inclusive of all relevant stakeholders of the risk assessment: the decision makers commissioning the assessment, society – on whose behalf the assessment is commissioned, and the scientists producing the assessment. In most existing frameworks, there is a sharp distinction between the 'scientific' part of the assessment – typically referred to as *risk assessment* and comprised of the (usually) numerical assessment of probabilities/uncertainties and consequences – and the 'non-scientific' management part, typically referred to as *risk management*, which in extreme cases (e.g. DTU Food, DTU Environment) consists of basically everything else from risk screening and scope setting to risk acceptance to risk treatment, monitoring and communication. In less extreme cases (e.g. DTU Civil Engineering, DTU Transport) a less sharp distinction exists between assessment and management whereby the twilight area of risk acceptance (assessed on the basis of relevant socio-economic methods) is better balanced as a joint consideration of both the assessment and the management strategy. Similarly, the use of decision theory for the optimization of alternatives bridges the divide between assessment and management. Finally, using prospect theory as theoretical background for accounting for errors from human judgments, together with revealed societal preference methods in determining risk acceptance criteria brings the realm of risk perception closer to the 'scientific' assessment than its historical treatment as an unsolvable problem of social phenomena that is excluded from the assessment altogether.

Researchers at DTU Management Engineering see themselves as being involved in both risk assessment and risk management, but it is difficult to interpret what this means in practice as there is no framework that is been adhered to. The approach in this report has been instead to provide a description of the methods and principles used. The generic framework which is in the process of being developed at the GDSI could be especially relevant for risk-related research at DTU Management Engineering.

2.3 Scientific Risk Frameworks

As stated earlier, it is assessed in this report that risk frameworks (procedural and scientific) are not necessarily field or department dependent but arise from the conceptual definition of the notion of risk. When risk is framed as expected value or expected utility, it can be scientifically framed as a decision analysis problem. Probability theory and statistics form the basis for solving decision problems under uncertainty, and thus constitute the cornerstone in risk decision analysis. The purpose of probability theory is to enable the quantitative assessments of uncertainties through probabilistic models such as random variables and random processes. The characterization of these models is based on statistical information. Classical, frequentistic and Bayesian interpretations of probability can result in different ways of framing risk even though they may use the same calculus.

In the frequentistic interpretation, probability is the relative frequency of occurrence of an event as observed in an experiment with a number of trials. The classical interpretation, dating to the foundation of probability theory in the 17th c. is inspired by games of cards and dice, and is essentially similar to the frequentistic definition, except that the experiment does not have to be carried out as the answer is known in advance. The classical interpretation gives no solution unless all equally possible ways can be derived analytically; hence it has limited application to practical engineering problems.

In the Bayesian interpretation, the probability of an event is formulated as a degree of belief that the event will occur. In as much as evidence is that which justifies belief, Bayesian probability theory can appropriately be used as the scientific philosophy underpinning evidence-based decision making and policy. The degree of belief is a subjective reflection of an individual (expert) in terms of experience, expertise and preferences. It is also referred to as a prior belief or prior probability, which refers to the belief that may be assigned prior to obtaining any further knowledge.

Structural reliability and risk analysis in the context of DTU Civil Engineering, risk analysis in the context of MURA at DTU Transport, Microbial Risk Assessment at DTU Food, and Flood Risk at DTU Environment use Bayesian methods in their risk analyses. It is typically areas, characterized by large gaps in data/knowledge and subject to significant uncertainty (both stochastic and epistemic) as well as areas where there is a large inter-dependency among risks and potential failures that typically tend to apply Bayesian methods.

Conditional probabilities (posterior and pre-posterior probabilities) are of special interest in risk analysis as they form the basis of the updating of prior probability estimates based on new information/knowledge/evidence. Posterior probabilities are used for assessing decision alternatives with regard to system changes, based on a combination of available knowledge and new information. This type of analysis can support the adaptation of loss reduction and adaptation strategies after a hazard event has occurred and specific information about the event has been observed. From a risk (and knowledge) management perspective, this is also a suitable method to incorporate information from lessons learned, which has been notoriously difficult to implement, into the process of updating risk assessments and revising strategy and policy options.

Pre-posterior probabilities (connected to the concept of Value of Information discussed below) facilitate not only the optimization of decisions with regard to system changes but also with regard to the collection of information which improves knowledge about the hazard processes and the efficiency of measures for managing them. The pre-posterior decision analysis is hardly utilized in practice, most likely because it is not well understood. At DTU, it is used only at DTU Civil Engineering where it is advocated that pre-posterior decision analysis is applicable in the same situations as the prior decision analysis, and that it should be utilized instead of that.

Finally, Bayesian probability theory is the backbone of the generic risk framework developed by the GDSI, where it will be used for representing knowledge and uncertainty associated with natural phenomena, the engineering models and the human and organizational factors which affect performance of engineered systems.

In some areas, probabilities may adequately be assessed by means of frequentistic information (also referred to as ‘objective probability’ in contrast to Bayesian ‘subjective probability’). However, there are a number of prerequisites in order to be able to utilize this approach. For example, the components in the system that is analyzed need to be in principle identical, subject to the same operational and/or loading conditions, and failures must be assumed to be independent. This methodology was developed for the process and manufacturing industry and is suitable for assessing the probability of mass produced components. The frequentistic approach is used at DTU Management Engineering in the context of Major Accident Hazard.

Another characteristic of this approach is that it requires a large amount of data or large number of similar activities with known variations, where expected loss (failure) is based on the so-called ‘law of large numbers’, according to which the number of similar, independent, identically distributed random variables converges to the expected value of one specific random variable. Such an approach, at least in principle, would be appropriate in the context of some natural hazards, with observed averaging events over time such as floods. This is typically the approach used in the insurance industry. The extent to which it is utilized at DTU could not be determined.

A further methodological distinction exists across research areas, based on whether predominantly deterministic (point estimate) or probabilistic approaches are used. This information is summarized in the table below. Qualitative and socio-economic methods are subsequently listed. The term *‘deterministic’* describes an approach in which numerical point values are used at each step in the risk assessment – for example, the mean or the 95th percentile value of measured data, such as, e.g. food intake or residue levels – to generate a single risk estimate. Deterministic approaches are the norm in chemical risk assessment for both human and environmental health, and are also applied in various life cycle assessments.

Predominantly probabilistic methods	**Predominantly deterministic methods**
DTU Civil Engineering • Structural Engineering • Risk and Decision Analysis • Natural Hazards	DTU Civil Engineering • Fire Safety
DTU Food • Epidemiological Microbiological Risk Modeling • Predictive Microbiology	DTU Food • Risk Assessment of Chemical Exposure • Cocktail Effects • Antimicrobial Resistance
DTU Environment • Flood Risk • Microorganisms in Water	DTU Environment • Ground/Surface Water Contamination • Chemicals
DTU Transport • MURA	DTU Transport • Traffic Safety
DTU Management Engineering • Major Accident Hazard • GDSI	DTU Management • Quant. Sust. Assessment

Qualitative and Socio-Economic	**methods**
Structured and semi-structured interviews	DTU Management Engineering • Occupational Health and Safety DTU Transport • Traffic Safety
Expert elicitation	DTU Food • Epidemiological Microbiological Risk Modeling DTU Management Engineering • Project Risk Management
Decision trees	DTU Management Engineering • Major Accident Hazard • Project Risk Management
Multi-criteria decision analysis	DTU Transport • MURA DTU Management Engineering • Quant.Sust.Assessment • Project Risk Management DTU Environment • Ground/surface Water Contamination • Flood Risk
Formal decision analysis	DTU Civil Engineering • Structural Engineering • Risk and Decision Analysis • Natural Hazards

	DTU Transport • MURA DTU Compute
Reference class forecasting	DTU Transport • MURA
Cost benefit analysis	DTU Civil Engineering • Structural Engineering • Risk and Decision Analysis • Natural Hazards DTU Transport • MURA DTU Management Engineering • Project Risk Management DTU Food • Food Risk and Benefit
Risk Value method	DTU Management Engineering • Project Risk Management

In general, the following theoretical underpinnings are seen as particularly suitable in the context of risk-informed decision making applicable across disciplines and the departments surveyed in this report: (i) Bayesian decision analysis, including Bayesian Probabilistic Networks and Value of Information; (ii) Multi-Criteria Decision Analysis; (iii) Socio-economic models and indicators such as DALYs, QALYs and the LQI index for the modeling of decision preferences and risk acceptance criteria; and (iv) synergetic analysis based on Life Cycle and Risk Assessment methodologies, utilizing sustainability indicators.

Bayesian Decision Analysis

The representation of risk in terms of expected utility facilitates decisions corresponding to the preferences of the decision maker. Decisions may be related to how to reduce or avoid exposures, how to reduce vulnerability and how to improve robustness and resilience. Decision problems should be formulated as explicit functions of information/evidence (risk indicators) concerning the exposure, vulnerability and robustness, which may become available in the future. Bayesian probability theory enables this type of decision analysis whereby the risk management process can be adapted to the available knowledge at a given point in time, i.e. prior, posterior and pre-posterior decision analysis. Currently, this method is applied in different contexts at DTU Civil Engineering, DTU Transport, DTU Environment, DTU Food and DTU Compute.

Value of Information

A subset of Bayesian decision analysis, the Value of Information analysis provides an analytic framework to establish the value of acquiring additional information to inform a decision problem. This allows a comparison of the potential benefits of further research with the costs of further investigation, a comparison and prioritization of alternative research recommendations as well as the assessment of the value of investing in research or other activities. Currently, this concept is considered only at DTU Civil Engineering for applied engineering problems and at DTU Compute from a theoretical perspective.

Bayesian Probabilistic Nets

Bayesian probabilistic nets (or networks), also referred to as Bayesian belief networks, were developed during the last two decades as a decision support tool in the context of artificial intelligence engineering. Until then, artificial intelligence systems were normally based on 'rule based' systems, which have a number of shortcomings with respect to accounting for uncertainties and introducing new knowledge. BPNs have been and are still evolving rapidly. At present, they can be utilized for almost any aspect of probabilistic modeling and decision making, ranging from inference problems, model building and data mining over to posterior decision analysis. BPNs can be used at any stage of the risk analysis, and may readily substitute both fault and event trees in logical tree analyses. Whereas common cause or more general dependency phenomena poses significant complications in classical fault trees, this is not the case for BPNs as they are designed to facilitate the modeling of dependencies between parameters which influence the risk. Currently, DTU Civil Engineering and DTU Environment (in the context of flood risk) are utilizing BPNs in applied research. DTU Compute carries out theoretical and methodological research in BPNs.

Multi-Criteria Decision Analysis

MCDA stems from the field of Operations Research. Seen from this perspective, the essence of decision support analysis is to break down complicated decisions into smaller pieces that can be dealt with individually and then recombine them in a logical way. For the MCDA method there is basically three such distinct pieces: the set of possible alternatives, their characteristics (represented by a set of criteria), and the preference structure of the decision maker, reflected in criteria weights. Generally, the alternatives and their criteria represent the objective part of the decision process, whereas the subjective part lies in the preference structure. Where a given criterion cannot be quantified in an obvious monetary way, a subjective proxy for the criteria is found through a process of involving all relevant stakeholders. MCDA is basically an extension of cost benefit analysis, which allows for the accommodation of both monetized impacts as well as more strategic impacts (e.g. human life and well being, environmental health and quality, etc.). Accordingly, equity considerations can be explicitly considered in MCDA, making it better compatible with decisions related to sustainability. Currently, MCDA is used at DTU Transport (MURA), DTU Environment (Surface and Ground Water Contamination) and DTU Management Engineering (QSA and Project Risk Management).

Socio-economic models for risk acceptance

The most commonly used format for representing acceptable risks is the Farmer diagram or FN-diagram (also known as a risk matrix), where risk is typically expressed in terms of the number of fatalities (or other negative consequences) and the probability of occurrence of the corresponding events. These diagrams can be applied to illustrate the risk profile for a specific activity or for specific types of hazards. In this way, the risk profiles can be compared at national or regional scales and resources for risk mitigation allocated. The acceptable and unacceptable areas are different for the different indicators of consequences. For activities found to lie in the area between acceptable and unacceptable, the generally applied philosophy is to implement risk reduction measures on the basis of cost efficiency considerations. A commonly used principle for this is the As Low as Reasonably

Practicable (ALARP) approach. It implies that risk reduction are not disproportionately large in comparison to their risk reducing effects.

At DTU, only the following research areas take into consideration issues related to risk acceptance criteria: DTU Civil Engineering, DTU Transport and DTU Management. From all three departments, research critiquing the present principles and methods for arriving at risk acceptance criteria has been discussed in detail in the individual department sections in the appendices. All other research areas surveyed, identified the issue as one pertaining to 'management' and therefore not part of their academic investigations. It is argued in this report that rational risk acceptance criteria in the context of societal decision making may be derived on the basis of socio-economic considerations. For societal decision making at the highest level, the focal issue concerns how to prioritize between investments into different sectors, e.g. the health sector, the public transportation sector, the energy sector, and so on. It is evident that such decisions cannot simply focus on the safety of individuals but that considerations must be given to the general development of society as well as those factors influencing the quality of life of the individuals in society. Stemming from this philosophical perspective, significant research has been carried out in the context of DTU Civil Engineering on the application of the so-called life quality index (LQI) for societal risk acceptance. During the writing of this report, the LQI has, on the basis of the aforementioned research, been adopted by the ISO risk framework in the context of structural reliability. How this is compatible with other sustainability metrics will briefly be outlined below.

An efficient life saving activity may be understood as a measure which in the most cost effective manner reduces the mortality or equivalently increases the statistical life expectancy. Time is seen as the only asset available to individuals in society, which could be spent for activities of self-realization, but could also be exchanged into goods, the exchange rate of which depends on the value assigned to time. A model of life quality thus critically considers time in good health. The incremental increase in life expectancy through risk reduction, the corresponding loss of economic resources, measured through the national GDP, together with the time used for work, all assessed for a statistical life in a given society, form the most important building stones for the assessment of risk reducing measures. Based on these demographic indicators, the LQI facilitates the development of risk acceptance criteria. The underlying idea of the LQI is to model societal preferences quantitatively as a scalar valued social indicator, based on the relationship between the part of the GDP per capita, which is available for risk reduction purposes, the expected life at birth and the proportion of life for earning a living. As such, the LQI is an indicator applicable across multiple hazard domains.

Trade-offs between monetary wealth and fatal safety risks are typically summarized in the value of a statistical life (VSL), which is the common metric for evaluating public policies in the health, environment and transport sectors. Two supplementary metrics are advocated in some research carried out by DTU Food – the Health Adjusted Life Years (HALYs) and Disability Adjusted Life Years (DALYs). HALYs are summary measures of population health that allow the combined impact of death and morbidity to be considered simultaneously, which makes them useful for comparisons across a range of illnesses, interventions and populations. HALYs are indices of the impact of illness on physical well being and function. They do not measure consumer preferences over reduction in risks of future health states, which leads to HALY measures placing greater weight on reducing chronic diseases than to reducing mortality. HALYs are theoretically based on principles of welfare economics and expected utility theory, so their choice in scientific risk assessments underpins public policies designed to do the greatest good for the greatest number of people.

DALYs were developed to quantify the burden of disease and disability in populations, and set priorities for resource allocation. DALYs measure the gap between a population's health and a hypothetical ideal for health achievement. They place different value weights on populations, based on their age structure so that DALYs in the very young and the very old are discounted compared to other age groups.

Synergy between Life Cycle and Risk Assessment

The GDSI is envisaged as a cross-departmental scientific platform, whose novel contribution will be to build a generic framework for risk assessment/management, which links together preferences with respect to sustainability, life cycle assessment and risk assessment. Basis for this framework is taken from current Bayesian theoretical framework of risk and sustainability assessment and their use in decision support. The representation and management of knowledge and uncertainty for engineering decision problems is based on principles from information and probability theories, while policy, preferences and metrics are based on different theories from welfare economics related to health, environment and economic growth in accordance with the three pillars of sustainability. The overall aim of this synergy is to facilitate that the three dimensions of sustainability are transformed into a social welfare function, which can provide basis for defining metrics of sustainability from both intra- and inter-generational perspectives. Similarities and differences between life cycle assessment and risk assessment are discussed in more detail in appendix IV, section 1. A detailed description of life cycle assessment and sustainability assessment methodologies and processes is provided in appendix V, section 3.

3. Educational Offers

There is a plethora of educational offerings organized around the notion of risk at all the surveyed departments. In the appendices, these courses are listed for each department and are organized according to keywords such as risk, safety, uncertainty, security, decision analysis, life cycle and sustainability. Their level of specialization is naturally different, though the vast majority of courses related to risk assessment/management are specific to the academic field of the offering department. At present there are only three generic courses:

42172 – Risk and Decision Making (MSc) – at DTU Management Engineering

02431 – Risk Management (MSc) – at DTU Compute

13233/13833 – Decision Support and Risk Analysis (MSc/PhD) – at DTU Transport

It is increasingly recognized that risk management before, during and after an adverse or crisis event represents a specialized discipline of its own rather than sub-discipline expertise. One approach DTU could take in the context of educational activities with regard to risk is to emphasize the need to educate and develop a cadre of professionals equipped to manage or facilitate the management of risk at all three stages. Professionalization would entail the identification of a body of knowledge relevant to the field of risk (e.g. decision theory, statistics, probability theory, systems theory, together with relevant methodologies from the natural, life, social and engineering sciences), core skills, and standards, including a code of ethics. Furthermore, when carrying out commissioned research by public authorities, partnerships between political decision makers and experts from various disciplines is essential. This means that decision makers, who are not experts or professionals in the field of risk, must be educated as to the nature of risk management, informed of what is required of them in all stages of the risk management process and equipped to engage in meaningful communication with risk experts. It is further important to emphasize that the same applies for risk experts who are not professional decision/policy makers. Scientific educational programs in risk management should incorporate in their curriculum basic familiarization with the goals, requirements, constraints and methodologies used in the policy area. In this sense, risk management education should be both conceptual and practical. Programs and courses should be organized with various stakeholders in mind and targeted to their particular needs. This implies that DTU could provide courses and programs to both 'regular' students pursuing Master and PhD studies at DTU as well as courses and programs geared to external students and working professionals outside the DTU framework.

It should be acknowledged that attempts to provide such educational pathways are already envisaged. For example, one of the GDSI's objectives is in the near future (1-3 years) to provide courses in the domain of risk assessment, sustainability assessment and engineering decision making based on already existing courses and curricula from the participating departments, but centrally coordinated and advertized by the GDSI. A mid-term objective (3-5 years) is to develop a full master program in risk-informed decision support.

With regard to professional courses, DTU Civil Engineering has already pioneered three such one-week long courses, offered jointly through the Joint Committee on Structural Safety Advanced School:

- Probabilistic Modeling and Risk Analysis in Engineering
- The JCSS Probabilistic Model Code
- Risk Informed Decision Making and Decision Analysis.

The courses are targeting engineers involved in probabilistic structural analysis, design and reliability assessment as well as their supervisors and managers, but are also open to (internal and external) PhD students and academics working in the field of structural risk assessment.

The conclusion of this report is that the educational activities outlined above should be supported by all stakeholder departments and DTU's central administration as well as promoted both nationally and internationally through, e.g. the future GDSI expert network. Strategically, such courses and programs could also be promoted through academic entities supporting development and capacity building such as the DTU-UNEP partnership, which would strengthen DTU's international profile in the field of risk even further.

4. Academic Networks, International Collaboration, Advisory Activities

A general trend in the area of advanced education, research and development is a shift from a functional or 'scientific' model toward an applied or 'entrepreneurial' model. The entrepreneurial university thus not only produces scientific knowledge but has a central role in the capitalization of that knowledge. University graduates are, seen from this perspective, only one type of product associated with higher education institutions; spin off companies, scientific advisory teams (ad hoc or more permanent) in direct competition with industry consultancies, are another.

As an economic actor, the entrepreneurial university engages in the production of knowledge and domain experts through a variety of networks: national and international, academic, public-private partnerships, partnerships with national and international normative and pre-normative institutions as well as partnerships with the so called 'third sector' – international organizations, not for profit foundations and non-governmental organizations. The value of mapping this distributed knowledge system and tapping into its network potential is indispensable for the successful management of academic activities with regard to all three DTU competencies: teaching, research and science-based advisory activities. Unfortunately, only fragmented information was possible to collect in this report with regard to DTU's collaborative and advisory activities in the area of risk. While all the surveyed departments list the names of their national and international academic and other partners on their websites, this information alone is not sufficient for practical purposes of mapping and engaging with these networks in a coherent and structured manner. During the personal interviews with the departments' representatives, information was solicited on the specific contact information of collaboration partners and on specific themes and arrangements of where and how collaboration took or is taking place. For the most part, this information was not provided as it was deemed too time consuming a process. More thorough information could be gained with regard to specific departments' collaboration and advisory activities for clients in the Danish public administration, i.e. sector relevant ministries and directives. This information is listed in the appendices.

Certain departments have a long history of international collaboration at a high policy level (e.g. DTU Food through engagements with the WHO, FAO and the WTO; DTU Environment through the WHO, EEA; and DTU Civil Engineering through the OECD). These experiences as well as the networks they provide could certainly be utilized for the greater benefit across DTU. In this regard, one of the GDSI's more ambitious objectives is to build a global expert network in the area of risk and sustainability assessment. However, it is assessed in this report that the resources budgeted for this purpose are strongly underestimated. With an administrative staff of one and severe constraints from the working schedules of the advisory board, this objective is not likely to be realized in the short-medium term. A professional outreach and dissemination strategy is recommended to be developed, including realistic budgeting for activities related to building the global expert network.

A further challenge is identified with regard to advisory activities related to risk, namely that much of these activities to-date have been carried out under the aegis of individual departments with specialized topical expertise and mostly through longer-term project research. The need for multi-disciplinary, multi-sectoral risk assessments, where multi-departmental teams have to be assembled ad hoc and for short time span durations poses an eminent challenge for scientists and administrators alike. A very current example of this challenge is a risk study commissioned by the Danish Directorate for the Environment on the risks of extracting shale gas in Denmark. Between October 2014 and March 2015, the author of the present report attended a number of meetings with representatives from the scientific staff from the different DTU departments involved in the scientific assessment and representatives from the central administration, who were assigned the role of knowledge mangers for the commissioned study. During these meetings it became increasingly apparent that all stakeholders had widely divergent views on what this study should constitute, whether it should be a risk assessment or a risk screening, whether it should be an environmental impact assessment or an environmental risk assessment, what should the level of detail be, what principles and methods should be applied and what indicators considered, and – not least – who should have ownership of the various stages of the assessment.

Time is yet another force multiplier in this context. Even if multi-disciplinary teams are not involved, the duration of producing a risk assessment from the collection of data over to the optimization of decision support alternatives could be a very lengthy process. This has often been pointed out from the client perspective (public and private), where the solution is typically required expediently if it is to be of practical use to rapidly evolving external conditions. Some research on real-time decision support has been carried out at DTU Civil Engineering in the context of natural hazards emergency response. DTU Food also has experience in the context of providing fast response under emergency. Expanding such capabilities to other areas of risk would certainly make DTU's advisory services more competitive in the consultancy market. Ultimately, this can be seen as a knowledge management problem, where the production of rigorous, evidence-based assessment is surely important, but so is the organizational culture of the institution providing it. In this sense, the willingness to share knowledge and the ease with which it can be done from an administrative point of view could facilitate to assure not only the accuracy of the solution but its timely response.

5. Knowledge Gaps

There are a number of risk-related research areas that are relevant for DTU's portfolio of risk specializations, which are not sufficiently covered or not covered at all, including:

(i) Risk perception, Risk Communication and Early Warning
(ii) Philosophy of risk in the context of theory of science and epistemic philosophy
(iii) Physical hazard modeling for most natural hazards

Risk perception, Risk Communication and Early Warning

Challenges related to risk perception (e.g. lay vs expert perception) and risk communication were identified as one of the most difficult challenges across all surveyed departments. Despite this common acknowledgement, little to no research is actually conducted in this context. Some attempts have been made at DTU Civil Engineering to frame risk communication with respect to different attributes of sustainable societal developments whereby risk communication is based on weighing of these attributes in terms of their relative valuations on the optimal choice of strategies. Following normal governmental/democratic procedures, it is then decided whether or not the considered societal change should be introduced, and if it is, according to which strategy.

DTU Transport adopts Prospect theory as theoretical background for optimism bias and reference class forecasting for transport project evaluation schemes to address the cognitive tendency of overestimating benefits and underestimating costs. In the context of project risk management at DTU Management Engineering, some research has been/is carried out with regard to perception and public acceptance of wind power technologies, accounting for cognitive biases also in accordance with Prospect theory. With these three exceptions, research in this domain, both in terms of theoretical and empirical studies, is lacking.

Similarly, the related sub-field of risk communication, Early Warning, is entirely absent from the research portfolio. While there is evidence that many departments and academic fields are putting a lot of emphasis on developing risk and sustainability indicators, which are the ‘technical’ basis for warning, there is no focus on the conceptual or management aspects of warning, which are essentially information and knowledge management domains. In this light, it should also be noted that there is a surprisingly weak link between DTU and the Danish Emergency Agency, which would seem an obvious client of DTU’s expert knowledge in the domain of risk.

To address the knowledge gap in the area of early warning, the author of this report proposes a PhD study through the framework of the GDSI, which would focus on conceptual and strategic aspects of warning. A detailed proposal is provided in a separate document. For the purposes of the present report, only a brief outline is provided below.

The aim of the proposed research will be to frame warning as an information and knowledge management problem by mathematically describing the effect of warning (indicators) through conditional Bayesian probability theory. An observation or indication of an emerging hazard is associated with the possibility of leading to a false conclusion that the hazard is not emerging (Type 1 error) despite the fact that it is in fact emerging, or the false conclusion that it is emerging, despite that it is not emerging (Type 2 error). Both situations are associated with potentially severe consequences. In the first case, the potential for damage reduction by means of evacuation is lost. In the second case – which is the case of false alarm – costly and potentially dangerous loss reduction activities associated with, e.g. evacuation are commissioned erroneously. Moreover, in the latter case, the public confidence and trust in the warning deteriorates, which could significantly affect the value of warning in subsequent situations where the indication could actually be true. Formulated as a problem of conditional probability, warning can be seen as subject to optimization on the basis of the value of information (pre-posterior decision analysis) principle whereby the added value of warning can be accounted for in relation to other possibilities for risk management as well as potentially improve the choice and qualities of indicators.

Philosophy of risk in the context of theory of science and epistemic philosophy

Another area which is poorly covered at DTU with regard to risk is philosophy. By this it is not meant cultural theories of risk and risk perception, which suitably find home at Copenhagen University, but risk seen through the perspective of philosophy/theory of science, epistemic philosophy and ethics, which are all relevant perspectives from an engineering point of view. At present, only one undergraduate course is offered in the philosophy/theory of science through DTU Management Engineering. However, risk is not part of the course’s curriculum. DTU Environment offers a master’s course in environmental management and ethics. DTU Food offers a PhD course in scientific methodologies and philosophies used in food research. Individual academic publications have addressed ethical issues from an engineering perspective in the context of specific hazards (e.g. nanotechnology, artificial intelligence), however, no coherent body of research or research entity exists in this area. In the present report, this gap is considered a shortcoming both in terms of education and research as it is only when we start asking the question '*Why?*' that we question the structure of knowledge, deliberately safeguard against assumptions and cognitive biases (our prior probabilities) and introduce the possibility for change (adjust our posterior probabilities). Not only from a scientific perspective, but also from the perspective of competitiveness and innovation, one has to do things differently, not just well or better. A deeper and expanded focus on the discipline of philosophy could enable students and seasoned researchers alike in their pursuit of turning knowledge into action – the very philosophy which DTU embodies. A practical approach to this could be to establish a course in the philosophy of risk and decision analysis in engineering, which would build on contributions from the fields of philosophy/theory of science (e.g. theories of evidence, confirmation, etc.), mathematics and epistemic philosophy (e.g. interpretations of probability) and ethics, together with field/application relevant input of the different departments.

Physical hazard modeling for most natural hazards

Natural hazards are only marginally covered at DTU in the contexts of DTU Civil Engineering and DTU Environment. DTU Civil Engineering conducts research in natural hazards mostly as they impact the built environment. Floods, wind storms and typhoon events are studied. DTU Environment conducts research on impacts of floods from an environmental perspective as well as models climate change impacts on extreme precipitation events. Many other research areas at DTU consider impacts of climate change, but not typically from a risk or a physical hazard perspective, rather from a socio-economic and/or developmental one. Some research is carried out on cryospheric hazards such as loss of permafrost in the Arctic at DTU Civil Engineering's Center for Arctic Technology as well as at DTU Space in the context of Polar DTU.

Physical hazard modeling of natural hazard is basically absent from DTU's portfolio with regard to:

- Climatic hazards (storms and hurricanes, droughts, floods – i.e. hydraulic and atmospheric modeling)
- Geological hazards (earthquakes, volcanic eruptions, tsunamis) and
- Mass movement hazards (landslides, soil erosion, debris and rock falls, avalanches).

6. Conclusion and Future Outlook

In conclusion, the present report should be seen as a situation assessment of DTU's strengths, challenges and opportunities with regard to education, research and advisory activities related to the field of risk. It is acknowledged that this is far from a complete representation of the University's full capabilities in that only six departments have been considered. Despite divergent perspectives on the conceptual notion of risk and the procedural and scientific framework applied across the surveyed departments in measuring, assessing and managing risk, a number of unifying principles and methodologies have been found and examined. These are: Bayesian decision theory, which forms the basis for risk-informed decision support; multi-criteria decision analysis, which combines objective scientific assessment with systematic accounting of subjective stakeholder preferences; prospect theory, which enables scientific, empirical accounting of cognitive biases in decisions and value judgments; socio-economic methods and models, which enable rational societal risk acceptance criteria such as the LQI index, HALYs and DALYs; and the novel synergy between life cycle and risk assessment methods in the context of sustainability considerations from an intra- and inter-generational perspectives.

Despite DTU's multi-sided expertise in the domain of risk, a number of challenges remain. These include establishing clearer consensus and better coordination among experts and departments with regard to the basic principles of risk assessment, risk management and risk-informed decision making in order to establish a consistent generic framework for prioritization of available resources for global risk reduction in relevant societal activities; establishing basis for the scientific framework of risk assessment and management that allows for updating information/knowledge and evidence as they become available in the future in order to support evidence-based policy; incorporating socio-economic principles and methods into the risk assessment and management processes to account for utility-based risk treatment strategies; incorporating insights from the sub-fields of risk perception and communication to counter cognitive biases and minimize strategic surprises; directly account for issues related to sustainability in risk-informed decision making by developing sustainability indicators on the basis of risk and life cycle assessment methods; and professionalizing risk educational programs and advisory services.

There is no doubt that the Global Decision Support Initiative can be the facilitating platform for addressing many of these challenges. It is hoped that this report will be of aid to its present planning and coordination activities and that the wider audience, including DTU scientific staff and central administration would have gained an insight into the potential of this initiative and support it accordingly.

Contact Information

This report was prepared by Linda Nielsen, who was employed as Research Assistant at DTU Management Engineering between October 2014 and April 2015. She holds a B.A. in Classics (Ancient Greek philosophy and language) from the University of Victoria, British Columbia, Canada, a cum laude graduate certificate in Applied Intelligence Analysis from the Mercyhurst Institute for Intelligence Studies, Pennsylvania, USA, and a master's degree in Strategic and Operational Management of Natural Hazards from the Swiss Federal Institute of Technology (ETH Zurich). She has previously worked as writer, editor and chief knowledge officer at the Center for Security Studies at ETH Zurich as well as consultant to the Swiss Ministries of Defense, Foreign Affairs and Development and Cooperation on matters related to knowledge management, open source intelligence and analytic methodologies and tools for threat and stability assessments. Her academic and professional interests include threat and risk perception and communication, particularly in the area of early warning, as well as epistemic philosophy, information theory and knowledge management.

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Appendix I: Risk at DTU Civil Engineering

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1. Introduction: Risk in Civil Engineering

Engineering facilities such as bridges, power plants, dams and offshore platforms are intended to benefit the quality of life of the individuals of society. On a societal level, a beneficial engineering facility can be understood as one that fulfills the following basic criteria:

- Being economically efficient in serving a specific purpose;
- Fulfilling given requirements with regard to safety of the personnel directly involved as well as indirectly exposed third parties;
- Fulfilling given requirements with regard to adverse effects of the facility on the environment.

Based on these requirements, the ultimate task of the engineer is to make decisions or provide decision support to others so that engineering facilities are established in such a way as to provide the largest possible benefit. The mathematical basis for such decision problems is called decision theory. Important aspects of decision theory are the assessment of consequences and probabilities, and in a very simplified manner one can say that risk and reliability analysis in civil engineering is concerned with the problem of decision making subject to uncertainty. (Fig. 1)

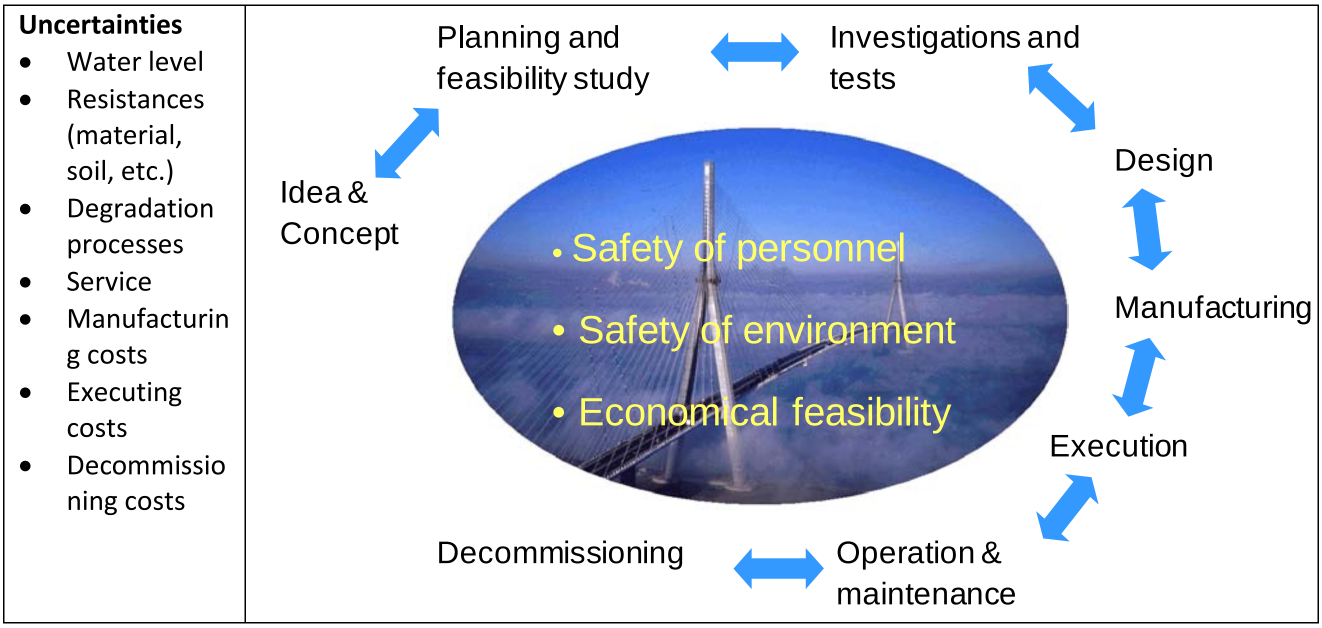

Fig. 1 Holistic life-cycle approach to risk analysis (Faber 2009)

Risk is to be understood as the expected consequences associated with a given activity, e.g. the construction, operation and decommissioning of a power plant. This definition of risk is consistent with the interpretation of risk used in the insurance industry, and risk may be expressed in monetary terms or the number of human fatalities. Even though most risk assessments focus on the possible negative consequences of events, the definition is also valid in the case where benefits are taken into account. In fact, this definition of risk is more general and consistent with *expected utility*, which forms the basis for decision analysis.

Uncertainties in Civil Engineering Problems

Risk analyses are typically made on the basis of information, which at least partly is subject to uncertainty or just incomplete. The variables influencing a risk and also decision analysis may be subject to several sources of uncertainty. The different types of uncertainties encountered in civil engineering problems are summarized in Table 1 below.

Inherent natural variability (aleatory) uncertainty	Model (epistemic) uncertainty	Statistical (epistemic) uncertainty
• Variations in material properties • Variations of wind loads • Variations in rain fall	• Lack of knowledge (future developments) • Inadequate/imprecise models (simplistic physical modeling)	• Sparse information/ Small number of data

Table 1 Types of uncertainties in engineering problems

Risks in civil engineering may be caused by a number of different sources, including natural hazards, structural failures, technical failures, operational errors and malevolence acts (terrorism).

Risk-based vs Risk-informed decision making

Over the past ten years there has been a gradual shift from a so-called risk-based to a risk-informed decision making approach. While there are clear differences between the two approaches, the terms are used inconsistently in the literature. At a very basic level the difference is one of scope: the risk-based approach encompasses the technical part of a risk assessment, or the so-called risk estimation (see section 2). The risk-based approach helps to identify the greatest risks and prioritize efforts to minimize or eliminate them. It is based primarily on a narrow set of model-based risk metrics, and generally does not lead much space for interpretation. Considerations of cost, feasibility and stakeholder concerns are generally not part of risk-based decision making.

In contrast, the risk-informed approach is a more holistic approach to risk assessment that incorporates risk acceptance and the modeling of preferences of the different stakeholders and integrates risk communication as a relevant risk reducing measure whereby negative consequences due to public perception of risk can be mitigated. The risk-informed approach acknowledges that human judgment has an important role in decisions, and that technical information cannot be the unique basis for decision making. This is partly due to inevitable gaps in the technical information, but also because decision making is an intrinsically subjective, value-based task.

Risk in Reliability Engineering vs Safety Engineering

Reliability and safety are core issues that must be addressed throughout the life cycle of engineering systems. In order to minimize failures in engineering systems, it is essential to understand why, how and how often failures occur. One principal difference between reliability engineers and safety engineers is that the former deal with the failure concept, whereas the latter deal with the consequences of failure.

A second important difference is that reliability engineering is ultimately concerned about cost. It relates to all reliability hazards that could transform into incidents with a particular level of loss. These can be losses due to loss of production due to system unavailability, unexpectedly high or low demand for spares, repair costs, interruptions on normal production, etc.

Safety engineering, on the other hand, relates to only very specific and system safety hazards that could lead to severe accidents and is primarily concerned with loss of life, injuries and loss of equipment. It deals with unwanted hazardous events (for life and property) in the same sense as reliability engineering, but does not normally look at cost directly.

A third difference is the level of impact of failures on society and the control of governments. Safety engineering is often strictly controlled by governments, e.g. nuclear, aerospace, defense and transport industries.

Although risk (as understood in the reliability context of engineering) and safety are popularly seen as two sides of the same coin and often grouped together as the same academic discipline, in practical terms they diverge in terms of both principles and methods. Safety is a major societal concern but despite the significance of the research in this area, still very few attempts have been made to establish a generally applicable framework for risk-informed decision making. Current best practice in the context of occupational safety and health is critiqued for being mainly empirical in nature and focused on the need of particular industries or sectors. Many approaches fail to address the entire spectrum of risks from causative factors to response to accidents and eventual strategies, and there is an almost complete absence of a numerate approach to the assessment and management of risks. Finally, hardly any research from the safety perspective addresses environmental and sustainability issues.

In this light, the harmonization of principles and approaches under a common generic framework which can be adapted and applied to any product, process, system, environment, undertaking and industry with risk and safety implications is seen as fundamental to the overall performance, reliability and safety. (See also DTU MAN ENG, section 2)

Risk Assessment and Sustainability Considerations in Civil Engineering

In order to assess the sustainability of a given engineering decision in quantitative terms, first a basis must be established for the representation of what is understood as sustainability in terms of observable indicators, which can be related to the preferences of society. It is generally agreed that sustainability refers to the joint consideration of three main "stakeholders", namely society, environment and economy. In addition, sustainability implies that these three stakeholders are taken into consideration not only for the present generation but also for all future generations. Presently, the direction of thinking is to formulate indicators of sustainability with regard to the environment by means of a large list of different observable environmental qualities, e.g. availability of drinking water, availability of non-recyclable resources, etc. However, in order to identify societal strategies and policies enhancing sustainability, it still remains a challenge to develop a firm theoretical basis for this; consistently assessing and weighing the costs and benefits for society, economy and the environment for the present and future generations.

For what concerns the simultaneous consideration of society and economy, a consistent framework for their joint consideration in a decision framework for socio-economic decision making is said to be available through the so-called Life Quality Index (LQI), which is discussed in more detail in Section 4 of the present annex.

Considering damages to environmental qualities with no known relation to human morbidity and mortality, one possible approach is the Nature Preservation Willingness Index which could enable the assessment of the societal willingness to pay (SWTP) for avoiding such damages in terms of character and duration of the damages.

With regard to damages to the eco-system which may occur as a consequence of extinction of species, there is still no basis for relating these to either societal or monetary scales. So far most of the reported research has been directed toward identifying the species which are assumed critical for the eco system of humans.

The exploitation of non-recycle natural resources has characteristics similar to damages in the form of extinction of species. In the short term, such damages may seem unimportant, but in the long-term, their significance is not well understood.

A general framework for sustainable decision making, which places special emphasis on inter-generational aspects is developed by DTU Civil Engineering scientists on the basis of decision utility theory. The principle is illustrated in Fig. 2, where it is indicated that the exploitation of resources and the benefits achieved by this can be transferred between decision makers at different times. In principle, if a generation decides to exploit a resource which is recyclable only to a certain degree, a part of the benefit achieved by this generation must be transferred to the next generation. In monetary terms this part must correspond to the recycling costs as well as compensate for the loss of the non-recycle resource. The latter compensation could be, e.g. in terms of invested research aiming to substitute the resource with fully recyclable resources.

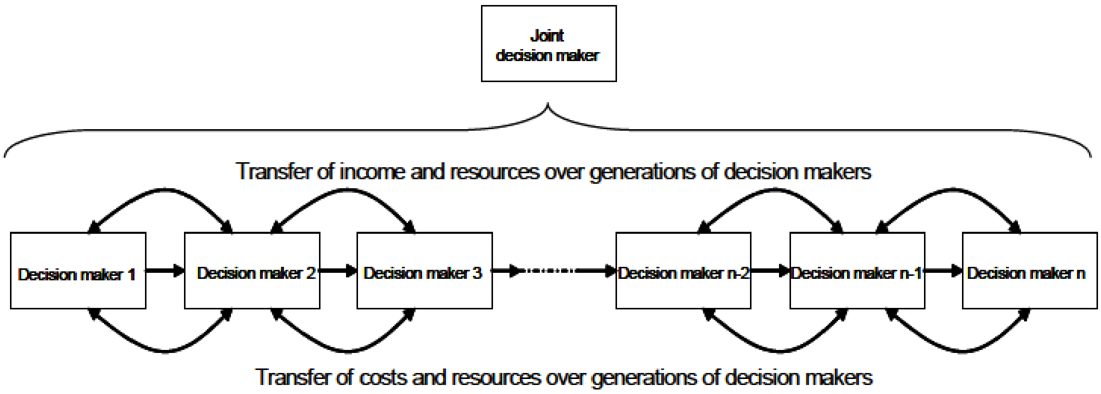

Fig. 2 Illustration of the interaction between present and future decision makers (Faber 2009)

Furthermore, costs associated with the maintenance of structures, may be transferred between decision makers at different times. In Fig. 2, the joint decision maker is assumed to make decisions for the best of all (also future decision makers) with equal weighing of the preferences of the present and all future decision makers. Following this principle, the benefits have to be summed up over the present and future decision makers as they are seen from their perspective, i.e. in accordance with the state of the world at their point in time and capitalized to their point in time. A discounting rate of 2 % per annum is suggested to be applied on all benefits and investments into engineering projects, including those related to life saving activities.

2. Concepts and processes

In the context of civil engineering risk management is the overarching term used to describe the complete process of risk assessment and risk control. (Fig. 3)

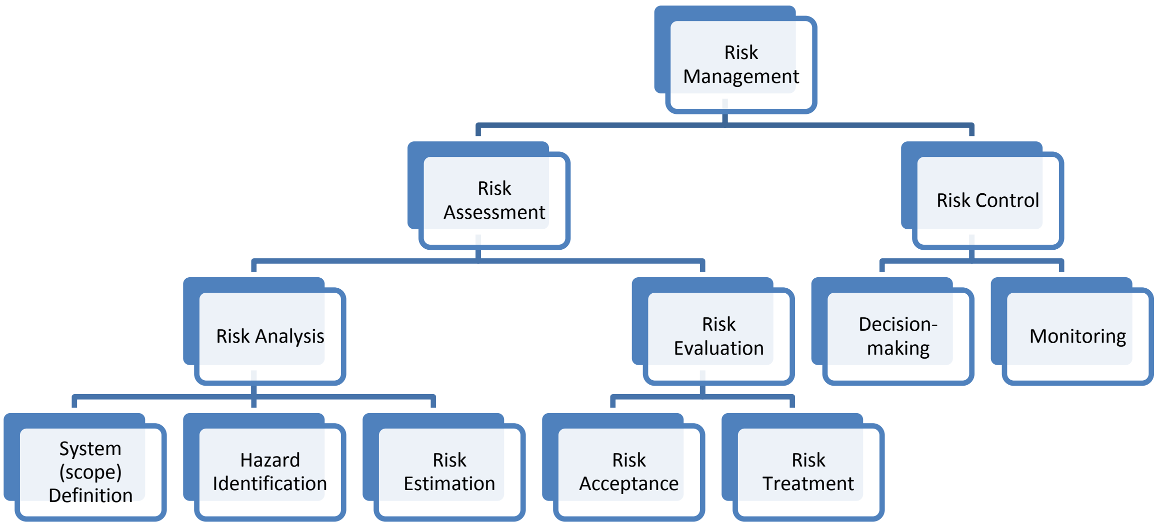

Fig. 3 Generic representation for risk management in civil engineering

Risk Assessment

Risk Assessment is comprised of the processes of Risk Analysis and Risk Evaluation. Typically the risk assessment is an iterative process as indicated by the flowchart in Fig 4.

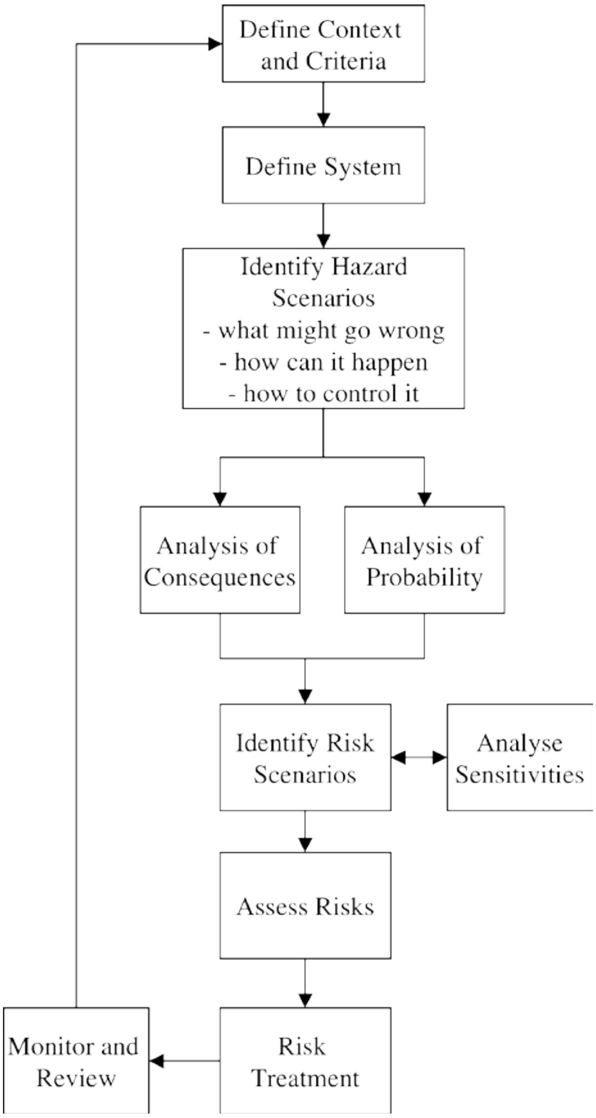

Fig. 4 Generic representation for risk assessment (JCSS 2008)

Risk Analysis

Risk Analysis is defined as the use of available information concerning relevant hazard situations for estimating the risk for individuals or populations, property or environment. It generally involves the context (scope) definition, hazard identification, and risk estimation. Risk analyses may be represented in a generic format, which is largely independent from the application or whether the risk analysis is performed in order to document that the risks associated with a given activity are acceptable or is performed to serve as a basis for a management decision.

System (Scope) Definition

A system definition is the spatial, temporal and relational representation of all relevant hazards (exposures), the assets (e.g. buildings, structures, components, lifelines, technical equipment, procedural processes, humans and the environment), direct consequences (related to damages on the individual constituents of the system, or marginal losses), and indirect consequences (associated with the loss of the functionalities of the system such as the sum of losses of the constituent failures or one or more constituent failures. (Fig. 5)

Fig. 5 Generic system representation with evolution to direct and indirect consequences (Faber et al. 2007)

The chosen level of detail must be sufficient to facilitate a logical representation of events and scenarios of events related to the constituents of the system which individually and/or in combination may lead to adverse consequences. A system representation must be developed in such a way as to facilitate risk assessment and ranking of decision alternatives (options) as well as allow for updating of the information (knowledge) about the individual constituents of the system which may be available in the future.

Hazard Identification

One of the first tasks in risk analysis of civil engineering facilities is to identify the potential hazards, i.e. the sources of risk. This process plays a crucial part of the risk analysis due to the fact that only the identified potential hazards, which are subjectively and objectively known, can be taken into account. If all the relevant hazards are not identified then the risk analysis will result in biased decision-making, which in general will be cost inefficient and ultimately could lead to unacceptably high risks to people and the environment. Methods and techniques for hazard identification are presented in section 3 of this appendix.

Risk Estimation

Risk estimation is the process used to produce the estimate of the risk measure. It generally contains the following steps: scope definition, probability analysis, consequence analysis and their integration. Methods and techniques for risk estimation are presented in section 3 of this appendix.

Hazards (Exposures)

The hazards (referred to as *exposures* in civil engineering) acting on the system and its constituents are understood as all possible endogenous and exogenous effects that may potentially cause consequences. A probabilistic characterization of the exposure to a system requires a joint probabilistic model for all relevant effects to time and space.

Consequence Analysis

The consequences strongly depend on the specific characteristics of the hazard as well as the location where it occurs and the assets which are exposed. In general consequence analyses assess the loss of lives or injuries to people, economic losses and damages to the quality of the environment. In the assessment of consequences it is further useful to distinguish between two types of indirect consequences, i.e. indirect consequences due to physical system changes and indirect consequences due to societal or public perception of those. Traditionally, risk assessments have focused on the assessment of direct consequences. Indirect consequences are included by simply amplifying the direct consequences by means of a risk aversion function assessed subjectively. It is argued that integrating risks due to public perception into the formal risk assessment is a preventive strategy option for risk management whereby through better and more targeted risk communication before, during and after the realization of hazardous events, the indirect consequences caused by public perception would be reduced.

Vulnerability, Robustness, Resilience and Adaptive Capacity

A range of different terms to characterize the effects of hazards are applied across the different disciplines. Among these vulnerability, robustness, resilience and adaptive capacity are used most often.

In civil engineering the vulnerability of the system is defined as the ratio between the risks due to direct consequences and the total value of the considered asset, or portfolio of assets, considering all relevant exposures and a specific time frame. Conditional vulnerability may be defined through the vulnerability conditional on given exposures.

The robustness of the system is defined as the ratio between the direct risks and the total risks (the sum of direct and indirect risks) for a specified time frame and considering all relevant exposure events and all relevant damage states for the constituents of the system. A conditional robustness may be defined through the robustness conditional on a given exposure and/or a given damage state. In the context of civil engineering risk assessment, the meaning of robustness is generally very close to the meaning of resilience and adaptive capacity.

The term resilience is associated with a system's elastic ability to return to its original state after some perturbation. In risk assessment, it is usually applied as a qualitative descriptor of a considered system's ability to rehabilitate its main functions. The same or similar meanings are typically associated with the term adaptive capacity which serves as the measure of the ability of a given system to adapt to new situations and thereby maintain and/or even improve functionality.

Risk Representation

Risks may be represented in various manners, including distribution functions of consequences, showing with what probability different ranges of consequences will occur. Other representations include density functions for risk estimates showing the uncertainty due to epistemic uncertainties.

In case risks are to be aggregated with risks from previous assessments, it is important that risks are represented consistently and that possible dependencies between the independently assessed risks are accounted for in the aggregation. Two types of aggregations are generally relevant for the management of risks: aggregated modeled risks and aggregated observed losses. The aggregation of risks may be performed at object/segment level as well as over object categories, geographical areas and hazard types. Aggregation is undertaken individually for the risk categories: persons, costs and environment, with an appropriate differentiation, e.g. for persons: injuries and fatalities; for costs: user costs, compensation costs and material losses, for environment: CO_2 emissions, toxic releases and energy use.

Fig 6 illustrates a possible representation of aggregated risks, where only one risk type is illustrated for each object.

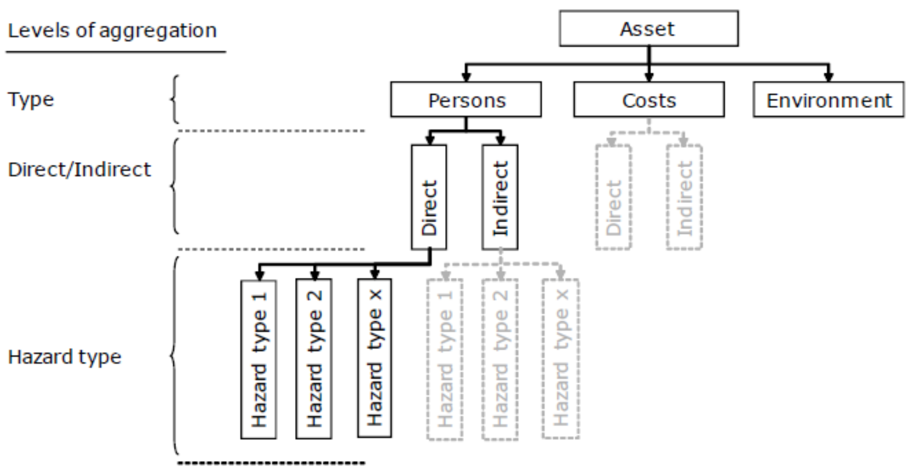

Fig. 6 Possible representation of aggregated risks (JCSS 2008)

This aggregation provides insight on how robust the considered asset is and thus points to a possible need to upgrade its performance in relation to its function in the context of the system.

If risks are aggregated for which the uncertainty associated with the risk is known, the aggregated risk should be assessed in such a way that these uncertainties are reflected in the result. This necessitates that dependencies between risks subject for aggregation are accounted for in the model. Hierarchical probabilistic models as illustrated in Fig 7 facilitate such aggregation.

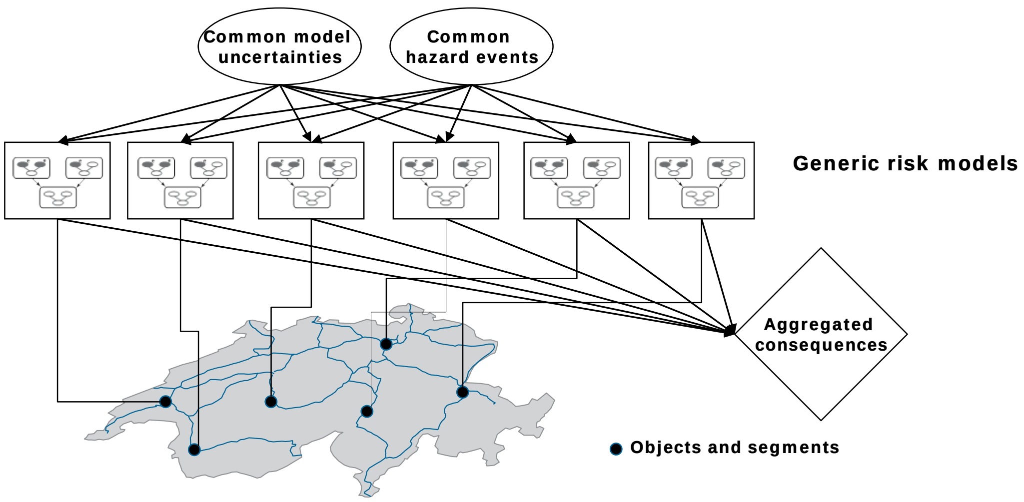

Fig. 7 Illustration of how dependencies may be accounted for in the aggregation of risks. (JCSS 2008)

Risk Evaluation

Risk evaluation encompasses the identification of risk treatment options, options analysis (or comparison of decision alternatives) and risk acceptance.

The term risk treatment refers to the process of selection and implementation of measures to modify the risk. Sometimes the term is used synonymously with the measures themselves. Risk treatment measures can include avoiding, optimizing, transferring or retaining risk.

Risk avoidance refers to the decision not to become involved in, or action to withdraw from, a risk situation.

Risk optimization is a process to minimize the negative and to maximize the positive consequences and their respective probabilities. In the context of safety, risk optimization is focused on reducing the risk.

Risk transfer refers to the decision to share with another party the burden of loss or benefit of gain. Risk transfer can be carried out through insurance or other agreements. It should be noted that legal or statutory requirements can limit, prohibit or mandate the transfer of certain risk.

Finally, risk retention refers to the acceptance of the burden of loss, or benefit gain, from a particular risk, including the acceptance of risks that have not been identified. However, risk retention does not include treatments involving insurance, or transfer by other means.

In the remaining of this section risk optimization and risk acceptance are presented in further detail as they have significant role in risk-informed decision making in the context of civil engineering.

Options Analysis (Comparison of Decision Alternatives)

Risk assessment may be used for ranking of optional decisions and activities in a consistent manner according to the expected utility (harm, costs or benefits). Different decisions will imply different risks and benefits. The representation of risk in terms of expected utility facilitates decisions corresponding to the preferences of the decision maker. Decisions may be related to how to reduce or avoid exposures, how to reduce vulnerability and how to improve robustness. Decision problems should be formulated as explicit functions of information (risk indicators) concerning the exposure, vulnerability and robustness, which may become available in the future. Thereby the risk management process can be adapted to the available knowledge at a given point in time. In principle three types of decision analysis are available for the optimization of the management:

- Prior decision analysis
- Posterior decision analysis
- Pre-posterior decision analysis

The simplest form of risk analysis is the so-called prior analysis. In the prior analysis the risk (expected utility) is evaluated on the basis of statistical information and probabilistic modelling available prior to any decision and/or activity. In practice, this would typically occur for the design of new facilities. (Fig. 8)

The posterior decision analysis is used for assessing decision alternatives with regards to system changes based on a combination of available knowledge and new information. This type of analysis can support the adaptation of loss reduction and adaptation strategies after the hazard event has taken place and specific information about the event has been observed. (Fig. 8)

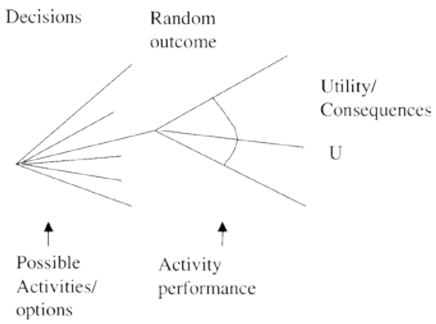

Fig. 8 Decision tree for prior and posterior decision analysis (Faber 2009)

The pre-posterior decision analysis is hardly utilized in practice, most likely because it is not well understood and appreciated. This analysis, however, facilitates not only the optimization of decision with regard to system changes but at the same time facilitates an optimization of possible decisions with regards to the collection of information which improves knowledge about the hazard processes and the efficiency of measures for managing them. This type of decision analyses is applicable in the same situations as the prior decision analyses and should as a rule be utilized instead of this. (Fig. 9)

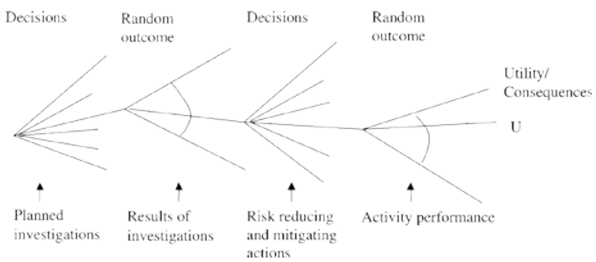

Fig. 9 Decision tree for pre-posterior decision analysis (Faber 2009)

Risk Acceptance

Having ranked the various decision alternatives with respect to their expected values of benefits, their conformity with legal frameworks and also their societal/corporate conformity must be assessed. When discussing the issue of 'acceptable risks' the issue is often confused by the fact that some individuals might have a different viewpoint to what is acceptable as compared to the viewpoint of society. Each individual has his/her own perception of risk, or as expressed in decision theoretical terms, his/her own '*preferences*'. Considering the acceptability of activities related to civil engineering or any other activities with possible implications to third parties for that matter, the main question is not the preferences of the individual member of society but rather the preference of society as expressed by the Universal Declaration of Human Rights or some other generally agreed convention.

Preferences may be assessed on different types of information. Questionnaires and interviews may provide what are commonly termed *'stated preferences'*. Analysis of statistics relating to causes of injuries and death in different types of activities as well as behavioral experiments may provide *'revealed preferences'*. Preferences based on a full understanding of the possible consequences of the preferences are called *'informed preferences'*. Stated preferences have proven to be very problematic because they depend heavily on how the information is collected or elicited, i.e. the formulation of the questions in the survey/interview. Revealed preferences form a better basis for understanding and modeling preferences but they may not always comply with basic prerequisites such as the Universal Declaration of Human Rights. Even informed preferences, which are usually the preferred form of modeling preferences, are not entirely unproblematic in that it may not be possible to provide information in an unbiased way about the consequences which will follow from given preferences as well as that the manner in which these consequences are communicated will also affect their perception.

Different decisions will imply different risks and benefits. The representation of risk in terms of expected utility facilitates decisions corresponding to the preferences of the decision maker. Decisions which do not yield a positive expected utility should not be taken. Optimally the decision yielding the largest expected utility/benefit is selected but there could be constraints on the optional decisions which are not explicitly included in the formulation of the utility function. In these cases not all feasible decisions may be acceptable or even tolerable. (Fig. 10)

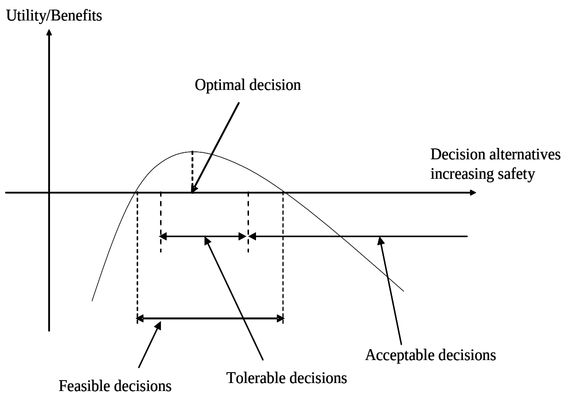

Fig. 10 Illustration of the identification of acceptable decisions (Faber 2009)

Risk criteria can be considered as a special form of general decision criteria which can be classified under three types:

- *Utility based criteria* - involve decisions that are based on the valuation of outcomes, i.e. on the comparison in monetary terms of the benefit obtained by adopting a particular risk prevention measure and the cost of introducing it.
- *Rights-based criteria* - are not primarily concerned with outcomes. Their concern is with process and allowed action or activity. An extreme example of this type is the "zero risk" criterion which says: independent of the benefits and costs, and of how big the risks are, eliminate, or do not allow the introduction of the risk. This type is typical for risk to humans.
- *Technology-based criteria* - require the use of the "best available technology" (or the best current practice) for the acceptable risk reduction or prevention. This type is widely used in environmental regulations.

It is suggested to differentiate between tangible and intangible risks, i.e. risks which may easily be expressed in monetary terms and risks which may not. Intangible values concern loss of life and injuries but may also include qualities of the environment.

With regard to life safety, many existing regulations specify requirements based on a distinction between so-called individual and collective risks. The former aim to protect individuals, mostly in situations of occupational hazards. The JCSS proposes to ignore such a differentiation as it is argued that risks for any individual at any given location engaged in occupational activities or exposed to hazards originating from societal infrastructures, buildings or activities should be limited according to the Societal Willingness To Pay (SWTP) to avoid fatalities. With regard to other intangible values such as loss of biodiversity, loss of scenic beauty, noise and pollution, there is at present no firm scientific basis for addressing the societal acceptability of potential losses.

Within the last decade a philosophically founded mathematical framework has been formulated and empirically verified which allows for the assessment of the preferences of a given society into investments of life saving. The idea underlying the framework is the use of a Life Quality Index encompassing the behavior of all individuals on an average scale, in terms of suitable societal indicators such as the gross domestic product per capita, the life expectancy and the time spent for earning a living. The LQI in this way is comparable to the UN Human Development Index. The LQI implicitly describes the large scale preferences of the individuals in society and as it also relates the economic capability of a society with life expectancy, it is possible to derive from the LQI how much a given society implicitly values life.

3. Methods and techniques

Methods and Techniques for System Definition and Hazard Identification

Generally the definition of systems including exposures, system constituents, logical or causal interrelations between constituents, damage and failure states of constituents and finally consequences is best carried out by multi-discipline teams. The system definition can best be seen as a preliminary hazard identification and analysis which serves the purpose of defining the relevant system and its boundary. The basic requirement for doing this is physical understanding of the system. This understanding can in excess of more general and overall hazard identification techniques, such as HAZID, be built on overall statistical modeling, with hypothesis testing, and on data-mining as a third.

The most commonly used techniques for identification of possible events or failures associated with adverse consequences are summarized in Table 2.

Hazard and Operability Analysis (HAZOP)	Critical Examination of System Safety
Hazard Identification Studies (HAZID)	Checklists
Failure Modes and Effects Analysis (FMEA)	Comparison of Design with Standards
What If? Analysis	Sneak Analysis
Goal Orientated Failure Analysis	Task Analysis
Concept Safety Review	Hazardous Human Error Analysis
Concept Hazard Analysis	

Table 2 Methods and techniques for system definition and hazard identification

Methods and Techniques for Overall System Modeling

The techniques for risk assessment of the overall system vary in complexity and range from purely qualitative techniques to fully quantified techniques including uncertainties. (Table 3) Some techniques provide for an integrated assessment of probabilities/frequencies and consequences whereas other have the focus of one or the other. Approaches also differ in the extent to which technical and human performance factors are considered and combined.

The most frequently used quantitative techniques for risk assessment, including assessment of consequences and probabilities, are fault and event tree analyses or some variety of these techniques such as the barrier diagrams. These techniques, however, all imply a deterministic relation between events/faults/causes and are therefore not able to reflect the uncertainty in the relations (the strength of relations). Therefore, these are not ideal as basis for decision making subject to uncertainty.

The Bayesian net provides a probabilistic approach combining the causal structure of the fault trees with uncertain causal relations resulting in a joint probability distribution of the entire system of causes and consequences. The probability distribution can be updated based on collected evidence.

Furthermore, the Bayesian nets can be extended to influence diagrams calculating the expected utility of alternative actions.

Quantitative	Semi-quantitative	Qualitative
Event Tree Analysis	Barrier Diagrams	Preliminary Hazard and Consequence Analysis
Fault Tree Analysis	Risk Matrix Technique	Delphi Technique
Cause-Consequence Diagrams	Hazard Analysis (HAZAN)	Method Organised Systematic Analysis of Risks
Failure Modes, Effects and Criticality Analysis (FMECA)	Short Cut Risk Assessment	
BayesianProbabilistic Netws	Influence Networks	
Influence Diagrams		
Barrier Diagrams		
Structural Reliability Analysis		

Table 3 Methods and techniques for overall system modeling

Methods and Techniques for Detailed/Dedicated Risk Assessment of Subsystems and Components

The techniques for detailed or dedicated assessment of the probability/frequency of specific components are many and the techniques are generally related to specific types of components. The assessed reliabilities generally form the basis for a specific entry in the overall system model and thus can be used where data is not directly obtainable or where new information needs to be combined with the a priori information available. Often dedicated assessments are made with respect to human and organizational factors, structural reliability etc. However, subsystems and individual constituents can in some cases depending on their nature, also be analyzed using the techniques applicable for the overall system. Table 4 provides examples of methods and techniques for the following application areas: (i) structural reliability analysis, (ii) human reliability analysis, (iii) human and organizational factor analysis, and (iv) plant and equipment reliability analysis.

Structural reliability analysis	Human reliability analysis	Human and organizational factor analysis	Plant and equipment reliability analysis
Time Independent Reliability Methods for Structures	Technique for Human Error Rate Prediction	Human Event Analysis	Failure Modes, Effects and Criticality Analysis (FMECA)
Time Independent Reliability Methods for Systems	Time Reliability Techniques	Cognitive Reliability and Error Analysis Method	Fault Tree Analysis
Time Dependent System Reliability Methods	Paired Comparisons	Confusion Matrix	Block Diagram Analysis
	Human Error Assessment Reduction Technique	Success Likelihood Index Methodology	Markov Analysis

	Tecnica Empirica Stima Errori Operaori	Methode dÉvaluation de la Realisation des Missions Operateurs pour la Surete	Monte Carlo Simulation
	Generic Error Modelling System	Influence Network	Petri Nets

Table 4 Methods and techniques for detailed/dedicated risk assessment of subsystems and components

Methods and Techniques for Analyses of Effects and Impacts

Methods for estimating the possible consequences to humans, the environment and assets following for example loss of containment of hazardous materials are very well developed for specific applications. Although this part of the risk analysis is of utmost importance for systems with handling of hazardous materials, reference is made to the literature on consequence calculations related to process safety. In the risk assessment the results are used of the suit of calculations and probability estimations related to, for example, the release rate and composition, dispersion of gas and toxic components, toxic effects, ignition probability, fire types, heat radiation, explosion pressure, explosion effects, collision and collapse.

4. Data and metrics

Different types of information are used when developing engineering models: subjective and frequentistic information. (Fig. 11)

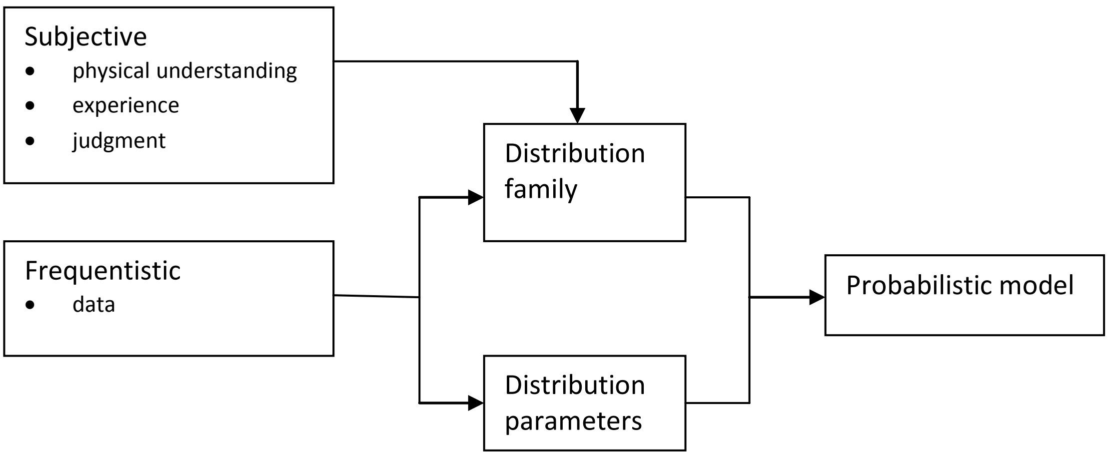

Fig. 11 Subjective and frequentistic information in engineering models

All activities (or decisions) are associated with potential losses. Risk can be understood as the expected value of the potential loss. Risk can thus have various metrics, such as:

- Number of fatalities
- Number of injuries
- Number of quality adjusted life years
- USD
- Damage to qualities of the environment
- Million barrels spilt oil

Of particular interest, however, is the Life Quality Index compound indicator applied in problems related to risk acceptance criteria.

The life quality index is derived to reflect the expected length of "good' life, in particular the enhancement of the quality of life by good health and wealth. The use of quality-adjusted life years, QALY, as a measure of substantial value to society has been advocated by many researchers of public policy, health and safety. The life quality index may be thought of as refinement of monetary measures commonly used in cost benefit analysis. The chart shows the three components of the life quality index that are related to important human concerns: the creation of wealth, the duration of life and the time available to enjoy life in good health. The amount of life available to enjoy wealth acts as a multiplying factor upon the value of that wealth. Conversely, the amount of money one has to enjoy that lifetime available also acts as a multiplier.

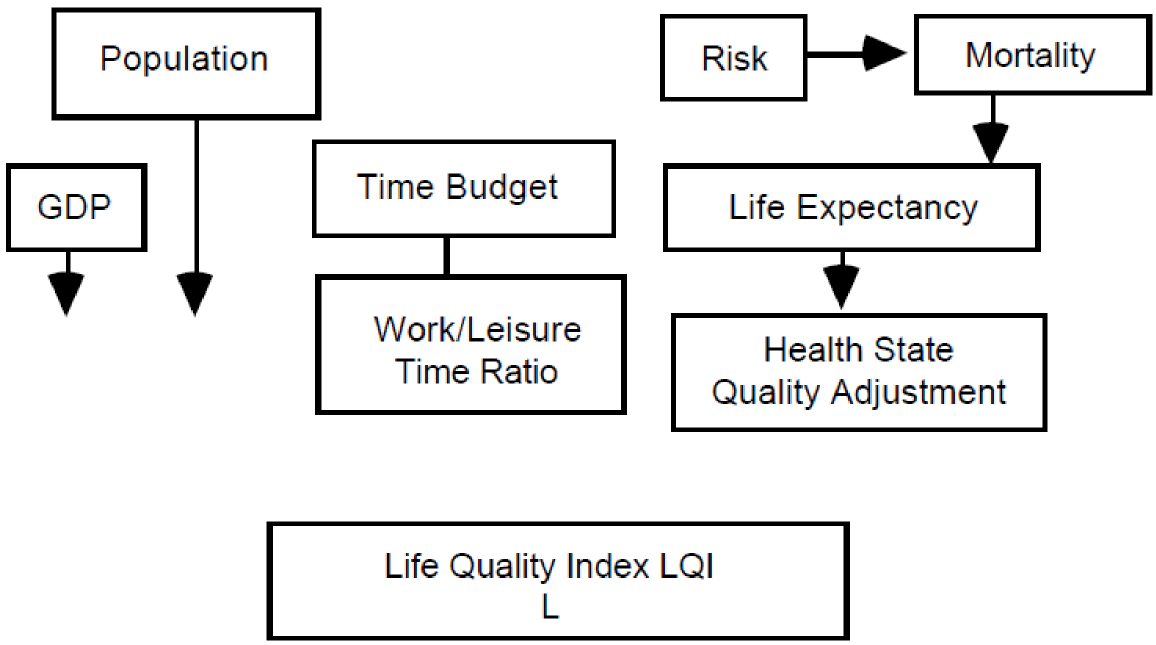

Fig. 12 A schematic representation of the Life Quality Index (Nathwani et al 1997)

The incremental increase in life expectancy through risk reduction, the corresponding loss of economic resources, measured through the national GDP, together with the time used for work, all assessed for a statistical life in a given society, form the most important building stones for the assessment of risk reducing measures. Based on these demographic indicators, the LQI facilitates the development of risk acceptance criteria. The underlying idea of the LQI is to model societal preferences quantitatively as a scalar valued social indicator, based on the relationship between the part of the GDP per capita, which is available for risk reduction purposes, the expected life at birth and the proportion of life for earning a living. As such, the LQI is an indicator applicable across multiple hazard domains.

5. Research topics

Research activities at DTU Civil Engineering are structured according to six research sections. Research topics with relevance to risk are listed below according to specific research sections. (Fig. 12) Only one research group, the Civil Engineering Risk and Decision Analysis group (CERDA), deals with the topic of risk explicitly. Risk is implicitly part of all the other research sections. Consequently, only 10-15% of the scientific staff at DTU Civil Engineering work with risk research as their primary activity.

In specific relation to risk research, the following three topics have been designated of particular interest to the Department:

- Hurricane Wind Modeling and Risk Management
- Value of Information (VoI) in Assets Integrity Management
- Probabilistic Modeling of Complex Systems

Hurricanes comprise a major risk for onshore/offshore assets. Probabilistic modeling of risks due to hurricane effects (waves, wind, storm surge, precipitation) is argued to enhance decision making in the following problem contexts: (i) design of offshore and onshore constructions/operations; (ii) assets integrity management of existing facilities/activities; (iii) evacuation of personnel; (iv) emergency shut-down of operations; and (v) assessment of effects of climate change on risks (wind, waves, etc.).

Theoretical and methodical developments on Bayesian decision analysis have been recognized and advocated by experts in the field as a strong framework for providing rational decision support. Despite this, applied decision analysis, especially the potential of the pre-posterior and Value of Information (VoI) analysis has not been realized and/or exploited**.** Research in the area of VoI sets out to illustrate different classes of engineering decision problems which may be address by decision analysis and highlights that management of structural safety may be seen as an information management problem.

With regard to probabilistic modeling of complex systems, it is argued that systems´ understanding is a key factor for sustainable societal developments. The available knowledge about the performance of systems is most often available in terms of *evidence* (incomplete and imprecise data and observations) and *physical laws* (assumed and idealized). The aim of this research area at DTU Civil Engineering is to model the available knowledge about the performance of systems in a manner which supports decision making by facilitating that decision alternatives may be ranked according to expected values of utility. Probabilistic representation is, in this sense, seen as the only alternative.

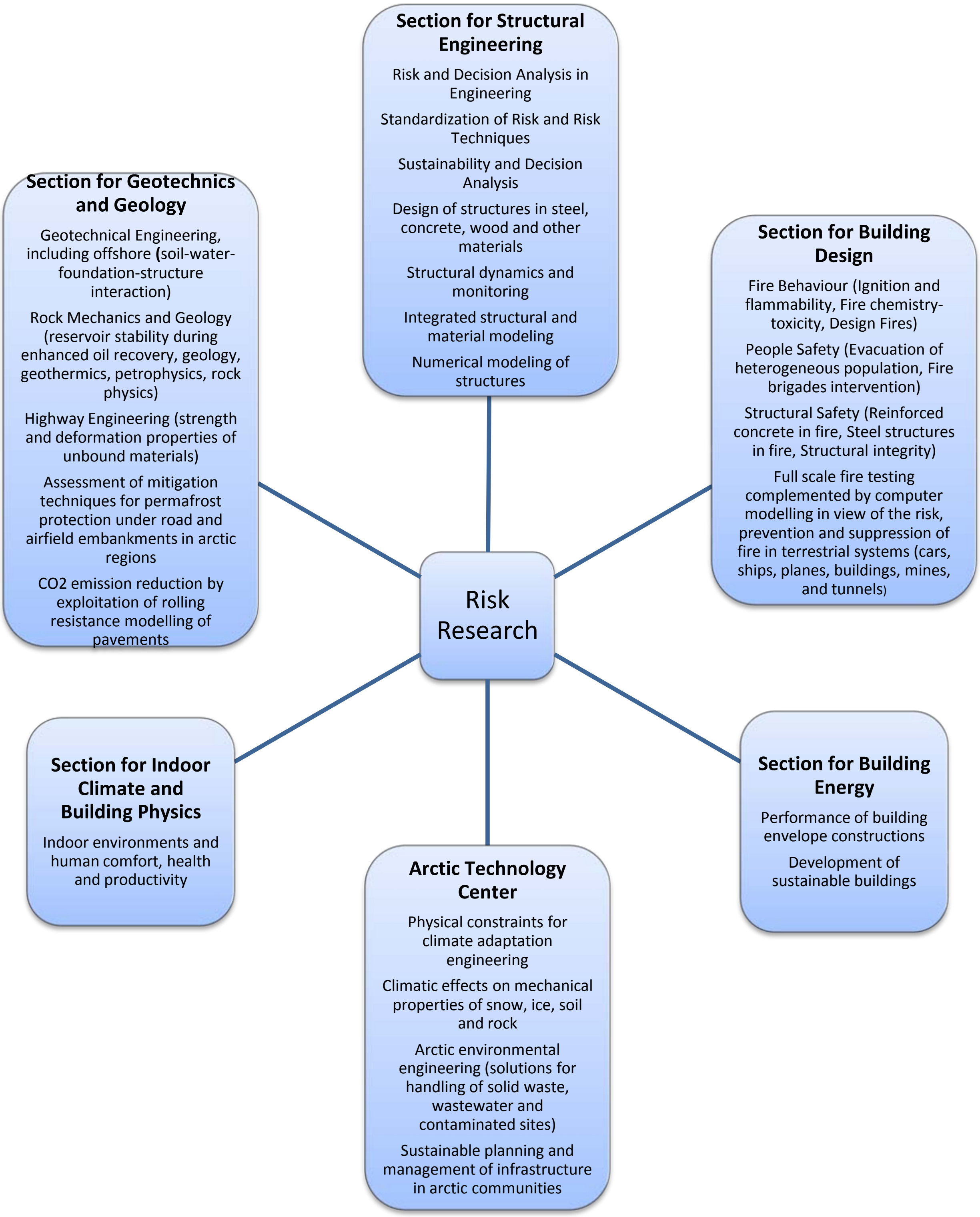

Fig. 12 Research topics related to risk at DTU Civil Engineering by research section

6. Research networks

The following is a list of research networks where DTU Civil Engineering is active with regard to the topic of risk.

International Forum on Engineering Decision Making (IFED)

IFED is a Six-University Consortium on uncertainty, risk and decision making in engineering. The six members are DTU (Denmark), University of Calgary (Canada), University of Newcastle (Australia), University of Tokyo (Japan), University of Sidney (Australia), and University of Colorado at Boulder (USA).

Joint Committee on Structural Safety (JCSS)

JCSS is a pre-normative committee in the field of structural related risk and reliability. It coordinates the activities of six international associations in civil engineering, composed of CEB, CIB, fib, IABSE and RILEM and publishes framework documents and guidelines concerning the design and construction of different types of structures and materials, including several ISO documents, Eurocodes and the CEB and ECCS Model Codes.

OECD High Level Risk Forum (HLRF)

The OECD High Level Risk Forum (HLRF) brings together policy makers from government, practitioners from the private sector and civil society, and experts from think tanks and academia to identify and share good practices with the aim to deepen understanding of how to govern and manage complex national risks. The Forum offers a venue to achieve a shared and defined vision of integrated risk management, with the intent to help countries strengthen strategic foresight capacity and preserve a sustainable growth path.

Global Decision Support Initiative (GDSI)

The GDSI is an interdisciplinary knowledge hub on sustainability, risk and decision support. It is hosted at DTU Management Engineering as a joint enterprise of DTU Management, DTU Civil Engineering, DTU Compute, DTU Environment, DTU Food, and DTU Transport.

7. Advisory activities

Advisory activities at DTU Civil Engineering can be carried out in the form of individual contracts, participation of scientific staff in normative and pre-normative institutions, through in-service training and industrial PhDs as well as through one of the so-called 'Development Areas'.

Public sector consultancy is carried out on contractual basis and trough participation of the Department's researchers in committees for normative and pre-normative work (e.g. JCSS, see section 6).

In teaching, special courses as well as exam projects are often carried out in direct collaboration with industrial partners in the building sector. Furthermore the Department is engaged in in-service training through its own master education in fire safety.

As a special instrument to enhance activities in the area of innovation and research-based public sector consultancy, DTU Civil Engineering defines so-called Development Areas. Development Areas are focused on the major challenges currently faced by society with sustainable development as the overall theme. The Development Areas are organized as interdisciplinary activities at the Department aiming to enhance cross disciplinary research and – through involvement of external stakeholders in the industry and public sector – facilitate innovation and research-based public sector consultancy in key areas. The Development Areas are dynamic activities founded on the organizational structure of the Department but with a limited lifetime, typically 5-10 years. Currently the following Development Areas are active:

Solar Decathlon

The decathlon is a combined event in athletics consisting of ten events. The Solar Decathlon includes 10 contests within the fields of: Architecture, Engineering and construction, Energy efficiency, Electric energy balance, Comfort conditions, House appliances, Communication and social awareness, Urban design, transportation and affordability, Innovation, and Sustainability.

ZeroWaste Byg

The overall aim of the research is redesign of construction materials towards a zero waste society. The interdisciplinary ZeroWaste Byg group is built on collaboration between researchers from all the different sections of the department.

Sustainable Light Concrete Structures

The building sector is responsible for application of large resources, consume of energy and production of CO_2, and it is expanding because large population groups these years want more space, better infrastructure, more interesting architecture, better fire safety, improved in-door climate and better acoustics. The development area "Sustainable Light Concrete Structures" gives solutions to these problems. It comprises people from most disciplines involved in building research and from companies of the building sector, and the results are communicated not only through teaching, but by innovation and implementation of actual solutions offering new products for practical application in the building industry.

ReBuild

ReBuild is a research, teaching and innovation platform at DTU Byg for sustainable transformation of our built environment. Once a decision to refurbish an existing building is taken, the ReBuild platform provides all the tools, analyses, tests and assistance in development that make it possible to get the maximum comfort, energy efficiency and good total economy out of the investment.

8. Educational offerings

DTU Civil Engineering is responsible for planning and executing BSc, BEng and MSc study programmes within all areas of civil engineering and building technology:

BEng programs	BSc programs	MSc programs
• Civil Engineering and Building Technology • Architectural Engineering • Arctic Engineering	• Civil Engineering • Architectural Engineering	• Civil Engineering • Architectural Engineering

DTU Civil Engineering offers a number of courses at the bachelor and master level which have explicit or implicit relevance to the subject of risk. Those courses, together with a brief outline of their content are presented in Table 5. This information was collected through DTU Kursusbasen by performing a search for the following keywords: *risk, safety, life cycle, sustainability, and decision analysis*.

Course Nr./ Keyword	Title	Content	Type
11020 risk	Building Fire Safety	Injuries after a building fire. The fire regulations in Denmark. Performance based codes. Fire tests and classification. Basic fire dynamics properties. Fire properties of common buildings materials. Active and passive fire safety systems. Evacuation analysis. Fire safety analysis and planning of building projects. Fire risk assessment. Sustainable fire safety design. Fire modeling.	MSc
11331 risk	Experimental Structural Meachanics	Measuring elastic and mechanical material properties for different materials with a tensile and compression testing machines. Full 3-D strain and displacement measurements using a digital image correlation system. Application of strain gauges, accelerometers and displacement sensors. Measuring structural response of a steel structure and determination of mechanical vibration characteristics. Performance of a wind tunnel test to simulate dynamic structural loading. Probability analysis and overload risk assessment.	MSc
11376 risk	Probabilistic Modeling in Civil Engineering	Elements of probability theory; random variables/vectors; descriptive statistics and parameter estimations; model verification; random processes; applications in civil engineering; Bayesian interpretation of probability; introduction to structural reliability theory; engineering decision analysis.	MSc
11428	Arctic Technology	Installation of and measurements on a micro hydropower	MSc

risk	Field Course	plant. Performance and efficiency of a micro wind turbine. Solar heating in the Arctic. A measurement system for an air heating panel. Mapping and risk assessment of oil contamination. Packaging waste in Greenland. Amounts, types and possibilities for recycling.	
11B05 risk	Fire Risk Management	Historical fires of relevance. Scenarios for fire and smoke spread. Occupant safety and evacuation scenarios. Basic probability calculations. Introduction to Bayesian Networks. Risk analysis and decision theory. Introduction to influence diagrams and decision graphs. Probabilistic modelling of fire risk.	p/t MAS
11B11 risk	Environmental Chemistry	Basic concepts and terms in environmental risk assessment. Physical-chemical and ecotoxicological data for chemical process in relation to environmental fate and environmental hazard. Simple quantitative calculations of substance fate. Classification of chemicals in accordance with regulatory guidelines for risk assessment.	p/t MAS
11023/11B01 safety	Structural Fire Safety Design	Performance-based fire safety design of structures. Behavior of a fire exposed structure. Damage of a fire exposed structure. Design and calculate load-bearing structures exposed to fully developed fires, standard fires and high temperatures.	MSc/ p/t MAS
11124 safety	Computational Fluid Dynamics for Buildings	Simulation models within the CFD code Fluent for heat and fluid flow investigations in rooms and buildings. Thermal conditions of buildings and comfort; Indoor air flow and ventilation; Wind around buildings and pedestrian comfort; Fire modeling and safety; Energy efficiency of building components and building services including solar heating systems; Optimal design of building envelops and building structures.	MSc
11311/11746 safety	Concrete Structures	Safety, loads, design and load carrying capacity of structural elements. Deformations of structural elements. Beams, plates and columns.	BSc D.Ing
11365 safety	Glass and Glass Structures	Structural use of glass: mechanical properties, specifications, safety, design, standards. Intensity of mechanical and other relevant loads as well as the safety level in structural design of glass structures. Structural norms and standards relevant to glass and glass structures as well as standard calculation methods.	MSc
11561 safety	Construction Materials – use and testing	Laboratory safety, testing of concrete aggregates, design of concrete mixes and testing of fresh concrete, testing of hardened concrete, wood properties, gypsum composites, Young's modulus for steel and aluminium, steel corrosion, drying of aerated concrete.	BSc
11702 safety	Concrete Beam Experiment	Strain-stress curve for concrete or steel. Construction/ manufacturing of concrete or steel beams. Deformation-stress curve of concrete or steel beam under flexural loading. Probabilistic design concept and partial safety factors. Bending stiffness, crack width, ultimate limit state, plastification.	D.Ing
11851 safety	The Arctic Nature and Societies	Safety course and SAR in the Arctic. Climate and climate change. Snow and ice conditions Geodesy and surveying, GIS. Historical background, business and educational conditions of the Arctic. Natural and living resources of the Arctic. Working conditions as an engineer in the Arctic.	MSc

11854 safety	Industrial Plants & Infrastructure Constructions in the Arctic	Construction of industrial plants (mines, smelters, on-shore oil installations, hydro-electric stations) and the related infrastructure (roads, ports, airports) on rock and permafrost in remote areas. Geotechnical investigations and geophysical measurements. Permafrost. Rocks for blasting and tunneling. Port facilities in icy waters. Logistics, safety, work and social environment in remote production facilities.	MSc
11B12 safety	CAD Fire	Theoretical background of CFD programs. Modeling of the fire. Modeling of the evacuation. Integration between fire and evacuation models.	p/t MAS
11450 life cycle	Basic course in road pavements	Road materials (soil, gravel, asphalt and recycled materials). Modifying / stabilization of materials for road construction. Laboratory exercises in relation to the study of materials for road construction, and analysis and evaluation of test results. Analyzing and evaluating data from other professions with input to pavement dimensioning. The elasticity theory for road pavements and its structural and functional degradation. Construction and verification of pavement work. LCC/LCA and CO2-accounts in relation to road construction.	BSc
11451 Life cycle	Highway pavements	Pavement structure. Empirical methods of pavement design. Theory of elasticity for pavements and structural and functional deterioration. Pavement condition evaluation and residual bearing capacity. Surface characteristics and their effects on users and society. Economical optimisation for pavement maintenance and management systems for capital works schemes and systems for steering of interventions in maintenance and operation of roads.	MSc
11968 Life cycle	Optimization, resources and environment	Optimizing methods and strategies. Discrete and continuous optimization. Optimization of main structure, elements and details. Michell structures. Low energy building design. Total economy. Total life cycle resource consumption. Design for low environmental impact. Introduction to LCA.	D.Ing
11997 Life cycle/ Sustainability	Sustainability and Life Cycle Assessment	Basic knowledge on the environmental impacts from buildings and how they are related to materials, the building process, use and operation, rebuilding/ refurbishment, and demolition. LCA as a method and a tool to analyse the environmental impact from buildings, components and products including the most important strengths and weaknesses.	BSc
11852 Sustainability	Arctic Infrastructure	Sustainable local and regional development. Strategic and physical planning. Settlement and infrastructure. Logistics in the Arctic	MSc
11115 Decision analysis	Building Energy and Technical Services – Integrated Design	The aim of the integrated design process is to combine calculations and evaluations in a rational decision process. The course enables the participants to perform an integrated design process with focus on building energy to meet the requirements for the indoor environment and total energy consumption in the best way. The course enables the participants to use simple and advanced tools for building performance simulation.	MSc
11836 Decision analysis	Environmental Engineering	The course imparts an understanding of the environment and resources in urban areas and sustainable development in Greenland, including waste management, technical	D.Ing

		supply systems adapted to Arctic conditions as well as the local and national decision-making processes related to the area.	

Table 5 Courses at DTU Civil Engineering explicitly and implicitly related to risk

Finally, DTU Civil Engineering PhD school presently houses 60 PhD students. Of these, the following PhD projects bear direct relevance to the topic of risk (Table 6).

PhD projects related to risk
Risk assessment of stay cable fatigue
Hierarchical modelling of flood risk for engineering decision analysis
Real time decision support in the face of evolving natural hazards
Evacuation of people with visual impairments
Evacuation of children
In-Situ Burning of Crude Oils under Arctic conditions
Human health, comfort and performance in relation to building certification schemes indoor environment in Danish dwellings
Modelling of soil-structure-water interaction
Numerical modelling of offshore foundations for jacket structures

Table 6 Current PhD projects related to risk

9. Data sources

Personal interview with Michael Havbro Faber, Head of Department DTU Civil Engineering

Michael Havbro Faber Head of Dept. DTU Civil Engineering Advisory Board GDSI mihf@byg.dtu.dk Special interests: Bayesian Decision Analysis, LQI	

Faber, M. H. and Stewart, M.G., *Risk Assessment for civil engineering facilities: critical overview and discussion*, Reliability Engineering and System Safety 80 (2003) 173-184

Faber, M.H., *Risk and Safety in Engineering: Lecture Notes*, Swiss Federal Institute of Technology 2009

Nathwani, J.S., Lind, N.C., Pandey, M.D., *Affordable Safety by Choice: The Life Quality Method*, University of Waterloo, 1997

Joint Committee on Structural Safety, *Risk Assessment in Engineering: Principles, System Representation & Risk Criteria*, June 2008

SAFERLNET *Framework Document on Integrated Risk Assessment*, 2006

DTU Civil Engineering website

10. Glossary of risk-related terms in civil engineering

General Concepts

risk	The expected adverse consequences associated with an event, an activity or a decision alternative. Risks may be related to adverse events for humans, qualities of the environment or economic values. In general the risk is the combination of probability of an event and its consequence. **Note 1:** The risk is often estimated by the mathematical expectation of the consequences of an undesired event. Then it is the product "probability × consequences". However, a more general interpretation of the risk may involve probability and consequences in a non-product form. This presentation is sometimes useful, particularly when a spectrum of consequences, with each having its own probability of occurrence, is considered. (JCSS 2008)
hazard	An event or a combination of events with a potential for undesirable consequences. **Note 1:** For instance an occurrence of abnormal action or environmental influence and/or insufficient strength or resistance or excessive deviation from intended dimensions. **Note 2:** In the draft of EN 1990 the hazard is defined similarly as an event. In other documents concerning risk analysis (CAN/CSA) it is considered as a condition with a potential for causing event, thus, as a synonym to danger. (JCSS 2008)
event	Occurrence of a particular set of circumstances. **Note:** Undesired event is an event, which can cause adverse consequences like human fatalities and injuries or environmental damage and economic losses. (JCSS 2008)
exposure	The exposure to a system is defined as all possible endogenous and exogenous effects with potential consequences for the considered system. A probabilistic characterization of the exposure to a system requires a joint probabilistic model for all relevant effects relative to time and space. (Faber 2009)
consequence	The utility assigned to the event in accordance with the preferences of the decision maker. **Note 1:** There can be more than one consequence from one event. **Note 2:** Consequences can range from beneficial to adverse. **Note 3:** Consequences can be expressed qualitatively or quantitatively. (JCSS 2008)
direct/indirect consequence	**Direct consequences:** The damages of a system caused by failures of the constituents are considered to be associated with direct consequences. Direct consequences may comprise different attributes of the system such as monetary losses, loss of lives, damages to the quality of the environment or just changed characteristics of the constituents. **Indirect consequences:** Indirect consequences could be caused by e.g. the sum of monetary losses associated with the constituent failures and the physical changes of the system as a whole caused by the combined effect of constituent failures. (Faber 2009)
vulnerability	The vulnerability of a system is related to the direct consequences caused by the damages of the constituents of a system for a given exposure event. The damage of the constituents of a system represents the damage state of the system. In risk terms, the vulnerability of a system is defined through the risk associated with all possible direct consequences integrated (or summed up) over all possible exposure events. (Faber 2009)
robustness	The robustness of a system is related to the ability of the considered system to sustain a given damage state subject to the prevailing exposure conditions and

	thereby limit the consequences of exposure events to the direct consequences. It is of importance to note that the indirect consequences for a system not only depend on the damage state but also the exposure of the damaged system. When the robustness of a system is assessed it is thus necessary to assess the probability of indirect consequences as an expected value over all possible damage states and exposure events. A conditional robustness may be defined through the robustness conditional on a given exposure and a given damage state. (Faber 2009)
adaptive capacity	Building measures into systems, society or organizations to reduce the impact of a risk if it occurs, e.g. measures to improve the ability of a building to resist earthquakes. **Note:** Also referred to as 'coping capacity' (Renn 2008)
resilience	The capacity of a system, community or society to adapt to disruptions resulting from hazards by persevering, recuperating or changing to reach and maintain an acceptable level of functioning. **Note:** Resilience is built through a process of empowering citizens, responders, organizations, communities, governments, systems and society to share the responsibility to keep hazards from becoming disasters. (AHRA 2012)
risk management	The complete process of risk assessment and risk control. (JCSS 2008)

Terms related to Risk Assessment

risk assessment	A process of risk analysis, risk acceptance and option analysis. Note: In some documents the risk assessment is defined as risk analysis and risk evaluation, where the risk evaluation covers risk acceptance and option analysis (see the definition of risk evaluation). (JCSS 2008)
risk analysis	The use of available information concerning relevant hazard situations for estimating the risk for individuals or populations, property or environment. The risk analysis generally involves the context (scope) definition, hazard identification, and risk estimation. (JCSS 2008)
hazard identification	A process to recognize the hazard and to define its characteristics. (JCSS 2008)
causal analysis	A systematic procedure for describing and/or calculating the probability of causes for desired or undesired events. (JCSS 2008)
consequence analysis	A systematic procedure to describe and/or calculate consequences. (JCSS 2008)
risk estimation	A process used to produce the estimate of the risk measure. **Note:** Risk estimation is based on hazard identification and generally contains the following steps: scope definition, probability analysis, consequence analysis and their integration. (JCSS 2008)
risk evaluation	A process of risk acceptance and option analysis. (JCSS 2008)
sensitivity analysis	A systematic procedure to describe and/or calculate the effect of variations in the input data and underlying assumptions in general on the final result. (JCSS 2008)
options/alternatives analysis	A process used to identify a range of possible alternatives for managing the risk. (JCSS 2008)

Terms related to Risk Control

risk control	Actions implementing risk management decisions. **Note:** Risk control may involve monitoring, reevaluation, and compliance with decisions. (JCSS 2008)
risk treatment	A process of selection and implementation of measures to modify risk. **Note:** The term "risk treatment" is sometimes used for the measures themselves. **Note:** Risk treatment measures can include avoiding, optimizing, transferring or retaining risk. (JCSS 2008)
risk perception	Way in which a stakeholder views a risk, based on a set of values or concerns. **Note:** Risk perception depends on the stakeholders' needs, issues, knowledge and preferences. Risk perception can be significantly subjective. (JCSS 2008)
risk communication	Exchange or sharing of information about risk between the decision-maker and other stakeholders. **Note:** The information can relate to the existence, nature, form, probability**,** severity, acceptability, treatment or other aspects of risk. (JCSS 2008)
risk acceptance	Decision to accept a risk. 'Acceptable risk': A level of risk, which is generally not seriously perceived by society, and which may be considered as a reference point in criteria of risk. **Note:** It is expectable that various aspects including cultural, social, psychological, economical and other aspects will influence risk perception in society. (JCSS 2008)
risk criteria	Reference points against which the results of the risk analysis are to be assessed. The criteria are generally based on regulations, standards, experience, and/or theoretical knowledge used as a basis of the decision on acceptable risk. **Note 1:** Various aspects may be considered, including cultural, social, psychological, economical and other aspects. **Note 2:** The acceptance criteria may be expressed verbally or numerically. (JCSS 2008)
risk tolerance	'Tolerable risk': A level of risk, which an individual or society is willing to accept to secure certain benefits assuming that the risk will be properly controlled. **Note:** The tolerable risk may not be negligible but it should be kept under review and permanent control. (JCSS 2008)
risk optimization	A process, related to a risk, to minimize the negative and to maximize the positive consequences and their respective probabilities. **Note 1:** In the context of safety, risk optimization is focused on reducing the risk. **Note 2:** Risk optimization depends upon risk criteria, including costs and legal requirements. **Note 3:** Risk associated with risk control can be considered. (JCSS 2008)
risk avoidance	Decision not to become involved in, or action to withdraw from, a risk situation. **Note:** The decision may be taken based on the result of risk evaluation. (JCSS 2008)
risk transfer	Sharing with another party the burden of loss or benefit of gain, for a risk. **Note 1:** Legal or statutory requirements can limit, prohibit or mandate the transfer of certain risk. **Note 2:** Risk transfer can be carried out through insurance or other agreements. **Note 3:** Risk transfer can create new risks or modify existing risk. **Note 4:** Relocation of the source is not risk transfer. (JCSS 2008)
risk financing	Provision of funds to meet the cost of implementing risk treatment and related

	costs. **Note:** In some industries, risk financing refers to funding the financial consequences related to the risk only. (JCSS 2008)
risk reduction	Actions taken to lessen the probability, negative consequences, or both, associated with a risk. (JCSS 2008)
risk mitigation	Limitation of any negative consequence of a particular event. (JCSS 2008)
risk retention	Acceptance of the burden of loss, or benefit gain, from a particular risk. **Note 1:** Risk retention includes the acceptance of risks that have not been identified. **Note 2:** Risk retention does not include treatments involving insurance, or transfer by other means. **Note 3:** There can be variability in the degree of acceptance and dependence on risk criteria. (JCSS 2008)
residual risk	Risk remaining after risk treatment. (JCSS 2008)

Interview Questions with Michael Faber, Head of Department, DTU Civil Engineering

1. In the context of engineering applications, risk is often grouped with reliability and safety. How is the concept of risk to be understood from the point of view of a) classical reliability theory, b) structural reliability theory and c) health and safety engineering domains? How are these differences reflected at DTU Civil Engineering?
2. Over the past decade there has been a gradual shift from risk-based decision making to risk-informed decision making. How do these approaches differ and what is the history and implications for this trend? What is DTU Civil Engineering's stance?
3. What are typical sources of risk in the field of Civil Engineering? What types of risks are the focus in DTU Civil Engineering's research, teaching and advisory activities?
4. Risk analyses in Civil Engineering may concern structural reliability of technical components and systems throughout their life cycle, human reliability evaluation in the case of accidents, natural hazards, explosions, fire and major accidents and failures at petrochemical and power plants as well as transport infrastructure. Is there a common framework for the different types of risk analyses? Are there any significant differences?
5. How are risk analysis, risk assessment and risk management defined in the context of Civil Engineering and what are the different components in each process? How can DTU Civil Engineering's competencies be described with regard to the different stages of the risk analysis process?
6. What qualitative and quantitative methods (and software) are used in the process of risk assessment?

7. What qualitative and quantitative methods (and software) are used in the process of risk management with regard to identifying and evaluating risk management options? Is decision analysis incorporated? What are the risk acceptance criteria?
8. What data and metrics are typically used in risk assessments carried out at DTU Civil Engineering?
9. What research topics are covered at DTU Civil Engineering that have explicit or implicit relation to risk?
10. What networks does DTU Civil Engineering participate in with regard to risk research? What are some of the key research institutions the department collaborates with on the topic of risk?
11. What educational offers are there at DTU Civil Engineering with regard to risk assessment and/or risk management?
12. What percentage of DTU Civil Engineering scientific staff is involved in work directly related to the topic of risk as: a) their main activity; b) their supplementary activity?
13. What does DTU Civil Engineering perceive to be the main challenges with regard to the department's risk-related activities in terms of education, research and public/private advisory?
14. Where does DTU Civil Engineering see opportunities for collaboration with other DTU institutes with regard to the department's risk-related activities?

Appendix II: Risk at DTU Transport

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1. Introduction: Risk in Transport

The transportation system framework is highly complex and consists of various subsystems such as road, rail, air and maritime systems, including the information systems connected to them. There is no single organization controlling all these infrastructures. Some of them are owned by national, regional or local governmental authorities; some – by private entities. The system is thus inherently decentralized and open, which can be seen as a benefit from the point of view of its many users in that it provides easy and reliable access. This benefit, however, comes at a price, namely that decentralization and openness expose the system to many risks. There are broadly eight categories of transportation risks related to surface transportation systems. (Figs. 1 & 2)

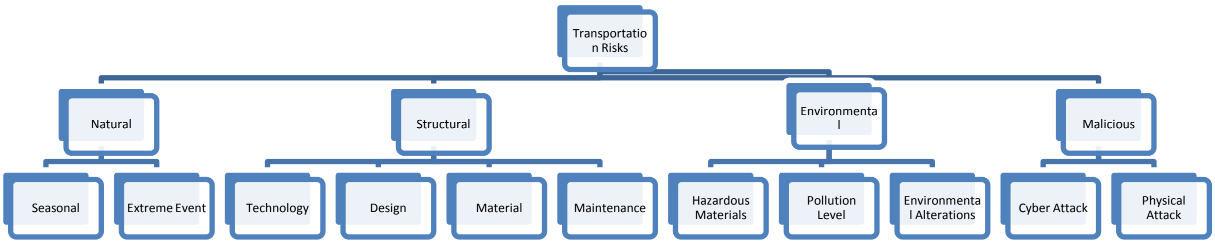

Fig. 1 Sources of risk in transport: natural, structural, environmental, malicious

Natural – This pertains to natural hazard. It is categorized as seasonal and extreme event. Since seasonal hazards are expected, these hazards allow for more readiness than do extreme events such as a 500-year flood or severe ice storms.

Structural – This pertains to hazards that threaten the structural aspect of an asset (e.g. motorway, bridge, port terminal, etc.), including untested new technology (e.g. new materials or construction technology), deterioration (wear and tear) and flawed design.

Environmental – This covers hazards that could have significant impact on the environment such as accidents involving hazardous materials, pollution levels and environmental alterations due to construction.

Malicious – This covers intentional man-made threats to the system, primarily acts of terrorism targeting cyber assets, physical assets and system users.

Supervisory Control and Data Acquisition (SCADA) – This pertains to hazards to SCADA systems which include failure of hardware, software, remote control, modeling, feedback systems, and signals.

Interdependencies – This pertains to hazards to systems that are dependent on transportation (people, businesses, other agencies) and systems that transportation depends on in order to function (power, communication, supplies).

Organizational – This pertains to hazards of the different aspects of the organization in charge that threaten its services and effectiveness. These include failure of leadership, management, communication, employees, and policies/regulation.

Usage – This pertains to hazards related to the use of an asset. These include problem in system capacity, flow design and regulation.

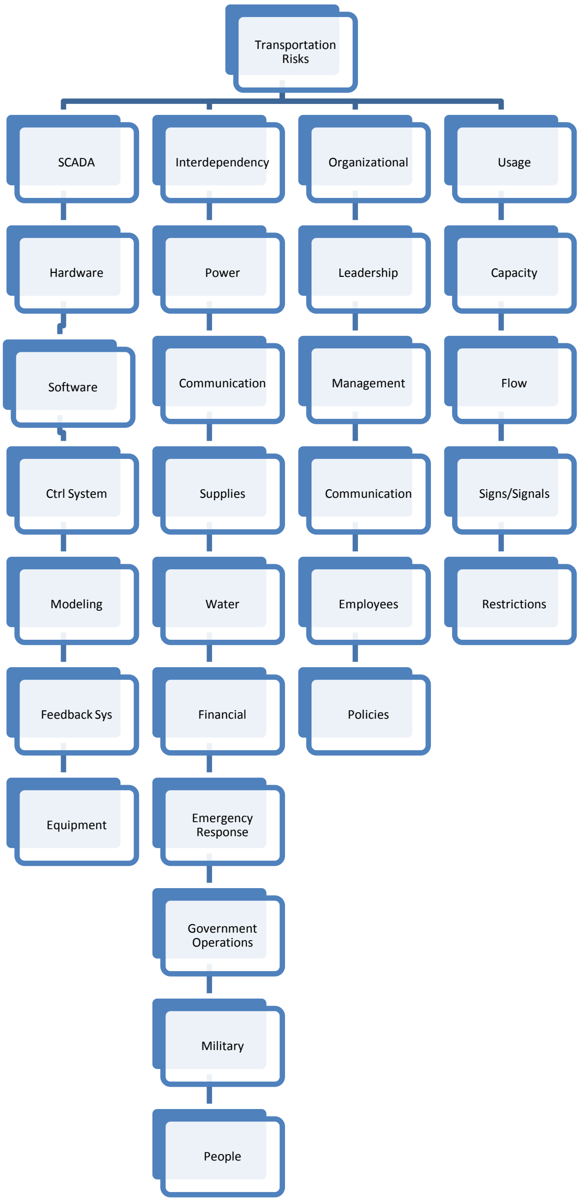

Fig. 2 Sources of risk in transport: SCADA, interdependency, organizational, usage

Risk in Road, Rail, Air and Maritime Transport

When modeling large-scale, complex systems such as the transportation system, more than one mathematical or conceptual model is likely to emerge. For instance, the transportation infrastructure can be modeled according to modal travelways, in which case the decomposition of the system would be in terms of land, rail, water, and air. This is the conceptual approach used in this report as it reflects the choice at DTU Transport. Other commonly used perspectives are spatial and functional. For example, regional decompositions could be used based on geographic boundaries to define responsibilities for road maintenance and construction. Regional decompositions are likely to be adopted for planning purposes. Other perspectives could be temporal (e.g. short, medium and long-term) or functional (e.g. operations, maintenance). The ability to view the system exhaustively from many perspectives facilitates the identification of a more comprehensive set of sources of risk.

At DTU Transport there are currently efforts underway to map the Department's competencies and activities with regard to road, rail and maritime transport. Air transport is not a subject of investigation at the Department. Research pertaining to risk and safety is carried out within the contexts of Transport Safety and Maritime Transport. As the majority of this research concerns land transport, this report will provide greater details for road and rail transport systems than any other systems.

Reduction of risk and consequent death injury and damage is the key objective of policy for transport safety. The systematic assessment of risk, the setting of targets for its reduction in the context of safety strategies, and the monitoring of progress towards such targets are playing an increasing role in the formulation and implementation of transport safety policy across the modes – road, rail, air and maritime.

Risk assessment ranges from the interpretation of data concerning numerous and frequent occurrences to the estimation of the likelihood of very rare events, combined in each case with the quantification of exposure to risk. Target setting requires forecasting of exposure, levels of risk, and the acceptability and effectiveness of policies and measures for risk reduction, in order to identify targets which strike a balance between challenge, achievability, and public and political acceptability. Monitoring requires tracking not only of the targeted outcomes but also of the ways in which developments in exposure, policy, implementation and external factors differ over the target period from what was anticipated when the targets were set. The context of the processes of risk assessment, target setting and monitoring in relation to safety differs between road, rail, air and maritime transport, and so do the extent to which and the manner in which these processes have been developed.

Risk assessment in controlled engineering systems such as rail and air, and to a somewhat lesser extent maritime, transport is more highly developed than in road transport. This reflects both the more comprehensively managed and controlled nature of these three systems than that of road transport and the relative rarity of accidents in them, which prevents the levels of many important risks from being reliably estimated simply from ratios of numbers of accidents occurring to measures of exposure to risk.

In these three systems it consists of:

1. Identifying the hazards in the system that could lead to accidents, typically those potentially causing death or injury to people;

2. Estimating the frequency of each type of accident, given the current safety measures;

3. Estimating accident consequences, often measured by the mean and the distribution of the number of deaths or injuries per accident;

4. Calculating various measures of risk, such as (a) deaths or injuries in the system per year, (b) *individual risk* – that is the risk of death or injury per year to representative individuals in groups such as railway track workers or regular airline passengers, or (c) the frequency of accidents of particular kinds;

The results of such assessment of risk can be used in deciding upon and implementing further safety measures, which can lead on to monitoring of changes in risk and repeating the cycle. They can also be used, in combination with information about likely future changes in circumstances affecting hazards or the occurrence or consequences of accidents, to help in setting targets.

Two kinds of criteria may be invoked in considering whether further safety measures are needed in the light of risk assessment. These are:

- absolute risk criteria: if, say, the estimated frequency of accidents or the risk to representative or specific individuals exceeds some threshold, then safety measures may be required without regard to costs; or
- criteria set in relation to safety measures: these deem that if safety measures are available that could reasonably reduce risk, then they should be implemented. The level of safety achieved is then not predetermined, but depends on what safety measures are regarded as reasonable. In this context, the benefits of safety measures are sometimes explicitly valued and compared with the costs.

Risk Assessment in Road Transport

The risks involved in using the roads differ greatly according to the kind of use (walking, cycling or use of motor vehicles of different types) and the circumstances of use (e.g. age of user, time of day, week and year, kind of road and surroundings of the road). The risks also differ greatly in the scope that exists for reducing them by action of various kinds. Assessment of risk on the basis of sound evidence therefore has the potential to make a powerful contribution to the development of effective strategies for casualty reduction and collision prevention, by helping to identify where the greatest scope for application of different safety measures lies.

The sadly large annual number of collisions in road transport that give rise to death or injury, make it possible in principle to obtain numerically reliable estimates of risk to road users by relating recorded numbers of collisions or casualties to measures of exposure to risk. This can be done at quite high levels of disaggregation by type of road user and type of risk, to the extent that information about collisions is recorded and estimates of appropriate measures of exposure can be made. This is the main form of risk assessment in road transport. Others are the identification of the nature of hazards and mechanisms of injury by in-depth multidisciplinary investigation of small numbers of collisions, and the safety audit and safety impact assessment of changes to road infrastructure in order not to build avoidable risk into newly constructed or modified roads.

Risk Assessment in Rail Transport

Most types of railway accident are familiar from past history, and these are a good indicator of railway hazards. Sometimes systematic brain-storming reviews are carried out, especially for new systems, such as new high-speed lines, bridges or tunnels.

There are three general methods for estimating risk. The first is to estimate risk directly from empirical data on past accidents; the second to develop and use a probability model to estimate the accident frequencies and consequences; the third is engineering judgment, based sometimes on knowledge of the results of the first two. Most practical methods involve a mixture of these three.

Given that railway accidents are relatively rare events, it may be difficult to estimate the likely risk reductions from specific safety measures, especially if these are local (such as an improvement to a depot) rather than system-wide (such as new control systems).

Probabilistic risk models are being used increasingly in railway risk assessment. Some railways have developed comprehensive risk models of the whole system. More usually, models are developed for engineering components such as proposed new signaling systems or rolling stock, or for new high-speed lines.

Finally, until fairly recently main line railways were single nationalized industries, but in recent years the trend has been towards a more open market with many participating organizations. There may now be many separate organizations for infrastructure management, train operation, train and track maintenance, and manufacturing. There is wider access for new train operators. All this has profound implications for safety. This is partly because interfaces such as between the track and the trains are no longer within a single organization but cross organizational boundaries. It is also because the possibility of new operators and suppliers requires more transparent regulatory machinery, both to test their competence and to approve their operation if they are shown to be competent.

One facet of greater transparency is a requirement on existing and would-be railway organizations to assess their risks and to produce public reports on the results of their risk assessments. These are typically included in *safety reports* or *safety cases* which describe how the organizations will manage and control the risks of their activities.

Risk Assessment in Maritime Transport

Risk assessment is finding a number of applications in maritime transport, partly under the influence of its use in the off-shore industry, and partly because exemptions from some provisions of international instruments depend on showing that risk is no higher under a preferred alternative than under a provision from which exemption is being sought.

The rarity of multi-fatality accidents and the international character of maritime transport make risk assessment and target setting in terms of resulting death or injury largely a matter to be addressed for the EU as a whole by the European Maritime Safety Agency (EMSA). There are related issues of loss of vessels and environmental damage resulting from maritime accidents.

The main safety instrument from the International Maritime Organisation (IMO) is the Convention on Safety of Life at Sea (SOLAS). This allows exemption from any of its rules provided that a proposed alternative can be shown to give the same or better protection compared with what is prescribed in the rules.

The Code on High Speed Craft (HSC-code) consists formally only of recommendations to countries belonging to the IMO, but once again, alternatives to the recommendations in the code may be allowed if it can be shown that the alternative is at least as good as what is recommended.

In both these examples, no risk assessment is necessary as long as what is recommended in the instrument is done. Anyone who wishes to do differently, however, has to show by some sort of risk assessment that the result will be as good or better.

In addition to the general rules prescribed by IMO, national administrations often require risk assessments when a ship is to be used in special operations such as the transport of hazardous material within certain areas. Another example is the assessment whether a cruising ship should have a helipad or not, which involves a comparison of the risk created by having a helicopter near the ship with the probability that people on board need transport ashore for medical treatment.

Quantification of risk in relation to routinely collected exposure data is less widespread in maritime transport than for road, rail and air. One possible approach to analyze collision rates is ship-miles and frequency of encounters closer than one mile as measures of exposure. Another is to use vehicle- and passenger-time and vehicle- and passenger-distance as measures of exposure in comparing the risk of ferry transport with those of other modes.

Estimation of the risk of ferry transport from accident data provides a particularly clear example of the difficulty identified at the end of Section above, namely the wide statistical fluctuations resulting from the occasional occurrence of multi-fatality accidents when there are few accidents in total and most of them result in few deaths.

Risk vs Safety

Risk research at DTU Transport is carried out in two different domains: Model Uncertainties and Risk Analysis (MURA) and Traffic Safety. As such, the understanding of risk is different as well. At MURA, risk is often defined in the context of cost benefit and decision analysis. The understanding is similar to that at DTU Civil Engineering, where risk is understood as *expected utility*. A risk assessment for transport appraisal is therefore a product of a socio-economic model, where important evaluation criteria are Net Present Value (NPV), Benefit-Cost Ratio (BCR) and Internal Rate of Return (IRR). (See also section 4.)

In the context of traffic safety, risk is defined as the occurrence of an unwanted event (e.g. dying in a car crash) considered relative to the *exposure* to this risk. As such, a risk assessment in this domain is better thought of as a safety assessment, where the probability of a risk being realized is just one input of the assessment, but the focus is on the consequence assessment and management options for mitigating life safety risks.

Sustainability Considerations in Transport

Sustainability is one research area that has had strong focus at DTU Transport through (but not exclusively) a large four year project SUSTAIN (2012-2016). The scientific objective of SUSTAIN is to establish national sustainable transport planning as a coherent research topic across the social and technical sciences, while the societal objective is to promote future-oriented planning for a sustainable transport system in Denmark.

Internationally, research on national transport planning systems and processes is limited, and it is not established as a coherent field of research. Transport planning frameworks are found to vary across countries, but there is no widely recognized way to typologize such frameworks to help explain their significance for national sustainable transport planning outcomes. The research area needs to be advanced through a combination of theory, empirical study and methodological experimentation.

A common way to incorporate sustainability in policy making has become by way of reference to three pillars that need to be addressed and somehow brought in balance, namely an environmental, an economic and a social one. At a more practical level, sustainable transport strategies put varying emphasis on efforts to improve the environmental, social, or economic performance of transport systems and technologies; to shift transport from cars and trucks to public transport, bicycles, rail and sea modes, and to avoid the need to travel altogether, e.g. through high-density, mixed-use urban planning and development.

Cross-disciplinary sustainability research finds that transition towards sustainability is a process that must involve three interlinked dimensions: a normative, an analytic and a governance dimension. The generic meaning of each dimension and its possible translation into national transport planning context is presented in Table 1 below.

Dimensions	**Generic meaning**	**National planning context**
Normative	The fundamental ethical principles and value-orientations of sustainability.	What sustainable transport is, what the 3 pillars (environmental, economic, social) imply in transport and which goals to pursue.
Analytic	Determine whether an action is sustainable or not.	Knowledge on consequences for sustainability of interventions, e.g. infrastructure and transport service projects and plans.
Governance	The system of governance that should promote and implement changes toward sustainability through policies, programs and plans.	Organizational forms in the transport sector (e.g. public, private partnerships), the set-up of key government institutions as well as transport planning and implementation procedures which promote integration of sustainability.

Table 1 Transition toward sustainability in the context of Transport (adapted from Sørensen and Leleur 2013)

These dimensions are interdependent, meaning that in the long-term, they all impact on one another. Thus political processes (and the populations experiences) as well as new knowledge provided might contribute to adjust values and goals, and the interpretation of sustainable transport, sustainability pillars and principles. Similarly, instruction and feedback from policymakers might contribute to calibration, development or application of new analytic tools. And finally, the values and goals will impact on policymakers indirectly (via incorporation in knowledge production), but also directly as inspiration and guidance in policy making. The dimensions and their interlinkages are illustrated in Fig. 3.

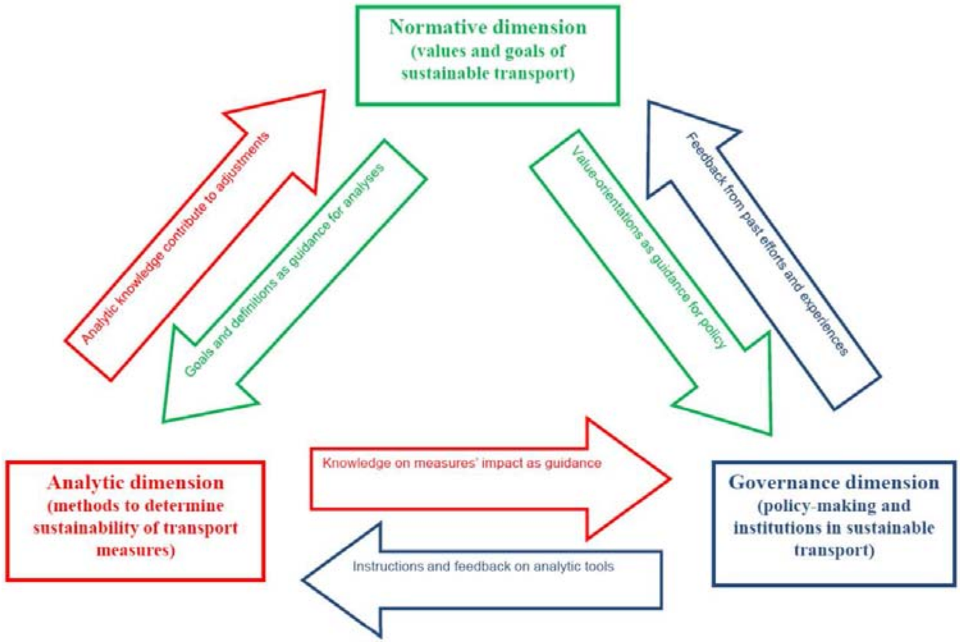

Fig. 3 National sustainable transport planning – dimensions and interlinkages (Sørensen and Leleur 2013)

It could be said then that sustainability at DTU Transport (and likewise at DTU Civil Engineering) is seen through the lens of decision analysis, and research focused on developing decision support tools for sustainable planning focuses on developing indicators and performance measures as the main operational mechanisms through which decisions related to sustainability goals can be optimized. Research in this area is carried out through the SUSTAIN project mentioned above as well as through a postdoctoral study within the framework of the GDSI. This study addresses the shortcoming of existing operational metrics on transport systems, which are typically confines to singular performance domains (e.g. traffic safety) or subsectors (e.g. railway punctuality, road pavement conditions). More comprehensive systems of sustainable transport indicators and performance measures are only advanced at the conceptual level. The undertaken study therefore focuses on the need to connect conceptual and operational aspects of sustainable transport metrics. Fig 4 illustrates work-in-progress in the development of sustainable transport metrics.

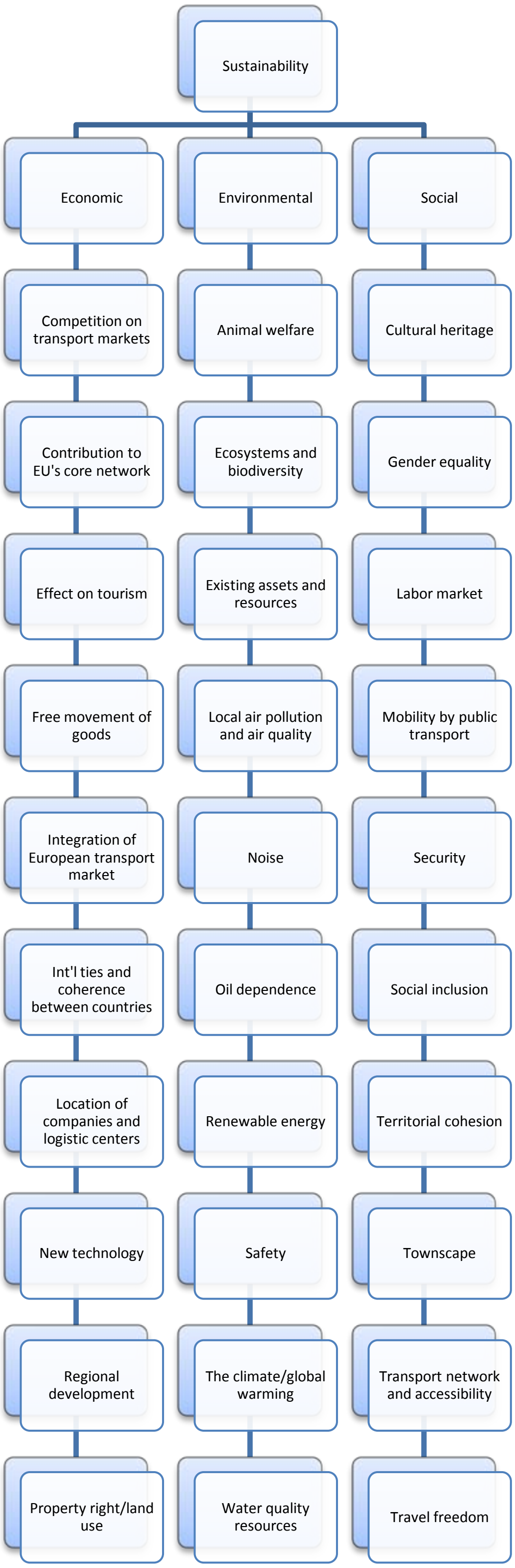

Fig. 4 Considerations for sustainable transport metrics (work-in-progress DTU Transport – GDSI)

2. Concepts and processes

The present knowledge review has identified that the transport sector in general has limited experience with regard to risk-based management. It appears that no one has the single overall responsibility for transport risk management at the national or international level. No common frameworks, guidelines or regulatory directives could be found with reference to risk assessment or risk management, and it appears that these are treated on an individual basis by particular national agencies, ministries or other public authorities. No glossary or taxonomy of terms related to transport risk could be found, hence no attempt was made to compile a glossary for this section of the report.

From a personal interview with a scientific member of MURA, it was revealed that the understanding of the terms risk management, risk assessment and risk analysis is close to that expressed at DTU Civil Engineering. Thus, work at MURA is closely identified with risk assessment and risk analysis, which is said to include probabilistic modeling and socio-economic analyses of the costs and benefits associated with decision alternatives in transport projects.

3. Methods and techniques

Table 2 presents a summary of the methods and approaches used by the two different research streams at DTU Transport – MURA and Traffic Safety. The following sub-sections briefly explain selected methods and approaches.

Model Uncertainty and Risk Analysis (MURA)	**Traffic Safety**
Statistical modeling: data fitting, simulation, empirical distributions, goodness of fit tests	Interviews and surveys
Empirical data analysis (used in Quant. RA): Reference Class Forecasting, Prospect Theory	Epidemiological studies
Qualitative risk analysis: HAZOP, Event Trees, Fault Trees, Bayesian Networks	Experimental studies
Quantitative risk analysis: Monte Carlo Simulation, probability distributions	Driving simulator based studies
	In-depth accident analysis
	Naturalistic driving using instrumented cars
	Statistical modeling
	Accident modeling
	Econometric modeling

Table 2 Summary of methods and approaches used at DTU Transport in relation to risk

Methods and approaches used in the context of MURA

Transport models output is a key input for a wide range of policy analyses, including financial analyses for new infrastructure, urban development planning strategy and sustainable mobility policy evaluation. Research in the MURA framework regarding construction cost estimates, traffic forecasts and socio-economic analyses comprise the majority of activities, with the aim to provide decision support concerning the use of public funds in the Danish transport sector. The principle methods applied are cost benefit analysis, Optimism bias and the associated reference class forecasting, quantitative risk assessment, feasibility risk assessment, and multi-criteria decision analysis.

Cost Benefit Analysis (CBA)

CBA is used within the transport sector as a basis for comparing different development projects and prioritizing those that are to be implemented. The overall feature of CBA is that of comparing costs and benefits with all such elements measured on the same scale, i.e. monetary units. This means that all relevant impacts have to be assigned a unit price. The underlying principle is that of maximizing the net socio-economic benefit of the project, which may be seen as society´s welfare gain. As society in some sense consists of the sum of its individuals, the social change in welfare from a given investment is seen as the aggregate value of the individual utility gains and losses. This means that the assumption underlying CBA is that social decisions can and should be founded on the aggregation of individuals' willingness to pay (WTP).

Even though a key advantage of using CBA is the transparency of the modeling, there are a number of shortcomings associated with this approach. First, it is difficult to quantify "non-market" impacts, such as accidents saved, air pollution, changes to the environment in monetary terms. Subsequently, in the discounting of costs and benefits, there is a large gap in fulfilling the desires and needs of the present and future generations, which makes CBA not in line with sustainability objectives.

Optimism Bias and Reference Class Forecasting (RCF)

The theoretical background for Optimism Bias is made up by prospect theory developed by Kahneman and Tversky in 1979, and for which Kahneman received the Nobel prize for Economics in 2002. Prospect theory describes decisions between alternatives that involve risk, i.e. alternatives where the outcome is uncertain but the associated probabilities are known. It is argued that general errors of judgment are often systematic and hence predictable rather than random errors or biases. Thus human judgment, including forecasts on construction cost schemes, is biased. The theoretical foundation from prospect theory was translated into so-called reference class forecasting, which is a method for "unbiasing" forecasts, or in other words, dealing with the errors from human judgments. A reference class denotes a pool of past projects similar to the one being appraised. Herein a systematical collection of past errors is gathered for a range of projects comparing the deficiencies at the planning stage so that errors in judgment can be avoided.

Fig. 5 illustrates how Optimism Bias and RCF represent two different perspectives, namely what is referred to as *inside* and *outside* view. The inside view is held by the project team and experts closely associated with the project. Herein optimism bias is present in some degree on the risks of cost increases, time schedule delays and benefit shortfalls. The outside view is associated with information on a reference class of similar or comparable projects, and is used to derive information about future events.

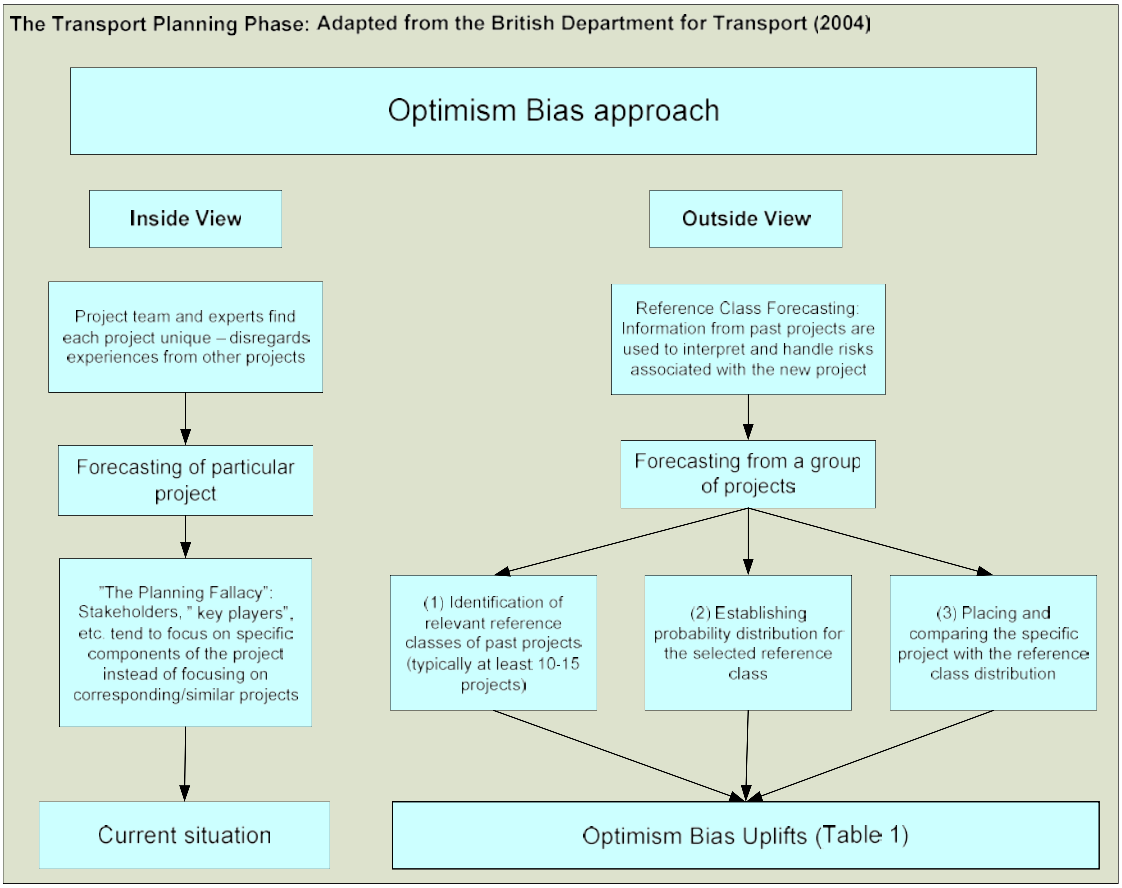

Fig. 5 Principles for Optimism Bias and Reference Class Forecasting (British Department of Transport 2004, Salling 2008)

These approaches are particularly applied within transport project evaluation schemes and address the general tendency of overestimating benefits and underestimating costs. RCF does not try to forecast specific uncertain events that will affect a particular project, but allows for the project to be evaluated in a statistical distribution of outcomes from this class of reference projects.

Quantitative Risk Assessment (QRA)

QRA, which has traditionally been used in finance to model risks related to the buying of stocks and bonds, has been converted to transportation problems by defining a set of uncertain transport related impacts in order to determine the most descriptive discrete or continuous probability distribution functions. The main structure of a QRA model is similar to a deterministic single value rate of return model in CBA, except that each variable in the QRA model is represented by a probability distribution function (PDF). The resulting single point estimate from the CBA is transformed into an interval estimate illustrated in terms of a probability distribution in the QRA. This involves the use of Monte Carlo simulation technique whereby a random sampling concerning each different probability distribution selected for the actual model set-up is simulated.

The Monte Carlo simulation is a common technique for analyzing complex problems. In the context of modeling uncertainty in transport investment projects, the MCS model is considered stochastic. Stochastic simulation is a statistical sampling method where the procedure collects random numbers from a particular probability distribution.

Feasibility Risk Assessment (FRA)

Complementing CBA with QRA is said to enable a more comprehensive type of assessment. This wider type of analysis is denoted feasibility risk assessment (FRA). Fig. 6 illustrates how FRA is connected by the CBA and QRA.

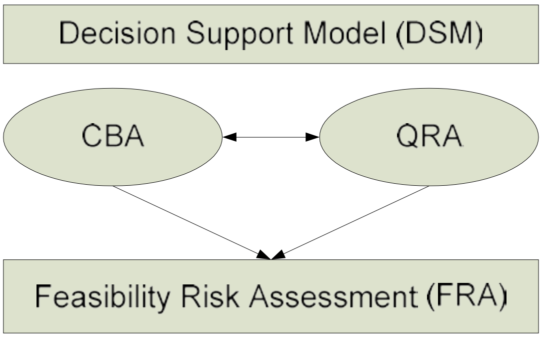

Fig. 6 The FRA procedure (Salling 2008)

Multi-Criteria Decision Analysis (MCDA)

MCDA, illustrated in Fig. 7, stems from the field of operations research. The essence of decision support analysis is to break down complicated decisions into smaller pieces that can be dealt with individually and then recombined in a logical way. For the MCDA methods there are basically three such distinct pieces: the set of possible alternatives, their characteristics (represented by a set of criteria), and the preference structure of the decision maker(s) – reflected in criteria weights.

Generally, the alternatives and their criteria represent the objective part of the decision process, whereas the subjective part lies in the preference structure. In the case where a given criterion cannot be quantified in an obvious way, the decision maker and the analyst may have to make subjective assessments of the criteria scores or find a surrogate measure that can function as a good proxy for the criteria.

MCDA can be seen as an extension of the CBA. In practice, the CBA represents only a part of the decision making basis; other non-monetized impacts represent another, and the final choice is based on weighing of these different parts. In MCDA both the monetized impacts of the CBA as well as more strategic impacts can be accommodated in one approach. This also implies that equity considerations can be explicitly accounted for in the MCDA, making the approach better compatible with decisions related to sustainability.

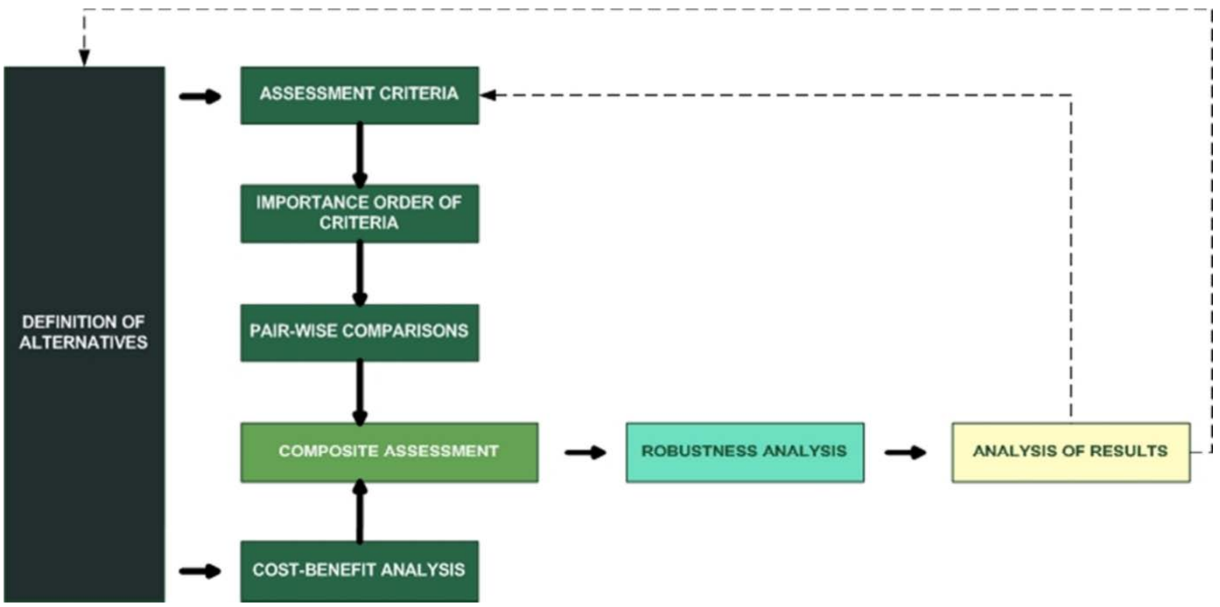

Fig. 7 Framework for the MCDA assessment methodology (Barford and Leleur, DTU Transport Lecture notes 2014)

Examples of Methods and approaches used in the context of Road Safety

<u>Naturalistic Driving Methods</u>

Naturalistic Driving methods are intended to gather data that represent the behavior of the population of drivers in its basic state. Data collected through Naturalistic Driving observation has the potential to provide a high level of detail of (normal) driver behavior in the pre-crash phase if a collision occurs and is thus a useful complement to traditional accidentology. In addition, it can provide important information on successful avoidance behavior in near crash situations and it offers opportunities to quantify mobility (exposure to risk). It focuses on safety performance indicators (SPIs) and exposure to risk (RED) and on how often drivers routinely engage in certain behaviors that are considered to increase the risk of a crash.

Risk Exposure Data	Safety Performance Indicators	Supplementary Performance Indicators
Vehicle mobility	Alcohol and drugs	Fatigue
Fuel consumption	Speed	Distraction/inattention
Person mobility	Protective systems (use of seat belts and child restraints)	Gap acceptance/headway
Number of trips	Daytime running lights	Near crashes
Time in traffic		Accident causation
		Safety technology

Table 3 Inventory of variables which would be relevant to be monitored within ND

Risk Exposure Data (RED) then is used to calculate road safety risk indicators, which enable comparisons over time and countries relative to the amount of exposure. In other words, risk (road safety risk indicator) can be defined as a rate:

$$risk = \frac{road\ safety\ outcome}{\text{amount of exposure}}$$

The calculation of RED requires basically the continuous measuring of a set of data including date/time and GPS position. The difficulty raised by the estimation of the RED is that we need to be exhaustive in the recording of the trips made by the instrumented vehicle. This means that the data acquisition systems (DAS) must be always present in the vehicle. This necessitates an on aboard system and not a mobile system, which may be forgotten at home. This also means that the DAS must be robust to limit the occurrence of breakdowns. The RED estimation is dependent on the GPS receiver that gives the position change of the vehicle. Unavailability and inaccuracy of GPS coordinates, will negatively impact their estimation.

4. Data and metrics

Data related to Traffic Safety

The following are typical examples of data collected in the context of traffic safety (Table 4):

Fact Finding and Diagnosis	Development of Safety Programs	Implementation	Monitoring and Evaluation
Information on crash causation factors	Information on the costs and benefits of road safety measures	A “good practice” collection on implementation	Serious injury counts, in addition to fatality counts
Information on road users’ behavior and attitudes	Information on the safety impacts of combined measures	Digital road maps for mapping crashes	Information regarding the evaluation of the safety impacts of road safety measures
*Exposure data**	A “good practice” catalogue of measures	Detailed information from road safety audits and road safety inspections	Information on the evaluation of costs and benefits of road safety measures
Crash databases that link police and hospital data	Information on the public acceptance of specific road safety measures	Information from in-depth crash analysis	Information regarding Statistical methods for following trends
Information on the under-reporting of road traffic crashes			

Table 4 Data used in Traffic Safety

**Exposure data*

There is no standard method for the collection of each exposure measure. In particular, different exposure measures may be derived from one collection method. For example, a travel survey may be used to collect vehicle kilometres, but may at the same time be used to obtain the number of trips, the time spent in traffic, vehicle ownership, or driver license holder ship. Accordingly, data collected by different methods may be used to produce an exposure estimate. For instance, passenger kilometres estimates may be obtained by using vehicle kilometres derived by traffic counts and vehicle occupancy rates obtained through surveys. The usual exposure data that are most of time accessible are:

- Travel Surveys
- Traffic counts
- Vehicle fleet registers
- Driving licenses registers
- Road registers

However, the new technologies and the associated methods based on risk exposure ask to have information on specific target population such one linked to the driver behavior depending on some context.

Regarding road safety, the accident data are the weak link. Without these data there are no observations, no understanding of the problems, no stakes, no statistical description, no risk estimation, no identification of the priorities, etc.

Metrics related to Appraisal of Transport Projects

- Net Present Value (NPV)
- Benefit Cost Ratio (BCR)
- Internal Rate of Return (IRR)

For a more detailed description of these metrics, see previous section.

Possible Metrics in the context of Road Safety

The theoretical example of the so-called *Road Safety Index* is presented below as it is considered relevant for the purpose of this report. However, it should be noted that this index is not used in practice at DTU.

The Road Safety Index is a so-called composite Index: an index composed of several indicators which each separately and all together measure a specific field, in this case road safety. Such an instrument is used in various policy fields. Examples of composite indexes in other fields are the Sustainable Development Index, the Innovation Index and the Human Development Index. A composite index is an instrument to benchmark performances between countries, in this case road safety performances. This enables countries to compare themselves to others, it stimulates positive competition and shows specific improvement possibilities. Composing various indicators into one figure prevents policymakers and politicians from having to construct a complete picture out of a large number of indicators themselves.

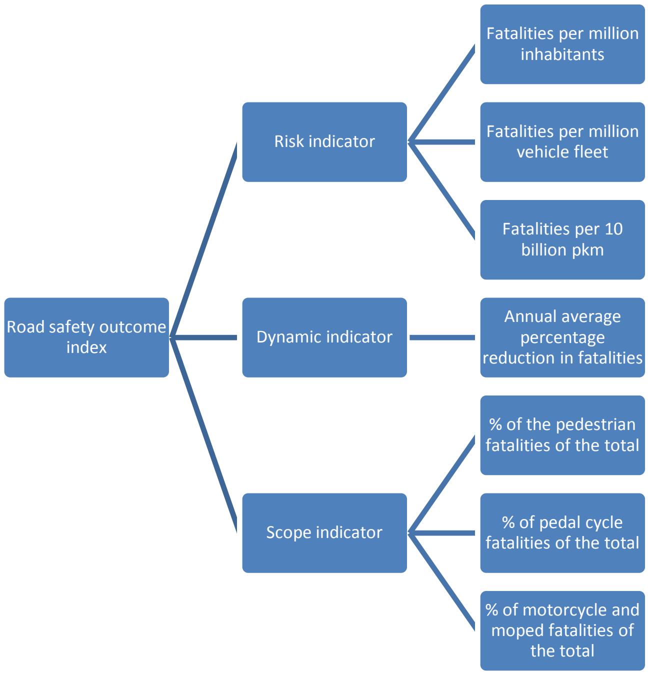

Fig. 8 Road Safety Outcome Index

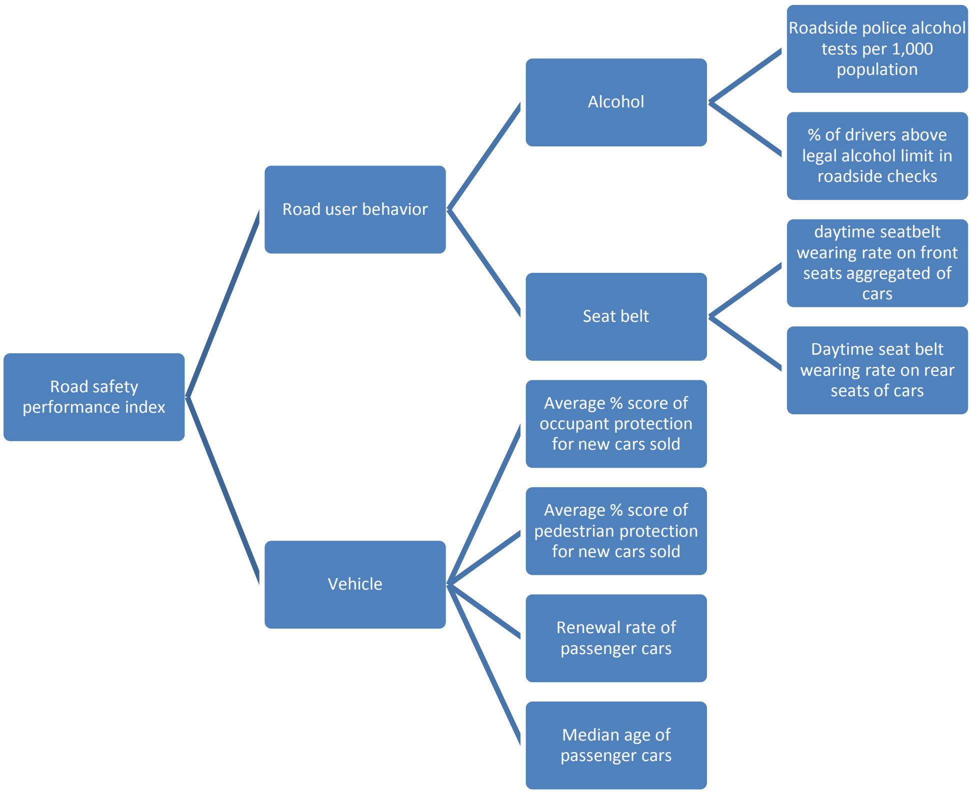

Fig. 9 Road safety performance index

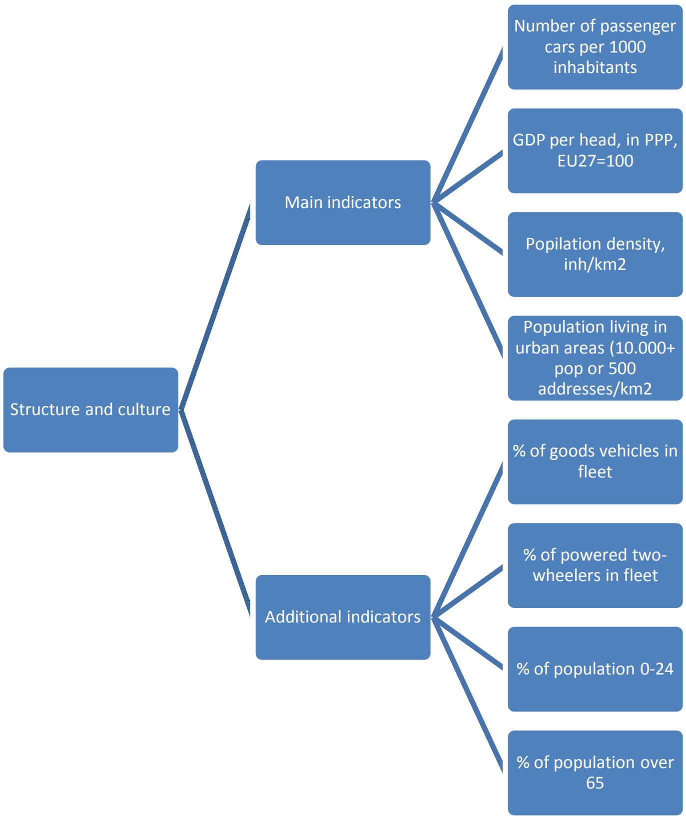

Fig. 10 Road safety structure and culture index

Possible Metrics in the context of Rail Safety

In the Rail sector in general, the following (Table 5) are typically used metrics in the context of safety to humans and/or the environment:

FRA Personal Injuries	Motor Vehicle Accidents
Non-FRA Personal Injuries	Average Days per Lost Time Injury
FRA Train Accidents	Crossing Accidents
Non-FRA Train Accidents	Trespassing Accidents
Cardinal Rule Violations	Safety Index
Greenhouse Gas (GHG)	Hydrocarbon Spills

Table 5 Typical Rail Safety Metrics

There are no standard international conventions for measuring exposure to risk on the railways. Railway casualties are classically divided into passengers, staff and third parties. The only exposure measure provided by The UIC (Union Internationale des Chemins de Fer) is the number of passenger kilometres, which is a suitable measure of risk to passengers, but only to them, and they represent a minority of railway casualties.

There is no generally accepted criterion for deciding what railway safety measures are needed. There is a widespread view that current safety performance is reasonably good, and this provides a benchmark against which system changes are judged. The explicit valuation of the benefits and costs of safety measures is uncommon in railways.

Three general principles for the adoption of safety measures are current. These are:

• GAME ('Globalement Au Moins Equivalente'), expressing that any change to a system must leave it at least as safe as it was beforehand. It is a formal adoption of the present level of safety as a benchmark, and is an absolute criterion.

• MEM ('Minimum Endogenous Mortality', expressing that the risk of death to individuals shall be less than a specified limit. This is also an absolute criterion.

• ALARP ('As Low As Reasonably Practicable'), which involves some trade-off between the costs and benefits of safety measures, though the terms of that trade-off remain subject to debate.

5. Research topics

Research activities at DTU Transport are organized according to nine research themes: Transport Economics, Transport behavior, Transport optimization, Traffic Safety, Governance and Evaluation, Modeling Uncertainty and Risk in Transport (MURA), Urban Transport, Large scale transport models, and Route choice and traffic flow.

Risk is the main topic of research in MURA, while safety is largely covered in Traffic Safety. However, all of the other research themes at DTU Transport are at least implicitly related to risk and safety in that they address broader risk analysis issues that are related to risk management, risk perception and risk governance. A further common characteristic among the different research themes is their application of decision theory and multi-criteria decision analysis for transport decision making. As in the case of DTU Civil Engineering, decision analysis is considered an integral part of the risk analysis process as it relates to optimization of decision alternatives. Thus, although risk-related research is the main domain of MURA, some of the principles and methodologies used in risk analysis are shared with the other research themes.

For the purposes of this report, only the research areas of the MURA and the Traffic Safety themes are elaborated on.

Model Uncertainty and Risk Analysis (MURA)

This research theme aims at implementing and/or minimizing the risks and uncertainties within transport systems and related issues both in terms of quantitative empirical efforts as well as qualitative. MURA is focused on applying various forms of risk and uncertainty analysis within all types of transportation disciplines as presented in Table 6.

Model Uncertainty and Risk Analysis (MURA) Research Topics
Statistical Modeling and Distributional Fitting Usually, mathematical models of transport systems rely on a number of assumptions. If the assumptions are not fulfilled by the system, the model may not perform as it is intended. With methods from mathematical modelling and distributional fitting, such as data fitting, simulation, empirical distributions, goodness of fit tests, etc., the model assumptions can be tested. Furthermore, the methods also provide a framework for simplifying vast data amounts with the purpose of easier manipulation or extraction of quantitative features.
Qualitative and Quantitative Risk Analysis The main objective of risk analysis (RA) is to establish a rational foundation for objective decision making. The risk analysis aims at quantifying the undesirable effects that a given activity may impose on humans, environment, and economical values. The objective of the decision process is then to identify the solution that in some sense minimizes the risk of the considered activity. RA, thus, is divided into a qualitative section covering among others Hazard and Operability (HAZOP) analyses, scenario identifications (Event and/or fault tree analyses), Bayesian networks (causal relationships between events/failures), etc. and a quantitative part exploring among others empirical data analysis (reference class forecasting and Prospect theory), Monte Carlo simulation, probability distributions, etc.
Calibration of Model and Input Parameters Theoretical methods to calibrate different types of models by adjusting their input parameters exist. However, often these models are not applicable on large-scale projects why more ad hoc methods – or even trial and error – are used. To achieve the best possible results of both new and existing models – whether it is transport models, railway simulation models, risk models or other types of mode choice models – research in how to calibrate these models are needed. This research will focus on both theoretical methods to calibrate the models and how to apply the theory on large-scale models.
Methodologies to Analyze and Quantify Transport Demand Model Uncertainties Transport models output is a key input for a wide range of policy analyses, including financial analyses for new infrastructures, urban development planning strategy and sustainable mobility policy evaluation. However, transport models are built to model complex systems so they are subject to uncertainty. If not properly analyzed and quantified, the uncertainty inherent to transport models makes analyses based on their output less reliable with potentially serious socio-economic consequences. Consequently, the knowledge for applying the existing models' uncertainty assessment methodologies and for developing new ones assume a strategic relevance from a theoretical and practical point of view.
Life Cycle Cost Assessment and Management Looking into LCC adopted in this context, it is mainly focusing on the development of a valid, flexible and functional Railway phase-based planning toolkit, as a Decision Support System (DSS), thus the planning, operation and management of railway infrastructure projects more economically, i.e. cost-effective. The toolkit (LCC-DSS) provides decision support in terms of ability to introduce and thus calculate LCCs through a systematic phase-based process. Therein, the railway Infrastructure

Managers (IMs) can be facilitated to estimate costs both at the strategic level (+10 years) and at the operational level (project level). Cost-oriented aspect of plan evaluation is implemented in the toolkit with which IMs can respectively compare and identify the best solution, and also efficient track tamping strategic plan for a certain line. The aim is henceforward to reduce the overall costs without impacting the railway infrastructure quality.
Uncertainties in Transport Project Evaluation Construction cost estimates, traffic forecasts, and socio-economic analyses are an important part of the decision support concerning the use of the public funds within the transport sector. Denmark faces large investments in the sector due to congestion problems in the road network, demands for improved public transport, and a need to reduce externalities from the sector, e.g. CO2 emissions and accidents. More accurate and less biased models will lead to better estimates and thereby a better use of the available investment funds. This also relates to societal transport impacts such as e.g. accessibility, congestion and economic development. Cost models and cost parameters are investigated among others by benchmarking, successive calculation and reference class forecasting (Optimism Bias).
Decision Support Systems Decisions about infrastructure projects or new policies have in the transport sector traditionally been based on cost benefit analysis (CBA). However, as society in general becomes more complex this affects the decision making process. Decision makers are confronted with the difficult problem of evaluating potential outcomes and choosing policies to achieve the desired outcomes in the presence of this complexity. Recently the evaluation of transport projects has evolved towards a comprehensive evaluation framework. This framework takes into account the complex environment and views of multiple and diversified stakeholders. Here multi criteria decision analysis (MCDA) is a useful tool for the decision makers as it is able to perform an assessment based on various stakeholder inputs. Hence, no quantification of impacts/criteria is needed to obtain a final result. However, in the MCDA framework there might be uncertainties e.g. incomplete information or uncertainties about the criteria weights and in order to provide a robust support for decision making it is important to be able to deal with these uncertainties.

Table 6 Model Uncertainty and Risk Analysis (MURA) Research Topics

Large research projects within the MURA framework with explicit relevance to risk research include the following:

- Uncertainties in Transport Evaluation (UNITE)
- National Transport Planning – Sustainability Institutions and Tools (SUSTAIN)
- Robustness in Railway Operations (RobustRAIL)
- Global Decision Support Initiative (GDSI)

Traffic Safety

The purpose of the road safety research theme is to create a scientific foundation for a continuous reduction in the number of road accidents and their injury severity in a society with a growing need for mobility. To achieve this, there is a need for both a fundamental understanding of the accident causes, risk factors and quantitative estimates of the effects of road safety measures in order to prioritize correctly.

A large number of research topics regarding the interaction between the road user, the vehicle and the road and its surroundings are covered by the road safety theme. The scientific topics include topics related to sub-groups of road users such as young road users, old road users, drivers, cyclists, pedestrians as well as particular safety related topics such as risk-taking behavior, driver training and education, impairment (alcohol and drugs, distraction, fatigue), speed, enforcement and use of technology.

A human factors approach is used which implies that the characteristics, needs, capabilities and limitations of the road users form the basis of the safety related research topics. Psychology and statistical modelling are the key disciplines applied.

Large research projects within the Traffic Safety framework with implicit relevance to risk research include:

- Improving Road Safety: Developing a Basis for Socio-economic Prioritizing of Road Safety Measures (IMPROSA)

6. Research Networks

Internally, DTU Transport collaborates on a number of projects with DTU Civil Engineering, DTU Management and DTU Compute.

At the national level, DTU Transport is primarily collaborating with Aalborg University’s Department for Planning.

International research networks include:

- Det Norske Veritas
- The Forum of European Road Safety Research Institutes (FERSI)
- The European Conference of Transport Research Institutes (ECTRI)
- The Nordic Organization for Behaviour in Traffic (NORBIT)
- The Transport Economics Institute of Norway
- The Swedish National Road and Transport Research Institute
- The Institute of Transport at the Technical University of Braunschweig
- The Centre for Sustainable Transport and Cities at Nagoya University
- TSU – Oxford University
- The Texas A&M Transportation Instite
- The Institute of Transport Studies at Leeds, UK

- The Centre for Regulatory Studies at Monash University

7. Advisory Activities

DTU Transport provides scientific advice to the Danish Ministry of Transport (Transportministeriet), the Danish Transport Authority (Trafikstyrelsen) and the Railway authority (Banedanmark).

Advisory services for the Ministry of Transport focus on three areas: transport policy and transport behavior, traffic modeling and planning, and data collection and dissemination. Specifically, DTU Transport provides scientific advice on the following topics:

- Development of land traffic models
- Research and surveys of traffic behavior of various user groups
- Communication and dissemination of data and models through the Data and Modeling Center among stakeholders in the sector
- Contribution to the development of socio-economic methods and models as well as continuous updating of transport unit prices
- Contribution of experts to various commissions related to traffic safety
- Ad hoc analyses in support of the Ministry's policy-making activities

Advisory services for the Danish Traffic Authority and Banedanmark aim to support the needs of these authorities in the area of railway technology. This includes the strengthening of research technological competencies in the sector, including establishing a number of collaborative PhD studies.

In addition, DTU Transport provides scientific support to these authorities on the brake systems of the IC4 trains.

DTU Transport further provides ad hoc advisory services to the following authorities:

- The Danish Ministry of Justice
- The Danish Road Safety Council
- The Danish Police
- The Danish Road Directorate
- The Danish Road Traffic Accident Investigation Board

8. Educational Offerings

DTU Transport currently provides two dedicated courses within the scope and frame of MURA:

- 13233 Risk Analysis and Decision Support (MSc)
- 13833 Risk Analysis and Decision Support (PhD)

Moreover, the following subset of courses are all treating model uncertainty and risk analysis:

- 13125 Rail Traffic Engineering (MSc)
- 13128 Signalling Systems for Railways (MSc)
- 13131 Transport Models (MSc)
- 13141 Route Choice Models (MSc)
- 13231 Appraisal Methodology (MSc)
- 13235 Planning Theory (MSc)
- 13525 Rail Traffic Engineering (BSc)
- 13538 Project Appraisal (BSc)
- Various lectures as part of other DTU Transport courses
- Supervision of BSc., MSc. and PhD theses at DTU Transport

In the domain of Traffic Safety, the following courses are offered:

- 13518 Road safety (BSc)
- 13535 Statistical modeling of traffic (MSc)
- 13232 Road safety (MSc)
- Supervision of diploma, master and PhD students

In addition, for the purpose of this report, a search of *Kursusbasen* was performed for the following keywords: *risk, safety, uncertainty, life cycle, sustainability, and decision analysis*. The results are presented in Table 7 below.

Course Nr./ Keyword	Title	Content	Type
13233 13833 risk	Decision Support and Risk Analysis	Basic principles of socio-economic analysis based on the use of cost-benefit analysis, risk analysis and multi-criteria decision analysis. Parameters and variables in socio economic analysis. Basic methods of risk analysis and multi-criteria decision analysis. Implement and explain the various aspects of risks within transport appraisals and conduct a risk analysis by the use of Monte Carlo simulation. Probability distribution functions adequate for risk analysis in the transportation field. Risk communication.	MSc PhD
13542 risk	Traffic Safety	Principles of recollection, analysis and interpretation of traffic accident data. The concept ”risk” and various risk measures. Different groups of road users and their risk profile in the traffic. Road users’ behavior and instruments to change it. Infrastructure and its importance for traffic safety. Various survey designs and their meaningfulness and validity. Criteria and methods to identify localities/traffic situations with a particularly high incidence of accidents.	D.Ing
13125 13524 safety	Rail Traffic Engineering	Theoretical and practical overview of the methods and models used in the planning of rail bound traffic. Introduction to safety issues on railways, infrastructure elements, signalling systems and	MSc D.Ing

		timetabling.	
13126 safety	Railway Design and Maintenance	Design of an expansion of an electrified railway line, incl. increased speed. Design of horizontal and vertical alignment, together with the catenary system by use of the CAD-system MicroStation and the application Bentley Rail Track. All phases in the project are carried out with respect to the safety standards used for railways.	MSc
13510 safety	Road Traffic Engineering	Traffic operational analysis: traffic counts, accident factors, urban and inter-urban conditions. Capacity calculations: traffic volume, maximum capacity, peak hour values relating to different categories of roads, road capacity design hours, speed-flow curves, free and queue traffic operation description and measurement, level-of-service categories, road design standards. Traffic signals: dimensioning of green times, calculation of safety times, flow controlled and coordinated traffic signals as well as optimization of signal systems.	D.Ing
13832 safety	Advanced topics in strategic public transport planning	Advanced procedures related to network infrastructure design, timetable development, vehicle scheduling, fleet management, and system appraisal in terms of service quality standards. Bus rapid transit. Deregulation and privatization. Safety and security.	PhD
13236 Life cycle/ sustainability	Sustainable Transport Assessment	How the concept of sustainability can be operationalized and transformed into strategic guidelines for transport planning. Identification and selection of indicators. Communication to decision-makers and the public using of indicators. Assessment tools for sustainability in the transport sector. Identification and calculation of effects such as accidents, emissions, barriers and resources, using GIS-based software. Environmental Impact Assessment at the project and strategic level (EIA, SEA). Introduction to life cycle analysis and multi-criteria decision support.	MSc
13133 Decision analysis	Introduction to Transport Models	Software for data management, data analysis and model estimation. Fundamental principles behind the four-stage modelling approach, incl. mathematical and statistical models. Models for trip generation with linear Poisson regression models. Models for trip distribution with gravity models. Models for mode choice with logit and nested logit models.	MSc
13134 Decision analysis	Advanced Transport Models	Software for data management, data analysis and model estimation. Fundamental principles behind the activity-based modelling approach, incl. mathematical and statistical models. Models for location choice and car ownership. Models for destination and mode choice in the activity-based framework. Count data models of accident frequency. Ordered models of accident severity. Models for scenarios' analysis and	MSc

		cost-benefit analysis calculations by quantifying user benefits as a result of a change in the supply (e.g., a change in an infrastructure or in the taxation).	
13301 Decision analysis	Transport, Economics, Management, Planning, Organisation and Policy	Basic understanding of the roles and the meaning of economies, management, planning, organization and policy in public administration within the transport sector. This will enable the student to act appropriately in a context with many conflicting public and private interests.	MSc
13437 Decision analysis	Optimisation of operational transport systems	Operational and real-time planning issues within the transportation sector. Strategic, operational and tactical problems in transport planning. Optimisation methods for operational transportation planning problems with specific focus on solution speed and data availability. Deterministic and stochastic as well as static and dynamic (real-time) distribution planning problems. Design a simple solution algorithm for solving a dynamic (real-time) distribution planning problem. Explain/apply methods for obtaining bounds for dynamic (real-time) distribution planning problems.	MSc
13442 Decision analysis	Vehicle Routing and Distribution Planning	Models and solutions methods for vehicle routing. Vehicle routing with time windows. Arc routing. Inventory routing. Routing with transshipment, including cross-docking. Stochastic vehicle routing problems.	MSc
13450 Decision analysis	Intelligent Transport Systems (ITS) – Modelling and Analysis	Introduction to systems approach, where the inputs, outputs and the ”boundaries” of a system are clearly delineated, with specific focus on decision variables (that effect the system) and system evaluation. Enhancement of transportation through ITS technologies. Transportation planning and how ITS data may improve it. Traffic operations, specifically real-time traffic control, and wide-area traffic management. Transit operations, specifically how they may be improved with potential ITS data. Real-time traffic monitoring. Traveler information systems. Other emerging technologies, such as smart sensors, remote monitoring, and vehicle infrastructure integrated systems.	MSc

Table 7 Courses at DTU Transport explicitly and implicitly related to risk

9. Data sources

Personal Interview with Kim Bang Salling, Associate Professor DTU Transport

Kim Bang Salling Rsearch Leader at MURA GDSI Advisory Board kbs@transport.dtu.dk Special Interests: Reference Class Forecasting, Optimism Bias, Assessment of Risk and Uncertainty, Decision Support System, Transport Project Evaluation, Quantitative Risk Analysis, Monte Carlo simulation, Successive Principle, Cost-benefit analysis, Multi-Criteria Analysis, Sustainable Transport Assessment, Risk Analysis and Risk Managment	

Barford, M.B. and Leleur, S., ed., Multi-criteria decision analysis for use in transport decision making, DTU Transport Compendium Series, part 2, 2014

European Transport Safety Council, Assessing Risk and Setting Targets in Transport Safety Programmes, 2003

Haimes, Y.Y. et al, A Risk Assessment Methodology for Critical Transportation Infrastructure, Contract research sponsored by the Virginia Transportation Research Council, US, 2002

Landex, A., Salling, K.B. and Andersen, J.L.E., Note about socio-economic calculations, Centre for Traffic and Transport, DTU

Salling, K.B., Assessment of Transport Projects: Risk Analysis and Decision Support, PhD Thesis, DTU Transport, 2008

Salling, K.B. and Leleur, S., Modeling of Transport Project Uncertainties: Feasibility Risk Assessment and Scenario Analysis, EJTIR 12 (1), 2012, pp. 21-38

Sørensen, C.H., Gudmundsson, H., Leleur, S., SUSTAIN - National sustainable transport planning – concepts and practices, Working paper DTU Transport

Thomas, P, Muhlrad, N, Hill, J, Yannis, G, Dupont, E, Martensen, H, Hermitte, T, Bos, N (2013) Final Project Report, Deliverable 0.1 of the EC FP7 project DaCoTA

DTU Transport website

Interview Questions with Kim Bang Salling – Associate Professor at DTU Transport

1. The context of the processes of risk assessment in relation to transport safety differs between road, rail, air and maritime transport, and so do the extent to which and the manner in which these processes have been developed. How are these differences accounted for in terms of education and research focus at DTU Transport?
2. How are risk analysis, risk assessment and risk management defined in the context of transport risk and safety and what are the different components in each process? How can DTU Transport's competencies be described with regard to the different stages of risk analysis?
3. What qualitative and quantitative methods are used in the process of risk assessment?
4. What qualitative and quantitative methods are used in the process of risk management with regard to identifying and evaluating risk management options? Is decision analysis incorporated? What are the risk acceptance criteria?
5. What data is typically used in transport risk assessment? How is this data collected?
6. DTU Transport has a large portfolio of advisory services it provides to Danish public sector authorities. Is there an established risk communication strategy and process? What are the challenges?
7. What research topics are covered at DTU Transport that have direct or indirect relevance to risk?
8. What current projects at DTU Transport have relevance to risk?
9. Is there collaboration in research activities and projects with other DTU institutes? On what topics and in which capacity?
10. Does DTU Food provide scientific advice to actors in the Danish and/or international public sector? On what topics and through what framework?
11. What percentage of DTU Transport scientific staff is involved in work directly related to the topic of risk as: a) their main activity; b) their supplementary activity?
12. How many current PhD students are working on a topic related to risk? What are these PhD projects?
13. What does DTU Transport perceive to be the main challenges with regard to the departments risk-related activities in terms of education, research and public/private advisory?
14. Where does DTU Transport see opportunities for collaboration with other DTU institutes with regard to the department's risk-related activities?

Appendix III: Risk at DTU Food

Table of Contents

1. Introduction: Risk in food safety

There are three general perspectives on risk in the context of food safety, the so-called *technical, psychological and sociological paradigms* (Table 1).

Technical paradigm	Focuses on and is limited to scientific evaluation of the likelihood and severity of harm. May include an economic subset in which harm can be described in terms of either health indices, such as Disability Adjusted Life Years (DALYs) or monetary values.
Psychological paradigm	Evaluates risk as a function of individual perception, giving weight to such attributes as voluntariness of exposure, controllability of risk, catastrophic nature of risk, and so on. Risk perceived in these ways may differ in "magnitude" from technical risk estimates.
Sociological paradigm	Views risk as a social and cultural construct, with the goal of distributing costs and benefits in socially acceptable and equitable ways.

Table 1 Perspectives on risk in food safety (FAO 2007)

The technical perspective is the primary one for decision making, where the overriding consideration is that risk assessment is specific to a described scenario. This is also the dominant perspective adopted at DTU Food.

From Traditional Food Safety toward Science-based Food Safety Management

The formal development of food safety policies and measures can be traced back to the early 20th century as a response to public scandals in the meat packing and food processing industries. During most of the last century food safety policy and management can be characterized by command and control mechanisms of safety regulation adopted from early industrial management practices such as line inspection, end-product control and specification of approved hygiene practices, and regulated by public authorities at national level.

The increasing globalization of the food trade, urbanization, changing consumer patterns, new food production technologies as well as the emergence of new pathogens and re-emergence of old ones are only some of the new challenges affecting food safety and the traditional food safety management systems. The course of the past 20 years has seen the adoption of risk analysis as the scientific foundation for developing new food safety systems and policies. This period has seen a shift from a hazards-based approach to food safety, whereby the mere presence of a hazard in a food would be considered unsafe, to a risk-based (also referred to as science-based) approach, whereby an estimate can be produced on the combination of exposure to the hazard and the impact from a hazard. At the heart of this second generation food policy is the need for a preventive, public health-focused policy that facilitates integrated management of foodborne hazards from farm-to-fork. In effect, this transition is being driven by three larger trends that are not specific to the food sector: globalization, use of risk analysis and cost-benefit analysis in public administration, and total quality management regimes in industry.

As a concept, a science-based approach to food safety is not completely new. It is related to processes such as good agricultural practices, good hygienic practices, good manufacturing practices and Hazard Analysis and Critical Control Point system (HACCP), which are already used in many countries. Scientific assessment of chemicals in general has also a rather long 'tradition'. What is new is the use of risk analysis as a framework to view and respond to food safety problems in a systematic, structured and scientific way in order to enhance the quality of decision-making throughout the food chain.

Food Safety, International Institutions and Trade Issues

Increased international food trade means that countries share the responsibility for food safety. Globalization of the food supply chain could introduce new food safety risks, revive previously controlled risks, and spread contaminated food wider. The General Agreement on Trade and Tariffs (GATT) has provided the central legal structure for international trade since its inception in the wake of World War II. The Uruguay Round of trade negotiations (1986-1994) created a permanent institutional home for GATT within the World Trade Organization (WTO) and resulted in the adoption of the Sanitary and Phytosanitary (SPS) Agreement. This agreement provides a basis for distinguishing legitimate from protectionist use of safety and phytosanitary laws. Like other GATT provisions, the SPS Agreement is enforced by international dispute resolution processes, and if necessary, trade sanctions levied by injured countries against offending ones. The agreement recognizes that compliance may make it more difficult for developing countries to be involved in international trade and encourages wealthier members to provide or fund technical assistance to help poorer countries develop food safety systems that comply with SPS requirements.

Under the SPS agreement, standards consistent with those agreed to by the Codex Alimentarius Commisssion (Codex) are presumed to be in compliance with GATT. The Codex Alimentarius Commisssion was established in 1963 by the UN's Food and Agriculture Organization (FAO) and World Health Organization (WHO) to provide a forum for international technical collaboration on the development of food safety and quality standards.These include quantitative standards for food additives, quantitative tolerances for contaminants such as pesticides and veterinary drugs, guidelines for microbial risk assessment, biotechnology risk assessment, microbial risk management, and validation of safety control measures as well as principles for traceability and risk analysis.

In addition to the Codex, World Organization for Animal Health (OIE) and the Secreatariat of the International Plant Protection Convention (IPPC) also set standards that on which WTO members should base their SPS methodologies.

Sustainability Considerations in Food Safety

According to FAO, food consumption and production trends and patterns are among the main causes of pressure on the environment. Fundamental changes in the ways food is produced, processed, transported and consumed therefore have a strong effect on sustainable development. Sustainable consumption and production in food and agriculture is described as a consumer-driven, holistic concept that refers to the integrated implementation of sustainable patterns of food consumption and production, respecting the carrying capacities of natural ecosystems. It requires consideration of all the aspects and phases in the life of a product, from production to consumption, and includes such issues as sustainable lifestyles, sustainable diets, food losses and food waste management and recycling, voluntary sustainability standards, and environmentally friendly behaviors and methods that minimize adverse impacts on the environment and do not jeopardize the needs of present and future generations. Sustainability, climate change, biodiversity, water, food and nutrition security, right to food and diets are all closely connected.

Although there seems to be an international consensus on the importance of promoting sustainable food consumption and production, the issue of sustainability has not been high on the agenda. This is also the situation at DTU Food, where sustainability is slowly becoming of concern to academic research but mostly through small individual projects, such as a project with ARLA Food on how to re-use water in dairy production to make the process more sustainable. There is also discussion about organic production, which is related to sustainability. It should be pointed out, however, that in terms of microbial risk, the risk is higher when organic production is used. Moreover, organic production does not necessarily have to be sustainable per definition. Public perception is a major factor in this instance.

At present, there is no framework or terminology developed with regard to sustainable food production/consumption at DTU Food or externally. The issue, however, has been raised in UN-led discussions about the post-2015 sustainable development agenda in light of the fact that the UN Millennium Development Goals (MDGs) are supposed to be achieved by 2015. Discussions at international for a consequently focus on developing a new set of goals, namely, Sustainable Devlopment Goals (SDGs) for the post-2015 era.

A paper published in Lancet in January 2015 presents a rationale and methods for the selection of health-related indicators to measure progress of post-2015 development goals in non-health sectors. Food is selected as one of these 'sectors' (the other being, cities, energy and water). For each sector potential indicators are identified based on epidemiological evidence of consistent associations as well as plausible mechanisms linking development action and its health effect, and availability of relevant monitoring data. With regard to food, three factors are identified to be of importance with regard to sustainability: nutrition, food security and climate change.

It is argued that present patterns of unsustainable food production and distribution are linked with hunger, undernutrition and obesity, which allows for the scientific estimation of attributable morbidity and mortality for a range of dietary risk factors. A link was further established between food price volatility and food security, driven by increase in consumption of cereals by livestock. Yet livestock are at the same time seen as essential source of income and food security to many small landowners and people living in rural areas, thereby presenting a complex web of causality that needs to be accounted for with regard to health-relevant indicators for sustainable food. Finally, animal products and processed foods are proven to have the highest effect on climate and environment, including water, air pollution and deforestation. It is argued that climate change poses major challenges to agricultural productivity in the face of rising demands.

DTU Food sees the DTU Global Decision Support Initiative as the forum where research in food safety can be integrated with research in other risk-relevant research domains, including sustainability. The scope of the activity includes the identification of appropriate risk, life quality (disease) and sustainability metrics for decision support in relation to the food production system.

2. Concepts and processes

In the context of Food Safety, risk analysis is the overarching term, which comprises the following three components: risk assessment, risk management and risk communication. (Fig. 1)

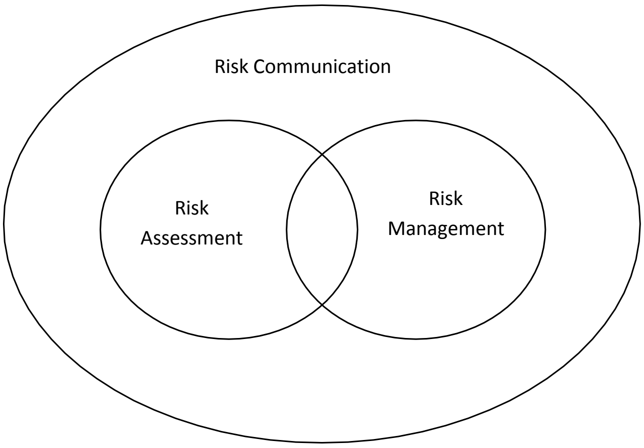

Fig. 1 Components of risk analysis (FAO 2005)

Risk Management

Risk management is defined (FAO 2005) as the process, distinct from risk assessment, of weighing policy alternatives in consultation with interested parties, considering risk assessment and other factors relevant for the health protection of consumers and for the promotion of fair trade practices, and, if needed, selecting appropriate prevention and control options.

A sample generic model for risk management is presented in Fig. 2.

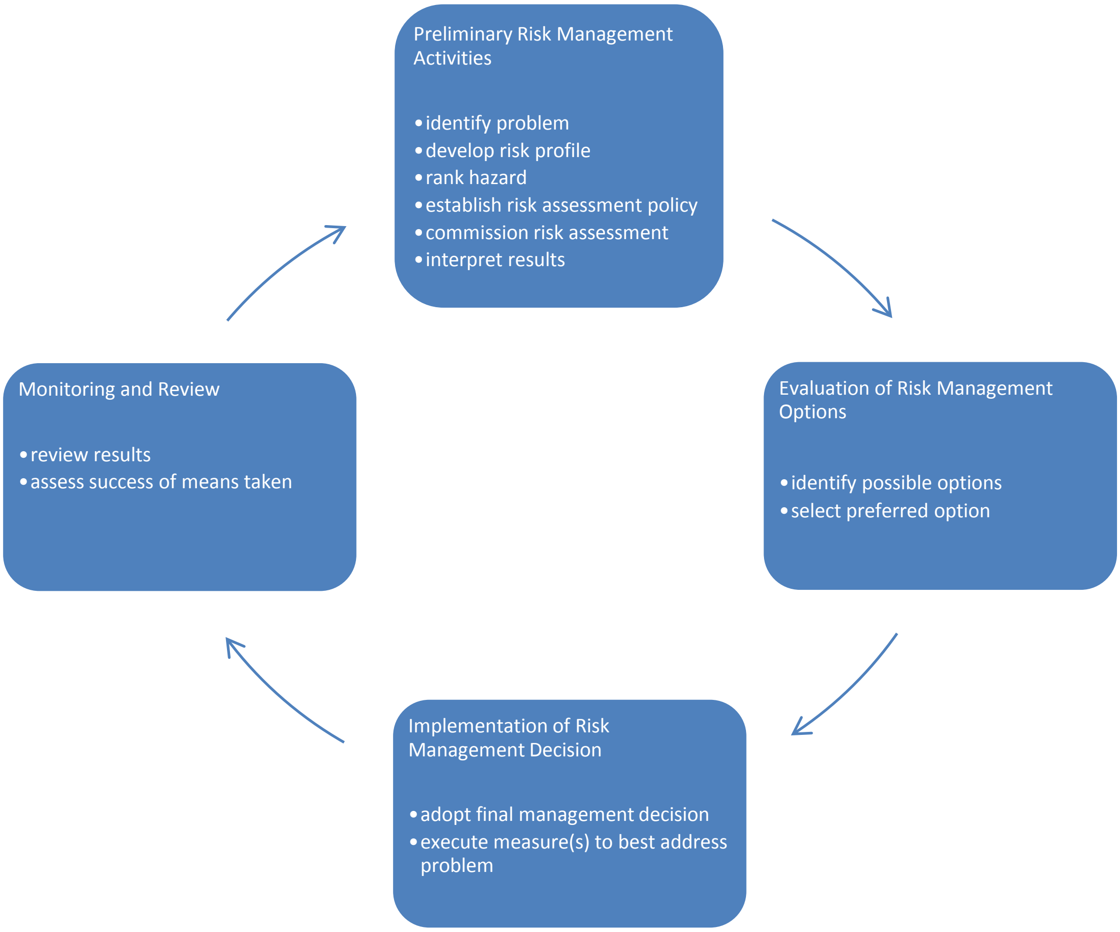

Fig. 2 Generic model for risk management (FAO 2005)

Preliminary Risk Management Activities

This initial step includes identifying and articulating the nature and characteristics of the food safety problem and the establishment of a risk profile to facilitate consideration of the issue within a particular context. A risk profile can be seen as a type of situation analysis, which presents everything known about the risk at that point in time. A typical risk profile might include a brief description of the situation, product or commodity involved; the values expected to be placed at risk (e.g. human health or economic concerns); potential consequences, consumer perception of the risks, and the distribution of risks and benefits. Further, as part of the risk profile, relevant aspects of the hazard(s) are identified for prioritizing with regard to the risk assessment policy and the choice of safety standards and management options. A risk profile is thus a decision support instrument to identify decision alternatives, including whether or not a risk assessment is needed.

Interpreting the results of the risk assessment is an additional part of the risk management activities and it is also linked to risk communication activities with internal and external stakeholders. The completed risk assessment should provide risk managers with sufficient science-based information to understand the nature and extent of the food safety risk and of the uncertainties in the assessment. This scientific information is then analyzed together with other information on economic, cultural, and environmental aspects of the risk, and the risk is evaluated as tolerable or not. The level of risk can be expressed in different ways and according to different purposes. For microbiological risk, the Appropriate Level of Protection (ALOP) is a widely used approach. For chemical contaminants, the level of risk could be expressed through a Tolerable Daily Intake (TDI). For food additives and residues of pesticides and veterinary drugs risk is typically expressed through an Acceptable Daily Intake (ADI). See also section 4 on metrics in Food Safety.

Evaluation of Risk Management Options

Formal decision analysis is not used in the context of Food Safety with regard to optimization of decision alternatives. Optimization of food control measures in terms of their efficiency, effectiveness, technological feasibility and practicality at selected points throughout the food chain is formulated through the setting of goals and criteria, e.g. a specific reduction in the lifetime risk associated with exposure to a particular chemical contaminant; a specific reduction in the pathogen load on a commodity at the point of sale; a specific reduction in illness caused by a particular pathogen, etc.

The first step in this process is to identify all the measures (i.e. a change that occurs somewhere along the farm-to-table food chain) that could possibly achieve or contribute to the identified risk management goal. The second step focuses on the creation of options based on the measures identified. The selection of a preferred risk management option, or a combination of options, involves a comparison of the effects of the different options on human health risk, the potential costs and benefits of each and the uncertainty in the output of the risk assessment. Ultimately, however, the selection of the 'best' option is a political process that balances scientific and other values, and weighs policy alternatives, usually on the basis of subjective value judgments.

Implementation of the Risk Management Decision

In principle, priority is to be given to preventing risks whenever possible, rather than simply controlling them. Possible implementation strategies may be based on formal regulatory mechanisms, on quality control systems or on public communication campaigns aimed at changing consumer behavior. The exact type of implementation will vary according to the situation and the types of stakeholders involved. Some governments or regulatory bodies will use traditional regulatory approaches based on periodic inspection or end-product testing, which places the burden of compliance with the regulatory authority. Food manufacturers may take specific measures via good manufacturing practices, good hygiene practices and Hazard Analysis and Critical Control Point (HACCP) systems. Education and information campaigns and product labelling targeted at consumers can encourage them to pay greater attention to safe preparation or cooking practices, for instance to avoid cross-contamination.

Monitoring and Review

This phase of risk management includes gathering and analyzing data on human health, and on food borne hazards to provide an overview of food safety and consumer health. Surveillance of human health offers evidence of changes in food-borne illness rates that may follow implementation, revision, or redesign of food safety controls by government and industry as well as potential for identifying new food safety risks as they emerge. (See also section 4 Data)

Risk Assessment

Risk assessment is the central scientific component of risk analysis and has evolved primarily because of the need to make decisions to protect health in the face of scientific uncertainty. Risk assessment can be generally described as characterizing the potential adverse effects to life and health resulting from exposure to hazards over a specified time period.

The four components of a risk assessment as illustrated in Fig. 3 are hazard identification, hazard characterization, exposure assessment and risk characterization.

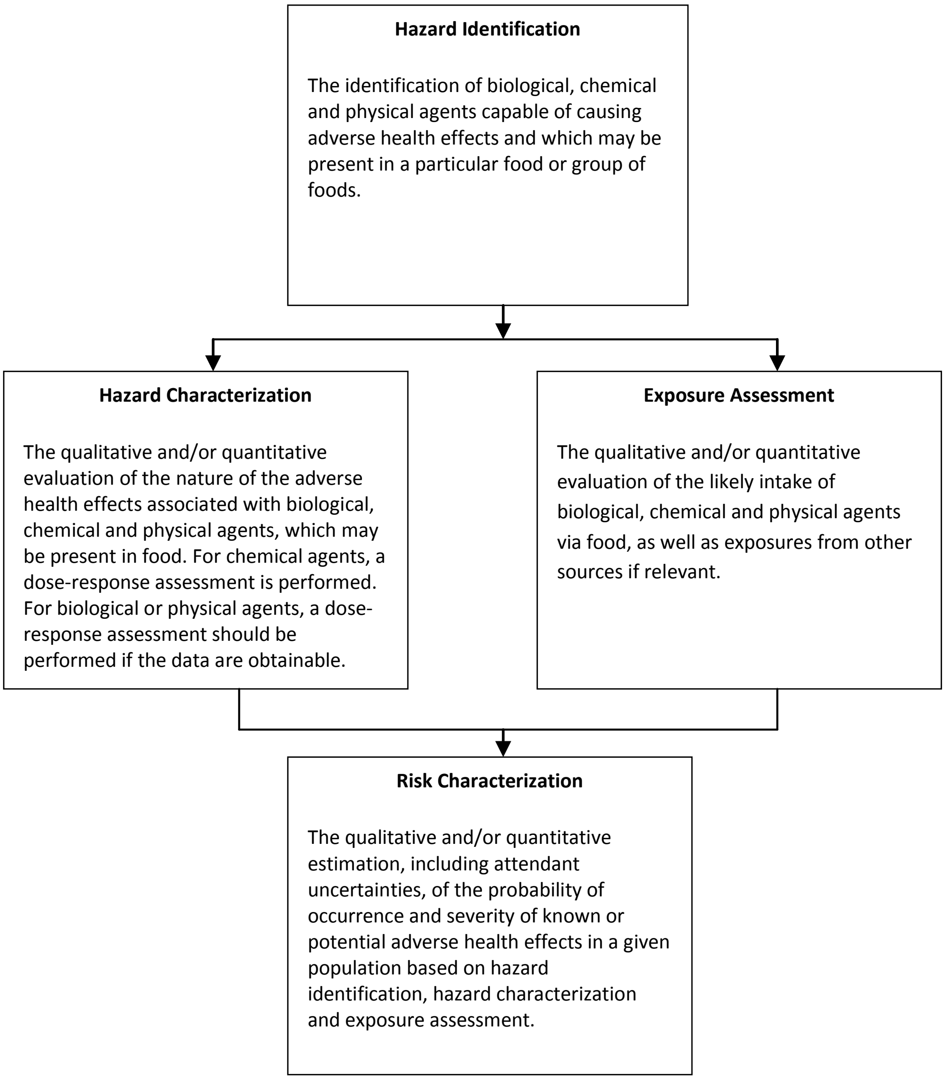

Fig. 3 Procedural framework for risk assessment (FAO 2005)

The type of risk assessment to be carried out depends on the nature of the hazard (chemical, microbial or physical) and the particular context in which it occurs (Table 2).

Biological Hazards	Chemical Hazards	Physical Hazards
• Bacteria • Toxin-producing micro-organisms • Moulds • Parasites • Viruses • Other biological hazard	• Naturally occurring toxins • Direct and indirect food additives • Pesticide residues • Residues of veterinary drugs • Chemical contaminants	• Metal, machine filings • Tools • Glass • Insect parts • Jewelry • Stones

Table 2 Examples of hazards (FAO 2005)

Differences in risk assessment methodology are most apparent for chemical compared with microbiological hazards. This is partly due to intrinsic differences between the two classes of hazards (Table 3). The differences also reflect the fact that for many chemical hazards, a choice can be made as to how much of the chemical may enter the food supply, e.g. for food additives, residues of veterinary drugs and pesticides used on crops. Use of these chemicals can be regulated or restricted so that residues at the point of consumption do not result in risks to human health. Microbial hazards, in contrast, are ubiquitous in the food chain, they grow and die, and despite control efforts, they often can exist at the point of consumption at levels that do present obvious risks to human health.

Microbial Hazards	Chemical Hazards
• Hazards can enter foods at many points from production to consumption.	Hazards usually enter foods in the raw food or ingredients, or through certain processing steps (e.g. acrylamide or packaging migrants).
• The prevalence and concentration of hazard changes markedly at different points along the food production chain.	The level of hazard present in a food after the point of introduction often does not significantly change.
• Health risks are usually acute and result from a single edible portion of food.	Health risks may be acute but are generally chronic.
• Individuals show a wide variability in health response to different levels of hazard.	Types of toxic effects are generally similar from person to person, but individual sensitivity may differ.

Table 3 Some characteristics of microbial and chemical hazards that influence the choice of risk assessment methodology (FAO 2007)

Biological risk assessments typically use a quantitative model to describe a baseline food safety situation and estimate a level of consumer protection currently afforded. Then, some of the inputs into the model are changed, such as the level of the hazard in the raw food at the time of the primary production, the conditions of processing, the temperature at which packaged material is held during retail and in the home. While the accuracy of estimated risks is often limited by uncertain dose-response information, the greatest strength of such risk assessments arguably lies in their ability to model the relative impacts of different food control measures on risk estimates.

In contrast, for chemical hazards, *safety evaluation* is a standard risk assessment methodology. The term *safety evaluation* is often used with regard to chemical hazards because the chief output is a definition of a presumptive 'safe' exposure level, without detailed assessment of how risk varies with exposure to differing doses. In that approach, maximum exposure levels are identified to fit a notional *zero risk* outcome (a dose level that is reasonably certain to pose no appreciable risk to the consumer). This approach does not produce precise estimates of risk versus dose and cannot model the impact of various interventions in terms of risk reduction.

Hazard Identification

The task of identifying a hazard is typically considered part of risk management, however, risk assessors usually take part, when possible hazards need to be analyzed and prioritized on the basis of scientific evidence.

In toxicological risk assessment (risk assessment for chemical hazards), hazard identification describes the adverse effects of the substance, the possibility of causing an adverse effect as an inherent property of the chemical, and the type (age group, gender, etc.) and extent of the population that may be at risk. Two kinds of models can be developed, based on *toxic kinetics* (how the human influences the toxins) or *toxico- dynamics* (how the toxins cause damage to the organisms). Because sufficient human data from epidemiological studies are often unavailable, risk assessors frequently rely on results from toxicological studies in experimental animals and in vitro studies.

In microbiological risk assessment the cause of food-borne illness can be due to a range of hazards, including microbes, viruses, parasites and toxins of biological origin as well as more newly identified ones, such as E.coli, the prion agent of BSE and multiantibiotic resistant strains of Salmonella. A specific hazard (pathogen) can have been defined by the public health sector. However, sometimes risk assessors are called in to identify and rank all potential microbiological hazards in a food item. Very often more than one potential hazard will be present in a food item.

Hazard Characterization

During hazard characterization, risk assessors develop a complete profile of the nature and extent of the adverse health effects associated with the identified hazard. The impact of varying amounts of the hazardous material on human health can be considered quantitatively (in a dose-response relationship) and/or qualitatively.

In toxicological risk assessment hazard characterization is about determining the dose-relationship and setting health based thresholds. In cases where the toxic effect results from a mechanism that has a threshold, hazard characterization usually results in the establishment of a safe level of intake, an acceptable daily intake (ADI), or tolerable daily intake (TDI) for contaminants.

In microbiological risk assessment a wide range of *hazard factors* (e.g. infectivity, virulence, antibiotic resistance) and *host factors* (e.g. physiological susceptibility, immune status, previous exposure history, concurrent illness) affect hazard characterization and its associated variability.

Epidemiological information is essential for full hazard characterization. Relatively little human data, however, is available to model dose-response curves for specific populations of interest, so assumptions often have to be made in this area, e.g. by using surrogate dose-response data from different pathogen. Dose-response relationships can be developed for a range of human responses, including morbidity, hospitalization and death rates associated with different doses.

Exposure Assessment

The exposure assessment provides scientific insight on the presence of the hazard in the product(s) consumed. It combines information on the prevalence and concentration of the hazardous material in the consumer's food supply and environment, and the likelihood that the consumer will be exposed to various quantities of this material in their food. The size of exposure is hence a function of the concentration of the hazard and the amount of food consumed. Information on the prevalence and concentration of the hazard could include estimates of the number of pathogens in a serving of food or the amount of a food additive consumed daily by a representative consumer. Depending on the nature of the problem, exposure assessment takes into account the relevant production, storage and handling practices along the food chain.

In toxicological risk assessment the amount of exposure is fixed due to the fact that the toxin cannot multiply (no increase) and is usually very stable (no decrease). The exposure is measured as [#microgram/kg bodyweight]. The concentration can usually be measured in a laboratory and the consumption of specific food items can be obtained from different databases. Compared to microbiological exposure assessment, toxicological exposure assessment is usually very straightforward.

In microbiological risk assessment the amount of the exposure (the number of pathogens) is variable due to multiplication and death of the pathogen throughout the whole process. The exposure is measured as [#pathogens/serving]. The exposure is generally very complex to estimate.

Risk Characterization

Risk characterization is a process that integrates the output from the first three steps to arrive at a risk estimate. A risk estimate is a function of the amount of exposure and dose-response relationship. Estimates can take a number of forms and uncertainty and variability must also be described. A risk characterization often includes a qualitative description on other aspects of the risk assessment, such as comparative rankings with risks from other foods and impacts on risk of various "what if" scenarios.

In toxicological risk assessment, risk characterization primarily concerns defining a level of exposure presumed to pose a "notional zero risk", i.e. the ALOP is set below a dose associated with any significant likelihood of harm to health. Standards are typically based on "worst case" exposure scenarios in order to keep risk below this ALOP. Quantitative risk assessment methodologies have only rarely been applied for chemical hazards thought to pose no appreciable risk below certain very low levels of exposure. Risk characterization is thus a conclusion of the hazard identification and exposure assessment, which can be expressed either quantitatively (e.g. calculated lifetime cancer risk) or qualitatively, in terms of 'high' or 'low' risk.

In microbiological risk assessment, risk characterization can similarly be expressed in qualitative terms such as 'high' and 'low', or expressed in quantitative terms through cumulative frequency distributions of risk per serving, annual risk for targeted populations, or relative risks for different foods or different pathogens.

Uncertainty and Variability in Risk Assessment

An uncertainty analysis is an important component of risk characterization. It provides a quantitative estimate of value ranges for an outcome, such as estimated numbers of health effects. The ranges in the outcome are attributable to the variance and uncertainties in data and the uncertainties in the structure of any models used to define the relationship between exposure and adverse health effects.

Variability refers to quantities that are distributed within a defined population, such as: food consumption rates, exposure duration, and expected lifetime. These are inherently variable and cannot be represented by a single value, so that we can only determine their moments (e.g., mean, variance, skewness, etc.) with precision. In contrast, true uncertainty or model-specification error (e.g., statistical estimation error) refers to a parameter that has a single value, which cannot be known with precision due to measurement or estimation error. Variability and true uncertainty may be formally classified as follows:

- Type A **uncertainty that is due to stochastic variability** with respect to the reference unit of the assessment question, and;
- Type B **uncertainty that is due to lack of knowledge** about items that are invariant with respect to the reference unit of the assessment question.

Uncertainty and Variability in Hazard Identification

The step is generally based on screening methods and short and long-term cell or animal assays. Some examples and assay systems include quantitative structure-activity relationships, short-term bioassays, and animal bioassays. This step provides a dichotomous answer - that is, the factor is or is not thought to be a human health hazard. The uncertainty involves the correct classification of the agent (i.e., it is or is not a human health hazard) and performance of the assay in classification of the agent.

Three issues are considered potentially significant contributions to uncertainty and variability in hazard identification. First, is the misclassification of an agent - either identification of an agent as a hazard when it is not or the reverse. Second, is the issue of the reliability of the screening method both for appropriately identifying a hazard and the reliability of the assays to give the same result each time the assay is performed. Third, is the issue of extrapolation because all screening methods are used to extrapolate the information provided by the test to predict human hazards.

Uncertainty and Variability in Hazard Characterization

Model uncertainty is likely to be an important issue in the hazard characterization step. Mathematical dose-response relationships have the greatest uncertainty in actual representation of the biological processes.

An important issue of both variability and uncertainty that arises in hazard characterization is in the variance in the dose-response at the dosage levels for the species studied. To increase power and the value of a negative study, typically large exposures are used in bioassays. These exposures are generally substantially greater than usual human exposures. That means that models including exposure response information gathered at high exposures may not be accurate at the low exposure levels of concern for human risk assessment. In addition, there is variance by animals in response at a given dose, despite the fact that most experimental animals are generally inbred and expected to be genetically identical. If outbred animals are used, the variability in the dose response relationship is expected to be larger, and if humans are exposed, the variance is also expected to be large.

Another issue of both uncertainty and variability that arises in hazard characterization is the need to extrapolate between species. Approaches used for extrapolation between species include both uncertainty about the appropriate model for performing the extrapolation as well as variability in the parameters used for extrapolation.

Uncertainty and Variability in Exposure Assessment

Defining exposure pathways is an important component of the exposure assessment. An exposure pathway is the course a biological, chemical, or physical agent takes from a known source to an exposed individual. In the case of agents in food, concentrations of chemicals and/or organisms (microbes, parasites, etc.) can change between what is measured in soil, plants, animals and raw food and what is ingested by an individual. In the case of chemicals, there can be some increases of contaminant concentration due to process (i.e. distillation), but more likely the storage, processing and preparation of the food product will result in a reduction of contaminant concentration. For organisms, there might be significant increases of microbe or contaminant concentration due to replication under favorable environmental conditions. Thus, significant uncertainties might be expected in the ratio of the concentration of a bacterial agent in food at the time of consumption to the concentration measured in raw foods or measured in animals, plants, or soil.

Uncertainty and Variability in Risk Characterization

Once hazard characterization and exposure information have been collected, risk characterization is carried out by constructing a model for the distribution of individual or population risk. This is done by summing the effect over all exposure .routes. Because of the uncertainties and variabilities involved in its constituent steps, the overall process of risk characterization might involve potentially large uncertainties.

3. Methods and techniques

Risk assessment outputs can range from qualitative to quantitative with various intermediate formats (Fig. 4). In qualitative risk assessments, outputs are expressed in descriptive terms such as high, medium or low. In quantitative risk assessments, the outputs are expressed numerically and may include a numerical description of uncertainty. In some cases, intermediate formats are referred to as semi-quantitative risk assessments. For instance, one semi-quantitative approach may be to assign scores at each step in the pathway and express outputs as risk rankings.

Deterministic (point estimate) approaches

The term “deterministic” describes an approach in which numerical point values are used at each step in the risk assessment; for example, the mean or the 95th percentile value of measured data (such as food intake or residue levels) may be used to generate a single risk estimate. Deterministic approaches are the norm in chemical risk assessment, for instance to determine whether any risk may arise from consumption of a single food containing a chemical residue arising from a use governed by a maximum residue level (MRL).

Stochastic (probabilistic) approaches

In stochastic approaches to risk assessment, scientific evidence is used to generate statements of probabilities of individual events, which are combined to determine the probability of an adverse health outcome. This requires mathematical modelling of the variability of the phenomena involved, and the final risk estimate is a probability distribution. Stochastic (probabilistic) models are then used to create and analyze different scenarios of risk.

Stochastic models are only now beginning to be used to complement the “safety evaluation” approaches traditionally used in managing chemical food-borne hazards, in particular for contaminants. On the other hand, probabilistic approaches are the norm in the newer discipline of microbial risk assessment and provide a mathematical description of the dynamics of hazard transmission from production to consumption. Exposure data are combined with dose-response information to generate probabilistic estimates of risk. Even one colony-forming unit of the pathogen in an edible portion of food is assumed to have some probability of causing infection; in this respect, such risk models resemble risk assessment methodology for chemical carcinogens.

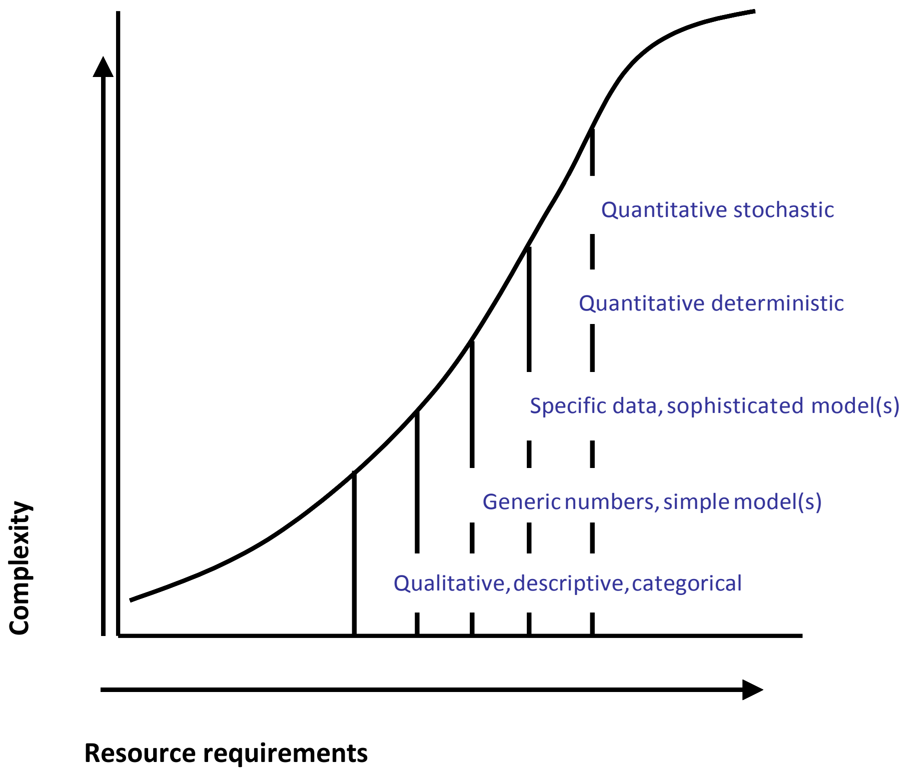

Fig. 4 Continuum of risk assessment types (FAO 2007)

Methods, techniques and approaches used at DTU Food

Methods used in Risk Assessment of Chemical Exposure

By comparing the human exposure assessments with toxicological values such as the co-called Acceptable Daily Intake (ADI) researchers can on a scientific basis evaluate and assess whether a certain chemical constitutes a health risk for humans. In research on human exposure, a deterministic approach using one value for the intake of a food item and a single value for the content of food per individual has normally been used. However, the methods continuously need to be developed and, at the same time, the use of probabilistic modelling is increasing.

Methods used in Risk Assessment of Epidemiological Microbiological Risk Modeling

The methods applied include stochastic mathematical modelling, Bayesian inference modelling, temporal and spatial analysis as well as regression analysis.

Methods used in Risk Benefit Analysis

Reduction in consumer health risks is usually the primary benefit of food safety policies. Willingness to pay (WTP) for health and mortality risk reduction is generally viewed as the most complete and correct welfare theoretic measure of these benefits, but in practical terms, cost of illness is more widely used. Cost of illness estimates (COI) typically include only the cost of treatment and loss of productivity, disregarding change in consumer utility. As a result, there is a lower bound on the benefits of preventing morbidity, which can significantly bias cost-benefit estimates.

Research in this area at DTU Food typically uses a combination of COI and DALYs metrics. A detailed discussed of these metrics and approaches are beyond the scope of this report, but a brief explanation of the terms is provided in section 4.2 for clarification.

Methods used in Predictive Microbiology

Predictive microbiology models are essential for risk assessments when concentrations of human pathogens in food cannot be measured and must be predicted, e.g. at the time of consumption after distribution of food to consumers.

Methods used in (source attribution of) Foodborne Diseases

With regard to source attribution of foodborne diseases, the most commonly used approaches are hazard- occurrence analysis, like models that use microbial subtyping surveillance data on humans and/or animals in mathematical and risk assessment models; and epidemiological methods, mostly analysis of outbreak data or case-control studies of sporadic infections. Other approaches include intervention studies, expert elicitations, and methods that integrate some of these approaches.

Disease burden is often quantified in terms of disability-adjusted life years (DALYs), which combine the burden due to both death and morbidity into one index. A DALY can be understood as the loss of "one year of perfect health", and the disease burden is a measure of the difference between the actual health status due to a specific foodborne problem and the ideal situation, where all live a long and healthy life without this specific problem. Data from national databases, and results from national and international research projects are used as input to simulations models.

The financial costs are often estimated by the cost-of-illness method (COI), that sum up health care costs (hospitals, general practitioners, medicine, etc.), loss of productivity and the cost of implementing control measures in the food producing industry and the national food and health authorities.

The overall DALY and COI estimates allow for the comparison of the disease burden due to various risk factors or diseases. It also makes it possible to predict the possible impact of health interventions.

Methods used in assessments of Chemical Contaminants

Risk assessments of the human exposure to environmental contaminants in food are estimated by National Food Institute on the basis of food intake calculations coupled with data for the occurrence of environmental contaminants in various foodstuffs. The sources of the contaminants are assessed, and for selected contaminants, possible mitigation prospects are investigated.

Methods used in assessments of Coctail Effects

Risk assessment of chemicals is generally based on a comparison of human exposure to a chemical to the NOAEL (No Observed Adverse Effect Level) for the chemical, i.e. the highest dose of chemical causing no adverse effects in laboratory animals. This is done for one chemical at a time. However, humans are daily exposed to many different chemicals. Risk studies in this area aim to determine whether exposure to several chemicals induce effects, although the doses for the single chemicals are below or around NOAEL.

Methods used in assessments of Antimicrobial Resistance

DTU Food performs a range of molecular and conventional microbiological studies in the laboratory, such as genetic characterization, horizontal gene transfer, and different assays and standardized methods. Laboratory studies are combined with various statistical-epidemiological-bioinformatics analyses. These reveal, for example, associations between consumption of antimicrobials agents used in animals and resistance in animals, or the evolution, clonal relationship and spread of resistance in isolates from animals and foods to humans.

4. Data and metrics

Scientific data to support food safety risk assessments is available from a variety of sources (Box 1 & 2).

- Published scientific studies.
- Specific research studies carried out (by the government agency or external contractors) in order to fill data gaps
- Unpublished studies and surveys carried out by industry, such as data on the identity and purity of a chemical under consideration as well as toxicity and residue studies carried out by the chemical's manufacturer
- National food monitoring data
- National human health surveillance and laboratory diagnostic data
- Disease outbreak investigations
- National food consumption surveys, and regional diets e.g. those constructed by FAO/WHO
- Use of panels to elicit expert opinion where specific data sets are not available
- Risk assessments carried out by other governments
- International food safety databases
- International risk assessments carried out by JECFA, JMPR and JEMRA

Box 1 Sources of scientific information for risk assessments (FAO 2007)

- National surveillance databases for notifiable diseases.
- Disease registries, death certificate databases, and time-series data derived from these.
- Targeted human surveys (active surveillance) and analytical epidemiological studies where specific risks and risk factors are being investigated.
- Outbreak investigation data for food-borne illness events, blended with sporadic food-borne illness statistics, for food source attribution purposes.
- Frequency and levels of occurrence of chemical or microbiological contaminants in foods at various points from production to consumption.
- Frequency of persistent organic pollutants (POPs) in human breast milk.
- Frequency of occurrence and levels of contaminants in blood, urine or other tissues gathered from representative samples of the population(s) at risk, such as mercury levels in hair and blood
- Food consumption survey data, updated periodically, and to the extent possible, for specific subpopulations that may be at risk because of dietary preferences.

Microbiological "fingerprinting" methods to trace specific genotypic strains of pathogens causing illness in humans through the food chain (e.g. multilocus gene sequence typing).

Box 2 Examples of data that can be used for monitoring the effects of risk management measures (FAO 2007)

With regard to human exposures to environmental emissions at least five important relationships that will demand data, modelling and evaluation resources:

1) the magnitude of the source medium concentration—that is, the level of contaminant that is released to indoor or outdoor air, soil, water, etc. or the level of contamination measured in or estimated in the air, soil, plants and water in the vicinity of the source;

2) the contaminant concentration ratio, which defines how much a source medium concentration changes as a result of transfers, degradation, partitioning, bioconcentration and/or dilution to other environmental media before human contact;

3) the level of human contact, which describes (often on a body weight basis) the frequency (days per year, minutes per day, etc.) and magnitude (cubic meters of air breathed per hour, kilograms of food ingested per day, square meters of surface contacted per hour, etc.) of human contact with a potentially contaminated exposure medium;

4) the duration of potential contact for the population of interest relating to the fraction of lifetime during which an individual is potentially exposed; and

5) the averaging time span for the type of health effects under consideration; that is, one must consider the appropriate averaging time span for the cumulative duration of exposure such as a human lifetime (which is typical for cancer and chronic diseases) or some relatively short time span (in the case of acute effects).

These factors typically converge as a sum of products or quotients to define a distribution of population exposure or a range of individual exposures. The reliability of population exposure estimates will depend strongly on the quantity and accuracy of the obtainable data associated with these five links.

Metrics used during the Risk Assessment Process

ADI, TDI, NOAEL/NOEL, LOAEL, Margin of Exposure/Safety, MRL, Safety Factor/Uncertainty Factor

Acceptable daily intake (ADI) is an estimate of the amount of a substance in food or drinking water, expressed on a bodyweight basis, that can be ingested daily over a lifetime without appreciable risk (standard human = 60kg). The ADI is listed in units of mg per kg of body weight.

Tolerable daily intake (TDI) is an analogous term to ADI. TDI is used for agents which are not deliberately added such as contaminants in food.

No Observed Adverse Effect Level (NOAEL/NOEL) - The highest tested dose of a substance that has been reported to have no harmful (adverse) health effects on people or animals. The difference between NOAEL and NOEL rests on the definition of adverse effect only, that is, an experimental study that produced a NOAEL will have stated the adverse effect to be observed before initiation.

Lowest Observed Adverse Effect Level (LOAEL)

Margin of exposure is the ratio of the no-observed-adverse-effect level (NOAEL) for the critical effect to the theoretical, predicted, or estimated exposure dose or concentration.

Margin of safety - for some experts, margin of safety has the same meaning as margin of exposure, while for others, margin of safety means the margin between the reference dose and the actual exposure.

Maximum residue level (MRL) – the maximum concentration of residue in a food or animal feed resulting from use of a veterinary drug or a pesticide, (expressed in mg/kg or µg/kg on a fresh weight basis).

Safety factor (also Uncertainty factor or Assessment factor) is a composite (reductive) factor by which an observed or estimated no-observed adverse- effect level (NOAEL) is divided to arrive at a criterion or standard that is considered safe or without appreciable risk.

Metrics used to determine Risk Benefit

VSL, HALYs, QUALYs and DALYs

Tradeoffs between monetary wealth and fatal safety risks are summarized in the value of a statistical life (VSL), a measure that is widely used for the evaluation of public policies in health, the environment, and transportation safety. VSL is a statistical term that simply expresses the cost of reducing the average number of deaths by one. The value of a life year takes on special significance in the context of human health because a life may be saved, but the person whose life is saved may have far less than a normal, or even acceptable, quality of life. This leads to attempts to estimate 'quality adjusted life years' (QALYs).

The public health literature often uses health adjusted life year (HALY) measures as an alternative to either cost of illness or willingness to pay (see section 3.3). HALYs are summary measures of population health that allow the combined impact of death and morbidity to be considered simultaneously. This feature makes HALYs useful for comparisons across a range of illnesses, interventions, and populations.

An umbrella term for a family of measures, HALYs includes disability-adjusted life years (DALYs) and quality-adjusted life years (QALYs). Although both QALYs and DALYs interweave estimates of morbidity and mortality, their original purposes are somewhat at variance and their methods of calculation differ. The original formulation of QALYs was drawn from the theoretical underpinnings of welfare economics and expected utility theory. In welfare economics, a social utility function is the aggregate of individuals' utilities, and economists hold that maximizing the social utility function is the primary goal for resource allocation. Quality-adjusted life years are often seen as inexorably linked with utilitarianism, a social theory that dictates that policies designed to improve social welfare should do the greatest good for the greatest number of people.

Disability-adjusted life years (DALYs) were developed to quantify the burden of disease and disability in populations, as well as to set priorities for resource allocation. Disability-adjusted life years measure the gap between a population's health and a hypothetical ideal for health achievement. Finally, DALYs, in their original formulation, place different value weights on populations based on their age structure so that DALYs in the very young and the very old are discounted compared to other age groups.

Metrics used in Implementation of Risk Management Options

ALOP, FSOs, POs and Microbiological Criteria

Whatever method is used to estimate the risk of foodborne illness, the next step is to decide whether this risk can be tolerated or needs to be reduced. The level of risk a society is willing to accept is referred to as the *Appropriate Level Of Protection* (ALOP).

When a government expresses public health goals relative to the incidence of disease, this does not provide food processors, producers, handlers, retailers or trade partners with information about what they need to do to reach this lower level of illness. To be meaningful, the targets for food safety set by governments need to be translated into parameters that can be assessed by government agencies and used by food producers to process foods. The concepts of *Food Safety Objectives* (FSOs) and *Performance Objectives* (POs) have been proposed to serve this purpose. FSOs and POs are new concepts that have been introduced to further assist government and industry in communicating and complying with public health goals. These tools are additional to the existing programs of GAPs, GHPs and HACCP which are the means by which the levels of POs and FSOs are to be met. (see also section 4.2.4)

An FSO is "The maximum frequency and/or concentration of a hazard in a food at the time of consumption that provides or contributes to the appropriate level of protection (ALOP). It transforms a public health goal to a concentration and/or frequency (level) of a hazard in a food. The FSO sets a target for the food chain to reach, but does not specify how the target is to be achieved. Hence, the FSO gives flexibility to the food chain to use different operations and processing techniques that best suit their situation, as long as the maximum hazard level specified at consumption is not exceeded.

For some food hazards, the FSO is likely to be very low, sometimes referred to as "absent in a serving of food at the time of consumption". For a processor that makes ingredients or foods that require cooking prior to consumption, this level may be very difficult to use as a guideline in the factory. Therefore, it is often required to set a level that must be met at earlier steps in the food chain. This level is called a Performance Objective (PO).

Microbiological criteria (MC) need to be accompanied by information such as the food product, the sampling plan, methods of examination and the microbiological limits to be met. Traditional MC are designed to be used for testing a shipment or lot of food for acceptance or rejection, especially in situations where no prior knowledge of the processing conditions is available. In contrast, the FSO or the PO are maximum levels and do not specify the details needed for testing. However, MC can be based on POs in certain instances where testing of foods for a specific microorganism can be an effective means for their verification.

FSOs and POs are changing the way the more traditional risk management metrics are being developed in that the key to this approach is to use risk modeling techniques to relate levels of exposure to the extent of public health consequences that are likely to occur. This information is then used to determine the levels of hazard control needed to be achieved at specific points along the food chain. It also provides a means of comparing the effectiveness and levels of control that can be achieved by focusing prevention/intervention efforts at different points along the food chain. For example, this approach is beginning to evaluate questions such as whether fresh-cut produce manufacturers would be better served by emphasizing on-farm prevention or post-harvest interventions.

Metrics used in Compliance of Risk Management Goals and Policies

HACCP, GAP, GHP, GMP

Industrial Food Safety Management includes various quality assurance systems, such as Hazard Analysis Critical Control Points (HACCP) and its prerequisite systems Good Manufacturing Practices (GMP) and Good Hygiene Practices (GHP). A newer measure related to sustainability is Good Agricultural Practices (GAP).

HACCP is recognized by the food industry as the global standard for food safety. It is a semi-quantitative risk management system that is based on a largely qualitative assessment of hazards. One major difference between HACCP and a microbial risk assessment (MRA) as carried out by scientists in academia is that through HACCP, industrial safety assessment assures the production of safe food products focusing on a single product and production site. In contrast, a MRA takes a broader view and considers safe food production encompassing groups of similar food products, multiple producers and/or specific consumer populations.

GMP refers to conformance with codes of practice, industry standards, regulations and laws concerning production, processing, handling, labelling and sale of foods decreed by industry, local, state, national and international bodies with the intention of protecting the consumer from food-borne disease, product alteration and fraud.

GHP are all practices regarding the conditions and measures necessary to ensure the safety and suitability of food at all stages of the food chain.

GAP relates to the application of knowledge that addresses environmental, economic and social sustainability for on-farm production and post-production processes resulting in safe and healthy food and non-food agriculture products.

5. Research topics

Research activities at DTU Food include all aspects of food products throughout the entire food chain, from primary agricultural production and industrial processing to preparation in the consumer's home, covering a wide range of applications with the focus areas biotechnology, nutrition, food quality, food safety, food technology as well as environment and human health. Food safety is the primary area for risk-related research. Figure 5 details the different research areas within Food Safety, which bear direct relationship to the study of risk.

Fig. 5 Risk-related research areas at DTU Food

Risk Assessment

The research-based risk assessment conducted by DTU Food can be divided into chemical and microbiological risk assessment with the chemical part covering both population exposure estimation and an assessment of potential effects in humans.

Chemical Exposure

By comparing the human exposure assessments with toxicological values such as the co-called Acceptable Daily Intake, ADI, the National Food Institute can on a scientific basis evaluate and assess whether a certain chemical constitutes a health risk for humans.

Epidemiological Microbiological Risk Modeling

This research area focuses on epidemiology, surveillance and control of zoonoses and foodborne disease in the entire production chain. The primary research is on the development of mathematical tools for evaluating food safety risks by applying national and international data from integrated monitoring and surveillance programs.

Toxicological Effect Assessment

DTU Food performs research-based toxicological risk assessments for both natural and synthetic chemicals. This research area also assesses the impact of GMOs on humans and methods for testing the effects of GMOs and chemicals.

Risk Benefit Analysis

Risk-benefit analysis of foods is the scientific comparison of risk and benefits for at specific food in a certain situation, making it possible to predict the health-related consequences for the consumer. DTU Food conducts research in this area in order to optimize the quality and relevance of risk-benefit analyses which for use in public sector consultancy. Economics plays a central role in modeling risk, costs and benefits of public programs. Economic research can potentially increase understanding of how food safety risks are generated in food production, processing, marketing and preparation, and how industrial structure influences these processes. Moreover, research carried out by economists on consumer perceptions and attitudes toward risk, their willingness to pay to reduce risks, and the economic burden of foodborne diseases supports such enhanced understanding.

Predictive Microbiology

Predictive microbiology models are essential for risk assessments when concentrations of human pathogens in food cannot be measured and must be predicted, e.g. at the time of consumption after distribution of food to consumers. At DTU Food, these models and software are used to facilitate the application of research in risk analysis as well as for teaching, public sector consultancy and innovation.

Burden of Foodborne Diseases

A simple and intuitive way of ranking diseases is based on their occurrence (e.g. incidence) or on the number of deaths that they cause (mortality). However, these disease measures do not provide a full picture of the impact of specific diseases on human health, because severity and duration of the disease are not taken into account, and because morbidity and mortality are not integrated in a single measure. As an example, how can we decide which is a larger public health problem: a high-incidence mild illness that typically lasts around 7 days, or a rare but severe or life-threating condition? How do compare diseases and how do we rank them by public health relevance?

We use Burden of Disease studies to assess the impact of diseases in terms of incidence, severity, duration and mortality in a population. In practical terms, these methods allow us to measure the burden of a disease in the population by accounting for the number of people getting ill each year, as well as on how ill (i.e. the severity of its symptoms) and for how long, and on the number of fatal cases.

Disease burden is often quantified in terms of disability-adjusted life years (DALYs), which combine the burden due to both death and morbidity into one index. A DALY can be understood as the loss of "one year of perfect health", and the disease burden is a measure of the difference between the actual health status due to a specific foodborne problem and the ideal situation, where all live a long and healthy life without this specific problem. Data from national databases, and results from national and international research projects are used as input to simulations models.

(Source Attribution of) Foodborne Diseases

Disease burden studies at DTU Food describe the impact of specific foodborne pathogens by estimating the number of human cases, the morbidity and mortality and the related financial costs. Source attribution of foodborne illnesses is the process of estimating the most important sources responsible for specific foodborne illnesses. Determining the sources of foodborne illness is an important part of identifying the most appropriate measures to improve food safety.

Chemical Contaminants

The research on environmental contaminants aims to explore the large number of potential problematic chemical compounds that could be harmful to humans, and the implications for a safe food supply. Risk assessments of the human exposure to environmental contaminants in food are estimated at DTU Food on the basis of food intake calculations coupled with data for the occurrence of environmental contaminants in various foodstuffs. The sources of the contaminants are assessed, and for selected contaminants, possible mitigation prospects are investigated. An important part of the work is the development of analytical methodologies for appropriate compounds.

Coctail Effects

The purposes of the research at the National Food Institute, Technical University of Denmark, in this area is to increase the knowledge on effects of chemicals and potential mixture effects, to develop methods for predicting mixture effects based on data for the single chemicals and to obtain new knowledge on human exposure to mixtures of chemicals.

Antimicrobial Resistance

Antimicrobial resistance is serious concern in industrialized as well as developing countries. There is now increasing awareness of the potential human health problems caused by antimicrobial resistance originating in food-producing animals. Resistant bacteria spread across borders via trade and travel and antimicrobial resistance is therefore a global problem. Research in this area at DTU Food tries to identify the microbial and epidemiological risk factors contributing to the emergence and spread of antimicrobial resistance as well as their interactions in order to limit the development at both national and global scales.

6. Research networks

National	International	Industry
Statens Serum Institut, Denmark	Federal Institute for Risk Assessment (BfR), Germany	Royal Greenland Seafood
Danish Agriculture and Food Council	Chemisches und Veterinäruntersuchungsamt (CVUA) Freiburg, Stuttgart, Germany	Arla Food
Danish Meat Research Institute	French Agency for Food, Environmental and Occupational Health and Safety (AFSSA), France	
Copenhagen University, Faculty of Health and Medical Sciences and Faculty of Science	Institute Pasteur, France	
	National Institute for Public Health and the Environment (RIVM), The Netherlands	
	Institute of Food Safety (RIKILT), Wageningen, The Netherlands	
	Centers for Disease Controls (CDC), USA	
	Food and Drug Administration, USA	
	Joint Institute for Food Safety and Applied Nutrition (JIFSAN), USA	
	Translational genomic Institute, USA	
	Animal Health and Veterinary Laboratories Agencies (AHVLA), UK	

	National Salmonella and Shigella Institute, Thailand	

7. Advisory activities

In Denmark, DTU Food provides consulting to the Danish Veterinary and Food Administration and the Danish Environmental Protection Agency in particular within the following areas:

The Danish Veterinary and Food Administration:

- Chemical food safety, including health and risk assessments of chemical compounds in food and animal feed
- Microbiological food safety, including zoonoses and antimicrobial resistance
- Nutrition, including dietary surveys, dietary advice and dietary health and risk assessments
- Food quality, including health claims, sensorics, traceability and food shelf life

The Danish Environmental Protection Agency:

- Toxicology
- Toxicological test methods
- (Q)SAR, models for predicting the connection between the structures and activity of chemical substances
- Hazard and risk assessments of chemical compounds and GMO

DTU Food provides scientific advice to a number of international authorities and organizations. The Institute contributes extensively to the work in the European Food Safety Authority (EFSA), and advisory services to, among others, the Organisation for Economic Co-operation and Development (OECD), the World Health Organization (WHO), and the European Medicines Agency (EMA).

DTU Food is a national reference laboratory for chemical and microbiological food contamination as well as an international reference laboratory for the EU and the WHO in a number of areas.

European Food Safety Authority (EFSA)

- Expert panel for Biological Hazards – BIOHAZ is advising the EU Commission
- Ad hoc working groups

World Health Organization (WHO)

- Expert advice (e.g. Foodborne Disease Epidemiology Reference Group – FERG, Joint FAO/WHO Expert meetings on Microbiological Risk Assessment – JEMRA, Working Group for Classification of Veterinary Medicines – ATCvet group) European Medicines Agency (EMA)
- Ad hoc advice

EU Scientific Committee for Consumer Safety (SCCS)

8. Educational offerings

DTU Food offers educational courses and programs in the following areas: risk analysis, food safety, food production, product development, biotechnology and management.

There are two master level programs:

- Master of Science in Food Technology (MSc)
- AQFood Aquatic Food Production - Safety and Quality

Apart from the master in food technology and the PhD studies, which are taught in English, the institute has a number of bachelor and diploma studies, which are being conducted in Danish.

Table 4 lists all courses related to risk at DTU Food, together with a brief outline of their content. This information was collected through DTU *Kursusbasen* by performing a search for the following keywords: *risk, safety, life cycle, sustainability, and decision analysis*.

The research group Epidemiology and Risk Modeling is coordinating and teaching several courses with regard to risk:

- PhD course in Quantitative Microbial Risk Assessment (23836)
- Food analysts (Diplom): Risk assessment and risk modelling (23921)
- Food Safety in Production Chains (23102)

2 courses that are part of the Master in Food Safety and Food Quality at KU-NAT

- Risk Analysis of foodborne contaminants (150542)
- Investigation of foodborne outbreaks (150553)

Internationally, the group is involved in several training and capacity building activities under the auspices of the WHO (e.g. the Global Foodborne Infections Network) and the EU DG SANCO.

Finally, the group regularly provides ad hoc training to governmental institutes and universities in for instance South America, the Middle East and South East Asia. International activities involve training in surveillance and control, epidemiology, outbreak investigations and risk assessment.

Course Nr./ Keyword	Title	Content	Type
23102 risk	Food Safety in Production Chains	Food safety issues with regard to microbiology, chemical hazards and toxicology. Hazards in specific food production chains, critical steps in the production, control or mitigation of hazards. Microbiological, chemical and toxicological aspects of the risk assessment. Elements of risk assessment: hazard identification, exposure assessment, hazard and risk characterization.	MSc
23153 Risk/ sustainability	Aquatic Food Supply Chain Management, Environment and Resources	Sustainability analysis of value chain. Logistics and mapping of activities using the SCOR model. Traceability and monitoring of indicators for quality and safety of products. Application of ICT and RFID (Radio frequency identification) for real time monitoring to enhance transparency of the supply chain. Tools for assessment of environmental impacts of processing and logistics, e.g. Life Cycle Analysis (LCA) and various indicators like carbon footprint and food miles for the aquatic food supply chain. Tools for assessment of economic and social aspects of processing and logistics. Tools for assessing simultaneously environmental, economic and social aspects such as multi-criteria assessment.	MSc
23154 risk	Safety and Health Effects of Aquatic Food	Identify hazards and to discuss how processing, distribution and consumption will influence safety and health effects of aquatic food. Relevant biological and chemical hazards in aquatic food and industrial and environmental contaminants. Quantitative microbial ecology, mathematical modelling and software for evaluation and management of hazards during processing and distribution of aquatic food to the end-consumers. Functional aquatic food components and their beneficial human health effects in relation to regulations, health claims and risk benefit analysis.	MSc
23271 risk	Risk Analysis in Food Safety	Risk pathways and identification and organization of data for risk assessment model. Assessment and management of foodborne hazards. Interpretation and communication of the results of a risk assessment, as well as the decisions taken on the basis of the assessment and other factors e.g. public risk perception and economic considerations.	MSc
23301 risk	Practical Chemical Food Safety	Approaches to food contaminant in legislation. Planning of chemical food control and principles of risk based sampling. Application areas of analytical techniques (LC, GC, MS). Requirements for methodologies used in chemical food control, including quality assurance. Data from analytical reports and their use in risk assessment.	MSc
23533 risk	One Health Summer University Summer school, on-campus and e-learning: 60 hours)	The One Health concept is a worldwide strategy for expanding interdisciplinary collaborations and communications in all aspects of health care for humans, animals and the environment. The acquired knowledge can be used to improve risk management decision making and facilitating solutions to the challenges.	MSc PhD
23832 risk	Lipid Biochemistry, Technology, Applications and Analysis	The course will include 2 ½ days seminar covering advanced lipid biochemistry, technology, applications and analysis as well as an introduction to lipid related chemical contaminants and compounds introduced during processing. Principles for risk- assessment and setting of	PhD

		maximum residue-levels will also be introduced.	
23833 risk	Applied Toxicology	The purpose of the course is to give a background for working with risk assessment. Risk assessment of chemicals are performed before determining limit values in working environments, limits for pollutants and before evaluation of chemicals and drugs.	PhD
23836 risk	Quantitative Microbiological Risk Assessment	Risks in food production chains. Elements in a risk analysis: risk assessment, risk communication and risk management. Risk pathways. Qualitative and quantitative mathematical risk assessment. Interpretation and analysis of the output from risk assessment.	MSc PhD
23838 risk	Microbial Fresh Produce Safety	Microbiological issues related to fresh produce safety. Risk factors and risk management strategies in fresh produce production. Certification, international regulations and food safety practices. Laboratory practices for testing fresh produce. Overview of pathogens that are usually involved in fresh produce outbreaks.	PhD
23921 risk	Risk Analysis and Modeling	Food safety related issues in food production. Elements of risk analysis and risk assessment. Chemical and microbiological hazards in foods and comparison of different hazards on health impact. Analysis of a food product safety based on the concept farm-to-table-to-consumer. Assessment of different steps in a production line on the amount of chemical and microbiological hazard in food. Integration of uncertainty in the risk assessment and the decision-making process. Similarities and differences between toxicological and microbiological risk analysis.	D.Ing
23101 safety	Introduction to food production chains	Understanding of the interactions between quality, chemical issues related to raw material and safety as well as process design, production planning and innovation aspects on a basic level.	MSc
23511 safety	Food Production Engineering Basics	Flow sheets, calculation of composition and physical properties of foods, Newtonian and Non-Newtonian fluid dynamics, steady-state heat transfer, unsteady-state heat transfer in the stirred vessel and in solids heated by convection, basic microbial ecology and safety of foods, calculation of microbial inactivation and F-values, calculation of freezing and drying processes, food rheology and texture.	BSc MSc
23551 safety	Predictive Food Microbiology	Overview of the quantitative microbial ecology of food and detailed insight in the development and validation of predictive food microbiology models. Software for development and application of deterministic and stochastic predictive models are presented in relation to assessment and management of microbial food quality and safety.	MSc
23835 safety	Rapid Detection, Enumeration and Characterization of Foodborne Pathogens	Modern traceability techniques in relation to food safety. Both classical and modern methods for detection of pathogens will be reviewed in relation to laboratory diagnostics, monitoring, surveillance and source attribution programs.	PhD
23837 safety	Introduction to Scientific Methodologies and Philosophies used in	The aim of the course is to give the PhD-students a holistic overview in the area food science in general, and especially to the research disciplines at DTU FOOD – biotechnology, nutrition, food quality, food safety, food technology and	PhD

	Food Research	environment and health – and how research is conducted in the different disciplines.	

Table 4 Courses at DTU Food explicitly and implicitly related to risk

9. Data sources

Personal Interview with Tine Hald, Senior Researcher DTU Food

Tine Hald Senior Researcher DTU Food GDSI Advisory Board tiha@food.dtu.dk Special Interests: Risk Assessment, Salmonella, Source attribution, Surveillance, Zoonosis, Epidemiology	

Personal Interview with Flemming Bager, Head of Division Risk Assessment and Nutrition DTU Food and Anette Schnipper, Acting Head of Division Toxicology and Risk DTU Food

Flemming Bager Head of Division Risk Assessment and Nutrition fbag@food.dtu.dk Special Interests: Surveillance of antimicrobial resistance	

Anette Schnipper Acting Head of Division Toxicology and Risk Assessment ansc@food.dtu.dk Special Interests: Toxicological risk evaluation	

Consultations with Jørgen Schlundt, Professor DTU Management Engineering/GDSI and Elena Boriani, GDSI postdoc

<table>
<tr><td>Jørgen Schlundt
Professor
GDSI Advisory Board
Formerly Head of Department DTU Food

jors@dtu.dk

Special Interests: Risk Assessment, Risk Governance, Food Safety and Zoonoses, Global Burden of Foodborne Diseases</td><td></td></tr>
</table>

<table>
<tr><td>Elena Boriani
GDSI Postdoc

ebor@food.dtu.dk</td><td></td></tr>
</table>

Application of Risk Analysis to Food Standards Issues, FAO/WHO 1995

Dora, C. et al., *Indicators linking health and sustainability in the post-2015 development agenda*, Lancet 2015; 385: 380-91

Food Safety Risk Analysis: An Overview and Framework Manual, FAO/WHO 2005

Food Safety Risk Analysis: A guide for national food safety authorities, FAO/WHO 2007

Gold, M.R. et al, *HALYs and QALYs and DALYs, Oh My: Similarities and Differences in Summary Measures of Population Health*, Annual Review of Public Health. 2002.23:115-134

Note about the similarities and differences between microbiological and toxicological risk assessment, prepared by Håkan Vigre and Max Hansen, DTU Food

Scientific Opinion on Risk Assessment Terminology, EFSA 2012

Uncertainty and Data Quality in Exposure Assessment, WHO/IPCS, Harmonization Project Document Nr. 6, 2008

DTU Food website

10. Glossary of risk-related terms in food safety

General Concepts

risk	A function of the probability of an adverse health effect and the severity of that effect, consequential to a hazard(s) in food (CAC, 2011**)** Likelihood of the occurrence and the likely magnitude of the biological and economic consequences of an adverse event or effect to animal or human health. (OIE, 2011) Pest risk (for quarantine pests): The probability of introduction and spread of a pest and the magnitude of the associated potential economic consequences (IPPC, 2011b) Pest risk (for regulated non-quarantine pests**):** The probability that a pest in plants for planting affects the intended use of those plants with an economically unacceptable impact (IPPC, 2011b)
hazard	A biological, chemical or physical agent in, or condition of, food with the potential to cause an adverse health effect (CAC, 2011) A biological, chemical or physical agent in, or condition of, a good with the potential to cause an adverse health effect (FAO/WHO, 2008) 'Hazard' not specified; Pest is any species, strain or biotype of plant, animal or pathogenic agent injurious to plants or plant products (IPPC, 2011b)
food	Any substance, whether processed, semi-processed or raw which is intended for human consumption, including drinks, chewing gum and any substance which has been used in the manufacture, preparation or treatment of "food" but excluding cosmetics, tobacco and substances used only as drugs. (WHO 1995)
food contaminant	Any substance not intentionally added to food, which is present in such food as a result of the production (including operations carried out in crop husbandry and veterinary medicine), manufacture, processing, preparation, treatment, packing, packaging, transport or holding of such food or as a result of environmental contamination. The term does not include insect fragments, rodent hairs and other extraneous matter. (FAO/WHO 2005)
food hygiene	Food hygiene comprises conditions and measures necessary for the production, processing, storage and distribution of food designed to ensure a safe, sound, wholesome product fit for human consumption. (FAO/WHO 2005)
food safety	A scientific discipline describing handling, preparation, and storage of food in ways that prevent foodborne illness. This includes a number of routines that should be followed to avoid potentially severe health hazards. The tracks within this line of thought are safety between industry and the market and then between the market and the consumer. In considering industry to market practices, food safety considerations include the origins of food including the practices relating to food labeling, food hygiene, food additives and pesticide residues, as well as policies on biotechnology and food and guidelines for the management of governmental import and export inspection and certification systems for foods. In considering market to consumer practices, the usual thought is that food ought to be safe in the market and the concern is safe delivery and preparation of the food for the consumer. (Wikipedia)

food security	Food security is a condition related to the supply of food, and individuals' access to it. At the 1974 World Food Conference the term "food security" was defined with an emphasis on supply. Food security, they said, is the "availability at all times of adequate world food supplies of basic foodstuffs to sustain a steady expansion of food consumption and to offset fluctuations in production and prices". Later definitions added demand and access issues to the definition. The final report of the 1996 World Food Summit states that food security "exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (Wikipedia)
food sustainability	As defined by the High Level Panel of Experts on food security and nutrition (HLPE) "a sustainable food system (SFS) is a food system that delivers food security and nutrition for all in such a way that the economic, social and environmental bases to generate food security and nutrition for future generations are not compromised". (FAO website)

Terms related to Risk Assessment

Risk assessment	A scientifically based process consisting of the following steps: (i) hazard identification, (ii) hazard characterization, (iii) exposure assessment, and (iv) risk characterization. (CAC, 2011) **Quantitative risk assessment** - A Risk Assessment that provides numerical expressions of risk and indication of the attendant uncertainties. **Qualitative risk assessment** - A Risk Assessment based on data, which, while forming an inadequate basis for numerical risk estimations, nonetheless, when conditioned by prior expert knowledge and identification of attendant uncertainties permits risk ranking or separation into descriptive categories of risk. (FAO 2007)
Hazard identification	The identification of biological, chemical and physical agents capable of causing adverse health effects and which may be present in a particular food or group of foods. (FAO 2005)
Hazard characterization	The qualitative and/or quantitative evaluation of the nature of the adverse health effects associated with biological, chemical and physical agents, which may be present in food. For chemical risk assessments, a dose-response assessment should be performed. For biological or physical agents, a dose-response assessment should be performed if the data are obtainable. (FAO 2005)
Exposure assessment	The qualitative and/or quantitative evaluation of the likely intake of biological, chemical and physical agents via food as well as exposures from other sources if relevant. (FAO 2005)
Risk characterization	The qualitative and/or quantitative estimation, including attendant uncertainties, of the probability of occurrence and severity of known or potential adverse health effects in a given population based on hazard identification, hazard characterization and exposure assessment. (FAO 2005)
Risk estimate	The quantitative estimation of risk resulting from risk characterization. (FAO 2005)
Safety assessment	A Safety Assessment is defined by CAC as a scientifically-based process consisting of: 1) the determination of a NOEL (No Observed Effect Level) for a chemical, biological, or physical agent from animal feeding studies and other scientific considerations; 2) the subsequent application of safety factors to establish an ADI or tolerable intake;

	3) comparison of the ADI or tolerable intake with probable exposure to the agent (Temporary definition to be modified when FAO/WHO/JECFA definition is available).
Exposure, entry, introduction, release, spread, establishment	**Exposure assessment**: The qualitative and/or quantitative evaluation of the likely intake of biological, chemical, and physical agents via food as well as exposures from other sources if relevant (CAC, 2011) **Release assessment** consists of describing the biological pathway(s) necessary for an importation activity to 'release' (that is, introduce) pathogenic agents into a particular environment, and estimating the probability of that complete process occurring, either qualitatively (in words) or quantitatively (as a numerical estimate). The release assessment describes the probability of the 'release' of each of the potential hazards (the pathogenic agents) under each specified set of conditions with respect to amounts and timing, and how these might change as a result of various actions, events or measures (OIE, 2011)
Consequence assessment	Consequence assessment consists of describing the relationship between specified exposures to a biological agent and the consequences of those exposures. A causal process should exist by which exposures produce adverse health or environmental consequences, which may in turn lead to socio-economic consequences. The consequence assessment describes the potential consequences of a given exposure and estimates the probability of them occurring. This estimate may be either qualitative (in words) or quantitative (a numerical estimate) (OIE, 2011).
Dose-response assessment	The determination of the relationship between the magnitude of exposure (dose) to a chemical, biological or physical agent and the severity and/or frequency of associated adverse health effects (response). (FAO 2005)
Uncertainty	**Uncertainty**: The (quantitative) expression of our lack of knowledge. Uncertainty can be reduced by additional measurement or information. (WHO/FAO, 2008); There are many types of uncertainty in exposure assessment, including process uncertainty, model uncertainty, parameter uncertainty, statistical uncertainty, and even uncertainty in variability: **Process uncertainty** refers to the uncertainty about the relationship between the food chain as documented in the exposure assessment and the processes that take place in reality. **Model uncertainty** comprises both the correctness of the way the complexity of the food chain is simplified, and the correctness of all the submodels that are used in the exposure assessment. **Parameter uncertainty** incorporates uncertainties dealing with errors resulting from the methods used for parameter estimation, like measurement errors, sampling errors and systematic errors. As part of this, **statistical uncertainty** is defined as the uncertainty quantified by applying statistical techniques such as classical statistics or Bayesian analysis. **Uncertainty:** Lack of knowledge regarding the true value of a quantity, such as a specific characteristic (e.g. mean, variance) of a distribution for variability, or regarding the appropriate and adequate inference options to use to structure a model or scenario. These are also referred to as model uncertainty and **scenario uncertainty** (FAO/WHO, 2003) **Measurement uncertainty** refers to the 'uncertainty' associated with data generated by

	a measurement process. In analytical chemistry, it generally defines the uncertainty associated with the laboratory process but may also include an uncertainty component associated with sampling. (CAC, 2006); non-negative parameter characterizing the dispersion of the values being attributed to a measure and, based on the information used (CAC, 2009); **Model uncertainty** Bias or imprecision associated with compromises made or lack of adequate knowledge in specifying the structure and calibration (parameter estimation) of a model (FAO/WHO, 2003) **Uncertainty analysis**: A method used to estimate the uncertainty associated with model inputs, assumptions and structure/form. (FAO/WHO, 2008)**;** an analysis designed to determine the contribution of the uncertainty associated with an input parameter to the degree of certainty in the estimate of exposure. (FAO/WHO, 2008)

Terms related to Risk Management and Risk Communication

Risk analysis	A process consisting of three components: risk assessment, risk management and risk communication. (FAO 2005)
Risk management	The process, distinct from risk assessment, of weighing policy alternatives in consultation with all interested parties, considering risk assessment and other factors relevant for the health protection of consumers and for the promotion of fair trade practices, and, if needed, selecting appropriate prevention and control options. (FAO 2005)
Risk communication	The interactive exchange of information and opinions throughout the risk analysis process concerning risk, risk-related factors and risk perceptions, among risk assessors, risk managers, consumers, industry, the academic community and other interested parties, including the explanation of risk assessment findings and the basis of risk management decisions. (FAO 2005)
Risk Assessment Policy	Documented guidelines on the choice of options and associated judgements for their application at appropriate decision points in the risk assessment such that the scientific integrity of the process is maintained. (FAO 2005)
Appropriate Level of Protection (ALOP)	The level of protection deemed appropriate by the Member (member country of WTO) establishing a sanitary or phytosanitary measure to protect human, animal or plant life or health within its territory. This concept is also referred to as the acceptable level of risk. (FAO 2007)
Risk profile	The description of the food safety problem and its context. (FAO 2005)
Food Safety Objectives (FSO)	The maximum frequency and/or concentration of a hazard in a food at the point of consumption that provides, or contributes to, achievement of the ALOP. (FAO 2007)
Performance Objectives (PO)	The maximum frequency and/or concentration of a hazard in a food at a specified step in the food chain that provides, or contributes to, achievement of the ALOP. (FAO 2007)
Performance Criterion (PC)	The effect in frequency and/or concentration of a hazard in a food that must be achieved by the application of one or more control measures to provide or contribute to a performance objective. (FAO 2007)
Good Manufacturing Practices (GMP)	Conformance with codes of practice, industry standards, regulations and laws concerning production, processing, handling, labelling and sale of foods decreed by industry, local, state, national and international bodies with the intention of protecting the consumer from foodborne disease, product adulteration and fraud. (FAO 2007)

Good Hygiene Practices (GHP)	All practices regarding the conditions and measures necessary to ensure the safety and suitability of food at all stages of food chain. (FAO 2007)
Good Agricultural Practices (GAP)	The application of knowledge that addresses environmental, economic and social sustainability for on-farm production and post-production processes resulting in safe and healthy food and non-food agricultural products. (FAO 2007)

Interview Questions with Tine Hald, Flemming Bager and Annette Schnipper, DTU Food

1) The traditional approach to food safety has focused on end-product control, mainly as the responsibility of government authorities and little, if any, structured risk analysis. There appears to be a distinct shift in philosophy in the area of food safety from end-product to process control and to using risk analysis. When and why did this shift occur and how is the overall role of risk analysis seen in the context of food safety?
2) How are risk analysis, risk assessment and risk management defined in the context of food safety and what are the different components in each process? How can DTU Food's competencies be described with regard to the different stages of risk analysis?
3) What qualitative and quantitative methods are used in the process of risk assessment?
4) What qualitative and quantitative methods are used in the process of risk management with regard to identifying and evaluating risk management options? Is decision analysis incorporated? What are the risk acceptance criteria?
5) DTU Food has a large portfolio of advisory services it provides to Danish and international public sector authorities. Is there an established risk communication strategy and process? What are the challenges?
6) What research topics are covered at DTU Food that have direct or indirect relevance to risk?
7) What current projects at DTU Food have relevance to risk?
8) Is there collaboration in research activities and projects with other DTU institutes? On what topics and in which capacity?
9) Does DTU Food provide scientific advice to actors in the Danish and/or international public sector? On what topics and through what framework?
10) Does DTU Food provide scientific advice to actors in the Danish and/or international private sector? On what topics and through what framework?
11) What percentage of DTU Food scientific staff is involved in work directly related to the topic of risk as: a) their main activity; b) their supplementary activity?
12) How many current PhD students are working on a topic related to risk? What are these PhD projects?
13) What does DTU Food perceive to be the main challenges with regard to the departments risk-related activities in terms of education, research and public/private advisory?
14) Where does DTU Food see opportunities for collaboration with other DTU institutes with regard to the departments risk-related activities?

Appendix IV: Risk at DTU Environment

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1. Introduction: Risk in environment

In order to understand what is meant by environmental risk assessment it is important to be familiar with the concepts of hazard and risk. These terms have different meanings and are not interchangeable. Hazard is understood to be the inherent potential for something to cause harm. Hazards can include substances, machines, energy forms, or the way work is carried out. Risk is understood as a combination of the likelihood or probability that the hazard will cause actual harm and the severity of the consequences. In general, the term environmental covers the physical surroundings that are common to everybody including air, water, land, plants and wildlife. Thus environmental risk assessment covers the risk to all ecosystems, including humans, exposed via, or impacted via, these media. The term environmental risk assessment does not normally cover the risks to individuals or the general public at large from consumer products or from exposure in the work place, where other specific legislation applies. A concept frequently used in environmental risk assessment is that of the source – pathway – receptor. (Table 1)

Example Sources	**Example Pathways**	**Example Receptors**
Contaminated soils	Air	People
Contaminated water	Water	Domestic and commercial property
Leaking drums	Soil	Infrastructure
Industrial releases	Food chain	Ecosystems
		Animals
		Plants
		Controlled waters

Table 1 Source-pathway-receptor concept in environmental risk assessment

Environmental Risk Assessment can further be divided into *Ecological risk assessment (ERA)* and *Human (health) risk assessment (HRA)*.

Ecological risk assessment evaluates the potential adverse effects that human activities have on plants, lakes and animals etc., that make up ecosystems, and implicitly the co-operation and function of the eco-system itself. The risk assessment process provides a way to develop, organize, and present scientific information making it relevant for environmental decisions. ERA has become more commonly used in the industry as a result of the use of ERA in regulations. Examples of such uses include compliance with legislation, product safety, site-specific decision making, prioritization and evaluation of risk reduction measures and financial planning.

Human (health) risk assessment evaluates the potential human health risks to people that may now, or at some time in the future, be exposed to a certain chemical substance. HRA is a tiered process that progresses from the use of short-term tests (acute oral and dermal toxicity, skin and eye irritation, mutagenicity, sensitization potential) and conservative assumptions to longer-term (chronic) tests paired with more realistic assumptions.

Uses of Environmental Risk Assessment

Some examples of the use of environmental risk assessment are given below.

- Assessing the impacts of chemicals used at existing sites (for example for the Control of Major Accident Hazards (COMAH) Regulations (1999), Environmental Permitting Regulations (2010) and other similar legislation).
- Assessing the impacts of products generated by individual companies/sites due to their use or transport etc.
- Assessing potential impacts of new developments, new sites or new processes as part of the planning procedure. This is often known as Environmental Impact Assessment or EIA.
- Assessing the impacts of products, processes or services over their life cycle (life cycle assessment or LCA).
- Consideration of risks to the environment in a company's environmental management system (EMS) or eco-management and audit scheme (EMAS)
- Registration, Evaluation, Authorization and Restriction of Chemicals Regulation. Environmental risk assessment is a key component of determining the safe use of chemicals under this legislation.

(Environmental) Risk Assessment (E)RA and Life Cycle Assessment (LCA)

Risk assessment and LCA are used to conduct inherently different types of analyses. Both purpose and perspective of the two methods are often different and the connections between them are not fully investigated in literature to date. When comparing risk assessment and LCA there are five different, alternative solutions or approaches; they could be seen as completely separated, overlapped i.e. there is an intersection between them, (E)RA could be a subset of LCA, LCA could be a subset of RA and finally they could be seen as complementary tools where they both are needed to get the whole picture.

Overview of LCA

Life Cycle Assessments were first made in the 1960s, aiming to optimize energy consumption in a context where strong energy consumption represented a restraint for the industry i.e. costs. The scope of these energy analyses were then widen to include raw materials, emissions and waste.

LCA is a method for analyzing and assessing the environmental impact of a material, product or service throughout its entire life cycle. It is an environmental management tool which aims at identifying all resources used and also emissions and waste generated to air, ground and soil, over the whole life cycle of a specific service or product, i.e. upstream from raw material extraction and downstream to final waste disposal aspects are included. The life cycle phases in a technical system are raw material extraction, raw material production, transports, manufacture of the product, use, recovery and/or scrapping of the product in the product's end of life phase.

The effects of product or services considered in LCA are overall potential environmental impacts, e.g. global warming, stratospheric ozone depletion, acidification, photochemical oxidant formation, toxicity and eutrophication, of all resources used and waste generated in a defined technical system.

The ISO framework of LCA describes LCA as four compulsory phases. In the first phase, called the *goal and scope definition* (ISO 14041:1998), the purpose of the study and its scope is defined, e.g. the system boundaries and functional unit is defined. The *inventory analysis* involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. Furthermore, in the *life cycle impact assessment (LCIA),* the data that constitutes the results of the inventory are associated with specific environmental impacts e.g. global warming, acidification and eutrophication, enabling evaluation of the significance of these potential impacts. Finally, in the *life cycle interpretation* phase, the results from the inventory analysis and impact assessment are interpreted to meet the beforehand defined goals of the study.

Fig 1 presents a logic structuring of LCA, based on the framework structured in ISO 14001 and 14004. A logic structure is a structured breakdown of a method or task into different parts or conditions required to fulfill the task. This figure can be compared to Fig 4 illustrating a logical breakdown of (E)RA.

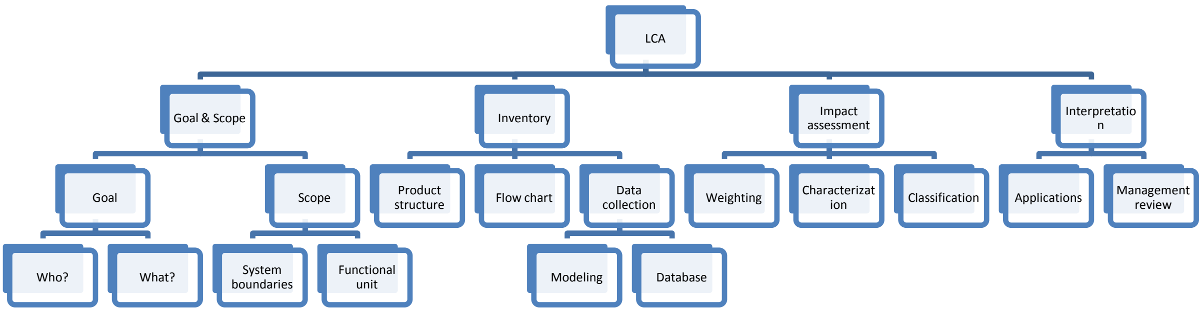

Fig 1 Logical structure of LCA based on ISO 14001 and 14004

Similarities between (E)RA and LCA

Both LCA and (E)RA provide a way of structuring, presenting and evaluating information relevant to one or more environmental aspects of the decision making process. In addition, both approaches have a life cycle perspective; however they differ in the way of viewing the life cycle.

The impact assessment part of LCA (LCIA) performs modelling of the potential impacts related to the provision of a product or service expressed in the functional unit of the technical system under study. (E)RA on the other hand, includes assessment of the risks related to emissions of single substances at local or regional scales. From these perspectives both methods make statements about potential or probability of effects.

The difficulty with data availability and the high cost of acquiring data is also common for the two methods. However, combining (E)RA and LCA would allow data to be shared easily as the same data can be used for both approaches. For instance, emission data for industrial processes can be used for risk assessment and in life cycle inventories. The same holds true for toxicity information usable in risk assessment and life cycle impact assessment.

Differences between (E)RA and LCA

There are two different systems in focus for LCA and (E)RA, respectively. From a *systems analysis perspective* it is two different systems and two different ways of viewing them, i.e. the systems analysis perspective differ for the methods. The scope and goal of the methods also differ.

The raw data used in risk assessment comes from experiments or extrapolations. Experiments have well-defined surroundings e.g. in terms of measurement techniques, light, heat and type of fluid, and also well-defined inputs and outputs. The experiences form the laboratory is then approximated to a real environment. Regarding time, space and boundaries; time could be the same for LCA and (E)RA, the definition of space is different since different systems are studied . The space for LCA is defined when the consequences are followed down or upstream and the space for (E)RA is a downstream analysis until the consequences occur.

While the objective of an (E)RA is to guarantee the environmental safety of a product by modeling the impact of the absolute quantities of an operation's emission of toxic substances (more "receptor focused"), LCA address the objective to reduce the overall pressure on the environment of an entire product system from cradle to grave focusing on the product system's total release of toxic substances (more "loading Focused".

Sustainability and Environmental Risk

LCA is the main method applied in environmental sustainability assessment. The LCA method is briefly outlined in the present, and is considered in greater detail in the DTU Management part of this report.

At DTU Environment, LCA has been used in combination with Multi-Criteria Decision Analysis (MCDA) in a number of research projects. One example is a PhD project, titled *Sustainable evaluation of water supply technologies – by using life-cycle and freshwater withdrawal impact assessment &*

multi-criteria decision analysis, during which a decision support system called ASTA (Assess the most SusTainable Alternative) was developed, incorporating the criteria of the three sustainability dimensions – environment, economy and society. (Fig. 2)

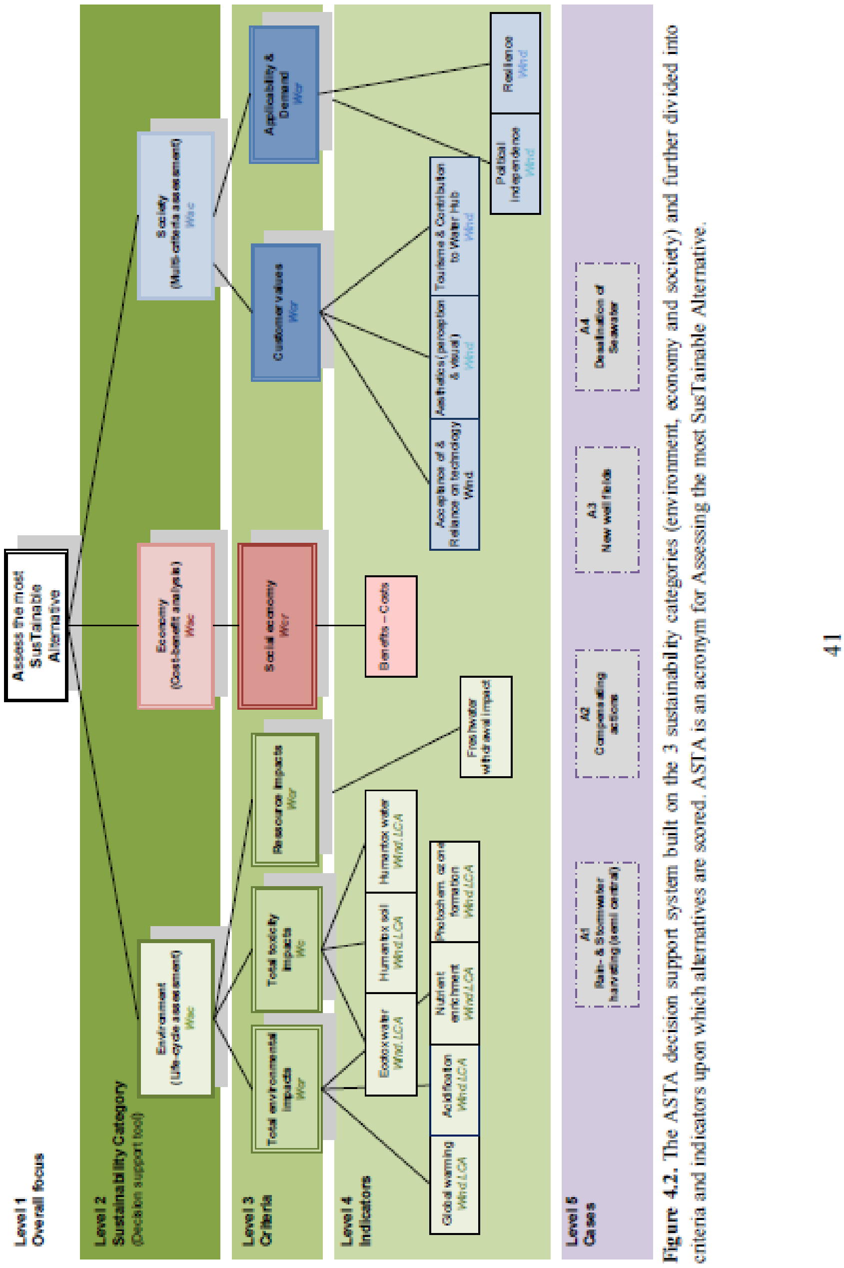

Fig 2 The ASTA decision support system, built on the 3 sustainability pillars (Godskesen 2012)

Another project investigated the applicability of life cycle assessment as a tool for environmental assessment of remediation of contaminated sites. (Fig. 3) It concluded that although LCA was useful in this problem context, conducting the LCA was very data and time consuming. Furthermore, the multi-indicator result is said to be difficult to interpret especially given the higher uncertainty of the toxicity-related impact categories. Thus, improvements of characterization methods for toxic impacts as well as expansion of remediation-relevant LCI databases were among issues identified for future attention in order to enhance the applicability of LCA. Moreover, it was argued that further development of methods for monetization of life cycle impacts may enhance the use of LCA within this field as it makes it easier to integrate the result of the environmental assessment with other decision criteria such as remediation cost.

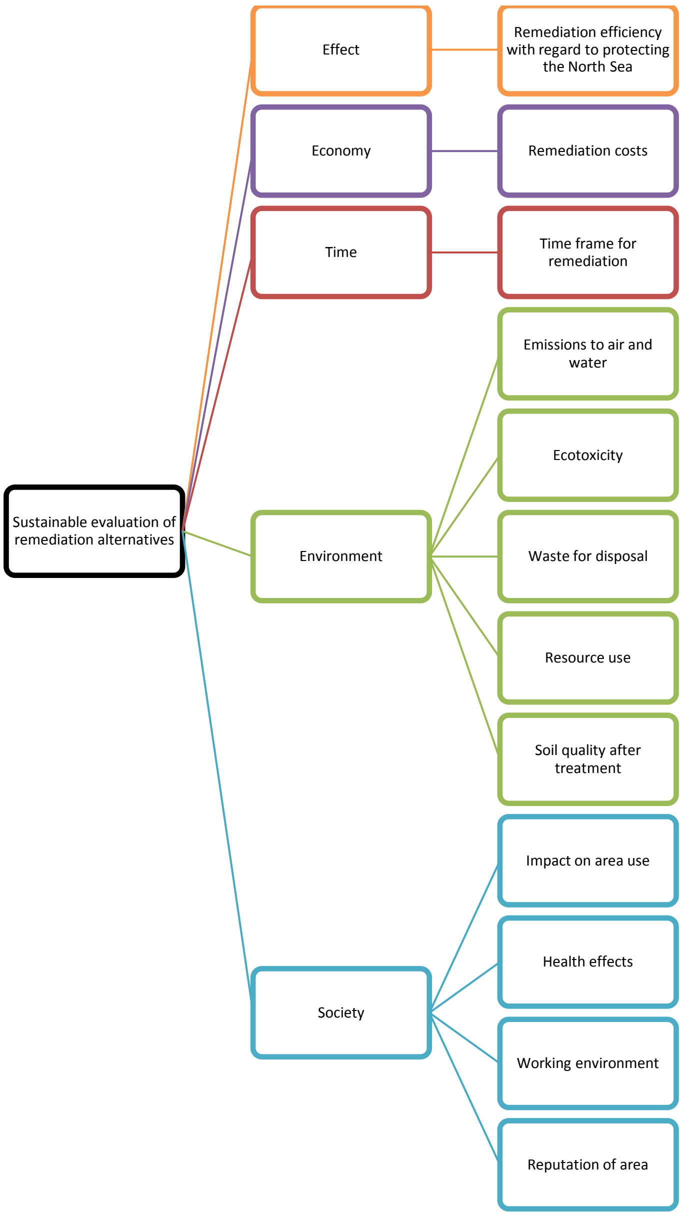

Fig 3 Schema for sustainable evaluation of remediation alternatives (Lemming 2010)

2. Concepts and processes

Before carrying out an environmental risk assessment it is important to clearly set out the problem being addressed and the boundaries within which any decisions on environmental risk are to be made. This is sometimes known as problem formulation and can typically define the risk of what, to whom (or which part of the environment), where (location) and when (in time). This can also assist in selecting the level and types of assessment methodology to be used in the environmental risk assessment itself. There is a wide range of different terminologies used in this area. However, most of the different terminologies can normally be related to one of the following steps:

Step 1: Hazard identification. This would typically include identification of the property or situation that could lead to harm.

Step 2: Identification of the consequences if the hazard was to occur.

Step 3: Estimation of the magnitude of the consequences. This can include consideration of the spatial and temporal scale of the consequences and the time to onset of the consequences. When considering chemicals, this step can sometimes be termed release assessment.

Step 4: Estimation of the probability of the consequences. There are three components to this, the presence of the hazard, the probability of the receptors being exposed to the hazard and the probability of harm resulting from exposure to the hazard. This step can sometimes be called exposure assessment or consequence assessment.

Step 5: Evaluating the significance of a risk (often termed risk characterization or risk estimation) is the product of the likelihood of the hazard being realized and the severity of the consequences. This step may also consider the uncertainty associated with both the hazard and the risk. An effect or hazard assessment are integrated and compared to an exposure assessment in completing a risk characterization to ensure that the concentration of a substance released to the environment, the Predicted Environmental Concentration (PEC) remains below harmful concentration i.e. the Predicted No Effect Concentration (PNEC). The risk characterisation or risk quotient is therefore defined as the ratio between PEC and PNEC (PEC/PNEC).

Step 6: A concept frequently used in environmental risk assessment is that of **the source – pathway – receptor.** In this conceptual model the pathway between a hazard source (for example a source of contamination) and a receptor (for example a particular ecosystem) is investigated. The pathway is the linkage by which the receptor could come into contact with the source (a number of pathways often need to be considered). If no pathway exists then no risk exists. If a pathway exists linking the source to the receptor, then the consequences of this are determined. This approach is used in the assessment of contaminated land, but can be, and is, applied to many other areas.

Step 7: At the end of the risk assessment process, **existing controls** should be recorded and **further measures** may need to be considered to reduce or eliminate the risks identified. Detailed consideration of risk management is beyond the scope of this report as activities at DTU Environment relate to environmental risk assessment, not risk management. In general terms, however, risk management can be achieved by reducing or modifying the source, by managing or breaking the pathway and/or modifying the receptor.

Step 8: The final stage is the evaluation of the significance of the risk which involves placing it in a context, for example with respect to an **environmental standard or other criterion defined in legislation, statutory or good practice guidance.**

Fig. 4 presents a detailed picture of risk assessment, using a logic structure, i.e. a breakdown of a method into conditions or parts that need to be fulfilled in order to complete the assessment.

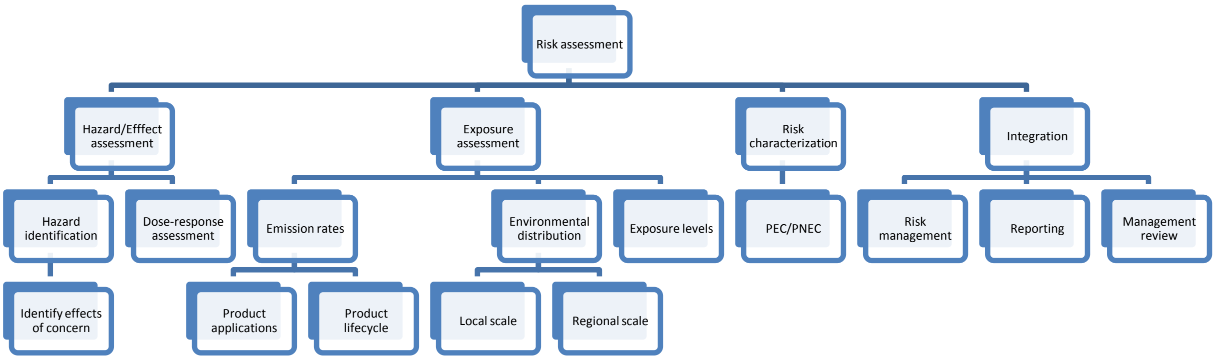

Fig. 4 Example of logic structure of risk assessment based on the framework set out in Commission Regulation (EC) 1488/94 and implemented in the detailed Technical Guidance Documents on Risk Assessment for New and Existing Substances (2003)

3. Methods and techniques

Environmental Risk Assessment for Chemicals

Environmental Risk Assessment for Chemicals is concerned with the potential impact of individual substances on the environment. It examines both exposures resulting from discharges and/or releases of chemicals and the effects of such emissions on the structure and function of the ecosystem.

A typical approach for such examination – also the approach applied at DTU Environment – is a quantitative PEC/PNEC estimation for environmental risk assessment of a substance, comparing compartmental concentrations (PEC) with the concentration below which unacceptable effects on organisms will most likely not occur (predicted no effect concentration (PNEC).

The PECs can be derived from available measured data and/or model calculations. The PNEC values are usually determined on the basis of results from single species laboratory tests or, in a few cases, established effect and/or no-effect concentrations from model ecosystem tests, taking into account adequate assessment factors. The PNEC can be derived using an assessment factor approach or, when sufficient data is available, using the statistical extrapolation methods. A PNEC is regarded as a concentration below which an unacceptable effect will most likely not occur.

Dependent on the PEC/PNEC ratio the decision whether a substance presents a risk to organisms in the environment is taken. If it is not possible to conduct a quantitative risk assessment, either because the PEC or the PNEC or both cannot be derived, a qualitative evaluation is carried out of the risk that an adverse effect may occur. For quantitative risk characterization in general, if PEC/PNEC ratio is < 1 then no further testing or risk reduction measures are needed, whereas if PEC/PNEC ratio is > 1 further testing/information or risk reduction measures may be needed. PEC/PNEC ratio should be < 1, which may be achieved through further testing, information gathering, or risk reduction measures.

Environmental Exposure Assessment

The environment may be exposed to chemical substances during all stages of their life-cycle from production to disposal or recovery. For each environmental compartment (air, soil, water, sediment) potentially exposed, the exposure concentrations should be derived. The assessment procedure in principle considers the following stages of the life-cycle of a substance:

• production;

• transport and storage;

• formulation (blending and mixing of substances in preparations);

• industrial/Professional use (large scale use including processing (industry) and/or small scale use (trade));

• private or consumer use;

• service life of articles;

• waste disposal (including waste treatment, landfill and recovery).

A comprehensive exposure assessment typically includes the following:

- Characterization of the physical setting, including climate, meteorology, geologic setting, soil type, groundwater hydrology
- Characterization of the potentially exposed populations
- Identification of the exposure pathways by identifying the sources and receiving media and evaluating the fate and transport in release media. This includes an assessment of the physical and chemical characteristics of the agent and the environmental fate parameters and a consideration of factors, such as degradation in the environment, inter-media transfer, possible reactions with other environmental chemicals, etc.
- Integration of the sources, releases, fate and transport, exposure points and exposure routes into exposure pathways.

In view of uncertainty in the assessment of exposure of the environment, the exposure levels should be derived on the basis of both measured data, if available, and model calculations. Relevant measured data from substances with analogous use and exposure patterns or analogous properties, if available, should also be considered when applying model calculations. Preference should be given to adequately measured, representative exposure data where these are available. Consideration should be given to whether the substance being assessed can be degraded, biotically or abiotically, to give stable and/or toxic degradation products. Where such degradation can occur, the assessment should give due consideration to the properties (including toxic effects) of the products that might arise.

Effects Assessment

The effects assessment comprises the following steps of the risk assessment procedure:

• *Hazard identification*: The aim of the hazard identification is to identify the effects of concern. For existing substances and biocidal active substances and substances of concern in biocidal products, the aim is also to review the classification of the substance while for new substances a proposal on classification is done;

• *Dose (concentration) - response (effect) assessment:* At this step the predicted no effect concentration (PNEC), is, where possible, determined.

For both steps of the effects assessment it is of high importance to evaluate the data with regard to their adequacy and completeness. The evaluation of data is of particular importance for existing substances as tests will often be available with non-standard organisms and/or non-standardized methods. It is suitable to start the effects assessment process with the evaluation of the available ecotoxicological data.

The environmental compartments considered for the inland environment are the aquatic and terrestrial ecosystem, top predators, microbial activity in a sewage treatment plant (STP), and the atmosphere. This means that for each of these compartments a PNEC has to be derived. In principle, the PNEC is calculated by dividing the lowest short-term L(E)C50 or long-term NOEC value by an appropriate assessment factor. The assessment factors reflect the degree of uncertainty in extrapolation from laboratory toxicity test data for a limited number of species to the 'real' environment. Assessment factors applied for long-term tests are smaller as the uncertainty of the extrapolation from laboratory data to the natural environment is reduced. For this reason long-term data are preferred to short-term data.

A detailed assessment of the environmental risk is often only feasible for the water compartment: for new substances the base-set consists of effect data for aquatic organisms only, while for existing substances most of the available data will be for aquatic organisms. For biocides, the core data set comprises effect data on aquatic organisms as well.

Effects Assessment for the Aquatic Compartment

For the aquatic environment, a PNEC is derived that, if not exceeded, ensures an overall protection of the environment. Certain assumptions are made concerning the aquatic environment which allow, however uncertain, an extrapolation to be made from single-species short-term toxicity data to ecosystem effects. It is

- ecosystem sensitivity depends on the most sensitive species, and;
- protecting ecosystem structure protects community function.

These two assumptions have important consequences. By establishing which species is the most sensitive to the toxic effects of a chemical in the laboratory, extrapolation can subsequently be based on the data from that species.

For most substances, the pool of data from which to predict ecosystem effects is very limited as, in general, only short-term toxicity data are available. In these circumstances, it is recognized that, while not having a strong scientific validity, empirically derived assessment factors must be used. In establishing the size of these assessment factors, a number of uncertainties must be addressed to extrapolate from single-species laboratory data to a multi-species ecosystem:

- intra- and inter-laboratory variation of toxicity data;
- intra- and inter-species variations (biological variance);
- short-term to long-term toxicity extrapolation;
- laboratory data to field impact extrapolation (additive, synergistic and antagonistic effects from the presence of other substances).

<u>Effects Assessment for Microorganisms in Sewage Treatment Plants (STPs)</u>

Since chemicals may cause adverse effects on microbial activity in STPs it is necessary to derive a $PNEC_{microorganisms}$ .The $PNEC_{microorganisms}$ will be used for the calculation of the PEC/PNEC ratio concerning microbial activity in STPs. Information available on the toxicity for microorganisms has also to be relevant for the endpoint considered, i.e. microbial degradation activity in a STP. Test systems such as the respiration inhibition test and the nitrification inhibition test can be used.

In general, the aim of the assessment is the protection of the degradation and nitrification functions and process performance and efficiency of domestic and industrial STPs – as also influenced by protozoan populations. The toxicity of a substance to microorganisms in a STP is assessed by comparing the concentration of a substance in STP aeration tank with the microbial effect concentration data for that substance.

<u>Effects Assessment for the Sediment</u>

Sediments may act as both a sink for chemicals through sorption of contaminants to particulate matter, and a source of chemicals through resuspension. Sediments integrate the effects of surface water contamination over time and space, and may thus present a hazard to aquatic communities which is not directly predictable from concentrations in the water column.

Various approaches (e.g. equilibrium partitioning, interstitial water quality, spiked sediment toxicity, tissue residue, derived sediment quality criteria and standards) can be used to investigate the effects that chemicals have on sediment and sediment organisms.

Effects Assessment for the Terrestrial Compartment

Chemicals can reach the soil via several routes: application of sewage sludge in agriculture, direct application of chemicals and deposition from the atmosphere. Consequently the possibility of adverse effects has to be assessed. In common with the aquatic compartment, the objective of the assessment is to identify substances that present an immediate or delayed danger to the soil communities.

Effects Assessment for the Air Compartment

For the risk assessment of the air compartment biotic and abiotic effects are considered.

Biotic effects

The methodology used for effects assessment (and therefore the risk characterisation) of chemicals in water and soil cannot be applied yet in the same manner to the atmosphere. Methods for the determination of effects of chemicals on species arising from atmospheric contamination have not yet been fully developed. It is evident that the quantitative characterisation of risk by comparison of the PECair to PNECair is not possible at the moment: only a qualitative assessment for air is feasible. For the air compartment toxicological data on animal species other than mammals are usually not or only scarcely available. Likewise, concerning the toxicity for plants, data from tests where a chemical is applied directly via air (gaseous or deposited) are normally scarce.

Abiotic effects

For the evaluation of an atmospheric risk, the following abiotic effects of a chemical on the atmosphere have to be considered:

- global warming;
- ozone depletion in the stratosphere;
- ozone formation in the troposphere;
- acidification.

Risk Characterization

In general, the risk characterization phase is carried out along the following steps (Fig. 6):

- determine the PEC/PNEC ratios for the different environmental compartments considered.

Dependent on these PEC/PNEC ratios:

- determine whether further information/testing may lead to a revision of these ratios;
- ask for further information/testing when appropriate;
- refine the PEC/PNEC ratio.

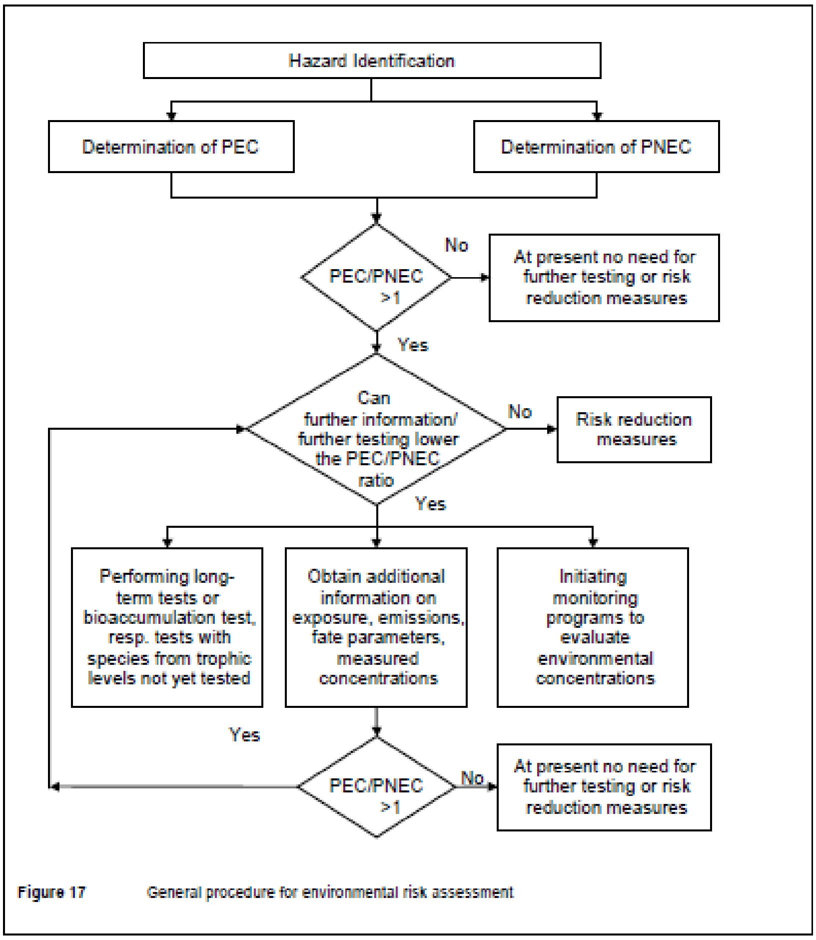

Fig. 6 General procedure for risk characterization

Essentially, risk characterization is a summary of the data compiled in the risk assessment process, including the uncertainties associated with each stage and the presentation of a risk estimate.

Deterministic vs Probabilistic Risk Assessment

For most non-carcinogenic end points, the effect is deterministic. It is accepted that a threshold exists below which no toxic effects are expected. It is possible to determine through toxicity tests, a No Observable Effect Level (NOEL) – the highest dose which has no effect, or if this is unavailable, a Lowest Observed Effect (LOEL) – the lowest dose to produce a toxic effect. These figures then need to be extrapolated from animals to humans, which involves the application of safety or uncertainty factors.

For carcinogenic end points, dose-response extrapolation can be based on the policy assumption that there may be no threshold for the carcinogenic effect. Probabilistic models may be used to determine a Virtually Safe Dose for exposure to carcinogens.

Environmental Risk Assessment of Nanomaterials

When risk assessment of nanomaterials is discussed, it is often in the context of previous experience with chemical risk assessment. While there has been steady progress made within the fields of nanotoxicology and nanoecotoxicology in recent years, the presence of large data gaps and significant uncertainties have resulted in the inability to successfully complete risk assessments based on standard approaches.

Risk assessment of nanomaterials and consequent policy and regulatory scientific advice is an area of specialization at DTU Environment, where over the last 5-6 years research has resulted in a number of PhD studies, scientific publications and international project participation as well as teaching activities.

According to scientists at DTU Environment, there are a number of limitations and flaws in relation to each of the four elements of the chemical risk assessment framework when applied to nanomaterials. For example, one author has argued that it is currently impossible to systematically link reported nanoparticle properties to the observed effects for effective hazard identification. For dose-response assessment, it is unclear whether a no effect threshold can be established and what the best hazard descriptor(s) of nanoparticles is and what the most relevant endpoints are. There is a serious lack of characterization of the nanoparticles tested, which makes it difficult to identify which key characteristics – or combinations of key characteristics – determine the hazards documented in (eco)toxicological studies of nanoparticles.

On this basis, it is argued that a true understanding of the hazardous properties that materials begin to exhibit at the nanoscale requires a level of interdisciplinary research that has not yet been reached. In order to conduct and interpret scientific studies on the hazardous properties of nanomaterials, strong interdisciplinary collaboration is needed between nanoscientists, (eco)toxicologists and physicists, chemists, and material engineers.

While chemical risk assessment is based on the fact that the chemical identity governs the fate and effects of a chemical, the situation for nanomaterials may be somewhat different. By definition, the properties of nanomaterials cannot be determined by their chemical composition alone, and hazard identification of nanomaterials – and specifically nanoparticles – has come under intense scrutiny in recent years.

Given the limitations of chemical risk assessment and given the future impact on every aspect of our lives and society that nanotechnology is expected to have, alternative decision making tools are being explored by researchers in this DTU Environment domain, particularly Multi-Criteria Decision Analysis, Bayesian Networks and Adaptive Management as well as a number of risk frameworks adapted for nanomaterials such as the International Risk Governance Framework (IRGC 2005, 2007, 2009), Comprehensive Environmental Assessment (US EPA 2009, 2010), Nano Risk Framework (Environmental Defense and Dupont 2007), Nano Screening Level Life Cycle Risk Assessment Framework (Nano LCRA 2008, 2009), etc.

Environmental Risk Assessment for Groundwater and Surface Water

Environmental Risk Assessment for Groundwater

Groundwater is water stored below the water table in rocks or other geological strata which are called aquifers. Groundwater in aquifers can be exploited via boreholes, wells or springs, or it can support other ecosystems such as rivers and wetlands.

Groundwater faces many risks and is easily polluted. Pollution of groundwater may be due to deliberate or accidental release of a pollutant. Or it may due to an activity that moves a pollutant so that it becomes a problem. In most circumstances the overlying soils and rocks naturally protect aquifers. However, when groundwater pollution does occur it can go unnoticed for long periods because the pollutants soak into the ground and disappear from view, often becoming 'out of sight and out of mind'.

The risk presented by a pollutant relates to:

- its use;
- how it enters groundwater;
- the degree of harm it may cause;
- its persistence;
- the ability to detect it;
- statutory requirements.

Leaks, spills and poor maintenance can all release significant volumes of chemicals. Activities that put groundwater at risk include:

- discharge of waste and wastewater (sewage) onto or into the ground;
- use of chemicals such as fertilizers and pesticides;
- poor storage of solvents, petroleum products (oils, petrol, diesel) and other materials;
- spreading of slurry, manure and abattoir wastes.

Groundwater Pollutants

Pollutants are substances that can either occur naturally but are concentrated by human activities, or they can be substances that are synthesized by humans and do not normally occur in nature. Common groundwater pollutants are Nitrate, Ammonia, Hydrocarbons, Pesticides, Solvents, Pharmaceuticals and endocrine disrupters and Microbiological contaminants.

Pollutants can be divided into those that break down easily (degradable pollutants) and those that do not (non-degradable pollutants). The Water Framework Directive introduced the concept of 'hazardous substances' and 'non-hazardous pollutants', which replaced the previous List I and List II of substances considered topose the greatest threat to the environment.

Hazardous substances are the most toxic and must be prevented from entering groundwater. Substances in this list may be disposed of to the ground, under a permit, but must not reach groundwater. They include pesticides, sheep dip, solvents, hydrocarbons, mercury, cadmium and cyanide.

Non-hazardous pollutants are less dangerous and can be discharged to groundwater under a permit, but must not cause pollution. Examples include sewage, trade effluent and most wastes. Non-hazardous pollutants include any substance capable of causing pollution and the list is much wider than the previous List II of substances.

A further distinction is made between Point source pollution and diffuse source pollution.

Point source pollution is localized and comes mostly from spills, leaks and discharges at a single point or over a small area. Point sources are relatively easy to identify because they are discrete and well-defined events or activities. Examples include:

- leaking underground fuel storage tanks, sewers or septic tanks;
- accidental spillages from the handling of chemicals;
- spills resulting from vehicle and other accidents;
- leaching from landfill sites;
- emissions from industrial plants.

The distinction between point and diffuse sources of pollution is not entirely clear cut in practice. Some sources described as diffuse are actually made up of multiple small point sources while others are more evenly distributed on the ground. However, the attributes such sources have in common are that:

- they tend to be spread over larger areas and time periods;
- it is often difficult to relate the pollution source to the impact on groundwater.

Diffuse sources cause pollution in two main ways:

- spread of pollutants over an area;
- cumulative effect of many individual and ill-defined events.

Sources of diffuse pollution include:

- deposition of atmospheric pollutants (from rain and dust);
- leaching from the land of fertilisers and pesticides (for example, nitrate from the application of chemical fertiliser to farmland is a longstanding problem);
- incorrect handling of farm wastes;
- leaks from the sewerage system;
- run-off from urban areas, highways, etc.

Individually these sources may be small and hard to detect. Together they have a significant impact on water quality. The distributed nature of diffuse pollution makes it a particular problem for groundwater. Potentially large volumes of pollutants can enter the subsurface and be stored in the unsaturated zone or within the aquifer before the pollution has been detected, linked to a particular activity and made subject to controls.

Groundwater Risk Assessment at the local and/or catchment scales

Various approaches exist for assessing whether a contaminated site constitutes a risk to groundwater. Most of these methods focus on a *local scale* and aim to evaluate if the resulting groundwater concentrations below or downstream of the contaminant source zone are above a certain limit value. If the concentrations do not comply with the regulatory standards the contaminated site is considered a risk. The resulting concentrations can in some case be measured directly, but often need to be calculated from site-specific information regarding released amounts of contaminants, type of contaminant, geology, hydrogeology etc. For the last decade this approach has been common practice in many countries, including Denmark.

However, the prioritization of point sources necessitates that the risk is considered not only on the local scale, but also on larger scales. For an initial prioritization of contaminated land aquifer vulnerability mapping methods such as DRASTIC are widely used. These methods assign scores to different spatially distributed indicators (e.g. top-layer geology, depth to groundwater, recharge and likely types of contaminants spilled), which subsequently are integrated into an overall risk index. Vulnerability mapping helps identify the areas most susceptible to contamination, but does not account for the degree and extent of contamination at actual sites. Vulnerability mapping can therefore not be used for a more detailed prioritization of point sources and to identify at which sites remediation should be initiated. Since the motivation for initiating clean-up is often governed by the possible impact on water supply wells, it has been proposed to conduct risk assessments at *catchment scale,* where the risk of a point source is assessed in terms of its ability to contaminate abstracted water at the supply wells in the catchment. In this context the estimation of contaminant mass discharges from the individual point sources within the catchment has been found valuable because such estimates are dynamic measures of the total contaminant impact.

Catchment scale risk assessment and prioritization is challenging. Simple GIS-based screening methods can effectively be used to generate a general overview, but more sophisticated methods are required to take advantage of more complex site data.

The purpose of catchment scale risk-based prioritization is primarily to provide an improved overview of the (often many) potential point sources within a catchment and act as a decision support tool for prioritizing further actions within the catchment. Furthermore, an improved overview may serve to identify neglected point sources within the catchment, if the identified sources fail to explain detected contamination in extraction- or monitoring wells.

The most widely tested prioritisation method in Denmark was developed by DTU Environment (Troldborg et al., 2008) and has been tested with different modifications in a number of catchments (Tuxen et al., 2006; Region Hovedstaden, 2009; Region Sjælland, 2010; Miljøministeriet, 2008).

The method assesses the individual contaminant discharges from a number of point sources in a catchment and calculates their cumulative impact on a specific waterworks or on the groundwater resource in general. The different elements of the methodology are illustrated in Figure 7.

The impact calculation for the waterworks or general resource can be used as a prioritization tool in itself but can also be extended with a prioritization scheme based on a number of factors tailored to the specific catchment, such as mass discharge, uncertainty, time frame, economy, etc.

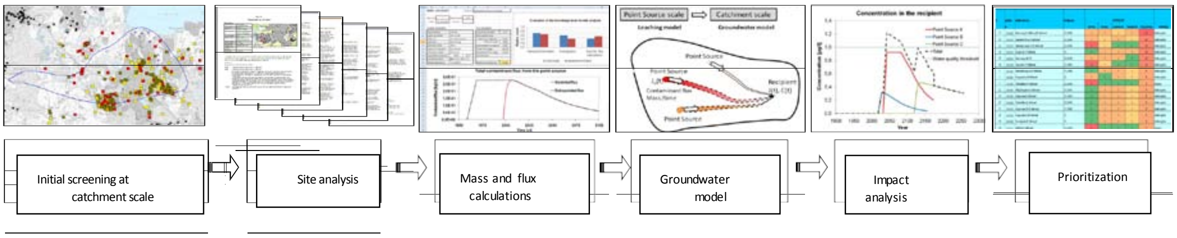

Fig. 7 General elements in catchment scale risk-based prioritization (Overheu et al.; Troldborg 2010)

The Groundwater Risk Assessment Procedure

Risk assessment of contaminated sites is a multidisciplinary task that requires insight into geology, hydrology, chemistry, microbiology, toxicology, statistics etc. and involves evaluation of large amount of information and data from various sources.

Risk assessments of contaminated sites are usually based on a source-pathway- receptor concept as explained and illustrated in Table 2 and Fig. 10.

Source	Pathway	Receptor
The source is the activity, e.g. the discharge of sewage effluent to an infiltration system, a landfill, etc.	The pathway is through engineered measures (e.g. a landfill lining system, infiltration system, etc.) and the migration of contaminants through the unsaturated zone and saturated zone to an agreed receptor incorporating all the processes of attenuation that may be present.	The receptor is a groundwater dependent ecosystem or use of groundwater and/or the groundwater resource itself or any other identified conservation site that may be at risk.

Table 2 Source-Pathway-Receptor terms in groundwater risk assessment

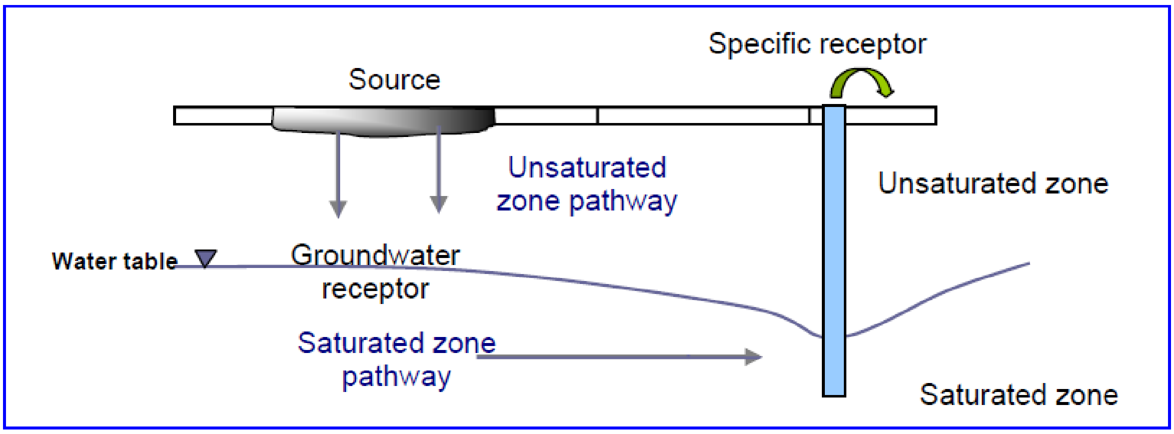

Fig. 8 Source-pathway-receptor concept in groundwater risk assessment

The pathway is the mechanism by which a contaminant gets from the source to the receptor. A given source can only be a risk if a complete pathway-linkage exists between the source and the receptor. A complete pathway consists of a contaminant release from the source, a transport media (the contaminant of concern can be carried to the receptor contact point in e.g. groundwater, air and/or soil) and an exposure route at the receptor contact point (e.g. the contaminant can reach a human being through ingestion, inhalation or dermal contact).

Generally, the following two endpoints are considered in environmental risk assessment: human health and ecological risk. A human health risk assessment evaluates the risks related to human exposures to the contamination, while the ecological risk assessment focuses on protection of flora and/or fauna. In both cases a source characterization and a pathway evaluation is needed to determine the concentration levels that the given receptor is exposed to.

In practice, an environmental risk assessment typically involves the following four distinct phases:

Phase 1: Data Collection and Evaluation

The risk assessment process usually begins with a source characterization, where data about the contaminant source and information about how the contamination will behave in the future are collected. This data collection and evaluation typically consists of:

- A **desktop study** that aims at identifying likely contaminants and involves an examination of the historical activities potentially causing contamination together with a study of the soil and aquifer properties affecting spreading (from maps, existing investigations etc.). Based on this, a hypothesis for the source and the possible pathways and receptors is made.
- A **field investigation** phase that aims at proving the hypothesis and to gather enough information for a complete assessment. This phase involves physical sampling to identify the contaminants of concern, the nature and extent of the contaminant source, the concentration levels, factors controlling transport/fate and the possible exposure pathways.
- A **hazard identification**, where the inherent properties of the identified contaminants are examined. This includes mapping the contaminants physical-chemical characteristics (e.g. solubility, vapor pressure and Henry's law constant), degradability, bio-accumulative ability and toxicity. This information is used for assembling an environmental profile for the contaminant that describes its possible behavior and distribution in the environment, and if it has the potential to cause harm following exposure.

The data collection and evaluation should result in the formulation of a conceptual model for the site. The conceptual site model should be updated continually as more data are collected. A conceptual model is a simplified representation of what is believed to be the physical, chemical and biological processes operating at a site. Conceptual models use available information to produce a 'picture' of how the groundwater flows and interacts with the environment. It shows geology, flow paths, pollution sources, abstractions and receptors.

Once this source characterization has been carried out and the possible pathways and receptors have been identified, an exposure assessment can be performed.

Phase 2: Exposure Assessment

Exposure is the condition of a chemical contacting the exterior of a receptor (e.g. a human). Usually, the chemical is contained in a carrier medium (e.g. water, air and food). Exposure assessment is the process of estimating the magnitude, frequency and duration of exposure that may occur due to contact with the contaminated media, both now and in the future. The exposure assessment therefore involves an identification of receptors, an evaluation of exposure pathways and a development of quantitative estimates of exposure for each pathway. The aim is to determine the exposure concentration (i.e. the chemical concentration in the carrier media at the receptor contact point) and the amount of contaminated media taken in by the receptor over time (intake/uptake rate). To quantify the magnitude of the exposure for each pathway, contaminant fate and transport modelling is typically required. The quantified exposures are often expressed as "chronic daily intakes" (CDIs).

Phase 3: Toxicity Assessment

The toxicity assessment deals with what happens when the contaminant enters the receptor and is the process of estimating exposure-response-relationships. The aim is to determine what the adverse effects are at different exposure levels, when no effects are observed and when responses start to appear. The exposure- response relationship depends on the specific contaminant, the exposure route (whether the contaminant enters the receptor through e.g. inhalation, ingestion or dermal contact) and the kind of response (tumour, weight loss, death, incidence of disease, etc.). The toxicity can be calculated as a "chronic reference dose" (RfD) or a "chronic reference concentration" (RfC), which both express the maximum daily uptake level of a contaminant that is likely not to result in any adverse effects. In soil and groundwater such calculations are often used to define generic standards for the different media and receptors. In practical risk assessments phase 2 and 3 are therefore often partly omitted. This is particularly the case for exposure to contaminated groundwater, where generic standards for groundwater or drinking water substitute the site-specific toxicity assessment and parts of the exposure assessment.

Phase 4: Risk Characterization

The risk characterization summarizes the results from the first 3 phases. The results are integrated into quantitative or qualitative expressions of risk, for example as a Hazard Index that relates the CDI to the RfD for all chemicals and exposure routes. Furthermore, the risk characterization should clearly and consistently present how these risks are assessed and state where assumptions and uncertainties exist. The calculated risks can be compared to acceptance criteria or to other risks to assess whether a risk reduction might be required.

Hydrogeological Assessment Tools

Various frameworks, maps, software and methods of numerical analysis are used to support the management and protection of groundwater. These include geological maps, proprietary models and basic groundwater flow equations.

Generic risk assessment tools tend to use a combination of generic data obtained from empirical or calculated properties in combination with some site-specific details. As the assessment moves into generic or detailed quantitative risk assessment, increasing amounts of site-specific data are needed. The tools used for detailed quantitative risk assessment are often tailored to the circumstances of a particular site and may need a large amount of site-specific data and technical expertise. In most cases the scale of the site reduces as the assessment process moves towards detailed quantitative risk assessment. However, numerical models may cover significant areas but nevertheless require large amounts of detailed data specific to the area being modeled.

Table 3 presents an inexhaustive list of available tools that are used in the context of groundwater risk assessment and management.

Geological maps
Soil maps
Hydrogeological maps
Thematic maps
Source protection zone maps
Groundwater vulnerability maps
Infiltration spreadsheets
LandSim
ConSim

Table 3 Possible tools for Groundwater Risk Assessment/Management

Risk Assessment of Surface Water

The risk assessment method is based on the source-transport-receptor model, where the receptor in this case is surface water bodies. The contaminant flux of the polluted site, either estimated or measured, will be mixed into the surface water and it is possible to calculate an expected concentration of relevant compounds in the surface water using a number of numerical and analytical mixing models.

The contaminant flux can be measured with a number of field methods, applicable for all types of surface water. The methods cover both qualitative methods for localization of inflow-zones into surface water and quantitative methods for estimation of groundwater flux and contaminant flux. The field methods cover temperature measurements for identification of inflow zones in the stream bottom, piezometer measurements, discharge measurements for estimation of the median minimum discharge and sampling of surface water.

The impact of surface water is measured according to the given criteria for surface water (BEK 1022). The different surface water bodies consist of streams, lakes and marine environments, subdivided into coast and fjords. Mixing conditions in these types of surface water is different for each one. For streams the median minimum discharge is a relatively well estimated parameter, which can be used as conservative estimate, but not a "worst case" scenario for the discharge in Danish streams. For the geometrical extension of a contaminant plume in a stream an analytical model for mixing has been developed in relation to the GIS based screening tool, based on equations for a point source. For mixing in fjords and lakes specific numerical models has been developed, also in relation to the GIS-based screening tool.

The final method for risk assessment is based on the automatic screening, where a number of suspected polluted sites (V1) and proved polluted sites (V2) can be assessed, initially in the automatic screening and, if a risk is found, further on in the manually adjusted screening, where location specific information based on investigation reports and other existing data can be considered. If the sites are still considered a risk, field studies and further data collection must be done. The results from the field studies are included in the Base Analysis done for each Water Plan of the relevant surface water body and the task of appointing remediation actions is then the task of the water authority.

Environmental Risk Assessment of Microorganisms in Water

Monitoring the occurrence of pathogens in order to assess the sanitary quality of drinking water and that used for recreational purposes has proved to be unfeasible, both from the technical as well as from the economic point of view, due to the large diversity of pathogens, the high cost and complexity of laboratory analyses and the health risk to technicians because of the constant manipulation of these organisms. Therefore, assessment of the microbial risk consists in having a tool that can be used for estimating the possible adverse effects to health when pathogenic organisms are present in water samples in order to guide control and intervention measures, as well as to assess the impact of the actions carried out.

A detailed explanation of the processes involved in conducting a microbial risk assessment (MRA) is given in the DTU FOOD section of this report. At DTU Environment, MRA has been applied to study the impacts of floods in urban areas on human health by combining quantitative microbial data with hydrological modeling. The purpose of this research is to generate a new quantitative microbial risk assessment of the impacts of urban flooding on human health with less uncertainty on the pathogenic concentrations and the dilution factor. It is recognized that unfortunately MRA for human health related to flooding relies on many assumptions, especially with regard to water quality and hydrological conditions due to lack of data on these parameters. To conduct MRA for flood water three essential parameters are required: the dose-response relationship, the pathogenic concentration and the dilution factor. While dose-response relationships are well established for several pathogenic microorganisms, e.g. Campylobacter jejuni, the pathogenic concentrations are difficult to quantify because they vary with time and season, and are furthermore catchment specific. As a result, many studies on human health impacts from flooding rely on insufficient water quality data.

The water quality in flood data is typically assumed by use of literature values or previous measured concentrations. This is said to be problematic because the water quality from flooding will vary because of the differences between the rain events, the prehistory of rain events and sedimentation in the combined sewer system as well as the influence by the catchment's variability. To overcome these uncertainties, hydraulic models can be applied to estimate the dilution factor of the system. To advance the quality of the MRA related to urban flooding, scientists at DTU Environment have used quantitative data on the microbial concentrations as input and for validation of the hydraulic model. The output of the simulation model can then be applied in a dose-response relationship of Campylobacter to better assess human health risk.

Environmental Risk Assessment in the context of Floods

Flood estimation and flood management have traditionally been the domain of hydrologists, water resources engineers and statisticians. A flood risk assessment is typically done in the form of a catastrophe model. In Box 1 a general outline is given of what constitutes a natural hazard catastrophe model. As this is not part of DTU Environment´s research, the risk assessment process is not elaborated on. Instead, more information is provided on the specific research carried out at the Department. Risk assessment for natural hazards is undertaken at DTU Civil Engineering to a small extent. Some disaster vulnerability research is conducted at DTU Management UNEP partnership division.

Box 1 Catastrophe models for natural hazards

Catastrophe models simulate the occurrence of a natural disaster and estimate its effects, usually through three modules: a hazard simulator, a vulnerability block, and a loss assessment module. Based on historical records and statistical analysis (using hydrologic information for floods, seismic and tectonic information for earthquakes, etc.), a catalogue of events is generated. Each event comprises a source, a magnitude, a duration, and an annual frequency. The area of concern is mapped in detail thanks to (micro)zonation, in order to describe the propagation of the hazard. Exposure is assessed for the main types of property and assets in the area: residential buildings, factories, agricultural land, etc. Buildings can be classified according to their function and architectural structure, and capacity curves and repair/replacement costs estimated for each of these classes. Finally, total casualties, displacements and economic losses are calculated for each event. Average and worst-case losses can also be computed for a given area across the range of events, without consideration for probabilities of occurrence. Each of the above assessment stages involves various sources of uncertainty. The influence of each of these sources on overall uncertainty can be estimated by varying the corresponding parameters (e.g. frequency of events, building resistance, etc.) and measuring the sensitivity of final results. Once all sources are included, sensitivity analysis often shows that catastrophe loss estimation remains a highly uncertain process.

Over the past two decades there has been a shift from a hazard-focused view to a broader risk-based perspective, which includes societal processes and implications in addition to modeling the physical processes of floods and the use of structural protection measures.

Flood disaster risk is now seen as a result from the interaction of hazard, exposure and vulnerability, where hazard represents the probability and intensity of flooding; exposure describes the elements at risk (the people and their assets that may be affected by flooding); and vulnerability describes the susceptibility or propensity of elements at risk to be adversely affected.

It is taken for granted that changes in climate or human interventions in catchments and river systems may change flood hazard and, as a consequence, flood risk. Within this view, floods are evaluated from a hazard perspective, focusing on hydrologic/hydraulic parameters such as discharge, water level or inundation extent. Societal processes are often neglected, which implicitly means they are assumed to be constant or, if random, a stationary process. However, some socio-economic processes, like population growth and economic development, may change at a faster pace than long-term physical changes (for example, the impacts of climate change on discharge), and exposure and vulnerability to floods can be highly dynamic.

Against this background, research in flood risk at DTU Environment focuses on developing new frameworks and methods for decision support on flood hazards as well as on studying interrelations between floods and climate.

Table 11, adapted from an international research project, where DTU Environment participated, contrasts the traditional narrow framing of floods with the broader perspective that is emerging from an improved understanding of the climatic context of flood generation.

Aspect	**Traditional View**	**Emerging Perspective**
	Understanding Climate – Flood Linkages	
Randomness	*Random:* floods are random events with flood magnitude quantified by a probability distribution.	*Causal:* flood occurrence and magnitude depend on a causal network of processes in atmosphere, catchment and river systems. A fraction of the flood variability is described by deterministic processes, e.g. by using climate information as co-variates in flood probability distributions.
Spatial perspective	*Local:* floods are events that can be described fully by processes on a catchment scale.	*Global:* floods occur within the spatial framework of large-scale circulation patterns and global climate mechanisms.
Natural variability and floods	*Stationary:* flood characteristics are stationary and represent the long-term natural variability of the climate-catchment system.	*Time-varying:* flood characteristics change in time due to climate variability at different time scales.
Temporal perspective	*Recent:* flood characteristics result	*Long-term:* flood characteristics

	from current catchment characteristics and are derived from recent observations.	result from the long-term interplay of climate, geology, topography, vegetation (biology), and humans. To fully understand floods, this long-term interplay is to be disentangled.
	Exploiting climate-flood linkages	
Flood estimation	*Process-neutral:* flood estimation does not differentiate between different flood event types and processes. Flood frequency analysis is based on iid assumption.	*Process-based:* flood events of different types occur in a given catchment. Knowledge on flood generation processes provides information on flood probability estimation.
Flood projections under climate change	*Model chain:* flood scenarios are the result of model chains, from emission scenarios to climate models to flood frequency estimation.	*Model-chain-augmented:* in addition to model chains, a range of approaches for assessing climate-related flood changes are used, such as assessing historical climate variability, or using ocean source-atmospheric moisture transport-flood linkages.
Flood risk management	*Hazard-focused, static:* flood management focuses on flood hazard reduction within a static framework, principally using structural or zoning flood proofing or financial instruments (insurance).	*Risk-oriented, dynamic:* risk management takes into account changing hazard, exposure and vulnerability, and the combined application of financial, structural and non-structural measures. The best way to mitigate floods depends on how well changes in flood risk can be predicted at short and long time scales.

Table 11 Contrasting traditional views with emerging perspectives on flood hazard and risk (Merz, B., et al. 2014)

Another study undertaken at the department concerns the development of a risk-based decision making framework for flood management, using a Bayesian network methodology. In this study it is argued that the traditional assessment of flood risk, based on single hazard events is inappropriate in the context of climate change, and that the risk assessment should be extended to consider several hazards and their possible simultaneous occurrence. Further, it is argued that there is a need to include additional drivers of extreme events into a risk assessment in order to obtain a robust description of the occurrence of these events.

A Bayesian Influence Diagram (ID) for risk-based decision-making purposes in flood management was developed, which shows how the method includes several hazards in the assessment and provides a flexible way to assess the benefits of different adaptation measures.

The construction of a BN starts with defining a graphical depiction of the causal dependencies between variables within the system being studied. Variables in the system are presented as elliptical nodes, called chance nodes. The dependencies between the nodes are presented as arrows, and the direction of the arrow defines the dependency. In risk assessments the system at risk can be complex, and the graphical representation is, therefore, an effective means to communicate the system at risk for involved stakeholders, decision-makers and experts and encourages to a critical discussion of the system configuration.

Once the system configuration has been agreed on, input data are added to each node. Input data to BNs are added as so called Conditional Probability Tables (CPTs) in which the domain of all possible states taken by that node is listed together with probabilities of these states conditional to the parent nodes. Input data to CPTs can be gathered from numerous sources; from expert opinions and statistical data analyses, and from various research fields. This makes BNs highly suitable for multi-disciplinary studies such as flood risk management.

When CPTs are set in the system, the posterior probability distributions are compiled using the Bayesian theorem according to the so-called chain-rule. Once the network is compiled, Bayesian inference can be performed, i.e. the posterior probabilities of the nodes in the network are computed when values of other nodes are observed and entered as evidence. When new evidence is entered the posterior probabilities are updated. A BN provides automatically a description of the uncertainty in the system, since each variable is defined as a probability distribution.

If the network only contains variables related to the system process, it is known as a Bayesian Network (BN). A Bayesian Influence Diagram (ID) is a BN that also contains nodes with actual decisions (decision nodes) and the costs and benefits (utility nodes) of those decisions. An ID does not only model the system process but also how decisions affect those processes and how the expected change affects the loss or payoff. Hence, an ID as a decision-making tool can adapt to change, re-assess the process when new evidence is gathered, and estimate the costs and benefits necessary for decision-making within flood risk management. The network is presented in Figure 9 and is divided into two parts 1) Risk assessment BN and 2) Decision-making extension.

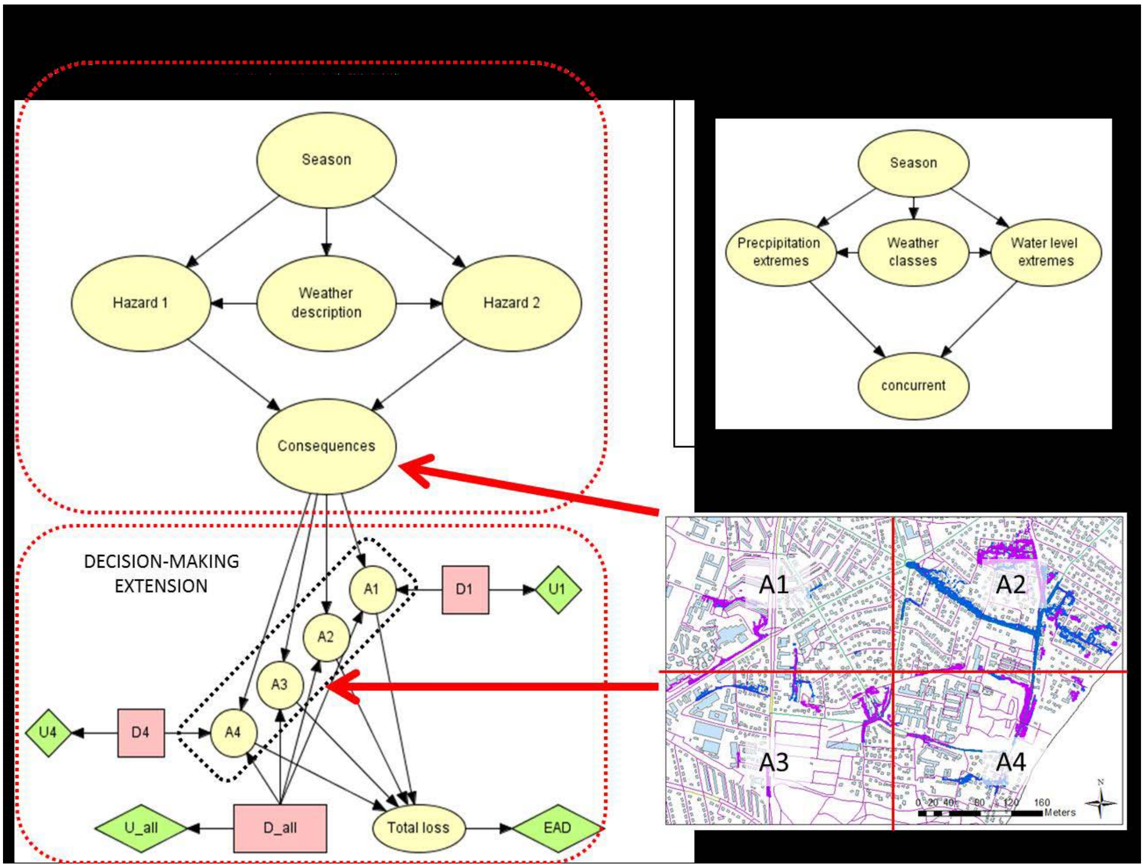

Fig. 9 Layout of the Bayesian Influence diagram for decision-making based on a risk assessment of several hazards (Åström et al. 2014)

4. Data and metrics

Physicochemical Data

The following data on substance identity are collected:

IUPAC name
structural formula
CAS registry number
EINECS number
chemical formula
SMILES code

Data on physicochemical parameters is collected as they provide information on the behavior of the compound in the environment:

molecular weight: *M*w, (g.mol-1)
melting point: *T*m, (°C)
boiling point: *T*b, (°C)
vapor pressure: *P*v (Pa)
Henry's law constant: *H* (Pa.m3.mol-1)
water solubility: *S*w (mg.L-1)
dissociation constant: p*K*a (-)
n-Octanol/water partition coefficient: *K*ow (-)
soil/sediment water partition coefficient: *K*p, (L.kg-1)

After evaluating a study, the results of the study are summarized by entering these into the appropriate data table (Table 5). The structural formula of the compound is also placed in this table.

Properties	**Value**	**Reference**
IUPAC Name		
Structural formula		
CAS number		
EINECS number		
Chemical formula		
SMILES code		
Molecular weight (g.mol-1)		
Melting point (°C)		
Boiling point (°C)		
Vapour pressure (Pa)		
Henry's law constant (Pa.m3.mol-1)		
Water solubility (mg.L-1)		
p*K*a		
n-Octanol/water partition coefficient (log *K*ow)		
Soil or sediment/water sorption coefficient (log *K*oc)		
Soil or sediment/water sorption coefficient (log *K*p)		
Suspended matter/water partition coefficient		

Table 5 Overview and default table structure for identity- and physicochemical parameters listed for each compound

Toxicity Data

Ecotoxicity studies conducted in all compartments are searched for: freshwater, seawater, brackish water, groundwater (usually no data), soil, sediment and air. In the case that secondary poisoning should be assessed, toxicity data for birds and mammals should be collected.

Aquatic toxicity data

The following 17 parameters are reported in the aquatic toxicity data tables for acute, chronic, freshwater and marine data. (Table 6)

Parameter	Explanation/Example
Species	**e.g. Bacteria** *Pseudomonas putida*, **Algae** *Chlorella vulgaris*, **Crustacea** *Daphnia pulex*
Species properties	e.g.age, size,weight, life stage or larval stage
Analyzed	Yes/No, i.e. whether the test compound is analyzed during the experiment
Test type	**S** static system **Sc** static system in closed bottles or test vessels **R** renewal system (semi-static) **F** flow-through system **CF** continuous flow system **IF** intermittent flow system
Test compound	can be deleted when the compound has only one structural molecular configuration
Purity	In % unit ag analytical grade lg laboratory grade pa pro analyse rg reagent grade tg technical grade
Test water	the test water or medium **am** artificial medium, such as media used for bacterial and algal tests **dtw** dechlorinated tap water **dw** de-ionised water, dechlorinated water or distilled water **nw** natural water, such as lake water, river water, sea water, well water **rw** reconstituted water: (natural) water with additional salts **rtw** reconstituted tap water: tap water with additional salts **tw** tap water
pH	If a pH range is given, this range is reported
Temperature	The temperature in °C at which the test is performed
Hardness	In mg CaCO3.L^{-1} (only for fresh water experiments, not marine)
Salinity	In % (only for saltwater experiments)
Exposure time	The duration of exposure to the toxicant in the toxicity experiment
Criterion	e.g. EC10, LC10, EC50, ECx, LCx, LC50,LOEC, NOEC, MATC
Test endpoint	The toxicological parameter for which the test result is obtained, e.g. • growth (weight, length, growth rate, biomass) • number (cells, population) • mortality • immobilization • reproduction • hatching (rate, time, percentage) • sex ratio • development (egg, embryo, life stage) • malformations (teratogenicity) • proliferation (cells)
Value	The unit in which the results of toxicity tests are expressed in mg.L^{-1}, µg.L^{-1} (optional)
Validity	A number (1, 2, 3 or 4), indicating the quality of the study summarized.
Notes	References to footnotes that are listed below the toxicity data tables
Reference	The reference to the study from which data are tabulated

Table 6 Parameters in aquatic toxicity data tables

Terrestrial and sediment toxicity data

The following parameters are reported in the toxicity data tables on acute and chronic toxicity data for terrestrial and benthic species and on terrestrial microbial processes and enzymatic reactions.

Parameter	**Explanation/Example**
Species/process/enzymatic activity	**Enzymatic activity**: Amylase Dehydrogenase Phosphatase Urease, etc. **Microbial processes**: Ammonification Nitrification Respiration, etc.
Species properties	e.g.age, size,weight, life stage or larval stage
Soil/sediment type	e.g. sandy loam, clay for soils; for sediments: fine sandy or organic rich, muddy.
Analyzed	Yes/No, i.e. whether the test compound is analyzed during the experiment
Test compound	can be deleted when the compound has only one structural molecular configuration
Purity	In % unit **ag** analytical grade **lg** laboratory grade **pa** pro analyse **rg** reagent grade **tg** technical grade
pH	the pH or the range of pH values, of the test soil or sediment
Organic matter (om)	the weight percentage of organic matter in the soil or sediment
Clay	the weight percentage of clay in the soil or sediment
Temperature	The temperature in °C at which the test is performed
Exposure time	The duration of exposure to the toxicant in the toxicity experiment
Criterion	e.g. EC10, LC10, EC50, ECx, LCx, LC50,LOEC, NOEC, MATC. In addition, in terrestrial ecotoxicology, microbial processes are often studied. In studies submitted in the pesticide registration framework, two concentrations are usually tested in such studies: one equal to and another one 10 times the application rate in the field.
Test endpoint	The toxicological parameter for which the test result is obtained, e.g. • growth (weight, length, growth rate, biomass) • number (cells, population) • mortality • immobilization • reproduction • hatching (rate, time, percentage) • sex ratio • development (egg, embryo, life stage) • malformations (teratogenicity) • proliferation (cells)
Result test soil/sediment	In mg.kg^{-1}, µg.kg^{-1} - the result as obtained in the experiment, expressed in weight units per kg dry weight of the test soil

Result standard soil/sediment	In $mg.kg^{-1}$, $\mu g.kg^{-1}$ - the result **recalculated** into weight units per kg of standard soil or sediment
Validity	A number (1, 2, 3 or 4), indicating the quality of the study summarized.
Notes	References to footnotes that are listed below the toxicity data tables
Reference	The reference to the study from which data are tabulated

Table 7 Parameters in terrestrial and sediment toxicity data tables

Bird and Mammal Toxicity Data

When secondary poisoning is assessed, results from toxicity studies with birds and mammals are tabulated in separate tables. (Table 8) Data on bioconcentration and biomagnification is collected as well.

Parameter	**Explanation/example**
Species	Same as aquatic data
Species Properties	e.g.age, size,weight, life stage
Product or Substance	Toxicity studies on birds or mammals may also be carried out with formulations or products rather than individual substances. Name of the substance, product of formulation that has been used
Purity or a.i. content	In the case that a product (or formulation) is tested, the content of active ingredient (a.i.) present in the product, expressed in %
Application route	Relevant are those toxicity tests in which the animals are dosed orally. This might be achieved via a direct method (intubation, gavage) or by dosing via the food or water. E.g.: • intubation • gavage • capsule • diet • water • feeding solution
Vehicle	A carrier used to dose the test substance to the test animals
Test duration	The total duration of the test (test duration might be the same or longer than the exposure time)
Exposure time	The duration of exposure to the toxicant in the toxicity experiment
Criterion	Short term toxicity tests will either yield an LC50 ($mg \cdot kgfood^{-1}$) or an LD50 ($mg \cdot kg\ bw^{-1} \cdot d^{-1}$ in the case of repetitive dosing). Long-term toxicity tests will generally result in a NOEC (no observed effect concentration in diet; $mg \cdot kgfood^{-1}$), or a NOEL (no observed effect level in a dosing study; $mg.kgbw^{-1}.d^{-1}$).
Test endpoint	Screening for clinical parameters at haematological, histopathological or biochemical level is common in these types of tests. E.g. relevant endpoints: • body weight • egg production • eggshell thickness • hatchability • hatchling survival

	• histopathological findings • mortality • reproduction • viability (percentage of viable embryos per total number of eggs)
Value from repetitive oral dosing studies	From short term toxicity experiments with repetitive dosing on consecutive days (5 d LD50 for birds) and long-term oral dosing studies, a value expressed in $mg.kgbw^{-1}.d^{-1}$
Value from diet studies	The results of toxicity tests in which the substance of interest is administered via the food are expressed in $mg.kg_{food}^{-1}$. The results of dietary studies (viz. LC50 or NOEC values) are reported here.
Validity	A number (1, 2, 3 or 4), indicating the quality of the study summarized.
Notes	References to footnotes that are listed below the toxicity data tables
Reference	The reference to the study from which data are tabulated

Table 8 Parameters in bird and mammal toxicity data tables

Bioconcentration and Biomagnification Data

In principle, the evaluation of bioaccumulation data follows the evaluation for toxicity to a large extent. All retrieved literature is read and evaluated with respect to its usefulness and reliability. The most relevant BCF studies are those performed with fish. BCF studies performed with molluscs are important for secondary poisoning as well. BCF data for other species should be carefully checked because they are prone to experimental errors. The accumulation may not reflect uptake but adsorption to the outside of the organism. For this reason, BCF values for algae should be regarded as unreliable.

The following parameters are reported in the BCF data tables. (Table 9)

Parameter	**Explanation/Example**
Species	Same as aquatic data
Species properties	Same as aquatic data
Test substance	Information on what compound is used. If a radiolabelled compound is used
Substance purity	Same as aquatic data
Analyzed	Similar to the toxicity data tables, a column in the BCF data table is included that gives information on the analysis of both the aqueous phase and biological material. However, as the determination of the water and biota concentration is a prerequisite of any good BCF study, this column should give information on how the concentration is determined, not on whether the concentration is determined
Test type	Same as aquatic data
Test water	Same as aquatic data
pH	Same as aquatic data
Hardness/Salinity	Same as aquatic data
Temperature	Same as aquatic data
Exposure Time	the times of the uptake phase and, if carried out, the depuration phase
Exposure concentration	The concentration at which the BCF study is performed
BCF	The basis for the BCF value is the ratio of the concentration in wet weight (ww) of the organism, mostly fish, divided by the water concentration. The unit of the BCF is $L.kg_{ww}^{-1}$

BCF type	Information on what part of the organism the BCF has been determined for. Possibilities are (e.g.): whole fish ww, whole fish dw, edible parts, non-edible parts viscera, etc.
Method	Information on the method to calculate the BCF can be based on equilibrium concentrations or on kinetics
Notes	Notes may include information on the analysis, a deviating basis of the BCF value (dry weight or lipid weight) or the method used to determine the BCF
Reference	Same as aquatic data

Table 9 Parameters in BCF data tables

Human Toxicological Data

The human toxicological threshold values that can be used are the ADI (acceptable daily intake) and TDI (Tolerable Daily Intake). The U.S. ATSDR uses the term MRL (minimum risk level) while the U.S. EPA uses the term RfD (reference dose). The basis for the human-toxicological threshold levels is in principle a NO(A)EL from a mammalian toxicity study, which is useful as well if established threshold levels are unavailable. However, the NOAEL is not a human toxicological threshold limit. To derive a TDI or ADI from a NOAEL a human toxicologist should be consulted in any case.

A human toxicological threshold value is needed primarily for three purposes:

− in the derivation of the $MPC_{hh\ food,\ water}$ (for consumption of fishery products)

− in the derivation of the $MPC_{dw,\ water}$ (for drinking water)

− in the derivation of the $MPC_{human,\ comp}$ (for exposure via soil, via multiple routes).

Table 10 lists the parameters needed to calculate $MPC_{human,\ soil}$ values.

Parameter	**Name/Description**	**Unit**
M_w	molecular weight (only needed when a value for *H* is absent)	[g.mol^{-1}]
P_v	vapour pressure (only needed when a value for *H* is absent)	[Pa]
S_w	water solubility	[mg.L^{-1}]
H	Henry coefficient	[Pa.m3.mol^{-1}]
K_{ow}	*n*-octanol water partition coefficient	[-]
K_{oc}	organic carbon normalised partition coefficient	[L.kg-1]
MPC_{human}, TDI, ADI or similar	maximum permissible concentration for humans	[µg.kgbw^{-1}.d^{-1}]

Table 10 Parameters required to calculate $MPC_{human,\ comp}$

Physicochemical metrics

ACR	Acute to Chronic Ratio
ADI	Acceptable Daily Intake
AF	Assessment Factor
BAF	Bioaccumulation Factor
BCF	Bioconcentration Factor
BMF	Biomagnification Factor
EAC	Environmentally Acceptable Concentration
EHC	Environmental Health Criteria
ERL	Environmental Risk Limit
LC_x	Effect concentration at which x% lethality is observed, generally LC50 and LC10 are calculated
LD50	Dose that is lethal to 50% of the tested animals
LOEC	Lowest Observed Effect Concentration
MAC	Maximum Acceptable Concentration
MATC	Maximum Acceptable Toxicant Concentration
MPA	Maximum Permissible Addition
MPC	Maximum Permissible Concentration
MRL	Minimum Risk Level
NA	Negligible Addition
NC	Negligible Concentration
NOEAEC	No Observed Ecologically Adverse Effect Concentration
NOAEL	No Observed Adverse Effect Level
NOEL	No Observed Effect Level
PEC	Predicted Environmental Concentration
PNEC	Predicted No Effect Concentration
QSAR	Quantitative Structure Activity Relationship
SRA_{eco}	Ecotoxicological Serious Risk Addition
SRC_{eco}	Ecotoxicological Serious Risk Concentration
TCA	Tolerable Concentration in Air
TDI	Tolerable Daily Intake
TL	Threshold Level

5. Research topics

Research at DTU Environment is organized according to four research sections: Environmental Chemistry, Residual Resource Engineering, Urban Water Engineering, and Water Resources Engineering. Research specifically related to risk is undertaken in four different areas: Chemicals, Ground- and surface water, Microorganisms in Water, and Floods. (Fig. 10) Each area is described in detail in section 3.

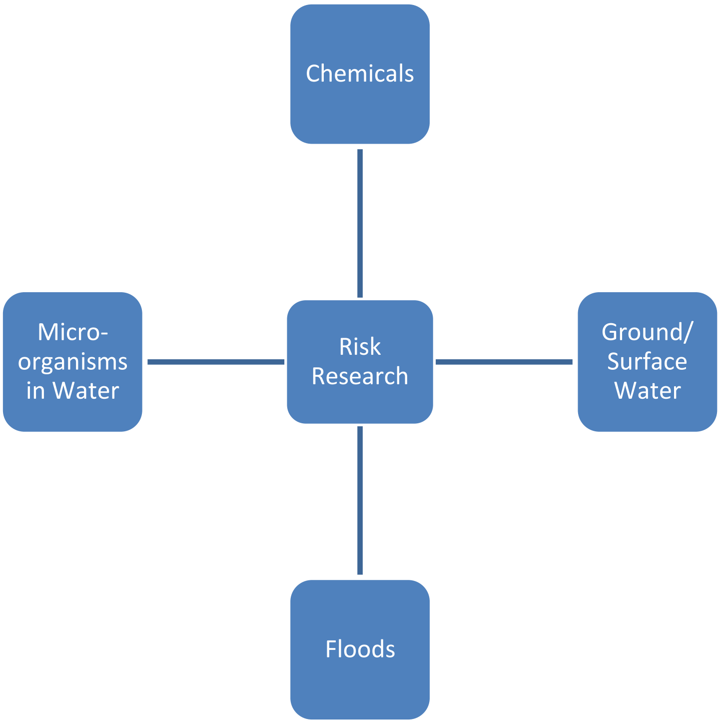

Fig 10 Risk Research areas at DTU Environment

6. Research Networks

(no information could be collected)

7. Advisory Activities

(no information could be collected)

8. Educational offerings

DTU Environment offers the following researched-based programs:

- Bachelor programme in Environmental Engineering (3 years/180 ECTS). The program requires Danish language skills. The program starts in September every year.
- Master programmes in Environmental Engineering (2 years/120 ECTS). The programmes are fully taught in English. The programmes start in September every year.
- 3 Years PhD Program - English instruction
- Continuing Education (in Danish)
  Combined degrees with other universities

The department also contributes to for instance the MSc programme at the Sino Danish Centre in Beijing and the elite MSc programme Environmental Chemistry and Health at University of Copenhagen.

Table 11 lists all courses related to risk at DTU Environment, together with a brief outline of their content. This information was collected through DTU *Kursusbasen* by performing a search for the following keywords: *risk, safety, uncertainty, life cycle, sustainability, and decision analysis*.

Course Nr./ Keyword	**Title**	**Content**	**Type**
12236 risk	Environmental and human health risk assessment of chemicals	Exposure scenarios, principles of the exposure and effect assessments of chemicals substances in the context of EU risk assessments. Principles for setting limit values in the environment and for human health. EU guidelines for chemical risk assessment. Methods for effect and exposure assessment of chemicals.	MSc
12237 risk	Chemicals in the environment	Fundamental concepts and terms in environmental toxicology, chemistry and risk assessment. Environmental exposure and effect assessment of organic chemicals. Classification and assessment chemicals in accordance with regulatory guidelines for environmental risk assessment	MSc
12240 risk	Environmental management and ethics	Basic principles of environmental management approaches: Command and control, consensus, economic tools and ethics. Basic theory of ethics, emphasis on environmental ethics. Introduction to environmental economics. The mass flow of matter in society and analysis of regulatory options. Challenging case studies. Cause-effect relationships and environmental impact assessment. The role of philosophy, science and engineering. Determinism, uncertainty, ignorance and indeterminacy. Wicked problems. Technical and chemical risk management. The precautionary principle. The climate challenge -	MSc

		mitigation and adaptation. The role of the specialist and ethical dilemmas. Interpretation of sustainability	
12330 risk	Contaminated sites	Sources to soil and groundwater pollution. Transport, attenuation and degradation of organic pollutants. Soil and groundwater chemistry of heavy metals. Methods for site investigation and risk assessment. In situ and ex-situ technologies for remediation of polluted soil and groundwater with special focus on thermal methods and microbial/abiotic degradation processes.	MSc
12331 risk	Field investifations of contaminated sites	Practical knowledge of planning, sampling and field analysis of soil, groundwater and air useful for investigations and risk assessment at contaminated sites.	MSc
12600 risk	Nanotechnology and the Environment	Present knowledge environmental and human health issues related to nanomaterials. Process of environmental and human health risk assessment (hazard identification, hazard assessment, risk characterization. Apply the theoretical knowledge from this course to analyse toxicity data relevant to risk assessment of a case-study nanomaterial. Evaluate the risks of the case-study application of nanomaterials and suggest potential risk management and risk reduction measures.	MSc
12104 uncertainty	Modelling of Environmental Processes and Technologies	Modelling of aquatic chemistry including gas equilibration in aquatic systems, ion exchange and sorption, redox processes, partial equilibrium, chemical kinetics; environmental statistics including uncertainty assessment, parameter optimisation, sensitivity analysis and stochastic modelling; environmental models based on coupled ordinary and partial differential equations including modelling of mass and energy conservation and reactive transport, and models of microbial processes; programming in MATLAB and MULTIPHYSICS	MSc
12104 uncertainty	LCA – Modeling of Waste Management Systems	Modeling approach to waste quantities, waste composition, collection, transport, source separation, mechanical sorting, incineration, composting, anaerobic digestion, landfilling, energy utilization, material recycling and material utilization. Brief summary of approach and methods in LCA. Introduction to the EASETECH model. Hand-on assignments in using EASETECH. Definition of waste management systems. Modeling of waste management systems. Interpretation of results, uncertainty analysis and communication of results.	MSc
12342 uncertainty	Uncertainty and Variability in	Decomposition of runoff time series and description of their deterministic and stochastic	MSc

	Hydrologic Applications	components. Stochastic models for description of extreme hydrological events.	
12902 uncertainty	Life Cycle Assessment Modelling of Solid Waste Systems – Application of the EASETECH Model	Apply knowledge in the definition and assumptions of waste LCA. EASETECH model. Energy flows in waste management. Sensitivity analysis and uncertainty, interpreting and communicating LCA results.	PhD
12139 Life cycle	Ressource Engineering	The course provides an overview of resource definitions, resource availability, depletion, criticality and functionality, typical resource flows in society, key economical aspects of resource management, challenges related to resource recovery, as well as introduces three engineering tools: resource criticality, exergy and statistical entropy analysis for evaluation of resources in technological and urban systems.	BSc MSc
12500 Life cycle	Energy Resources	Energy balance, energy economics, coal, hydrocarbons, geothermal energy, nuclear power, bio energy, wind- sun- and wave energy, fuel cells, air pollution, life cycle analysis.	MSc
12333 Decision analysis	Water Resources Management	Key elements of a river basin water resources system: Resources (rivers, lakes, aquifers), water users (irrigation agriculture, industry, domestic), institutions (governments, cooperatives, water rights). Model water resources and water users in the river basin. Quantitatively determine the spatially and temporally variable water availability and the water demand by various users. Design policy scenarios for water resources management and allocation and evaluate the scenario results with respect to environmental sustainability, economic efficiency and social equity.	MSc
12918 Decision analysis	Modelling of integrated urban drainage-wastewater systems	Introduction to integrated modelling concepts. Conceptual hydraulic modelling. Conceptual modelling of transport and fate of macropollutants (TSS, nutrients) and micropollutants. Utilization of the WEST® Integrated Urban Wastewater System model library. Application of integrated models for fulfilling the EU Water Framework Directive. How to find the compromise between data requirements and actual data availability. Use of integrated models for decision support and scenario evaluation. Evaluation of the effects of climate change. Brief overview of approaches for evaluating uncertainty in model results. Brief overview of water-quality based approaches to real time control of urban drainage and wastewater systems.	PhD

Table 11 Courses at DTU Environment explicitly and implicitly related to risk

9. Data sources

Personal interview with Anders Baun, Professor, Head of Environmental Chemistry Section DTU Environment

Anders Baun Professor in Risk Assessment of Nanomaterials Head of Environmental Chemistry Section abau@env.dtu.dk Special Interests: Environmental Chemistry, Nanomaterials, Risk assessment, Ecotoxicology	

Andersen, S.T., Mark, O. and Albrechtsen, H.-J., *Quantitative microbial risk assessment of the impacts of flooded basements in urban areas by combining quantitative microbial data with hydrological software*, part of the Storm and wastewater Informatics (SWI) project, partly funded by the Danish Agency for Science, Technology and Innovation

Flemström, K., Carlson, R. and Erixon, M., *Relationship between Life Cycle Assessment and Risk Assessment: Potentials and Obstacles*, Swedish Environmental Protection Agency Report nr. 5379, June 2004

Godskesen, B., *Sustainability evaluation of water supply technologies – by using life-cycle and freshwater withdrawal impact assessment & multi-criteria decision analysis*, PhD Thesis, DTU Environment, 2012

Grieger, H.G., *Understanding and Assessing Potential Environmental Risks of Nanomaterials: Emerging Tools for Emerging Risks*, PhD Thesis, DTU Environment 2011

Groundwater protection: Principles and practice (GP3), Environmental Agency, UK, 2013

Hansen, S.F., *Regulation and Risk Assessment of Nanomaterials – Too Little, Too Late?,* PhD Thesis, DTU Environment 2009

Lemming, G., *Environmental assessment of contaminated site remediation in a life cycle perspective*, PhD Thesis, DTU Environment, 2010

Merz, B. et al.: *Floods and climate: emerging perspectives for flood risk assessment and management*, Nat. Hazards Earth Syst. Sci., 14, 1921–1942, 2014

Moser, D.A., *Flood Risk Terminology for National Flood Risk Characterization Workshop*, USACE Chief Economist and Dam and Levee Safety Policy and Procedures Teams, Draft version, 2014

Note on Environmental Risk Assessment, Environment, Health and Safety Committee (EHSC) of the Royal Society of Chemistry, 2013

Risikovurdering af overfladevand, som er påvirket af punktkildeforurenet grundvand, Miljøprojekt nr. 1575, 2014

Troldborg, M., *Risk assessment models and uncertainty estimation of groundwater contamination from point sources*, PhD Thesis, DTU Environment 2010

van Vlaardingen, P.L.A. and Verbruggen, E.M.J. , *Guidance for the derivation of environmental risk limits within the framework of 'International and national environmental quality standards for substances in the Netherlands (INS)*', RIVM report 601782001/2007

Værktøjer til brug for risikovurdering og prioritering af grundvandstruende forureninger, Miljøprojekt Nr. 1366 2011, Teknologiprogrammet for jord- og grundvandsforurening, Miløstyrelsen

Åström, H.L.A., et al., *Describing Concurrent Flood Hazards in a Risk Assessment Decision Framework Using a Bayesian Network Methodology,* 13th International Conference on Urban Drainage, Sarawak, Malaysia, September 2014

DTU Environment website

10. Glossary of risk-related terms in environment

General Concepts

risk	The probability of an adverse effect in an organism, system, or (sub)population caused under specified circumstances by exposure to an agent. (IPCS/OECD 2004) The expected frequency or probability of undesirable effects resulting from exposure to known or expected stressors. (EPA)
hazard	Inherent property of an agent or situation having the potential to cause adverse effects when an organism, system, or (sub)population is exposed to that agent. (IPCS/OECD 2004) The likelihood that a substance will cause an injury or adverse effect under specified conditions. (EPA) **'Hazardous substance':** CERCLA defines a hazardous substance as "(A) any substance designated pursuant to section 1321(b0(2)(A) of Title 33, (B) any element, compound, mixture, solution or substance designated pursuant to section 9602 of this title, (C) any hazardous waste having the characteristics identified in under or listed pursuant to section 3001 of the Solid Waste Disposal Act (but not including any waste the regulation of which the Solid Waste Disposal Act has been suspended by Act or Congress), (D) any toxic pollutant listed under section 1317(a) of Title 33, (E) any imminently hazardous chemical substance or mixture with respect to which the (EPA) Administrator has taken action pursuant to section 2606 of Title 15. The term does not (within the context of CERCLA) include petroleum, crude oil or any fraction thereof which is not otherwise specifically listed or designated as a hazardous substance (by CERCLA)...The term (hazardous substance) does not include natural gas, natural gas liquids, liquified natural gas, or synthetic natural gas usable for fuel (or mixtures of natural gas and such synthetic gas).
Exposure scenario	A set of conditions or assumptions about sources, exposure pathways, amounts or concentrations of agent(s)involved, and exposed organism, system, or (sub)population (i.e., numbers, characteristics, habits) used to aid in the evaluation and quantification of exposure(s) in a given situation. (IPCS/OECD 2004) A set of assumptions concerning how an exposure takes place, including assumptions about the exposure setting, stressor characteristics, and activities of an organism that can lead to exposure. (EPA)
Exposure	Concentration or amount of a particular agent that reaches a target organism, system, or (sub)population in a specific frequency for a defined duration. (IPCS/OECD 2004) The contact or co-occurrence of a stressor with a receptor. (A stressor is any physical, chemical, or biological entity that can induce an adverse response. A receptor is an ecological entity exposed to the stressor.) (EPA)
Effect/Impact	**'Effect':** Change in the state or dynamics of an organism, system, or (sub)population caused by the exposure to an agent. (IPCS/OECD 2004)

	'Effect assessment': Combination of analysis and inference of possible consequences of the exposure to a particular agent based on knowledge of the dose–effect relationship associated with that agent in a specific target organism, system, or (sub)population. (IPCS/OECD 2004) **'Primary effect'**: An effect where the stressor acts on the ecological component of interest itself, not through effects on other components of the ecosystem. **'Indirect effect' or 'Secondary effect'**: An effect where the stressor acts on supporting components of the ecosystem, which in turn have an effect on the ecological component of interest. (EPA) **'Environmental Impact Assessment':** evaluates the environmental consequences of proposed actions. It describes baseline environmental conditions; the purpose of, need for, and consequences of a proposed action; the no-action alternative; and the consequences of a reasonable range of alternative actions. A separate risk assessment could be prepared for each alternative, or a comparative risk assessment might be developed. However, risk assessment is not the only approach used in EIAs. (EPA) **'Life cycle sustainability assessment (LCSA)'**: refers to the evaluation of all environmental, social and economic negative impacts and benefits in decision making processes towards more sustainable products throughout their life cycle. (UNEP/SETAC, 2011) **'Life cycle impact assessment':** phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product. (ISO 2006) **'Social and socio-economic life cycle assessment (S-LCA)':** a social impact (real and potential impacts) assessment technique that aims to assess the social and socio-economic aspects of products and their positive and negative impacts along their life cycle encompassing extraction and processing of raw materials; manufacturing; distribution; use; reuse; maintenance; recycling; and final disposal. (UNEP/SETAC, 2009)
Model	A mathematical function with parameters that can be adjusted so the function closely describes a set of empirical data. A mechanistic model usually reflects observed or hypothesized biological or physical mechanisms, and has model parameters with real world interpretation. In contrast, statistical or empirical models selected for particular numerical properties are fitted to data; model parameters may or may not have real world interpretation. When data quality is otherwise equivalent, extrapolation from mechanistic models (e.g., biologically based dose-response models) often carries higher confidence than extrapolation using empirical models (e.g., logistic model). (EPA 2011)

Terms related to Risk Assessment

Risk assessment	The evaluation of scientific information on the hazardous properties of environmental agents (hazard characterization), the dose-response relationship (dose-response assessment), and the extent of human exposure to those agents (exposure assessment). The product of the risk assessment is a statement regarding the probability that populations or individuals so exposed will be harmed and to what degree (risk characterization). (EPA 2011) A process intended to calculate or estimate the risk to a given target organism, system, or (sub)population, including the identification of attendant uncertainties, following exposure to a particular agent, taking into account the inherent characteristics of the agent of concern as well as the characteristics of the specific target system. The risk assessment process includes four steps: hazard identification, hazard characterization (related term: *Dose–response assessment*), exposure assessment, and risk characterization. It is the first component in a risk analysis process. (IPCS 2004)
Baseline risk assessment	A baseline risk assessment is an assessment conducted before cleanup activities begin at a site to identify and evaluate the threat to human health and the environment. After remediation has been completed, the information obtained during a baseline risk assessment can be used to determine whether the cleanup levels were reached. (EPA 2011)
Ecological risk assessment	The application of a formal framework, analytical process, or model to estimate the effects of human actions(s) on a natural resource and to interpret the significance of those effects in light of the uncertainties identified in each component of the assessment process. Such analysis includes initial hazard identification, exposure and dose-response assessments, and risk characterization. (EPA 2011)
Cumulative ecological risk assessment	A process that involves consideration of the aggregate ecological risk to the target entity caused by the accumulation of risk from multiple stressors. (EPA 2011)
Hazard identification	The identification of the type and nature of adverse effects that an agent has an inherent capacity to cause in an organism, system, or (sub)population. Hazard identification is the first stage in hazard assessment and the first of four steps in risk assessment. (IPCS 2004)
Hazard characterization	The qualitative and, wherever possible, quantitative description of the inherent property of an agent or situation having the potential to cause adverse effects. This should, where possible, include a dose–response assessment and its attendant uncertainties. (IPCS 2004)
Exposure assessment	Evaluation of the exposure of an organism, system, or (sub)population to an agent (and its derivatives). (IPCS 2004)
Risk Characterization	The qualitative and, wherever possible, quantitative determination, including attendant uncertainties, of the probability of occurrence of known and potential adverse effects of an agent in a given organism, system, or (sub)population, under defined exposure conditions. (IPCS 2004)
Uncertainty	Uncertainty occurs because of a lack of knowledge. It is not the same as variability. For example, a risk assessor may be very certain that different people drink different amounts of water but may be uncertain about how much variability there is in water intakes within the population. Uncertainty can often be reduced by collecting more and better data, whereas variability is an inherent property of the population being evaluated. Variability can be better

	characterized with more data but it cannot be reduced or eliminated. Efforts to clearly distinguish between variability and uncertainty are important for both risk assessment and risk characterization. (EPA 2011) Imperfect knowledge concerning the present or future state of an organism, system, or (sub)population under consideration. (IPCS 2004)
Risk estimation	Quantification of the probability, including attendant uncertainties, that specific adverse effects will occur in an organism, system, or (sub)population due to actual or predicted exposure. (IPCS 2004)
Risk evaluation	Establishment of a qualitative or quantitative relationship between risks and benefits of exposure to an agent, involving the complex process of determining the significance of the identified hazards and estimated risks to the system concerned or affected by the exposure, as well as the significance of the benefits brought about by the agent. Risk evaluation is an element of risk management. Risk evaluation is synonymous with risk–benefit evaluation. (IPCS 2004)

Terms related to Flood Risk

risk	The likelihood and consequences that may arise from inundation by flood water. Flood risk is determined by the following components: flood load (magnitude and likelihood of the hazard); the performance or response of any flood defense system (e.g., levee system – if such is present) to the flood load; the exposure to flood water of the item(s) at risk that might be harmed by flood water (population, property, infrastructure, etc.); the vulnerability of the items at risk to harm from flood water; and the resulting measure of the harm, i.e., consequences that result from the flooding event (number of fatalities, economic damages, environmental impacts, etc.)
Flood risk assessment	A systematic, evidence-based approach to qualitatively and/or quantitatively describe one or more determinants or elements of flood risk for assets and people, and the expected effects of flood risk reduction actions on flood risk. Risk assessment includes explicit acknowledgment of the uncertainties in the risk.
Flood risk management	The mix of public sector government policies and programs that influence the decisions made by communities and individuals relating to floodplain location and their choice of actions to reduce flood risk and manage residual risk. The term also includes the decisions made by all levels of government and by individuals to implement actions to reduce flood hazard, exposure, and vulnerability as well as to increase resiliency. More generally risk management is the process of problem finding and initiating action to identify, evaluate, select, implement, monitor and modify actions taken to alter levels of risk, as compared to taking no action. The purpose of risk management is to choose and prioritize work required to reduce risk.
Residual flood risk	The level of flood risk for people and assets located in a floodplain that remains after implementation of flood risk reduction actions. Residual risk includes "transformed risk." Residual risk is often defined as the risk beyond the "level-of-protection" provided by hazard reduction infrastructure. However, level of protection refers only to the return frequency of a specific flood elevation, and so does not include all of the determinants of residual risk.
Transformed flood risk	The change in the nature of flood risk for some area associated with the presence of hazard reduction infrastructure. For example, the presence of a levee system can result in a more sudden inundation of a floodplain location if

	the levee breaches (with or without overtopping), thus increasing the vulnerability of exposed populations in that location.
Transferred flood risk	Change in flood risk (or financial costs) in one location due to a floodplain location and use choice and/or implementation of a risk reduction action in another location. Transferred risk occurs when floodplain location and use and/or risk reduction actions result in: 1) financial costs for risk reduction actions paid by another entity, such as from general tax revenues of a higher level of government instead of by the floodplain occupants; 2) induced flood hazard in another location, and; 3) diminution of natural functions of floodplains that adversely affect the well-being of others (e.g.,. reduction in recreational fishing success).
Flood resilience	The ability to avoid, minimize, withstand, and recover from the adverse effects of a flood.
Flood risk robustness	The ability of a system (physical, social, cultural or economic) to continue to operate correctly across a wide range of flood conditions, with minimal harm, alteration or loss of functionality, and to fail gracefully outside of that range. The wider the range of conditions included, the more robust the system.
Incremental consequences	The consequences for a leveed area attributed to the levee system in its existing condition is determined by subtracting the without breach flood risk from the flood risk with the levee performing in its existing condition (all failure modes and consequences assessed). As a manner of policy this difference is called the incremental consequences due to the presence of the levee system. Note that for a floodplain that is non-leveed, there is no infrastructure present to impede the flood hazard from inundating the floodplain, so there are no incremental consequences. In incremental consequences for a dam are defined in a similar manner.
Risk characterization	Risk characterization is the qualitative or quantitative description of the nature, magnitude and likelihood of the adverse effects associated with a hazard with and without a risk management action. A risk characterization often includes: one or more estimates of risk; risk descriptions; evaluations of risk management options; economic and other evaluations; estimates of changes in risk attributable to the management options.
Exposure assessment	Exposure occurs when a susceptible asset comes in contact with a hazard. An exposure assessment, then, is the determination or estimation (which may be qualitative or quantitative) of the magnitude, frequency, or duration, and route of exposure.
Uncertainty	Used to describe any situations without sureness, whether or not described by a probability distribution. In the context of flood risk, uncertainty can be attributed to (i) inherent variability in natural properties and events such as inherent variability in annual peak flood flows, and (ii) incomplete knowledge of parameters, variables, quantities and the relationships between them and the values of interest.
Individual risk	The increment of risk imposed on a particular individual by the existence of a hazardous facility. This increment of risk is an addition to the background risk to life, which the person would live with on a daily basis if the facility did not exist.
Societal risk	The risk of widespread or large scale detriment from the realization of a defined risk, the implication being that the consequence would be on such a scale as to provoke a socio/political response, and/or that the risk (that is, the likelihood combined with the consequence) provokes public discussion and is effectively regulated by society as a whole through its political processes and regulatory mechanisms. Such large risks are typically unevenly distributed, as are their

	attendant benefits.

Interview Questions with Anders Baun, Professor of Risk Assessment in Nanomaterials DTU Environment

1. There has been a gradual move in environmental management and policy from a hazard-based to a risk-based approach. This trend is observable in other fields such as natural hazards management, transport, national security, etc. What is the history and implications of this trend in the context of environment?

2. Environmental risk assessment may comprise Human health risk assessment, Ecological risk assessment and Applied industrial risk assessment. Is there a common framework for carrying out environmental risk assessment and what are the differences among the three types of risk assessment mentioned above? What is DTU's Environment research focus and priorities?

3. Are research/education/advisory activities at DTU Environment more focused on risk or on environmental impact assessment?

4. How are risk analysis, risk assessment and risk management defined in the context of environmental risk and what are the different components in each process? How can DTU Environment's competencies be described with regard to the different stages of the risk analysis process? And how does it interact with environmental impact assessment?

5. What qualitative and quantitative methods are used in the process of risk- and environmental assessment?

6. What qualitative and quantitative methods (and software) are used in the process of risk management with regard to identifying and evaluating risk management options? Is decision analysis incorporated? What are the risk acceptance criteria?

7. What data and metrics are typically used in environmental risk assessment? How is the data collected?

8. Are there common metrics for risk assessment and environmental impact assessment?

9. What research topics are covered at DTU Environment that have explicit or implicit relation to risk?

10. What current projects at DTU Environment have explicit relevance to risk research?

11. Which educational offers are there at DTU Environment with regard to risk assessment and/or risk management?
12. What percentage of DTU Environment scientific staff is involved in work directly related to the topic of risk as: a) their main activity; b) their supplementary activity?

13. How many PhD students are currently working on a topic related to risk? What are these projects?

14. EU-projects? Networks? Key research institutions? Key scientists?

15. In the context of research commissioned by public authorities or industry that includes risk assessment and/or risk characterization, is there an established risk communication strategy? What are the challenges in communicating results from risk studies?

16. What does DTU Environment perceive to be the main challenges with regard to the department's risk-related activities in terms of education, research and public/private advisory?

17. Where does DTU Environment see opportunities for collaboration with other DTU institutes with regard to the department's risk-related activities?

Appendix V: Risk at DTU Management Engineering

Table of Contents

1. Introduction: Risk in the context of DTU Management Engineering

DTU Management Engineering is based on the premise that in order to benefit society, it is not enough to develop new technology but also to implement it in new products and services. DTU Management Engineering's purpose is therefore to provide understanding of relevant frameworks at the individual, organizational and broader system level. The Department's core competence lies in developing and utilizing new knowledge about Systems Analysis, Production and Service Management, Management Science, and Technology and Innovation Management. It could be said that the study of risk is and is not both an inherent part of this field. It is, to the extent that all activities whether at the project/program, process or system level are subject to risk. It is not, to the extent that research activities are directed toward an applied level in various sectors and industries, as a result of which the perspective adopted on risk is the one that corresponds to the particular application field. For example, risk research at DTU Management is carried out in the context of risk assessment for major hazard accident in e.g. onshore and offshore installation, nuclear plants, etc.; in the context of occupational health and safety in e.g. the construction transport and health (hospital workers) sectors; in the context of operational project/program management in e.g. the energy sector; in the context of Operations Research and Operations Management with regard to financial engineering and supply chain risks; in the context of Development through the DTU-UNEP partnership with regard to climate change policy, conflict and political risk; and finally, in the context of Quantitative Sustainability Assessment and the newly established Global Decision Support Initiative, where research is focusing on combining methods from Life Cycle Assessment with risk assessment methodologies.

It is clear from the above that there is no common concept or framework for constitutes risk assessment, risk analysis and risk management; rather each research area is either adhering to best practice of the sector their research relates to, or are developing/have developed their own framework. The present report considers three areas, where risk research has been carried out in the Department: Major Accident Hazard and Occupational Health and Safety, Project Risk Management for large engineering project and Quantitative Sustainability Assessment. Not all three areas have been considered in equal detail due to the breadth, scope and sheer manpower involved in each respective area. Hence, a large part of this section of the report is devoted to Quantitative Sustainability Assessment, where about 30 scientific staff concentrate their work on the topic as opposed to a much smaller part dedicated to project risk management, where one person is only partly engaged in this activity. Regrettably, due to time constraints, other areas with smaller involvement in risk activities (Systems Analysis, Management Science and UNEP-DTU Partnership) have not been considered.

2. Risk Management Framework

There is no uniform risk management framework that is followed at DTU Management. In the context of Major Accident Hazard and Occupational Health as well as Risk Project Management, the ISO 31000 is typically referred to, though there is an acknowledgment that there are many other possible frameworks available. With regard to Risk Project Management, it was felt that a different framework to risk altogether, i.e. one based on quality management is better suitable. Some definitions of common concepts and processes related to risk assessment and risk management are provided in the appendices to this section.

Researchers in the area of Quantitative Sustainability Assessment are guided by the LCA framework outlined in the ILCD 2010 Guidebook. A very brief overview of this is given in section 3.3.

Researchers at the GDSI are yet to develop their own framework as activities there have only just commenced. Nevertheless, information on the scope and scientific basis of their activities are provided in section 3.4.

3. Research Areas related to Risk

3.1 Major Accident Hazard and Occupational Health and Safety

Research in this area is carried out by the Risk Research Group in the Production and Service Management division of the department. Major Accident Hazard analysis and Occupational Health and Safety are fundamentally linked in that both apply cause and consequence analysis to evaluate the probability of hazardous events and accidents to facilitate decision making with regard to prioritizing, organizing and establishing of safety and risk reduction measures. There are, however, a number of differences associated with these two domains. Major Accident Hazard analysis falls in the domain of Process Safety, which addresses major hazards that are more likely to result in major accidents with big consequences. Occupational safety addresses accidents involving personal safety at an individual level with small consequences. Process safety deals with mitigating big accidents such as fire, explosions, pollution, etc., whereas occupational health and safety mitigates small accidents such as cuts, burns, broken bones, etc.

Process safety accidents happen at a lower frequency; occupational safety incidents happen at a higher frequency. With regard to risk management, this implies that often a proactive approach to safety would focus on the highest occurrences of accidents rather than on the most serious ones.

Process safety protects workers and the public alike; occupational safety protects workers. The consequences of not implementing process safety can thus be far reaching, involving a number of third parties. This also has implications for the public perception of risks and subsequent integration of societal preferences into risk acceptance criteria.

Process safety considers the consequences of accidents at the human, environmental and business level; occupational safety considers consequences at a human level only.

Process safety focuses on changing system design in which behavior occurs rather than bringing in new equipment; occupational safety focusing on changing an individual's behavior.

Finally, with regard to implementation of risk control measures, process safety focuses on a top-down management approach, where approval of measures is the responsibility of senior management; occupational safety, on the other hand, focuses on educating staff.

Fig 1 illustrates the basic features of different hazard categories, their related hazard sources and possible risk management strategies.

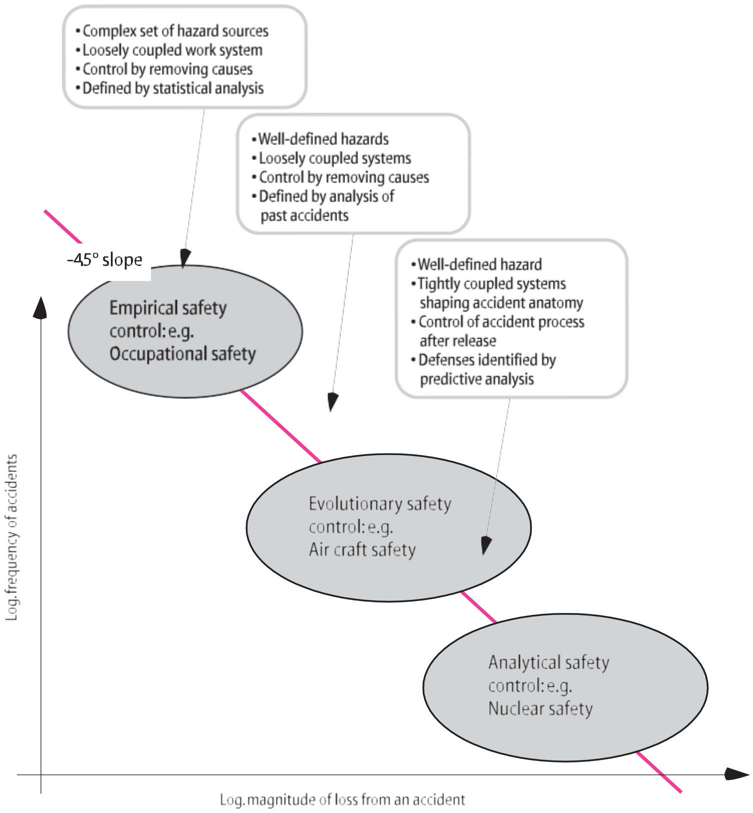

Fig. 1 Hazard categories, sources and risk management strategies (Rasmussen 1997)

It can be seen that occupational safety focuses on frequent, small-scale accidents. The hazard is related to a very large number of work processes and the level of safety is normally measured directly by the number of LTIs (lost-time in juries) and casualties. Consequently, the average level of safety across activities is controlled empirically from epidemiological studies of past accidents.

For medium size, *infrequent accidents* such as hotel fires, aircraft accidents, train collisions, etc., safer systems evolve from *design improvements in response to analyses of the individual*, *latest major accident*. Safety control is focused on the control of particular accident-creating processes and, normally, several lines of defenses against accidents have been established by an evolutionary, incremental effort toward improved safety. In this case, risk management is focused on the removal of causes of particular accidents.

For industrial installations that have a potential for large scale accidents, the acceptable frequency of accidents will be so low, that design cannot be based on empirical evidence from accidents. This is particularly so, when the pace of technological innovation becomes fast, as is the case in e.g., the chemical industry where the time span from conception of a new product or process to large-scale production becomes very short. In that case, an incremental evolution of low risk systems guided by past accident scenarios is no longer acceptable. The risk from new industrial installations must then be predicted from models of the processes applied and the hazards involved. For this purpose, probabilistic risk analysis (PRA) has been developed and system design is then based on an estimation of the probability of a full-scale accident considering the likelihood of simultaneous violations of all the designed defenses. Given the level of acceptable risk, and the reliability (including maintenance) of the individual defenses (which can be determined empirically from operational data), the necessary number of causally independent defenses can be estimated. The assumption then is that the probability of violation of the defenses individually can and will be verified empirically during operation even if the probability of a stochastic coincidence has to be extremely low. In this case, the reference for monitoring the performance of the staff during work is derived from the system design assumptions used for predictive risk analysis, not from empirical evidence from past errors and accidents.

The Risk Research Group combine methods from management science, system safety and engineering risk management disciplines, including the following:

- For causal modelling: barrier diagrams, bowtie analysis, cause-consequence analysis.
- For uncertainty analysis and propagation: interval-valued probability measures.
- For simulation of human performance: cognitive task analysis and discrete event simulation.
- For risk and reliability analyses: discrete event simulation (mimicking real processes and events by random sampling).
- For consequence analyses: simplified engineering models predicting release, extent, damages and effects to people, property and environment.
- A combination of quantitative and qualitative methods to analyze data from surveys, observations, interviews etc.

Figs. 2 and 3 illustrate the use of a fault tree and a barrier diagram as common methods in risk analysis for occupational safety and process safety.

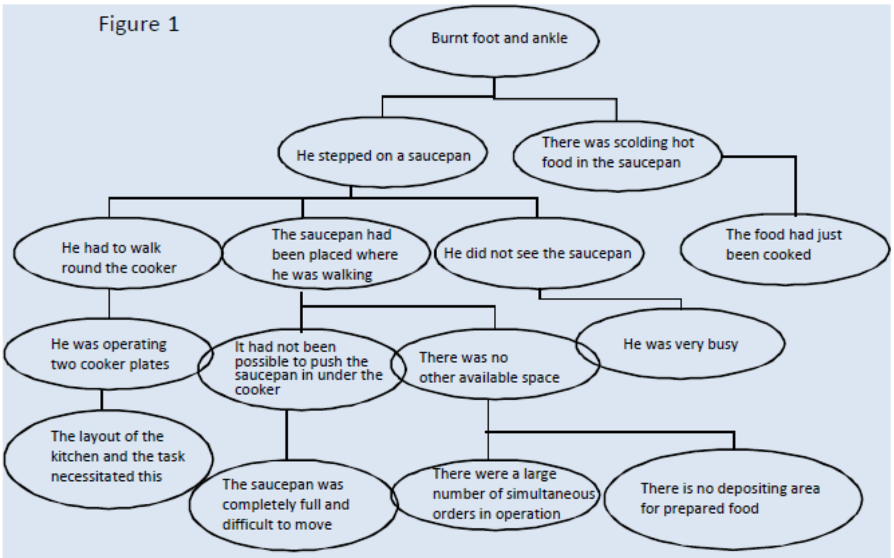

Fig. 2 A fault tree analysis for an accident example a trainee chef who burnt his foot (Andersen 1991, Rasmussen et al 1987, Jørgensen 2001, 2002)

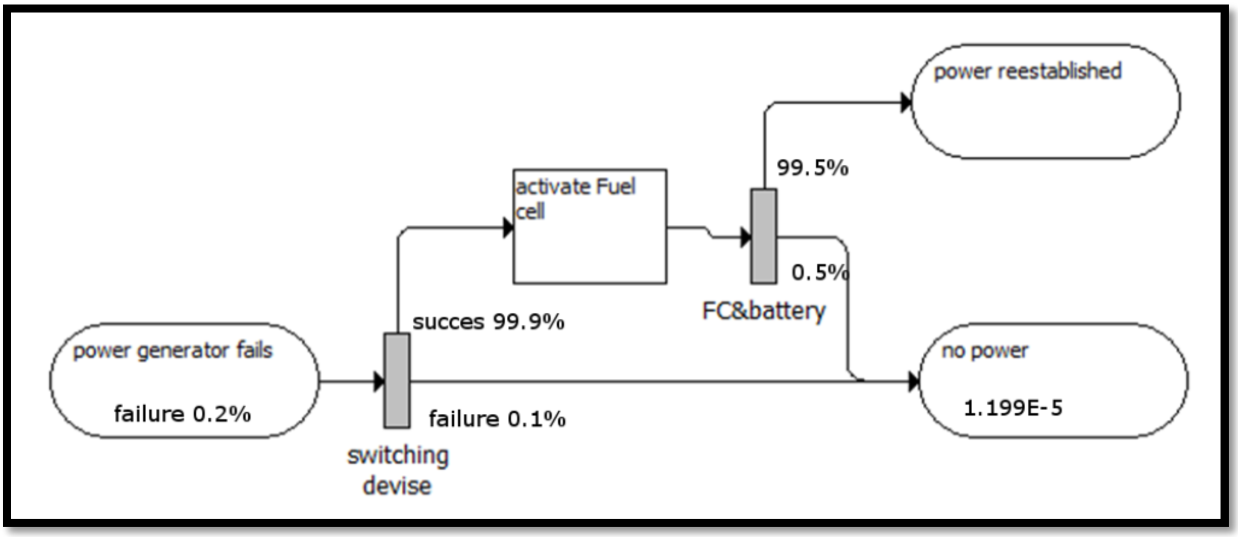

Fig. 3 Barrier diagram as e.g. power back-up system (Markert and Kozine 2014)

Selected Research and Application Fields

Research at the Risk Research Group has included a number of industrial sectors and application fields: nuclear, oil and gas production and transportation, wind energy production, railway transportation, maritime operations, safety in design in the construction sector, safety culture, and land-use planning.

In what follows some specific research topics are presented, which are of current interest in this research unit:

Modeling of Safety Barriers, including Human and Organizational Factors

The Risk Research Group has developed an approach to include human and organizational factors into the simulation of the reliability of a technical system, using event trees, fault trees and the concept of safety barriers.

Safety barriers are physical and/or non-physical means planned to prevent, control or mitigate undesired events or accidents. The means may range from a single technical unit or human actions, to a complex socio-technical system. Planned implies that at least one of the purposes of the means is to reduce the risk. Prevention means reduction of the likelihood of a hazardous event, control means limiting the extent and/or duration of a hazardous event to prevent escalation, while mitigation means reduction of the effects of a hazardous event. Undesired events may, for example, be technical failures, human errors, external events, or a combination of these occurrences that may realize potential hazards, while accidents are undesired and unplanned events that lead to loss of human lives, personal injuries, environmental damage, and/or material damage.

A possible way to classify barrier systems is shown in Fig. 4. Active barrier systems often are based on a combination of technical and human/operational elements. With regard to the time aspect, some barrier systems are on-line (functioning continuously), while some are off-line (need to be activated). Further, some barriers are permanent, while some are temporary. Permanent barriers are implemented as an integrated part of the whole operational life cycle, while temporary barriers only are used in a specified time period, often during specific activities or conditions.

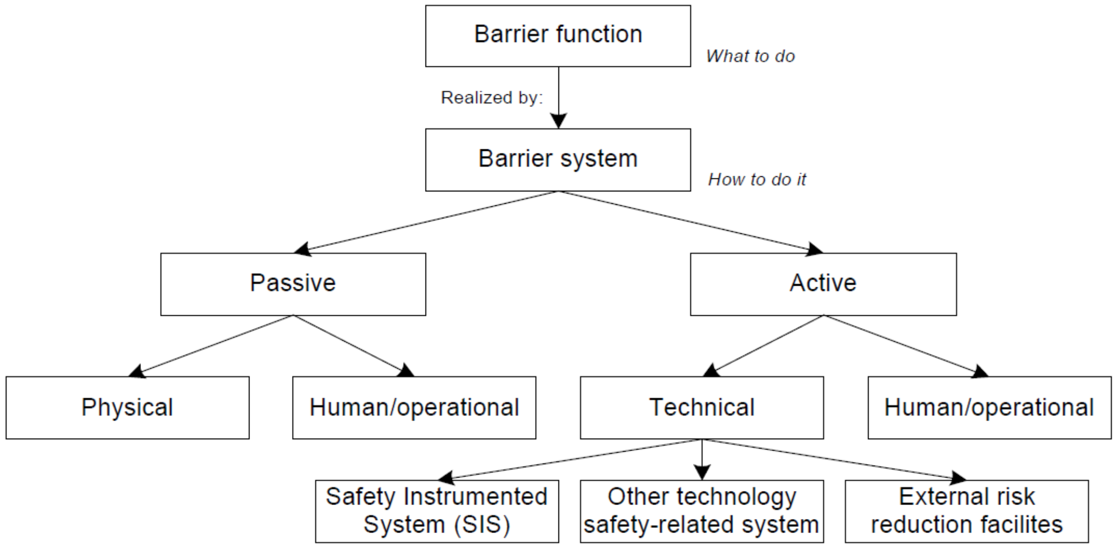

Fig. 4 Classification of Safety Barriers (Sklet 2005)

The methodology developed by the Risk Research Group in this context includes the effect of deficiencies in management processes (and possible higher level company policies and leadership) as common causes for the failure of safety barriers. Each deficiency or failure at some organizational level can thus be considered as having systemic causes and non-systemic (independent, random) causes. The methodology is similar to using Influence diagrams or Bayesian Belief Networks, but is limited to two states only, i.e. a condition is faulty or not faulty, which means a barrier either fulfills or does not fulfill its functional requirements.

Dynamic Simulation Modeling of Fire and Egress Scenarios on Off-shore Platforms

Risk assessment is an important part in the permitting process of off-shore platforms. The conventional approach is to develop static event trees for events following a loss of containment. The volume and spread of the hydrocarbons are assessed making up various ignition scenarios and their impact on people are evaluated. The prediction of the impact and consequences in terms of serious injuries and fatalities is based on deterministic assignments by simplified engineering models to the characteristics of the system, physical and environmental phenomena and workers responses or averaged/expected values of those.

A novel risk assessment approach is developed by the Risk Research Group, which is based on simulation of the dynamic interactions between concurrent phenomena following loss of containment, specifically:

- The physical processes (outflow, dispersion, ignition, heat radiation, explosion)
- Detection, alarming and emergency shutdown

- Escape and evacuation
- Impact on persons, escalation and impairment of safety functions

The simulation model runs repeatedly loss of containment scenarios to evaluate the associated stochastic events in time with random delays, durations, instances of occurrences and others. The output data sets are collected over all the simulated scenarios and are further processed to predict risk indicators as the Individual Fatality Risk (IR), the Potential Loss of Life (PLL), the Fatal Accident Rate (FAR, at platform and workplace level), and the group risk (distribution of number of simultaneous fatalities).

This way of tackling the problem allows capturing a great deal of specific characteristics of different platforms, dynamic change of people responses and other characteristics. Scenarios with severe consequences can be 'played back' to learn from them and can be animated, which except for the learning effect provides a new way of validation. This also makes the simulation models a good communication tool between system analysts and domain experts.

Risk Matrices

Recent research in the Risk Research Group has focused on a critical evaluation of risk matrices as a commonly used tool in a variety of risk management applications. The objectives of this research are to explore the weaknesses of risk matrices as they are presently used and provide recommendations for their better use and design. The recommendations cover a range of issues, including the relation between coloring the risk matrix and the definition of risk and major hazard aversion; the qualitative, subjective assessment of likelihood and consequences; the scaling of the discrete likelihood and consequence categories; and the use of corporate risk matrix standards. Finally, it proposes a probability consequence diagram with continuous scales, providing in some cases an alternative to the risk matrix.

Risk Acceptance Criteria

Research at the Risk Research Group has further included the use of risk acceptance criteria to identify conflicts between major hazard establishments (i.e. those covered by the Seveso-directives) and surrounding land-use with respect to protection of human life and environment. The focus of this study has been to describe risk analysis methods and risk acceptance criteria in relation to land-use planning in the context of the European Union, including selection of accident scenarios for decision optimization, information on the frequency of critical events, and consequence modeling and damage impact. Risk acceptance criteria are distinguished and examined in terms of the following: environmental damage, personal injury, societal risk aversion, and specific vulnerable objects (e.g. hospitals, schools and infrastructure).

Integrated Safety in Design

On-going research at the Risk Research Group investigates the inclusion of health and safety considerations in the design phase as a means to achieve a higher level of health and safety in the construction industry. Based on a number of empirical studies, the working hypothesis of this research is that health and safety problems in execution can be prevented through efforts in design and engineering in the early stages of the construction process. The first stage in the research focused on understanding how occupational health and safety (OHS) is included or omitted in traditional design phases in construction by considering 1) the level of knowledge on OHS among the actors in the design phases; 2) the designers' view on prioritization, duties and responsibilities in connection to OHS in design; and 3) how OHS is integrated in current construction design and engineering processes in general. The theoretical framework that was subsequently developed is illustrated in Fig 5.

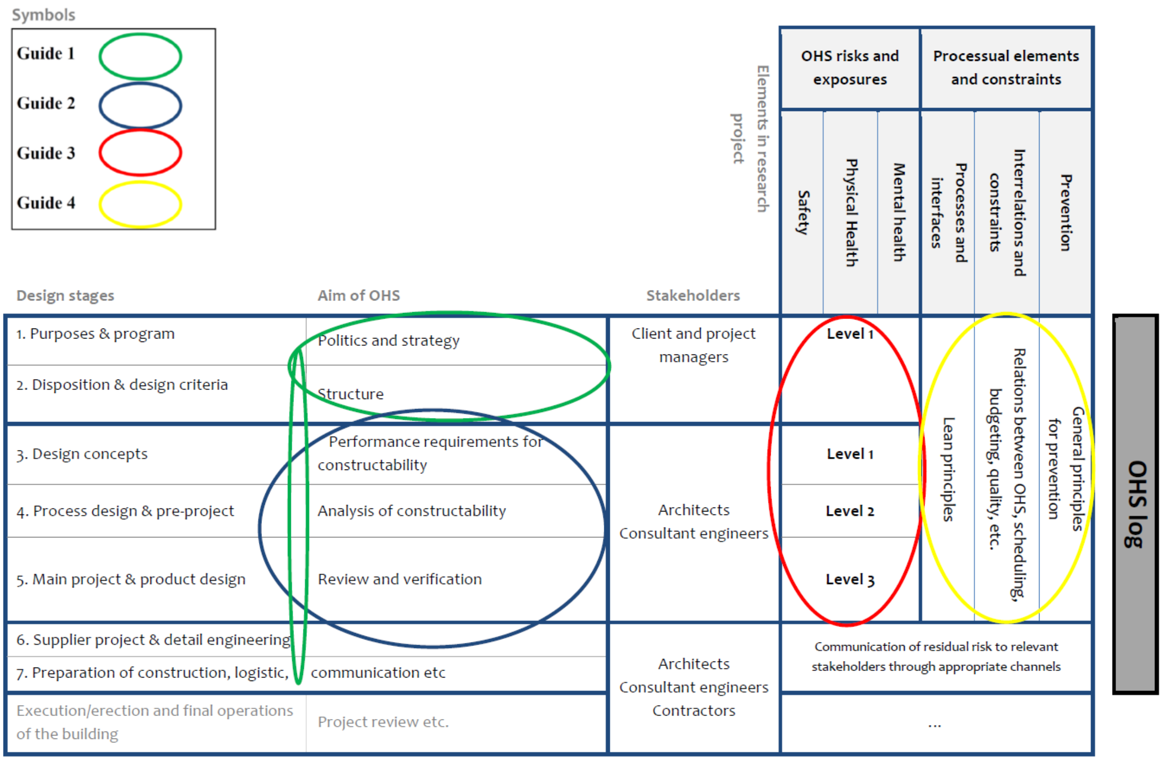

Fig. 5 Conceptual framework for integration of OHS in design in construction (Schultz, C.S. and Jørgensen, K. 2014)

The next stage of the research currently tests and evaluates the developed framework through interventions in the design process in a number of construction projects.

<u>Safety Culture</u>

Research is also carried out on the theme of Safety Culture, with particular application to the transport sector. The main emphasis here is on applied research customary in the social psychological or organizational psychological traditions.

Methods and Techniques used in Risk Assessment in the Context of Process Safety

The following is a selection of commonly used methods and techniques in process safety risk assessments. Only methods and techniques used by the Risk Research Group specifically have been selected.

HAZOP

Hazard and Operability Study or HAZOP is probably the most widely used hazard identification technique in Process Safety risk assessments. It uses a series of guidewords to prompt study participants to identify possible hazards and their causes and consequences by using their imaginations. It is carried out by a multi-disciplinary team to ensure maximum input of experience. HAZOP will identify potential operability deficiencies as well as hazards.

HAZID

HAZID is similar to HAZOP in that it uses guidewords to prompt study team members to identify hazards by using their imaginations. HAZOP typically focuses on detailed piping and instrument diagrams (or their equivalent) and operational and maintenance procedures, whereas HAZID typically focuses on plant layout drawings, as it aims to identify intrinsic hazards. HAZID can be very useful at an early stage of a new design so that all potential hazards can be taken into account. HAZID is also the technique of choice for identifying hazards as the first stage of demonstration of ALARP.

Check-lists

A check-list is a list of hazards that may be associated with particular plant or operations. It will specify those aspects of plant or operations that require attention from the point of view of safe design. Checklists are derived from industry codes of practice, regulations and past incidents. They are helpful in ensuring designers address hazards that are known and obvious. They are not effective in identifying hazards arising from either the application of novel technology, or from complex interactions.

Failure Modes and Effects Analysis (FMEA)

Failure mode and effects analysis considers each item of equipment or operation in turn and evaluates the consequences of each failure mode in turn. It provides a thorough investigation of the causes and consequences of single failures and is useful where the main danger comes from equipment failure. However, it is not so effective in dealing with complex interactions where more than one failure can occur at a time, nor where the main danger comes from the properties of hazardous materials.

Consequence Analysis

Consequence analysis is the study of the possible extent of harmful effects of potential incidents. It is carried out by making calculations for an idealized description of one or more potential incidents (or scenarios).

A source term is a consequence model that describes the rate at which hazardous material reaches the environment and the conditions of the hazardous material, such as temperature and composition. They are often used to provide input for other consequence models.

Gas/aerosol dispersion models are used to determine outputs such as the distance from the release point to a concentration of interest and the mass of flammable material within a cloud. Upwind and cross wind dispersion can also be important.

There are two parts to the modeling of fire hazards, the modeling of the fire, including thermal heat flux and smoke generation, and the effect on people, structures and equipment. Modeling of fire behavior is done at DTU Civil Engineering. The Risk Research Group collaborates with researchers at DTU Civil Engineering in the area of fire safety and risk assessment.

Fault Trees

The basic process of fault tree construction is to take the scenario definition (top event) and to trace it back to the possible causes, which can be component failures, human errors, environmental conditions or other pertinent events. Fault trees mostly use two types of logic gates, AND and OR. Each gate has a number of inputs, but only one output. The frequency/probability of the output is calculated by multiplying the inputs. Even if a fault tree is not quantified, it can still be useful as a graphical display, not only of the potential causes of the top event, but also of the way in which the individual causes can combine to lead to the top-event.

Event Trees

The basic process of event tree analysis is to take the initial state of the scenario and work through to the possible outcomes. Possible outcomes may be affected by such factors as prevailing environmental conditions, safety systems, actions by personnel and presence of ignition sources. At each branch point in the event tree, a choice is made between two or more possible outcomes. Usually the choice between two outcomes is sufficient, but occasionally three or more outcomes of a single gate can be used.

Cognitive Reliability and Error Analysis Method (CREAM)

Human Reliability Assessment is a tool to assess the reliability of human operators in technical systems. The outcome of such assessment shows the numerical (estimated) probability of a certain physical event in an industrial plant, based on dynamically generated fault trees, fault models and human operator models. There are various methodologies to execute a human reliability assessment. The methodology applied by the Risk Research Group in the context of nuclear power plants is the so-called Cognitive Reliability and Error Analysis Method (CREAM), which is briefly described below.

CREAM is a Human Reliability Analysis (HRA) technique. It emphasizes the importance of the context in determining human performance and the intrinsic role of cognition in all actions, and hence errors. CREAM attempts to explicitly account for how context and cognition affect the cause-effect relations that underlie the failures of action. Causes and effects are classified based on distinguishing between error modes or manifestations (phenotypes) and their causes (genotypes). Error modes include, e.g. “action at wrong time” and “action on wrong object”. The error causes fall into 12 categories, which can be divided more generally into person-related, system-related and environment-related.

Furthermore, each cause in the 12 groups has potential causes, e.g. some causes for communication failures (as a cause of the error mode “action at wrong time”) include distraction, inattention, etc. The steps in CREAM analysis are:

Step 1: Application analysis (task analysis) – description of operator, control, organization and technical system tasks

Step 2: Context description – description of Common Performance Conditions (CPCs)

Step 3: Specification of target events – analysis of the human failure events, based on the Probability Safety Assessment (PSA) and the task analysis

Step 4: Qualitative performance analysis: description of possible causes for a target event, based on the CPCs

Step 5: Selection of events for further analysis:

Step 6: Quantitative performance prediction

Data

Data used in Process safety risk assessment typically include:

- Accident records
- Near miss records
- Maintenance records
- Reliability and other performance related data bases
- Human error trials

Common Forms of Presentation of Risk

- **Individual risk** - a single number representing the risk of a particular level of harm to a person or location.
- **Risk contours** - individual risk plotted over an area so as to show the relative risk between locations.
- **Potential loss of life** - a summation of individual risks over an exposed population. Similar parameters can be derived for outcome types other than fatality.
- **Cumulative Frequency Curves or F-N Curves** - a graph of the frequency of events with a particular consequence or greater versus the consequence magnitude.

3.2 Project Risk Management for Large Engineering Projects

Project risk is a type of operational risk, related to the planning and delivery of a product or service, and of not being able to meet project "triple constraints", i.e. scope/quality, schedule and cost, including technology and other factors.

In general, unexpected events occur in projects and may result in either positive or negative outcomes that are a deviation from the project plan. Positive outcomes are opportunities while negative outcomes generate a loss. Risk focuses on the avoidance of loss from unexpected events. There are many definitions of risk in the context of project management, typically referring to exposure to losses and probability of losses in a project. At DTU Management Engineering Systems Group, where research in project risk is carried out, the working definition of risk is the broader definition in ISO 31000, where risk is defined as the "effect of uncertainty on objectives," and risk management as something that "aids decision making by taking account of uncertainty and its effect on achieving objectives and assessing the need for any actions." The objectives can either focus on project-level metrics such as budget, schedule and process standard adherence, product-related metrics, such as time-to-market, performance level and product cost, or higher level metrics, such as the net present value of the project, customer satisfaction, or market share.

In Table 1 the most common sources of risk in project development are outlined.

Technical capability of the product does not meet the expectations and wishes to the customers
Complicated design of product for manufacturing, the expenses of the product development process exceeded the limits and budget forecast
The durability of the product development process is longer as it was planned and therefore the product could not enter to the market in a right time
The problems in manufacturing are caused very complicated and complexity of the product, increase the cost of producing the product
Critical people left the project
Critical resources needed for the project was not available at the right times
The project missed critical milestones
Cost of the product exceeded the market expectations, exceeded budget
Introduction of new tools, technology, or processes during the project development life cycle
The competence of the product development team is not at this level as it was expected and there is a lack of key competence
The project management team don´t follow the best practices and rules in project management

The subcontractors and supplies do not fulfill the schedule
The mistakes in design cause problems in manufacturing. There are misunderstandings between designers and manufacture. Re-design is expensive and takes additional time

Table 1 Sources of risk in project development

Project risk management endeavors to supplement project management practices by investigating project structure, organizational environment, external environment, products, processes and procedures in detail. It further, supplements the existing knowledge with lessons learnt, best business practices, industry benchmarks and case studies such that risk mitigation plans are in place when risk events are realized.

Risk management in project involves:

- Identifying and assessing the risks in terms of impact and probability.
- Establishing and maintaining a joint risk register, agreed by the integrated project team.
- Establishing procedures for actively managing and monitoring risks throughout the project and during occupation on completion.
- Ensuring that members of the team have the opportunity to engage in a dialogue that will promote agreement of an appropriate allocation of risk.
- Updating risk information throughout the life of the project.
- Ensuring control of risks by planning how risks are to be managed through the life cycle of the project to contain them within acceptable limits.
- Allocating responsibility for managing each risk with the party best able to do so.

At the Engineering Systems Group, risk management aspects are seen as inherent in many activities that are already performed in product development such as quality management, knowledge management, design automation and early supplier or customer integration. Common working definitions of quality include notions such as *zero defects, customer satisfaction, control of process variance, reliability, security, and fit for purpose*. If one were to switch to a risk perspective, these common definitions of quality could be substituted with *risk of defects, risk of customer dissatisfaction, risk of uncontrolled process variance, risk of product unreliability, risk of security breach, risk of lack of fitness*; or in other words, failure to achieve objectives.

Thus in the risk domain, the focus is not on the objectives per se, but on the risk to achieving the objectives. Risk management is applied to control the risks and enhance the likelihood of achieving the objectives. Quality management can be thought of as the process of designing and executing products and services effectively, efficiently, and economically. In this context, effectiveness primarily involves the ability of the products and services to meet or exceed customers' expectations, while efficiency involves the ability to provide products and services without wasting any resources.

In what follows, a conceptual framework for adapting generic risk management processes for product development risk management is presented, together with an overview of current research methods, including portfolio level risk management. Together, these constitute the core of research in risk management at the Engineering Systems Group.

Framework for Product Development Risk Management

Building on the generic process outlined in the ISO 31000, an interpretation in the context of product development risk management is developed (Fig. 6)

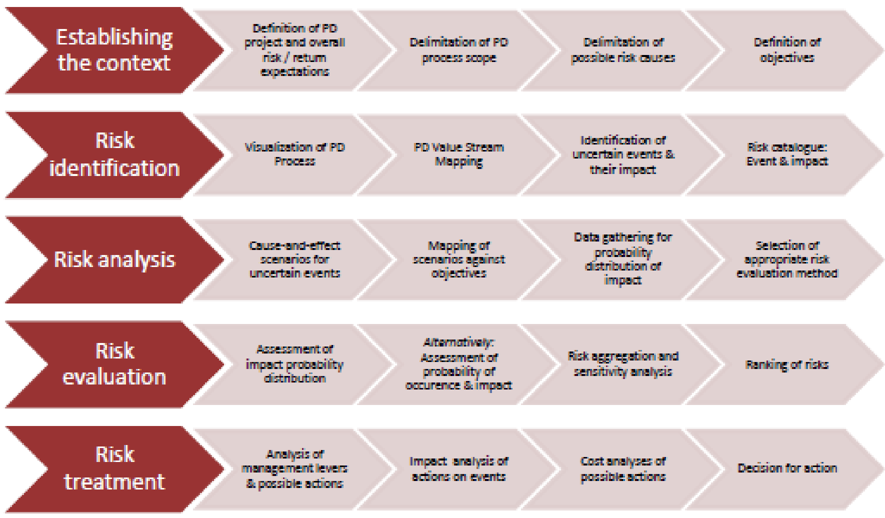

Figure 5: PDRM Reference Process for Core Process Elements

Fig. 6 PDRM Reference Process for Core Process Elements (Oehmen, J. and Rebentisch, E. 2010)

Overview of Risk Management Methods used in Product Development

Method	**Establishing the context**	**Risk identificatio n**	**Risk analysis**	**Risk evaluation**	**Risk treatment**
PD project context analysis	x				
Structured and semi-structured interviews	x	x			
Checklists	x	x			
Brainstorming		X			
Delphi techniques		X			
Process/value stream analysis		X			
Quality function deployment		x	x		
Technology readiness scales		x	x	x	
Scenario analysis		x	x		
Root cause analysis		x	x		
Structured What-if analysis		x	x	x	
Fault tree analysis		x	x	x	
Event tree analysis		x	x	x	
Failure mode and effects analysis		x	x	x	x

Cause-effect analysis		x			
Portfolio management			x	x	x
Monte Carlo simulation				x	
Consequence/probability matrix				x	
Risk value method				x	
Real options					x
Cost/benefit analysis					x
Multi-criteria decision analysis					x

Table 2 Overview of Risk Management Methods (Oehmen, J. and Rebentisch, E. 2010)

In practice, the risk quantities are either quantitative or qualitative in nature. The quantitative approach to determination of risk parameters requires analysis of historical data through statistical analysis. In many instances, quantitative data is hard to achieve and is restricted to very small domain of the problem where historical trends could be sustained. Where quantitative data is not available when needed or not in the form required, a qualitative approach using subjective assessment techniques are used. Though the subjective approach is influenced by individual bias, preferences and expertise, it provides a basis for risk assessment where it is more important to highlight risk events that are possible, rather than an exact prediction of a catastrophic event.

Portfolio-level Risk Management

Portfolio management compares multiple projects with respect to risk in investment and returns. Projects are positioned on a matrix of risk magnitude and return, with high risk low return projects being located at a different location to low risk and high return projects. This enables decisions to be derived for corporate governance, based on the company strategy and the maximum portfolio value, through calculation of a utility value for a project. In project risk management, multiple risk events may be compared by placing them on a matrix of risk magnitude against return. Mitigation options are then derived from predefined utility values.

Portfolio-level risk management extends project-level risk management and aggregates its outcomes – ideally – to the next higher level. Research points out that although managing product portfolios through a conceptual risk measure common across the products in the portfolio is desirable, it is rarely done in practice as it is considered too hard to do. Portfolio management tools and techniques have emerged over time using traditional project financial information that may be construed to include risk as a factor. These include the Growth-share matrix (Boston or BCG matrix), the GE multi-factoral analysis (McKinsey matrix), the advantage Matrix (another BCG matrix), the Ansoff Product-Market Growth matrix and the Contribution Margin Analysis method. These matrices attempt to put different projects into different categories to simplify managing towards the benefits of portfolio management.

3.3. Quantitative Sustainable Assessment

Quantitative sustainability assessment (QSA) is to a large extent based on the methodology of Life Cycle Assessment (LCA) and its related and constituent fields, such as environmental risk assessment, environmental chemistry, environmental/ecosystem modelling, human toxicity and ecotoxicity, climate change, biotic and abiotic resource availability (e.g. water, land, minerals, etc.), biodiversity, and social impact assessment.

Research at the QSA division at DTU Management primarily focuses on the following:

- Life cycle impact assessment in general (e.g. spatial differentiation, damage modeling, new impact categories) and improvements in the assessment of toxicity related impacts (e.g. simplified characterization models, indoor exposure, assessment of nanomaterials, terrestrial and marine ecotoxicity)
- Social life cycle assessment: framework, selection of impact categories, development of impact assessment, feasibility and data availability
- Adaptation and testing of life cycle assessment tools for specific industries and contexts.

In what follows, first some basic concepts and methodologies in LCA are described, and examples are given of the application of LCA research in industry and the public sector. Subsequently, similarities and differences between LCA and (environmental) risk assessment (E)RA are presented, together with potential synergies of the philosophies and methods underlying these disciplines. Finally, some specific examples are given of current research carried out in the division.

Concepts

It is generally acknowledged that the term “sustainable development” (SD) was introduced in the report of the World Commission on Environment and Development that appeared as Our Common Future in 1987 (the Brundtland report). Since then, sustainable development is invariably defined as “development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs”.

Strongly connected to SD – and often confused with it – is another term: sustainability. A thing is sustainable when it can be maintained in a specific state for an indefinite (or very long) time. Hence, sustainability is the property of a thing being sustainable. The thing can be anything: a policy, a situation, a product, a process, a technology.

The definition of SD establishes clear links with many issues of concern: poverty, equity, environmental quality, safety, population control, and so on. In general, the field of SD is subdivided into three areas: economic, environmental, and social. These so-called pillars or dimensions of sustainability need to be addressed in assessing the sustainability of a product, system, project, policy, etc. Thus, the narrow interpretation in which sustainability and SD is restricted to the environmental pillar alone, is replaced by the wider interpretation where all three pillars are covered.

A sustainability analysis has become a common requirement for public policy as well as corporate accountability. As such, sustainability assessment may be part of the justification to adopt a policy, to implement a technology, to purchase a product, etc. So-called sustainability indicators are an important ingredient in the process of communication, bench-marking and decision-making. Numerous schemes of such indicators have been developed, by the UN, the OECD and the EU, as well as by companies and NGOs. For instance, the United Nations Commission on Sustainable Development has developed a list of 134 such indicators, divided over 14 themes:

- Poverty
- Governance
- Health
- Education
- Demographics
- Natural hazards
- Atmosphere
- Land
- Oceans, seas and coasts
- Freshwater
- Biodiversity
- Economic development
- Global economic partnership
- Consumption and production patterns

Terms like sustainability indicators and sustainability analysis occur in many contexts, but the validity of such indicators is a crucial factor. In that sustainability analysis is intended to support decision making, it can be delineated as applied science. It tries to predict what will happen if a certain choice is made, what may happen if no action is taken, how certain present problems may be solved in future by choosing a certain strategy. Many of the issues in the field of sustainability have causes or consequences that extend beyond the here-and-now of the original decision situation and decision maker. As a global concept, sustainability analysis calls for a system-wide analysis, hence applying a life cycle perspective is a logical choice. Like sustainability and sustainable development, the terms life cycle and life cycle analysis (LCA) have been used in a variety of ways. The life cycle concept is present in a variety of disciplines from the life sciences to engineering to manufacturing and commerce. LCA is defined as a tool to assess the environmental impacts and resources used throughout a product's (system's) life cycle, i.e. from material acquisition, via production and use phases, to waste management (ISO 2006a).

LCA traditionally focuses on the environmental dimension. As such, it has been defined in terms of physical exchanges between processes, and between a process and the environment. Life cycle sustainability assessment (LCSA) is an LCA that covers all three dimensions of sustainability.

Sustainability assessment of products and technologies is normally seen as encompassing impacts in the three dimensions mentioned above – the social, the environmental and the economic. On all three a life cycle perspective is relevant to avoid problem shifting in the product system. The approach for assessing a product's sustainability (LCSA) has therefore been to combine three life cycle methodologies: LCA, social LCA (SLCA) and life cycle costing (LCC), in the following way: LCSA =LCA+LCC+SLCA. This approach is challenged by researchers at the QSA division of DTU Management, who interpret the Brundtland definition of sustainable development as comprising two goals – alleviation of poverty and conservation of capital, and suggest that current LC methodologies are unable to capture the entire breadth of the concept of sustainable development, and that SLCA should be modified and expanded to cover issues related to poverty alleviation and produced capital.

Applications of LCA

Private sector applications

Product Development

Design for the Environment (DfE) is a general term for a number of methods for incorporating environmental factors into the design process. Although the cocept of DfE has been developed without formal links to LCA, it conceptually addresses the same problem areas as LCA. DfE seeks to optimize the environmental performance of a product throughout its life cycle. It integrates concepts of pollution prevention in manufacturing and concerns about energy efficiency of products. Another major objective of DfE among manufacturers is to design products with the goal of minimizing after-life impacts and costs.

Marketing

As the level of environmental consciousness is increasing, more attention is being paid by the consumer to the environmental properties of goods and services. This is being used (and misused) by many companies to attempt to increase their market share, and development of criteria and guidelines for environmental marketing has a high priority. At least four different kinds of environmental marketing can be distinguished:

- Environmental labelling (ISO Type I labeling)
- Environmental claims (ISO Type II labeling)
- Environmental declarations (ISO Type II labeling)
- Organization marketing

Strategic planning

Integration of environmental aspects in strategic business planning is now a common feature in many companies. The environmental performance is thus changed from being a mandatory property of many products to being a strong positioning property on the market. LCA - or rather the Life Cycle Approach - can in this context be used both in relation to existing products (do they fulfil current and near-future environmental demands from the consumers?) and to identify market segments to be opened for environmentally benign products.

Public sector applications

Sustainable development has been included as a major item on most governmental agendas since the 1992 Rio summit. Although a precise definition of sustainable development has not been given, it is obvious that LCA or a life cycle approach must be used to ensure that actions towards a more sustainable future will have the desired effect. LCA as a specific tool can ensure this in some cases, while LCA as an approach or as a strategic tool can give directions but not the whole answer, and must therefore be applied along with other tools such as risk assessment, environmental impacts assessment, cost-benefit analysis and others.

The main governmental applications are

- Product-oriented policy
- Deposit-refund schemes, including waste management policies
- Subsidies and taxation, and
- General (process-oriented) policies

Environmental Labeling

The general objective of national and supranational eco labeling schemes is to make products with less environmental impacts visible to the consumer. The nature of and criteria for private labeling schemes is often obscure, while official schemes like the Nordic “Swan”, the EU “Flower” and the German “Blue angel” explicitly demand that the award of the label is based on the life cycle approach (Type I labelling).

Green Procurement

Public procurement accounts for a large share of the overall market and can thus be an important factor in the development and marketing of environmentally friendly products. In those cases where an official ecolabel exists for the product in question the obvious choice is to demand products fulfilling the criteria for the ecolabel. Public procurement organizations can then make their choice without time-consuming evaluations and comparisons of all incoming offers. However, as criteria for ecolabels have only been developed for relatively few product groups, it is often necessary to choose another methodology if new product groups are to be included in programs for green procurement. The major problem in this context is to develop criteria which ensure that the products have a good environmental performance, and at the same time give the responsible persons a tool which enables them to choose between a number of products with different environmental features.

Packaging Policies

The most prominent governmental use of LCA has been in the field of packaging. LCAs on milk packaging (cartons, glass or plastic bottles), beer bottles and beer cans, impact of PVC from packaging etc. have in many countries been used as a decision support in the political arena, although the LCAs have seldom given an unequivocal answer as to which system is environmentally preferable.

Other Public Sector Uses

Other areas where LCA has been used as a decision support tool are environmental taxes, integrated life cycle management and deposit/refund schemes. An LCA can in these cases be used to analyze the environmental consequences of a change in human behavior.

Table 3 summarizes the most frequent applications of LCA for both industry and the public sector.

Identification of Key Environmental Performance Indicators (KEPI) of a product group for Ecodesign / simplified LCA
Weak point analysis of a specific product

Detailed Ecodesign / Design-for-recycling
Perform simplified KEPI-type LCA / Ecodesign study
Comparison of specific goods or services
Benchmarking of specific products against the product group's average
Green Public or Private Procurement (GPP)
Development of life cycle based Type I Ecolabel criteria
Development of Product Category Rules (PCR) or a similar specific guide for a product group
Development of a life cycle based Type III environmental declaration (e.g. Environmental Product Declaration (EPD)) for a specific good or service
Development of the "Carbon footprint", "Primary energy consumption" or similar indicator for a specific product
Greening the supply chain
Providing quantitative life cycle data as annex to an Environmental Technology Verification (ETV) for comparative use
Clean Development Mechanism (CDM) and Joint Implementation (JI)
Policy development: Forecasting & analysis of the environmental impact of pervasive technologies, raw material strategies, etc. and related policy development
Policy information: Basket-of-products (or -product groups) type of studies
Policy information: Identifying product groups with the largest environmental impact
Policy information: Identifying product groups with the largest environmental improvement potential
Monitoring environmental impacts of a nation, industry sector, product group, or product
Corporate or site environmental reporting including calculation of indirect effects in Environmental Management Systems (EMS)
Certified supply type studies or parts of the analyzed system with fixed guarantees along the supply-chain
Accounting studies that according to their goal definition do not include any interaction with other systems
Development of specific, average or generic unit process or LCI results data sets for use in specified types of LCA applications

Table 3 Frequently used LCA applications (ILCD 2010)

Levels of sophistication in LCA for different applications

Most of the efforts in the development and standardization of LCA have been directed towards a *detailed* LCA. This type of LCA is the focus in the academic community in terms of both principles and methods. (See section 3.3.2 above.) In practice, however, very few detailed LCAs have been carried out based on a coherent methodology. Two other levels of LCA, i.e. the *conceptual* and *simplified* levels, are briefly outlined in what follows. The three levels should be regarded as a continuum with an increasing level of detail, suitable for decision making in different applications.

Conceptual LCA (also referred to as *Life Cycle Thinking*) is the simplest level of LCA, where the life cycle approach is used to make an assessment of environmental aspects based on a limited and usually qualitative inventory. The results of a conceptual LCA can be presented using qualitative statements or simple scoring systems, indicating which components or materials have the largest environmental impacts – and why.

Simplified LCA is an application of the LCA methodology for a comprehensive screening assessment, i.e. covering the whole life cycle but superficial, e.g. using generic data (qualitative and/or quantitative), standard modules for transportation or energy production, followed by a simplifies assessment, focusing on the most important environmental aspects and/or potential environmental impacts and/or stages of the life cycle and/or phases of the LCA and a thorough assessment of the reliability of the results. The aim of a simplified LCA is to provide essentially the same results as a detailed LCA, but with a significant reduction in expenses and time used. However, since simplification may affect the accuracy of the assessment, the primary objective of simplification is to identify the areas within the LCA which can be omitted or simplified without significantly compromising the overall result.

Table 4 gives an overview of the level of detail in LCA in some typical applications. **"x"** in bold indicates the most frequently used level.

		Level of detail in LCA		
Application	Conceptual	Simplified	Detailed	Comments
Design for Environment	**x**	x		No formal links to LCA
Product development	x	**x**	x	Large variation in sophistication
Product improvement		x		Often based on already existing products
Environmental claims (ISO type II labeling)	**x**			Seldom based on LCA
Ecolabeling (ISO type I labeling)	x			Only criteria development requires an LCA
Environmental declaration (ISO type III labeling)			x	Inventory and/or impact assessment

Organization marketing		**x**	x	Inclusion of LCA in environmental reporting
Strategic planning	**x**	**x**		Gradual development of LCA knowledge
Green procurement	x	**x**		LCA not as detailed as in ecolabeling
Deposit/refund schemes		x		Reduced number of parameters is often sufficient
Environmental ("green") taxes		x		Reduced number of parameters is often sufficient
Choice between packaging systems	x		**x**	Detailed inventory, Scope disputed LCA results not the only information

Table 4 Level of detail in some applications of LCA (EEA 1997)

Conceptually related approaches

The following is a selection of further approaches to environmental management used to support environmental decision making. They can be seen as complementary decision support tools to LCA and attempts are been made in the academic community to find possible synergies between them. One such endeavor is research undertaken in the QSA division of DTU Management as well as the DTU Global Decision Support Initiative, whereby the potential of combing LCA and risk assessment methodologies for the purpose of risk-informed decision making is currently undertaken.

Life Cycle Management

The basic idea in Life cycle management is to establish a thorough knowledge of the environmental burdens of the products manufactured by the company and use this for improvement actions. The process includes employees at most levels of the company and starts with an identification of all unit processes at the production site and an analysis of the related in- and outputs. In the next step up- and downstream processes are examined. The results from the process can be used to establish an LCA, but it is more important that the results are used to minimize the environmental burdens. This is done by using a set of tools tailored to meet the needs of a given company, e.g. design for the environment, pollution prevention strategies, waste audits, green procurement etc.

Product Stewardship

Product Stewardship is defined as "the responsible and ethical management of a product during its progress from inception to ultimate use and beyond". The purpose of Product Stewardship is to make health, safety and environmental protection an integral part of designing, manufacturing, marketing, distributing, using, recycling and disposing of products. The concept was developed by the chemical industry in 1980s in order to reduce the risks associated with chemical products at all stages of the life cycle, but today Product Stewardship is also applied to complex products and services. The relationship to LCA is obvious, a major difference being that the environmental impacts are not aggregated over the whole life cycle.

Cleaner Production

Cleaner production is defined by UNEP as the continuous application of an integrated preventive environmental strategy to processes and products to reduce risks to humans and the environment. For production processes, Cleaner Production includes conserving raw materials, and reducing the quantity and toxicity of all emissions and wastes before they leave a process. For products the strategy focuses on reducing impacts along the entire life cycle of the product, from raw material extraction to the ultimate disposal of the product. In relation to LCA, dissemination of the results from cleaner production programs may prove to be a valuable source of information with regard to both specific processes and products.

Industrial Ecology

Industrial ecology can be defined as the network of industrial processes as they may interact with each other and live with each other, not only in the economic sense but also in the sense of direct use of each other's material and energy wastes. Its object of analysis is industrial processes rather than products and it emphasizes the need for greater synergy, i.e. the potential for reduction in environmental impacts by linking different manufacturing process via their waste streams and encouraging cyclic flows of materials.

Technology Assessment

Technology assessment (TA) can be defined as the assessment of the impacts of introduction of new technologies. The major difference between TA and LCA is that in technology assessment a wide range of economic, social and environmental aspects is taken into account, whereas in LCA only environmental issues are addressed. LCA can thus be regarded as an integral part of technology assessment. Technology Assessment and Technology Needs Assessment are subject of research at a number of other research divisions at DTU Management Engineering, including the UNEP DTU Partnership, Systems Analysis, Production and Service Management.

Substance Flow Analysis

The objective of SFA is to make an inflow and outflow balance of one particular substance (or group of substances) through the material economy, giving the opportunity of identifying environmental improvements related to the substance. The modelling and data collection approach is in many cases quite similar to that used in LCA, except that the substance flow is not being related to a functional unit. SFA may thus be a useful data source for LCA (and *vice versa*) but its main application is to identify environmental policy options, e.g. by showing which flows might be restricted in order to reduce the emissions of a substance or a material. Most SFAs are limited to specific geographic boundaries, e.g. the national level.

Energy and Material Analysis

Energy and materials analysis is to a large extent similar to the inventory phase in a LCA since it quantifies all materials and energy that enter or exit the system under study. One major difference is that EMA does not necessarily involve the whole life cycle of a product or a service, instead focusing on one specific phase or production process. Another difference is that the results from an EMA is not explicitly translated into potential environmental impacts.

<u>Integrated Substance Chain Management</u>

Integrated substance chain management is a decision support tool in which the life cycle approach is combined with economic considerations in order to analyze and reduce the overall environmental impacts of substance chains.

<u>Environmental Impact Assessment</u>

EIA is an activity directed at the identification and quantification of the impacts of people's actions on human health and wellbeing and at the interpretation and communication of information about these impacts. EIA is generally used during the planning phase to investigate changes to the environment at a specific site caused, for instance, by construction projects. The level of detail in an EIA is often higher than in LCA because aspects like concentration of emitted pollutants and duration of exposure are taken into account. EIAs can thus be used to supply precise data to site-specific LCAs and as control reference in generic LCAs.

<u>Risk Assessment</u>

RA is not one unique tool but rather a number of tools developed to investigate the potential risk to human health or the environment from specific situations. In all cases, RA includes at least two steps which also are used in many LCAs, namely hazard identification and exposure assessment. The exposure assessment may yield valuable information on emissions from a given activity and the hazard identification may be of help in the impact assessment, depending on the methodology used. (See also Section 1 in DTU Environment appendix)

Methodological Framework

(For the purposes of this report, the methodological framework described in this section is a procedural framework, based on ISO and ILCD guidelines. A scientific framework is proposed and described through the EU's 6th framework Coordination Action for Innovation in Life-Cycle Analysis for Sustainability (CALCAS 2009). The latter framework would be better suited in the context of scientific inter-department collaboration that may ensue in the aftermath of the risk mapping project and/or through the medium of the GDSI.)

As shown in Fig. 7, the life cycle assessment framework is described by four phases:

- Goal and scope definitions
- Inventory analysis
- Impact assessment
- Interpretation

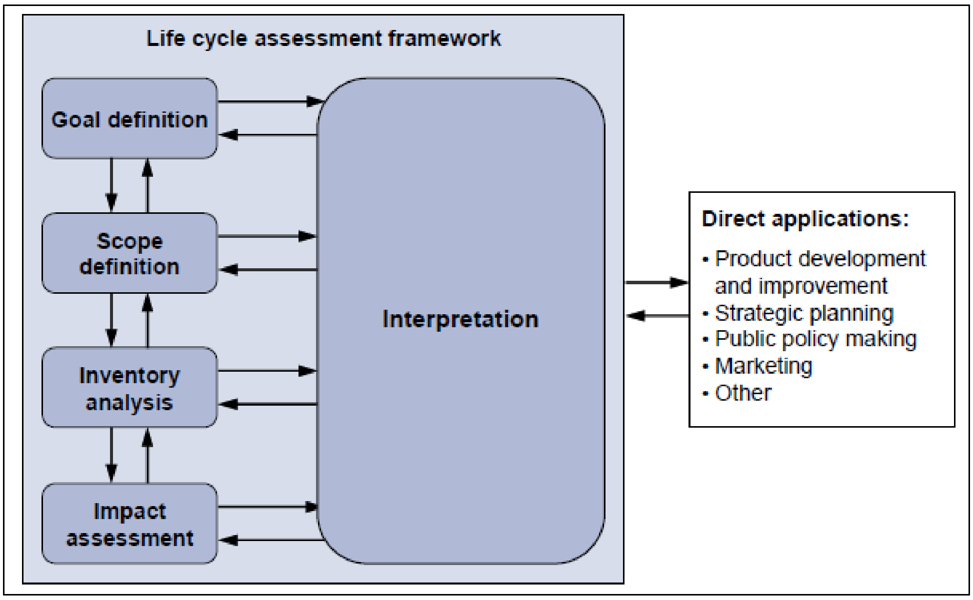

Fig. 7 Framework for life cycle assessment (ISO 14040: 2006; modified; ILCD 2010)

Goal and scope definition

Goal and scope definition is the first phase in a life cycle assessment, containing the following main issues:

- Goal
- Scope
- Functional unit
- System boundaries
- Data quality
- Critical review process

For the purposes of this report, the process of defining the goal and scope is explained in more detail as it relates to defining the decision context – a process of concern with regard to risk-informed decision making. The Goal and scope definition includes the reasons for carrying out the study, the intended application and the intended audience. It is also the place where the system boundaries of the study are described and the functional unit is defined.

According to ILCD 2010, three different decision-context situations of practical relevance in LCA can be differentiated. They are referred to as Situation A, B and C. (Table 5) Their differences are of particular relevance for the Inventory Analysis modeling.

Situation A: "Micro-level decision support"	Situation B: "Meso/macro-level decision support"	Situation C: "Accounting"
Situation A relates to a life cycle based decision support on micro-level (e.g. for product-related questions). It is typically, but not necessarily referring to the short-term (up to 5 years from present) or mid-term (5 to 10 years from present) future. I.e. the analyzed changes directly or indirectly relate to inform the purchase of products that are already offered in the market or the design / development of products that are foreseen to entering the market typically. Key criteria is that the analyzed e.g. product has a limited share of the total production of its sector, so that its production, use and end-of-life can be reasonably expected to have no large-scale consequences in terms of additionally installed or reduced capacity in the background system or other systems, i.e. not structurally change it.	Situation B refers to life cycle based decision support on a meso or macro-level, such as for strategies (e.g. raw materials strategies, technology scenarios, policy options, etc.). It typically refers to the mid-term (5 to 10 years from present) or long-term (beyond 10 years from present) future, given the nature of the study. Key criterion is that the analyzed decision has consequences on changes in production, use and end-of-life activities that will directly or indirectly change relevant parts of the economy by having large-scale structural effects.	Situation C relates to studies that require an entirely descriptive, accounting-type of life cycle model, typically referring to the past or present (while individually also to the future via extrapolation). The object of the analysis can be both on a micro-level and on a meso or macro-level; the amount of production or consumption and of co-functions does not change the modeling. Key difference from Situations A and B is that the study is interested in documenting what has happened (or will happen) based on decisions that have already been taken; there is hence no small-scale or large-scale consequences on the background system or other systems in the rest of the society that would be in the interest of the analysis. However, existing benefits and negative interactions with other systems (e.g. recycling credits) may be included. This leads to the two differentiated cases C1 and C2. For the two sub-types of Situation C, the key difference is whether existing benefits outside the analyzed system are considered or not.

Table 5 Decision-context situations in LCA (ILCD 2010)

A further distinction is made between *attributional* and *consequential* LCA. Attributional LCA is defined by its focus on describing the environmentally relevant physical flows to and from a life cycle and its subsystems. It depicts the system as it can be observed/measured, linking the single processes within the technosphere along the flow of matter, energy, and services, i.e. the existing supply-chain (Fig. 8). Consequential LCA is defined by its aim to describe how environmentally relevant physical flows will change in response to possible decisions. The different focuses of attributional and consequential LCA are reflected in several methodological choices, such as the choice between average and marginal data in the modeling of subsystems of the life cycle. Average data for a system are those representing the average environment burdens for producing a unit of the good and/or service in the system. Marginal data represent the effects of a small change in the output of goods and/or services from a system on the environmental burdens of the system. Attributional LCA excludes the use of marginal data. A consequential LCA is likely to be conceptually complex because it includes additional, economic concepts such as marginal production costs, elasticity of supply and demand, etc. (Fig. 9) The distinction between attributional and consequential

LCA is an example of how choices in the Goal and Scope Definition of an LCA will influence methodological and data choices for the subsequent LCI and LCIA phases.

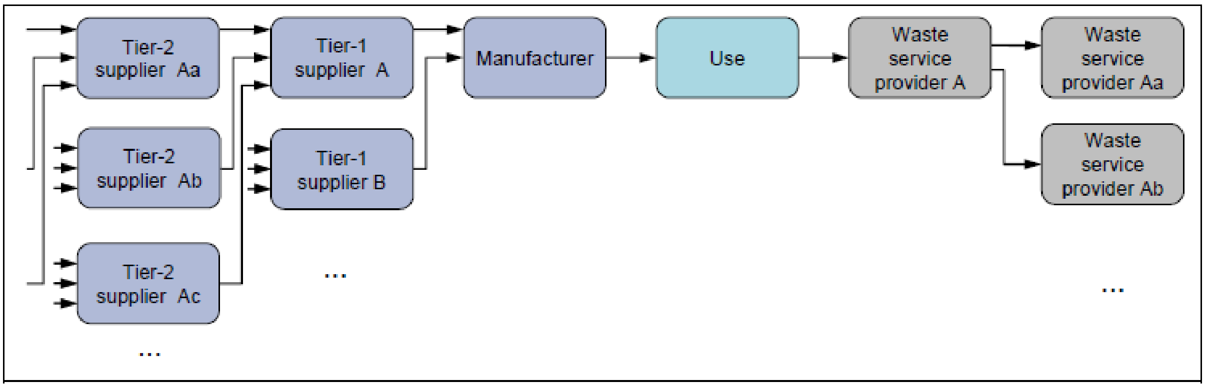

Fig. 8 Schematic and simplified supply-chain LCA model of a product (ILCD 2010)

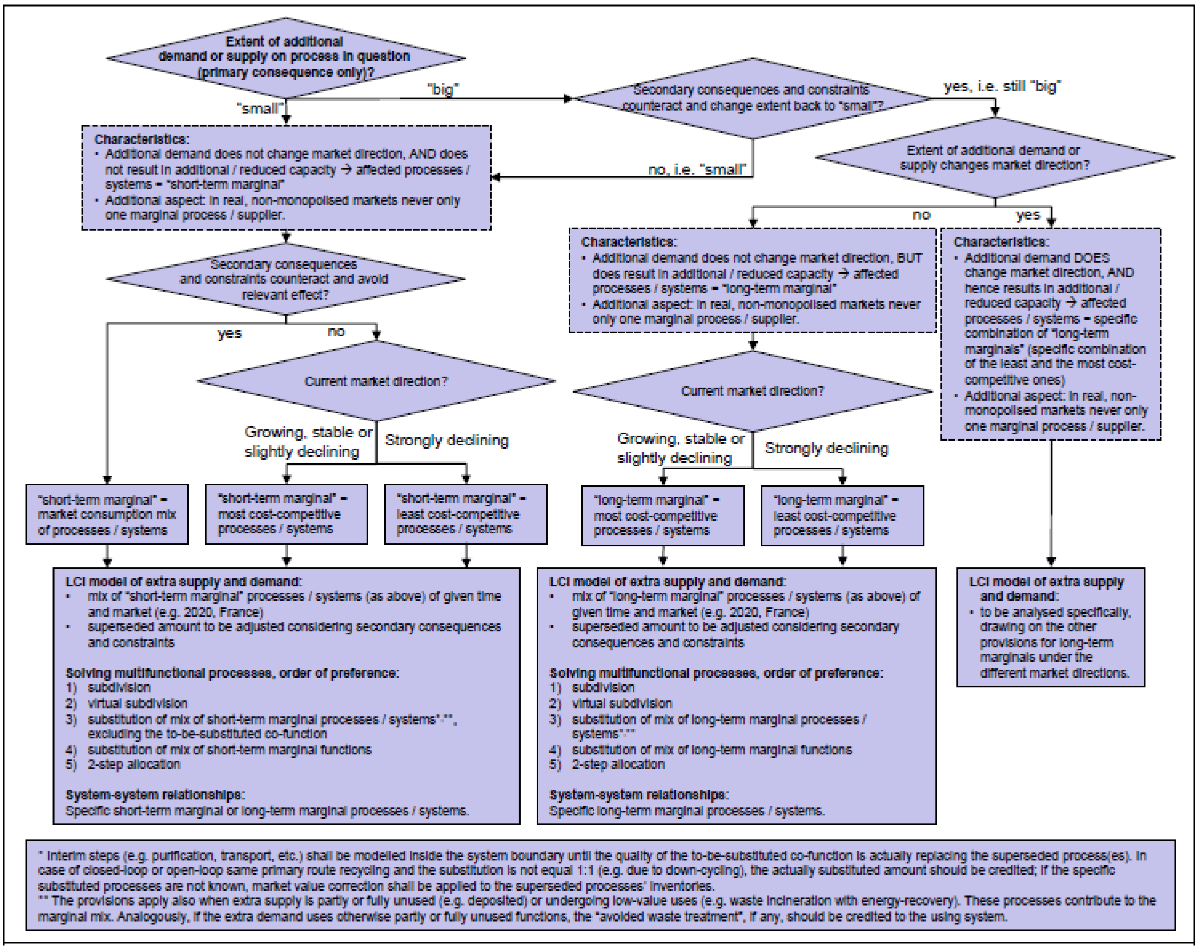

Fig. 9 Decision tree for consequential modeling (ILCD 2010)

Also at this stage, the *functional unit* is defined. Definition of the functional unit or performance characteristics is the foundation of an LCA because the functional unit sets the scale for comparison of two or more products including improvement to one product (system). All data collected in the inventory phase will be related to the functional unit. When comparing different products fulfilling the same function, definition of the functional unit is of particular importance. In defining the functional unit, the following three aspects are typically taken into account:

- The efficiency of the product (system)
- The durability of the product (system)
- The performance quality standard

Life cycle inventory (LCI) modeling framework

Inventory analysis is the second phase in a life cycle containing the following main issues:

- Data collection
- Refining system boundaries
- Calculation
- Validation of data
- Relating data to the specific system
- Allocation

The result from the LCI is a compilation of the inputs (resources) and the outputs (emissions) from the product (system) over its life cycle in relation to the functional unit.

Data collection is often the most work intensive part of LCA, especially if site specific data are required for all the single processes in the life cycle. In many cases average data from the literature (often previous investigations of the same or similar products or materials) or data from trade organisations are used.

The fundamental input and output data are often delivered from industry in arbitrary units e.g. energy consumption as MJ/ machine/week or emissions to the sewage system as mg metals/liter wastewater. The specific machine or wastewater stream is rarely connected to the production of the considered product alone but often to a number of similar products or perhaps to the whole production activity. Thus, for each unit process, an appropriate reference flow needs to be determined (e.g. one kilogram of material or one megajoule for energy). The quantitative input and output data of the unit process is calculated in relation to this reference flow.

Impact assessment

Impact assessment is the third phase in a life cycle assessment, which aims at understanding and evaluating the magnitude and significance of the potential environmental impacts of the studies system. It contains the following main issues, which are briefly described below:

- category definition
- classification
- characterization
- valuation/weighting

The LCIA should ideally interpret the inventory results into their potential impacts on what is referred to as the "areas of protection" of the LCIA, i.e. the entities that are to be protected by using the LCA. The common consensus is that these areas encompass human health, natural environment, natural resources, and to some extent man-made environment. Impacts are modeled based on available knowledge about relationships between interventions in the form of resource extractions, emissions, land and water use, and their impacts in the environment, as illustrated in Fig. 10 for emissions of substances.

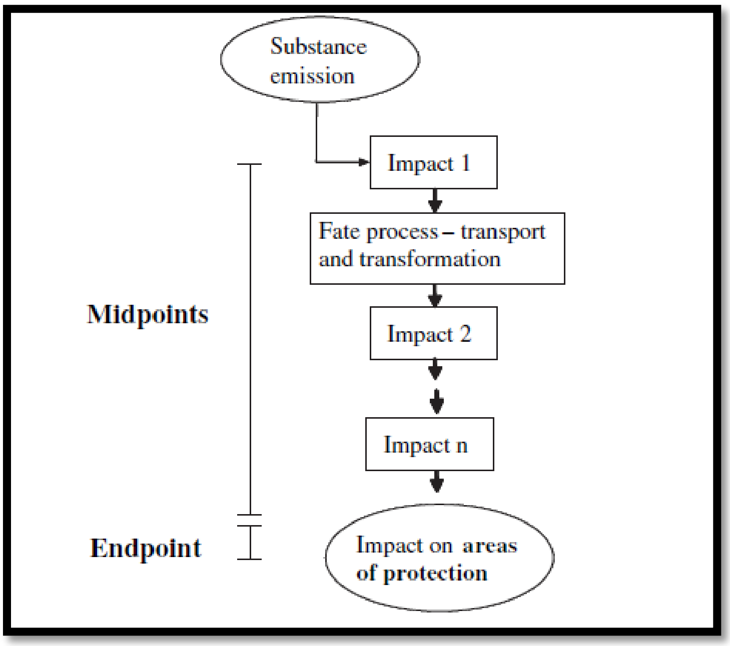

Fig. 10 Schematic presentation of an environmental mechanism underlying the modeling of impacts and damages in LCIA (Hauschild and Potting 2005)

It could be seen that a distinction is made between midpoint and endpoint, where endpoint indicators are defined at the level of the areas of protection and midpoint indicators indicate impacts somewhere between the emission and the endpoint. Fig. 11 provides further illustration of possible midpoints.

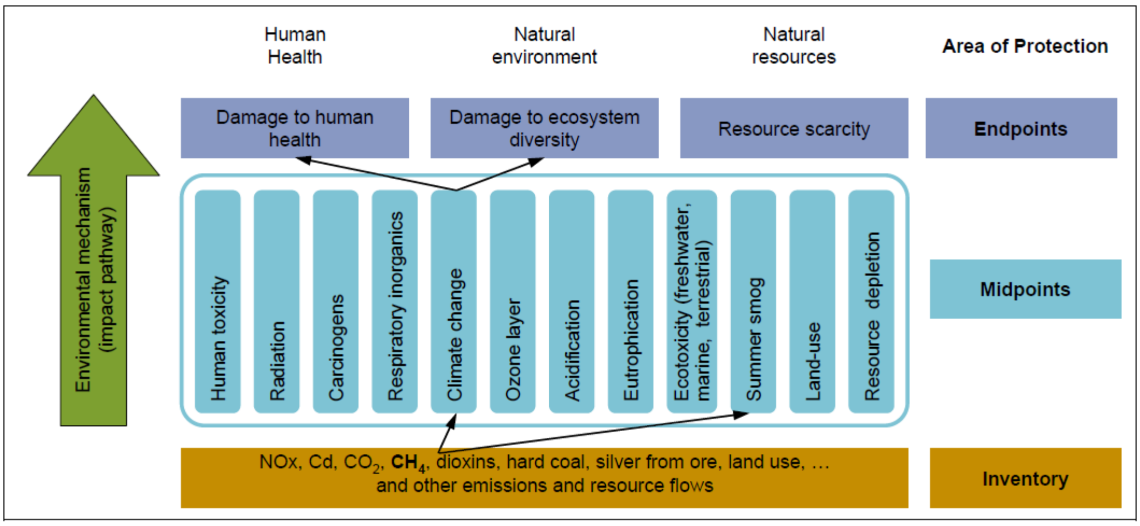

Fig. 11 Schematic steps from inventory to category endpoints (ILCD 2010)

Category definition

The impact categories are selected in order to describe the impacts caused by the considered products or product systems. The completeness and extent of the survey of categories is goal and scope dependent. The impact categories considered are:

- Abiotic resources
- Biotic resources
- Land use
- Global warming
- Stratospheric ozone depletion
- Ecotoxicological impacts
- Human toxicological impacts
- Photochemical oxidant formation
- Acidification
- Eutrophication
- Work environment

Classification

Classification is a qualitative step based on scientific analysis of relevant environmental processes. The classification has to assign the inventory input and output data to potential environmental impacts i.e. impact categories. Some outputs contribute to different impact categories and therefore, they have to be mentioned twice. The resulting double counting is acceptable if the effects are independent of each other whereas double counting of different effects in the same effect chain (e.g. stratospheric ozone depletion and human toxicological effects as e.g. skin cancer) is not allowed.

The impact categories can be placed on a scale dividing the categories into three (four) different space groups: global impacts, (continental impacts,) regional impacts and local impacts. The impact categories is often related directly to exposure i.e. global exposure is leading to global impacts, continental exposure is leading to continental impacts.

Characterization

The purpose of characterization is to model categories in terms of indicators, and, if possible, to provide a basis for the aggregation of the inventory input and output within the category. This is also done in terms of the indicator to represent an overall change or loading to that category. The result of characterization is that the combination of category indicators represents initial loading and resource depletion profile.

Normalization/Weighting

Weighting aims to rank, weight, or, possible, aggregate the results of different life cycle impact assessment categories in order to arrive at the relative importance of these different results. The weighting process is not technical, scientific, or objective as these various life cycle impact assessment results e.g., indicators for greenhouse gases or resource depletion, are not directly comparable. However, weighting may be assisted by applying scientifically-based analytical techniques (Table 6).

Proxy approach	In this approach one or several quantitative measures are stated to be indicative for the total environmental impact. Energy consumption, material displacement and space consumption are examples on using this approach.
Technology abatement approach	The possibility of reducing environmental burdens by using different technological abatement methods can be used to set a value on the specific environmental burden. This approach can be applied to inventory data as well as impact scores.
Monetization	This approach can be described with the following premises: • "utilitarianism (values are measured by the aggregation of human preferences) • willingness to pay/accept is an adequate measure of preferences • values of environmental quality can be substituted by other commodities" This approach can be applied to inventory data as well as impact scores.
Authorized goals or standards	Environmental standards and quality targets as well as political reduction targets can be used to calculate critical volumes for emissions to air, water, soil or work environment. The targets or standards can be formulated by national or local authorities, within a company etc.
Authoritative panels	The authoritative panel can be made up of lay people, of societal group panels, of scientific experts, of governments or international bodies.

Table 6 Possible weighting techniques (EEA 1997)

A distinction can also be made between methods based on stated and revealed preferences. (See also section 2 DTU Civil Engineering appendix.) In methods based on stated preferences, people are asked about their preferences in surveys and interviews. All methods involving panels as well as some monetization methods are based on stated preferences. In methods based on revealed preferences, empirical data on human behavior is used to calculate the weighting factors. Monetization methods such as hedonic pricing are an example.

Finally, a distinction can be made between midpoint and endpoint methods as discussed above.

New weighting methods that have been developed since the late 1990s include:

- EPS method (Steen 1999) – an endpoint method, based on monetary measures
- Ecoindicator '99 (Goedkoop and Spriensma 2000) – an endpoint method, based on a panel approach
- EDIP (Wenzel et al.) – distance-to-target method
- Ecoscarcity (Frischknecht et al 2008) - distance-to-target method
- LIME (Itsubo et al. 2004, Weidema 2009) – based on monetary valuation of endpoints

- Ecotax (Finnveden et al. 2006) - based on monetary valuation of midpoints
- Panel methods for midpoints (Zhang et al. 2006)
- Cumulative fossil energy demand and the ecological footprint methods (Huijbregts et al. 2006, 2008) – proxy methods

The decision of inclusion/exclusion of normalization and weighting is made and documented in the initial scope definition. If a study is intended to support a comparative assertion to be disclosed to the public, no form of numerical, value-based weighting of the indicator results is permitted to be published in accordance with ISO 14040 and 14044:2006. For in-house purposes, the use of normalization and weighting – preferably using several different approaches and value perspectives – can help to demonstrate the robustness of the analysis.

Interpretation

The life cycle interpretation is the phase of the LCA where the results of the other phases are hence considered collectively and analyzed in the light of the achieved accuracy, completeness and precision of the applied data, and the assumptions, which have been made throughout the LCI/LCA study. The interpretation proceeds through three activities:

- First, the significant issues (i.e. the key processes, parameters, assumptions and elementary flows) are identified
- Then these issues are evaluated with regard to their sensitivity or influence on the overall results of the LCA. This includes and evaluation of the completeness and consistency with which the significant issues have been handled in the LCI/LCA study
- Finally, the results of the evaluation are used in the formulation of conclusions and recommendations from the LCA study.

For the purposes of this report more detailed information is given only with reference to the sensitivity analysis as the evaluation of model assumptions and uncertainties is of direct correspondence to the same phase in risk analysis.

In the interpretation step of LCA, the sensitivity analysis is used together with information about the uncertainties of significant issues among inventory data, impact assessment data and methodological assumptions and choices to assess the reliability of the final results and the conclusions and recommendations which are based on them.

Uncertainties in LCA

Uncertainties in the results of an LCA originate in:

- the data that is used in the inventory analysis to represent the elementary flows for all the processes in the system
- the data that is used in the impact assessment for translating the inventory flows into environmental impact scores
- the assumptions that are made when constructing the system, (related to the representativeness of the processes that are used in the model)

- the choices that are made on central decisions like allocation key, choice impact assessment methodology or on which future developments are considered in future studies

The uncertainty of the data for elementary flows is statistic uncertainty, i.e. of a stochastic nature. The same holds true for impact assessment factors within a given impact assessment methodology, while the uncertainty introduced by the key assumptions and choices is of a different nature in that a number of discrete outcomes are possible.

The stochastic uncertainties of the inventory and assessment data must be known together with the important choice-related uncertainties in order to determine how they propagate into the final results of the LCA. For the stochastic uncertainties, the influence on the stochastic uncertainty of final results can be assessed in two fundamentally different ways – through an analytical solution or through simulation. Both require knowledge about distribution type, mean and variation for the process and assessment data.

<u>Analytical Solution</u>

When the inventory results are calculated disregarding the variation of the individual inventory data (i.e. just using the mean values), the result is the true mean value of final results, but this approach fails to give any information about the uncertainty of this mean. The analytical approach to meet this challenge develops an equation describing the distribution (and hence also variation) of the final results as function of the distributions of process data for all processes in the system. The analytical solution becomes a very complex expression for even a simple system but it can be approximated with a Taylor series expressing the error on the results as a function of the error on the process data for each process. Although it can be simplified in this way, the analytical approach requires qualified simplifying assumptions in order to be operational for the types of systems normally modeled in LCAs. Therefore, the simulation approach is normally applied in software used for modeling of systems.

<u>Simulation</u>

Simulation of the error on the total results of an LCA is typically done using a Monte Carlo approach. Each piece of inventory data is varied independently of the other inventory data around its mean following the distribution that is specified for it (type of distribution and measure of variation). A calculation of the inventory results is performed and stored, and the inventory data is varied again at random within the distributions to arrive at a new set of inventory results. The distribution of the calculated inventory results will approach the true distribution of the results when the number of calculations gets sufficiently high (often above 1000), and thus give an estimate of the variation around the mean for the final results.

In Monte Carlo simulation it is a default assumption that all processes and elementary flows are independent and hence vary independently of each other, both within the system and among the systems that are compared in a comparative LCA. This is often not the case as the processes may have a technically based mutual dependency or even be the same process occurring at different places in the system (e.g. for background processes like power production or transportation). Next to positive correlation also negative correlation occurs. Rather than independent variation, these cases may have a high degree of co-variation which will tend to either reduce or increase the variation of the final results, and it must therefore be taken into account when setting up the simulation, which is often not straight forward.

Choice-related Variation

The variation in the final results that is caused by choice-related differences must be handled by separate calculations for each combination of the identified relevant choices. Where the stochastic uncertainties can be handled and aggregated into one set of final results as described above, the choice-related variation thus leads to a number of discrete results that may be presented to the decision maker together with a specification of the underlying choices as possible outcomes of the LCA, dependent on which choices are made. In order to strengthen the decision-making support of the LCA results it is important to reduce the number of choices that are considered to the required minimum.

Sensitivity analysis is a useful tool to identify where good basic statistic information is most needed. The processes and flows that contribute most to the final results are also the ones with the strongest potential to contribute to the uncertainty of the final results, and particularly for these key figures, it is thus crucial that the statistical information is correct.

In the absence of tools to support a Monte Carlo simulation, an analysis of the uncertainty of the final results may still be performed along this line, using a sensitivity analysis to identify the key processes, key elementary flows and key choices. For each of these, the potential variation is analyzed and basically handled as discrete choices (for stochastic uncertainties as realistic worst case and realistic best case values) in a number of what-if calculations. The outcome in some cases allows an indicative answer to the question of the goal definition. In other cases the outcome is inconclusive meaning that a more detailed approach is needed in a new iteration, but then it helps focus the effort on some of the identified key data and assumptions.

3.4 The Global Decision Support Initiative

The Global Decision Support Initiative (GDSI) is a knowledge collaboration initiative of the six DTU departments examined in the present report, and it is hosted by DTU Management. Formally established at the end of 2014, activities are only presently beginning. The present report could be seen in this light as a knowledge gathering to aid the planned activities.

GDSI is envisaged as a scientific platform to support national and global decision and policy makers with riskassessment and sustainability assessment knowledge for evidence-based decision and policy making.

The GDSI aims at bringing all the expertise fields required for sustainability and risk-informed decision making under one roof, which will allow for a close collaboration between experts from the respective areas to harmonize methodologies, learn from each other and combine the insights offered by these two approaches for an enhanced decision support. The collaboration is seen as foundation for large synergies and potential innovation.

The scientific rationale behind the GDSI is that the overarching theoretical and methodical framework for decision support can be found in the Bayesian decision theory. This framework facilitates for an assessment and ranking of decision alternatives in full consistency with available knowledge, prevailing uncertainties and preferences. Moreover, this framework facilitates the inclusion of, and adaptation to, new information at the same phase as this becomes available. A major challenge in decision making concerns the representation of preferences and it is in this respect that the GDSI will provide a novel and scientifically significant contribution by building the link between preferences with respect to sustainability, life cycle assessment and risk assessment (Fig. 12).

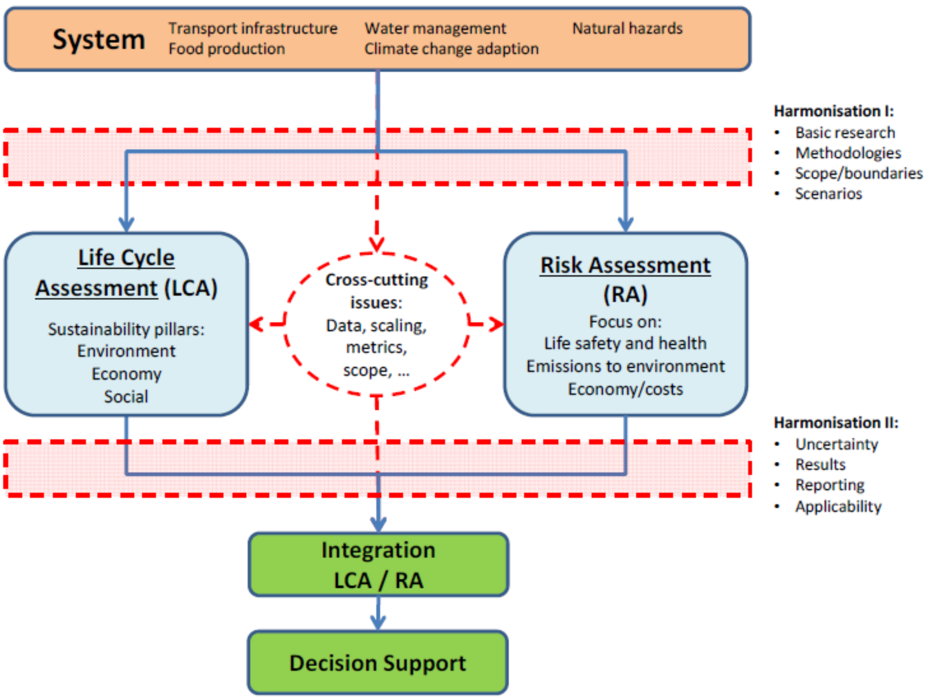

Fig. 12 Illustration of framework for sustainability and risk-informed decision support (GDSI 2014)

GDSI's main deliverables during its first 3 years of existence are planned to be seven project and research activities, which are briefly described in Table 7.

	Aims & Objectives	Basis
Activity 1 **System Identification**	Establish the general philosophical and methodological basis for the generic decision support framework and in particular it is concerned with coherent system identification and representation. An important outcome of the activity is a general recommended framework for the classification and treatment of the various types of uncertainties and dependencies in engineering decision making.	Basis is taken in the current theoretical framework of risk and sustainability assessment and their use in decision support. The representation and management of knowledge and uncertainty in engineering decision problems is based upon available formulations of information theory, probability theory and uncertainty modeling. Policy, preferences and metrics are based on different prevailing theories of welfare economics related to health, of environment and ecosystem services, and of economic growth, individual and social preferences prevail at different societal levels and scales, which in an intra- and intergenerational perspective, individually and in a social context facilitates that these three dimensions of sustainability are transformed into a social welfare function, which can provide the basis for defining metrics of sustainability (e.g. Life Quality Index).
Activity 2 **Decision Theory and Decision Support Tools**	The objective is to provide sound modeling guidelines for different types of decision situations alongside a set of decision support tools ready to be implemented.	The theoretical basis for the activities is found the in available theories for engineering decision making, such as the Bayesian decision theory.
Activity 3 **IT infrastructure and computational uncertainty and probability models**	This activity aims at providing a general competence for IT and computational issues at the GDSI and it has two main objectives. Firstly, the development of an IT framework for the Open Decision Support Platform for the storage, organization and representation of data and information processing models. Secondly to provide the center with expertise on advanced computational techniques in analysis and optimization of probabilistic systems that are relevant for risk assessment and decision analysis.	The generic framework, which is established in Activities 1 and 2, underlying the Open Decision Support Platform is based upon well-established theoretical frameworks for risk assessment, life cycle assessment and decision theory. Computational uncertainty and probability models take basis in a number of important techniques in analysis and optimization of probabilistic systems are relevant for risk assessment and decision analysis.
Activity 4 **Decision support for food production systems**	This activity will focus on the use of risk assessment models, based in stochastic modeling and attempting to cover full farm-to-fork continuum. The potential to combine such assessments with the use of sustainability models and disease burden metrics, specifically the Disability Adjusted Life Year (DALY) metric, will be investigated as per its use in risk informed decision support.	Risk assessment has been used in estimating chemical risks in food for more than 60 years, primarily based in a deterministic frame. Microbiological risk assessment is more recent in relation to foods and has only been used since stochastic modeling was introduced in the area in the 1990'ies. Life Quality Index concepts, such as the WHO Disability Adjusted Life Year measurements, have typically not been used in the area, and sustainability models have only been used in

		very specific cases.
Activity 5 **Climate change adaptation in relation to urban water management**	The aim of this activity is to develop state of the art decision support models for climate change adaptation in relation to urban water management, taking into account both risk of flooding and overall sustainability of the analyzed solutions.	All three dimensions of sustainability (social, economic, and environmental) are currently being threatened by the observed increase in climatic extremes. Climate projections foresee that the increase will continue in the decades to come and hence it is of paramount importance to identify measures that enable transition to more resilient cities. The same projections also foresee summers that are in general warmer and drier, and hence it becomes more important to retain water to preserve livability by utilizing the obvious amenity values of water while minimizing the risk of damage due to climatic extremes.
Activity 6 **Application of decision support for transport infrastructure assessment**	This activity rests heavily upon data, model and impact calculations, thus, especially transferred uncertainties and parameter calibration of stochastic variables will be investigated further. Current concerns within decision support in the transport sector is the tendency to overestimate the benefits and underestimate the costs – thus, the main objective of this activity will be to treat and disclose the uncertainties.	The decision support framework is based upon a set of well-established theoretical frameworks within the area of quantitative risk analysis (such as Monte Carlo simulation), Reference Class Forecasting (and Prospect Theory), decision theory and analysis and Economical Theory (such as cost-benefit analysis, welfare theory, etc.). These methods and theories will be utilized and compiled in a manner to establish a generic framework for assessment and decision making.
Activity 7 **Application of decision support to natural hazard risk management and real time decision-making**	The aim of this activity is to develop state of the art decision support models for relevant natural hazard risks management.	For several years natural hazard risk models have been available in the research community. Moreover, recently the number of decision models in regard to natural hazard risk management and real time emergency management has been increasing. These models are used as a starting point for this activity. In particular, several models developed under the supervision of Michael Faber at ETH Zurich and DTU Civil Engineering in earthquake risk management, typhoon risk modeling and typhoon real-time decision making as well as in flood risk management are considered as a basis for this activity.

Table 7 Planned activities at the GDSI for 2015-2018

4. Advisory Activities

DTU Management Engineering develops decision-supporting models and systems within the areas of sustainable energy, climate, transportation, health and urban development and contributes in this way to giving national and international authorities various tools for making the right decisions. The Department contributes for instance to developing public databases and indicators of sustainability and innovation to facilitate the development of benchmarks and policy tools.

The Department's primary public sector consultancy tasks are managed by UNEP Risø Centre whose main task is to provide counselling to United Nations Environment Programme (UNEP) within the areas of energy efficiency improvement and climate change in developing countries.

In addition, the Department provides counselling through research projects where authorities form part as collaborators (e.g. project Robust Rails).

Finally, the newly established Global Decision Support Initiative, hosted by DTU Management has as its core aim, the provision of science-based decision support to national and international authorities. (See section 3.4)

5. Educational Offerings

Table 8 lists all courses related to risk at DTU Management Engineering, together with a brief outline of their content. This information was collected through DTU *Kursusbasen* by performing a search for the following keywords: *risk, safety, uncertainty, life cycle, sustainability, and decision analysis*.

Course Nr./ Keyword	**Title**	**Content**	**Type**
42106 risk	Financial Risk Management	Introduction to main sources of financial risks namely credit risk, market risk and operational risk. Practical measurement and management of these risks. Basel accords and their role in risk management. Stress testing. Lessons learned from well-known financial crises. Use of Matlab.	MSc
42123 risk	Optimization in Finance	Introduction to financial markets and instruments, modeling in GAMS, classification of risks and their modeling (tracking, Value at Risk, Conditional Value at Risk), classical concepts (duration, convexity) and models for fixed-income and stock portfolios (immunization, dedication, Markowitz), interest rate and stock price models, scenario-based modeling and stochastic programming.	MSc
42171 risk	System Safety and Reliability Engineering	Fundamental concepts and terminology of safety, risk and reliability. Principles of safety assessment as required by legislation, regulations and standards. Technical risk analysis: a general accident model, hazard	MSc

		identification, accident scenario, probability measures for reliability and risk, damage and consequence assessment of accidental events, risk evaluation. Techniques and approaches to domain specific hazard identifications and quantitative risk assessments including what-if analysis, rapid risk ranking, FMEA, risk matrix, barrier diagrams, event trees and fault trees. Models for reliability assessment Data sources for reliability assessment and risk analysis. Accounting for uncertainty: stochastic and epistemic uncertainty, probabilistic reliability and risk measures, mathematics of probability, approaches to the assessments of the measures. Utilization and role of quantified risk analysis in management of system safety and reliability. Link between technological system and organizational management, and role of inspection, maintenance, procedures, etc. in safeguarding technological systems.	
42172 risk	Risk and Decision-making	Fundamental concepts, principles and terminology of risk assessment and management process as defined by ISO standards. Internal, external and risk management context; SWOT. Risk identification: overview of existing methods and their strengths and limitations. Specific identification methods including structured brainstorming, check lists, preliminary hazard analysis, structured what-if technique (SWIFT), business impact analysis and failure mode and effect analysis (FMEA). Tools and approaches to scenario development: fault, success, decision and event trees; barrier and bow-tie diagrams. Qualitative and semi-quantitative risk analysis and presentation of the results in the form of risk matrix. Risk evaluation: setting priorities over risk-reducing measures and comparing against criteria. Basics of probability. Normative decision making theory (maximising expected utility) and rational agent. Deviations from a normative decision making theory: accounting for different attitudes towards risk and uncertainty, dread factors, different human values and non-linearity of utilities. Making decisions under ignorance: rules of Laplace, Wald, Hurwicz and Savage. Multi-criteria decision making: problem statement and solving approaches. The ALARP principle, value of human life and the role of different human values and biases.	MSc
42255	Working Environment in	Statutory role of a safety-coordinator	BSc

risk	the Construction Process	throughout the design and production stages in construction. Specific forms of organization and management which have a positive influence on health and safety (H&S) in the construction process. Regulatory demands of The Danish Working Environment Act in relation to a construction project. Relevant H&S factors and risks typical to work processes in construction.	
42378 risk	Evaluation of environmental and health impacts from products and systems	Main types of decision situations concerning management of environmental and health impacts from man-made activities. Principles of different impact assessment methods and underlying models. Identification, application and interpretation of results of appropriate assessment methods and tools for quantifying environmental, health and life cycle impacts from chemical emissions from different stakeholder perspectives and regulatory contexts.	MSc PhD
42430 risk	Project Management	Main elements of project management: to set up objectives and success criteria, stakeholder and risk analyses, milestone and activity planning, organizing and managing the project, learning and knowledge management in projects.	BSc
42430 risk	Advanced Engineering Project, Program and Portfolio Management	Complexity - with a particular focus on the relationship of technical and organizational complexity. Uncertainty - with a focus on identifying and mitigating key risks and uncertainties throughout the long life cycles of engineering systems. Human behavior - addressing the social and organizational intricacies caused by public opinion formation as well as inner- and intra-organizational factors.	MSc
42871 risk	Planning and Control of Building Projects	The course introduces the students to real construction management scenarios in which a risk management approach is a central tool for the students in making priorities and decisions.	D.Ing
42M01 safety	The Company´s Environment, Health and Safety Work	Coordination of the company's environmental, health and safety work and the priorities that are primarily driven by economic and commercial motives, with the protection of nature and people	p/t MAS
42M02 safety	The Company and Society	Planning of an effective regulations performance facing environment and work environment issues. Incorporating environment and work environment in other forms of regulation, e.g. standards.	p/t MAS
42348 Life cycle	Sustainable Development of Emerging Technologies	Actor network analysis of the many entities that can influence the technological field. Analysis of governance and development of regulations and legislation in the field. Life cycle check of the	MSc PhD

		product, and paths for optimizing the lifecycle to reduced footprint. Resource supply security and forecasts of involved materials. Toxicological aspects and ecotoxicological aspects. The historical development in the field, competing technologies, fundamental limitations on performance, and future market analysis.	
42259 Life cycle	Facilities Management	General introduction to Facilities Management with focus on the usability of buildings during the whole life cycle and the integration of operational aspects in the planning of new buildings.	MSc
42281 Life cycle	Co-Creation against Climate Change	Entrepreneurship through Co-Creation across Technology, Business and Media. Technological Innovation in Renewable Materials, Clean Energy, Clean Urban Mobility. Media, Communication and Marketing of Sustainable Innovation.	MSc
42340 Life cycle	Sustainability in Engineering Solutions	Introduction to environmental assessment of products and solutions in their life cycle through the use of simple tools. On this basis methods and tools are presented for the development of environmentally improved products and solutions.	BSc
42342 Life cycle	Sustainable Production	Introduction to the industrial society and its central technical systems, the resource and environmental problems, it faces and industry's role in these problems. Discussion of sustainability concepts and their implementation in the assessment of eco efficiency and resource efficiency. Introduction of tools to perform such assessments.	BSc
42372 Life cycle	Life Cycle Assessment of Products and Systems	Introduction of the life cycle concept and the history of life cycle assessment. Application of LCA in industry and public organisations. Level of institutionalisation of LCA in an organisation. Purpose of using LCA in industrial production and management in a life cycle perspective. Presentation of methodological foundation of LCA step by step from goal and scope definition over inventory analysis and assessment of impacts on environment, resources and working environment to interpretation and sensitivity analysis. Operational parameters representing environment, work environment, resource use (energy, materials etc.), and social aspects. Introduction to the practical applications of LCA (eco-labelling, environmental management, product development, policy development etc.) Introduction of software tools supporting the practical performance of LCA. In parallel to the	MSc PhD

		theoretical introduction the participants work in project teams applying the theory in practice in a life cycle assessment of a product or system, typically in collaboration with an external company.	
42375 Life cycle	Advanced Life Cycle Assessment, System Modelling and Hybrid Analysis	Advanced product system modelling: construction and application of coupled parameterized products system models. Characterization models: Coupling of recognized characterization models (ReCiPe, USEtox etc.) with own product system models. Model sensitivity and uncertainty: Execution and assessment of product system model sensitivity and uncertainty analysis. Inventory models: Development of own simple inventory models, application of 3rd party models and implementation of results hereof. Hybrid analysis: Understanding the fundamental principle of I/O-analysis, execution of coupled I/O analysis and LCA (i.e. hybrid analysis) and understanding the differences between stringent LCA and hybrid analysis.	MSc
42377 Life cycle	Life Cycle Management in industry	Introduction to the concept of life cycle thinking and to Life Cycle Management (LCM) incl. its history. Examples of applications of LCM in industry and public organisations. Introduction to the implementation processes of LCM in an organization, incl. design and use of Key Performance Indicators (KPIs). Review of Life Cycle Assessments (LCAs) and their use as an assessment tool for environmental effects, incl. simplified versions such as Screening LCAs, MECO analyses and Carbon Footprinting. Introduction to Actor-Network Theory and its application for stakeholder analysis. Review of tools to support typical decisions in the various stages of the product life cycle - both quantitative calculation programs for environmental and rough economic assessments - and qualitative environmental tools such as design guidelines.	MSc
42005 Decision analysis	Micro and Macroeconomics	Basic microeconomic theory: consumption theory, theory of the firm and efficiency. Basic macroeconomic theory: Macroeconomic balances, The difference between supply and demand driven effects on production, labour supply, employment etc., Economic fluctuations, Economic policy and The open economy, foreign trade, competitiveness, comparative advantages and exchange rates.	BSc
42101	Introduction to	Operations research (OR) is about applying	BSc

Decision analysis	Operations Research	mathematical models to help decision makers. Linear programming: model formulation, the Simplex method, theory, duality, sensitivity analysis, and other algorithms. The transportation problem: model formulation and solution. The assignment problem. Dynamic programming. Game theory. Queueing models: theory and applications. Inventory models: deterministic and stochastic.	
42111 Decision analysis	Static and Dynamic Optimisation	Static optimization: Linear programming and duality, Convexity and optimality, Karush-Kuhn-Tucker conditions, Lagrangian duality, Solution methods. Examples of economic and technical applications: production planning, portfolio planning. Dynamic optimization: Control theory, Pontriagin's maximum principle, dynamic programming, Bellman's optimality principle. Examples of economic and technical applications: pipe line problem, production planning, economic models.	MSc
42286 Decision analysis	Planning and Management in Construction	Recent developments in construction in Denmark and abroad. Understand a construction project in its societal and business context. Identify main client, user and other actor/stakeholder interests. Analyse contractual, legal and financial conditions. Set up a project organisation considering the specific project type and its external framework. Assess process and management aspects with the view of employing modern procurement forms and planning methods, like PPP, Partnering, lean, ICT etc. Work with risk and life cycle perspectives to optimise the project value with regard to technical and operational criteria.	MSc
42376 Decision analysis	Operations Management in Health Care and Service Systems	Analysis and evaluation of patient / customer flow Development of optimization criteria.	MSc
42406 Decision analysis	Introduction to Decision Models for Production and Operations Management	Strategy of production systems. Designing production systems (product and service design, quality management, process planning and layout, supply chain). Operating production systems (capacity planning, material planning, process control, project management). General subjects (influence of the IT-development, ERP-systems/Enterprise Resource Planning, Business Excellence, continual improvements, environmental management, marketing).	BSc
42580	Engineering Work 1	Introduce engineering work related to planning	BSc

Decision analysis		and decision-taking including the building of a professional vocabulary. The course is an introduction to engineering work with focus on the following topics: • planning and decision • strategy and systems design • ethics and sustainability • energy systems and transport systems • group work including giving / receiving feedback • self-management in study planning	

Table 8 Courses at DTU Management Engineering explicitly and implicitly related to risk

9. Data sources

Personal Interview/Consultation with Frank Markert and Igor Kozine, Senior Researchers, Risk Research Group DTU Management Engineering

Frank Markert Senior Researcher (Major Accident Hazard) fram@dtu.dk Special Interests: Major Accident Hazard, Consequence Modeling, Safety Barriers, Static and Dynamic Models for Risk Assessment	

Igor Kozine Senior Researcher (Major Accident Hazard) igko@dtu.dk Special Interests: Risk Analysis, Reliability, Human Factor Analysis	

Personal Interview with Josef Oehmen, Associate Professor, Engineering Systems Group DTU Management Engineering

<table>
<tr>
<td>Josef Oehmen
Associate Professor (Project Risk Management)

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Special Interests: Risk Management, Engineering Systems, Product development, Lean Management, Systems Engineering, Program Management</td>
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DTU Management Engineering website

7. Glossary of terms related to Major Accident Hazard and Project Risk Management

All the terms in this section are from ISO 31000 as interviewed researchers at DTU Management working in the context of Major Accident Hazard and Project Risk Management indicated that they refer to the ISO standard.

Risk	In ISO 31000, *risk* is defined as the "effect of uncertainty on objectives", with *effect* being a positive or negative deviation from what is expected.
Risk management	Risk management refers to a coordinated set of activities and methods that is used to direct an organization and to control the risks that can affect its ability to achieve objectives. The term risk management may also refer to the architecture that is used to manage risk. This architecture includes risk management principles, a risk management framework, and a risk management process.
Risk management framework	A risk management framework is a set of components that support and sustain risk management throughout an organization. There are two types of components: foundations and organizational arrangements. Foundations include risk management policy, objectives, mandate, and commitment. Organizational arrangements include the plans, relationships, accountabilities, resources, processes, and activities used to manage an organization's risk.
Risk management policy	A risk management policy statement expresses an organization's commitment to risk management and clarifies its general direction or intention.
Risk attitude	An organization's risk attitude defines its general approach to risk. An organization's risk attitude (and its risk criteria) influence how risks are assessed and addressed, e.g. whether or not risks are taken, tolerated, retained, shared, reduced, or avoided, and whether or not risk treatments are implemented or postponed.
Risk owner	A risk owner is a person or entity that has been given the authority to manage a particular risk and is accountable for doing so.
Establishing the context	To establish the context means to define the external and internal parameters that organizations must consider when they manage risk.
External context	An organization's external context includes all of the external environmental parameters and factors that influence how it manages risk and tries to achieve its objectives, e.g. external stakeholders, local, national, and international environment, as well as key drivers and trends that influence its objectives. It includes stakeholder values, perceptions, and relationships, as well as its social, cultural, political, legal, regulatory, financial, technological, economic, natural, and competitive environment.
Internal context	An organization's internal context includes all of the internal

	environmental parameters and factors that influence how it manages risk and tries to achieve its objectives, e.g. internal stakeholders, its approach to governance, its contractual relationships, and its capabilities, culture, and standards. *Governance* includes the organization's structure, policies, objectives, roles, accountabilities, and decision making process, and *capabilities* include its knowledge and human, technological, capital, and systemic resources.
Risk assessment	Risk assessment is a process that is, in turn, made up of three processes: risk identification, risk analysis, and risk evaluation. *Risk identification* is a process that is used to find, recognize, and describe the risks that could affect the achievement of objectives. *Risk analysis* is a process that is used to understand the nature, sources, and causes of the risks that have been identified and to estimate the level of risk. It is also used to study impacts and consequences and to examine the controls that currently exist. *Risk evaluation* is a process that is used to compare risk analysis results with risk criteria in order to determine whether or not a specified level of risk is acceptable or tolerable.
Risk source	A risk source has the intrinsic potential to give rise to risk.
Consequence	A consequence is the outcome of an event and has an effect on objectives. A single event can generate a range of consequences which can have both positive and negative effects on objectives. A distinction is made between direct consequences and follow-up consequences.
Likelihood	Likelihood is the chance that something might happen. Likelihood can be defined, determined, or measured objectively or subjectively and can be expressed either qualitatively or quantitatively.
Risk profile	A risk profile is a written description of a set of risks. A risk profile can include the risks that the entire organization must manage or only those that a particular function or part of the organization must address.
Risk criteria	Risk criteria are terms of reference and are used to evaluate the significance or importance of an organization's risks. They are used to determine whether a specified level of risk is acceptable or tolerable.
Level of risk	The level of risk is its magnitude. It is estimated by considering and combining consequences and likelihoods. A level of risk can be assigned to a single risk or to a combination of risks.
Risk treatment	Risk treatment is a risk modification process. It involves selecting and implementing one or more treatment options. Once a treatment has been implemented, it becomes a control or it modifies existing controls. You have many treatment options: avoid the risk, reduce the risk, remove the source of the risk, modify the consequences, change the probabilities, share the risk with

	others, retain the risk, or increase the risk in order to pursue an opportunity.
Risk Control	Risk control is any measure or action that modifies risk. Risk controls include any policy, procedure, practice, process, technology, technique, method, or device that modifies or manages risk. Risk treatments become controls, or modify existing controls, once they have been implemented.
Residual risk	Residual risk is the risk left over after a risk treatment option has been implemented.

8. Glossary of terms related to Occupational Health and Safety

All the terms in this section are from OHSAS 18001. With some exceptions, the terms used in the context of Major Hazard are also relevant for this area.

Risk	Risk combines three elements: it starts with a *potential event*, and then combines its *probability* with its *potential severity*. In the context of OH&S, the concept of risk asks two future oriented questions: 1. What is the *probability* that a particular hazardous event or exposure will actually occur in the future? 2. How *severe* would the impact on health and safety be if the hazardous event or exposure actually occurred? A high risk hazardous event or exposure would have both a high probability of occurring and a severe impact on OH&S if it actually occurred. A high risk event or exposure is one that is likely to cause severe injury or ill health.
Hazard	A hazard is any situation, substance, activity, event, or environment that could potentially cause injury or ill health. • *Hazardous situations* can cause injury or ill health. Examples include slippery or uneven walking surfaces, cramped working conditions, badly ventilated areas, high altitudes, noisy locations, poorly lit areas, and confined spaces. • *Hazardous substances* can cause injury or ill health. Examples of potentially hazardous substances include corrosive and toxic chemicals, flammable and explosive materials, dangerous gases and liquids, radioactive substances, particulates, poisons, bacteria, and viruses. • *Hazardous activities* can cause injury or ill health. Examples include dangerous tasks, unnatural movements and postures, heavy lifting, repetitive work, interpersonal conflicts, bullying, and intimidation.

	• *Hazardous events* can cause injury or ill health. Examples include explosions, implosions, collisions, vibrations, fires, leaks, releases, chemical reactions, electric shocks, falling objects, loud noises, structural breakdowns, software failures, equipment malfunctions, and unscheduled shutdowns.
Hazard identification	Hazard identification is a process that involves recognizing that an OH&S hazard exists and then describing its characteristics.
Risk assessment	A risk assessment considers the effectiveness of existing OH&S controls and then evaluates the probability and the potential severity of specific hazardous events and exposures. On the basis of such an assessment, organizations decide whether or not the risk is acceptable.
Occupational Health and Safety	When OHSAS 18001 uses the term occupational health and safety, it refers to all of the factors and conditions that: 1. affect health and safety in the workplace, or 2. could affect health and safety in the workplace. Occupational health and safety (OH&S) factors affect employees (permanent and temporary), contractors, visitors, and anyone else who is in the workplace.
Health	Ill health is an adverse physical or mental condition. In order to qualify as an occupational health and safety problem, an adverse physical or mental condition must be identifiable and be caused or aggravated by a work activity or a work related situation.
Incident/Accident	An incident is a work related event during which: 1. injury, ill health, or fatality actually occurs, or 2. injury, ill health, or fatality could have occurred. An accident is a type of incident. It is a work-related event during which injury, ill health, or fatality actually *occurs*. It is a type of incident. A close call, near miss, near hit, or dangerous occurrence is also a type of incident. It is a work-related event during which injury, ill health, or fatality could have occurred, but didn't actually occur.
Preventive Action	Preventive actions are steps that are taken to remove the causes of potential nonconformities or other undesirable situations that have not yet occurred. In general, the preventive action process can be thought of as a risk analysis process.

9. Glossary of terms related to Life Cycle Assessment and Sustainability

Sustainability	Sustainability is the capacity to endure. In ecology, the word describes how biological systems remain diverse and productive over time. For humans, sustainability is the potential for long-term maintenance of well- being, which has environmental, economic, and social dimensions.
Sustainable development	The Brundtland Commission (Our Common Future, 1987) defined sustainable development as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. The concept was a compromise between rich economies pushing for stronger environmental protection and developing economies focused on poverty alleviation. Sustainable development attempts to achieve equitable development within the current generation, while also protecting the rights of future generations.
Aggregation	The action of summing or bringing together information (e.g., data, indicator results) from smaller units into a larger unit. (e.g., from inventory indicator to subcategory). (Benoit and Mazijn 2009)
Allocation (partitioning)	Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems. (ISO 2006)
Attributional approach	System modelling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule.
Consequential approach	System modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit.
Cradle-to-gate	An assessment that includes part of the product’s life cycle, including material acquisition through the production of the studied product and excluding the use or end-of-life stages. (WRI and WBCSD 2010)
Cradle-to-grave	A cradle→to→grave assessment considers impacts at each stage of a product’s life cycle, from the time natural resources are extracted from the ground and processed through each subsequent stage of manufacturing, transportation, product use, recycling, and ultimately, disposal. (Athena Institute & National Renewable Energy Laboratory draft 2010)
Cut-off-criteria	Specification of the amount of material or energy flow or the level of environmental significance associated with unit processes or product system to be excluded from a study. (ISO 2006)
System	Any good, service, event, basket-of-products, average consumption of a citizen, or similar object that is analyzed in the context of the LCA study. Note that ISO 14044:2006 generally refers to "product system", while broader systems than single products can be analyzed in an LCA study; hence here the term "system" is used. In many but not

	all cases the term will hence refer to products, depending on the specific study object.
System perspective	In contrast to a unit process or a part of a life cycle, the system perspective relates to the entire life cycle of an analyzed system or process. For processes, that implies that the life cycle is completed. This term is used mainly in context of identifying significant issues and quantifying inventory completeness / cut-off.
Unit process	Smallest element considered in the life cycle inventory analysis for which input and output data are quantified. (Source: ISO 14040) In practice of LCA, both physically not further separable processes (such as unit operations in production plants) and also whole production sites are covered under "unit process".
Background System	The background system consists of processes on which no or, at best, indirect influence may be exercised by the decision-maker for which an LCA is carried out. Such processes are called "background processes." (Frischknecht 1998)
Foreground system	The foreground system consists of processes which are under the control of the decision-maker for which an LCA is carried out. They are called foreground processes. (Frischknecht 1998)
System boundary	Set of criteria specifying which unit processes are part of a product system. (ISO 2006)
Substitution	Solving multi-functionality of processes by expanding the system boundaries and substituting the non-reference products with an alternative way of providing them, i.e., the processes or products that the non-reference product supersedes. Effectively the non-reference products are moved from being outputs of the multi-functional process to be negative inputs of this process, so that the life cycle inventory of the superseded processes or products is subtracted from the system, i.e., it is "credited." Substitution is a special (subtractive) case of applying the system expansion principle. (Definition prepared by merging the definitions from ISO 14040ff and the European Commission – Joint Research Centre – Institute for Environment and Sustainability 2010)
Elementary flow	Material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation (ISO 14040, 2006).
Reference flow	Measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit. (ISO 2006)
Impact category	Impact Categories are logical groupings of Life Cycle Assessment results of interest to stakeholders and decision makers. (UNEP/SETAC, 2009)
Life cycle	Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal. (ISO 2006)
Life cycle approaches	Techniques and tools to inventory and assess the impacts along the life cycle of products.
Life cycle assessment (LCA)	Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

	(ISO 2006)
Life cycle costing (LCC)	Life cycle costing, or LCC, is a compilation and assessment of all costs related to a product, over its entire life cycle, from production to use, maintenance and disposal. (UNEP/SETAC, 2009)
Life cycle inventory analysis (LCI)	Phase of Life Cycle Assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle. (ISO 2006)
Life cycle impact assessment (LCIA)	Phase of Life Cycle Assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product. (ISO 2006)
Social Life Cycle Assessment (SLCA)	A social and socio-economic life cycle assessment (S-LCA) is a social impact (real and potential impacts) assessment technique that aims to assess the social and socio-economic aspects of products and their positive and negative impacts along their life cycle encompassing extraction and processing of raw materials; manufacturing; distribution; use; reuse; maintenance; recycling; and final disposal. (UNEP/SETAC, 2009)
Life cycle sustainability assessment (LCSA)	Life cycle sustainability assessment (LCSA) refers to the evaluation of all environmental, social and economic negative impacts and benefits in decision making processes towards more sustainable products throughout their life cycle. (UNEP/SETAC, 2011)
Life cycle thinking	Life Cycle Thinking is a mostly qualitative discussion to identify stages of the life cycle and/or the potential environmental impacts of greatest significance e.g. for use in a design brief or in an introductory discussion of policy measures. The greatest benefit is that it helps focus consideration of the full life cycle of the product or system; data are typically qualitative (statements) or very general and available-by-heart quantitative data. (Christiansen et al., 1997)
Life cycle management	Life cycle management is a product management system aiming to minimize environmental and socio- economic burdens associated with an organization's product or product portfolio during its entire life cycle and across its value chain. LCM is not a single tool or methodology, but a management system collecting, structuring and disseminating product- related information from various programs, concepts, and tools.
Product life cycle	Product life cycle is a term that has different meanings for different functional groups. It can refer to the purchase, use and disposal of the product from the owner/ user perspective. The marketing product life cycle refers to the distinct stages every product goes through: introduction, growth in sales revenue, maturity, and finally, decline and withdrawal. The environmental product life cycle consists of all the direct and supporting processes (see product system) required to build, distribute, use, maintain, and retire a product, from extraction of raw materials to their final disposal or recycle, i.e. cradle-to-grave.
Product system	ISO defines product system as a collection of materially and energetically connected unit processes, which perform one or more defined functions. The term "product" used alone includes not only product systems but can also include service systems.
Supply chain	A supply chain is a system of organizations, people, technology,

	activities, information and resources involved in moving a product or service from supplier to customer. Supply chain activities transform natural resources, raw materials and components into a finished product that is delivered to the end customer.
Value chain	A value chain is a high- level model describing the activities that a firm operating in a specific industry conducts to receive raw materials as input, add value to the raw materials through various processes, and deliver finished products to customers. Michael Porter popularized the concept in his 1985 best seller, Competitive Advantage: Creating and Sustaining Superior Performance. He suggested that the activities of a business could be grouped under two headings: (1) Primary Activities – those that are directly concerned with creating and delivering a product; and (2) Support Activities – those not directly involved in production, but may increase effectiveness or efficiency (e.g. human resource management).

Interview/Survey Questions - DTU Management Engineering

1. Please describe the nature of your research activities as they relate to risk:

- Research topics
- Research projects
- Academic and application fields

2. What percentage of your work that relates to risk is connected to:

- Academic research
- Teaching activities
- Advisory activities (public sector or industry)?

3. Does your research relate to risk assessment or to risk management? In the field(s) that you've been working with regard to risk, how are risk analysis, risk assessment and risk management defined?

4. What is the purpose of the risk assessments you are involved in:

- Risk from a (structural) reliability point of view?
- Risk from a health and safety point of view?
- Risk from a cost-benefit point of view?
- Risk from a quality assurance point of view?

5. What methods and approaches do you use in your risk-related research?

- Qualitative/quantitative
- Deterministic/stochastic

6. What data and metrics do you use in your risk-related research?
7. Do you use formal decision analysis in terms of evaluating risk management options?
8. What are common risk acceptance criteria in the application domain of your research?

9. Does your work related to risk assessment/management include any consideration of sustainability? Do you see a link between risk and sustainability that could be important in your research area?

10. In relation to your risk-related research, do you collaborate with other:

- DTU departments
- Academic institutions (nationally/internationally)
- Other relevant research and/or normative institutions?

11. What do you perceive to be the main challenges with regard to your risk-related research?

12. In what way(s) can collaboration with researchers from other departments enhance your own research in the area of risk?

Appendix VI: Risk at DTU Compute

Table of Contents

1. Introduction: Risk in the context of DTU Compute

Risk research in the context of DTU Compute can be considered in two distinct ways. One is the enabling capacity of mathematics and information sciences that underpins all quantitative risk assessment methodologies; another one is risk in the context of Information, ICT and cyber security. In this report, they are considered separately in sections 2.1 and 2.2 respectively.

2. Research Areas related to Risk

The Department's core competencies lie in the fields of Mathematics, Statistics and Computer Science. Research activities are organized according to 11 research sections. Among these, the following have been judged to be of particular relevance in the broader context of risk: Statistics and Data Analysis, Dynamical Systems, Scientific Computing, and Algorithms, Logic and Graphs (Fig. 1); whereas the Language-Based Technology and Cryptology sections are particularly concerned with information security risk (Table 1).

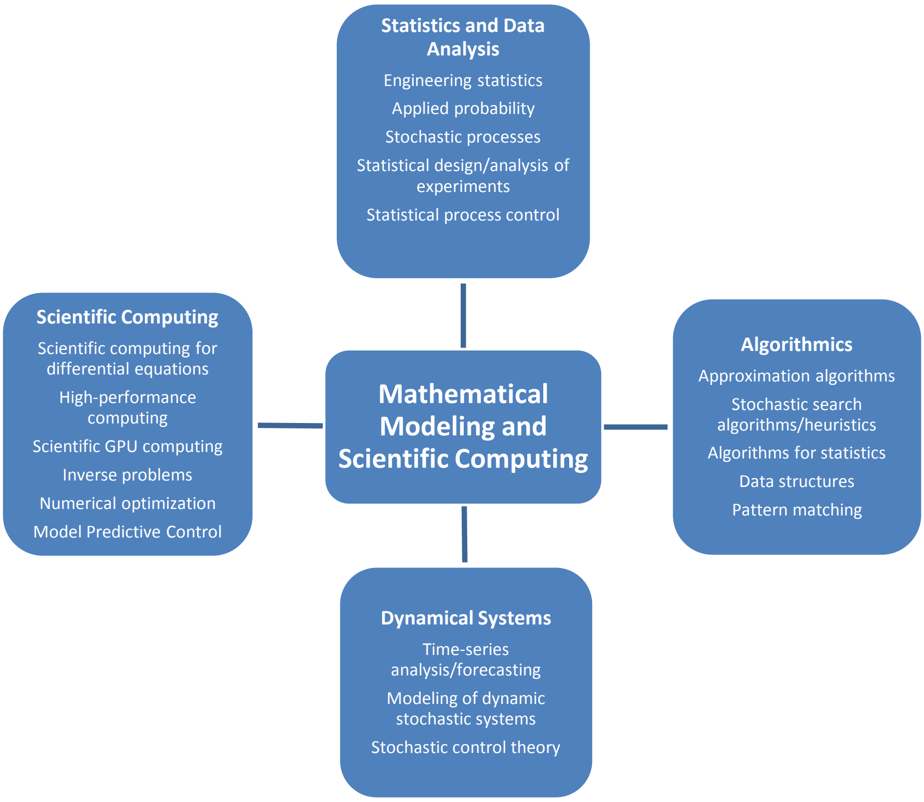

Fig. 1 Areas of research in mathematical modeling and scientific computing with relevance to risk research

Information Security Risk	
Language-Based Technology	**Cryptology**
• Security concepts: confidentiality, integrity, authenticity, availability etc. Symmetric and asymmetric cryptography and their uses; key distribution and digital signatures; discretionary and mandatory access control policies for confidentiality and integrity. Communication protocols for authentication, confidentiality and message integrity; network security; system security, intrusion detection and malicious code. Security models and security evaluation.	• Symmetric encryption • Cryptographic hashing
• Programming languages' support for robustness and advanced techniques for ensuring robustness such as Design by Contract, formal methods, and methodical test tools.	• Message Authentication
• Techniques for language based security such as Information Flow, Access Control, and low-level support for security.	• Boolean functions
• Discrete and stochastic specification and validation/verification techniques for systems, such as service oriented systems and embedded systems.	
• The structure of the Internet and its protocol stack. Standards for Local Area Networks (LANs), advantages and disadvantages of different types of networks. Detection and correction of transmission errors. Network topologies and the solution of routing problems in already existing networks. Socket Programming.	

Table 1 Areas of research in Language-Based Technology and Cryptology with relation to information security risk

2.1 Mathematical Modeling and Scientific Computing in the Context of Risk Research

Mathematics is an enabling discipline that underpins science, engineering and technology. DTU Compute takes on problems and challenges from other disciplines and positions them in a virtual world where its scientists can build models, perform calculations and run simulations.

The mathematical and information sciences provide the scientific basis for a number of key steps in risk analysis in support of decision making irrespective of the application area:

Mathematical Modeling	representation of complex systems by analytical or numerical models, relationships between variables, performance metrics
Data Collection	model inputs, system observations, validation, tracking of performance metrics
Solution Methods	optimization, stochastic processes, simulation, heuristics, and other mathematical techniques
Validation and Analysis	model testing, calibration, sensitivity analysis, model robustness
Interpretation and Implementation	solution ranges, trade-offs, visual or graphical representation of results, decision support systems

Mathematics underpins optimization problems, which are often explicitly or implicitly an objective of risk analysis in various disciplines and application sectors. Many problems require finding the maximum or minimum of an objective function of a set of decision variables, subject to a set of constraints on those variables. Typical objectives are maximum profit, minimum cost, or minimum delay. Frequently there are many decision variables and the solution is not obvious. Techniques of mathematical programming for optimization include linear programming (optimization where both the objective function and constraints depend linearly on the decision variables), non-linear programming (non-linear objective function or constraints), integer programming (decision variables restricted to integer solutions), stochastic programming (uncertainty in model parameter values) and dynamic programming (stage-wise, nested, and periodic decision-making).

Another area where DTU Compute's expertise is applied in the context of risk is the analysis of stochastic processes, which relies on results from applied probability and statistical modeling. Modeling uncertainty is an integral part of risk assessment conducted at all the departments considered in this report.

Information Technology Issues in Risk Modeling

Integrated modeling is a systems analysis-based approach that is used in the process of various risk assessments (e.g. environmental risk assessments, natural hazards risk assessments). It includes a set of interdependent science based components (models, data and assessment methods) that together form the basis for constructing a modeling system capable of simulating environmental systems relevant to a specified problem context.

By adopting a systems approach, the goal is to facilitate better problem conceptualization, assessment of cumulative exposure and risk, development and comparison of policy options and the holistic determination of the likely impacts of alternative management actions and policies. While science must form the basis for integrated designs, IT provides the mechanistic means by which to implement integrated solutions. The relationship between IT and science, like the relationship between modeler and decision-maker, is closely linked. Among the known and important issues facing integrating modeling from an IT perspective are: interoperability; automated data access, retrieval, and processing; and the development of decision support interfaces.

<u>Interoperability</u>

Sources of data available from national and international monitoring programs, including those provided by satellites, continue to increase at a prolific rate. Modeling components that simulate physical, chemical, and biological processes are under constant development. These latter models are based on specific assumptions and are intended for use within defined application boundaries. Models and data are combined and applied in numerous ways to provide for specific assessments. Modeling results are processed and presented to stakeholders in diverse ways. Facilitating the selection and processing of this wide and deep assortment of components for the purpose of constructing modeling systems that efficiently respond to a similarly wide range of problem statements in a timely manner is a major challenging. Barriers to interoperability remain a major constraint to accessing usable modeling resources. Facilitating interoperability among models requires sophisticated supporting software infrastructures, often referred to as modeling frameworks. A modeling framework provides a standards-based software architecture that performs the support functions necessary to both define and operate a modeling system (i.e. a collection of components and related interrelationships). In defining a modeling system, a framework provides protocols and utilities to allow a user to inform the infrastructure concerning component attributes, most importantly information about data inputs/ outputs and rules for execution. Operationally, a framework manages the rules-based execution schemes for components and the information/ data flow through the system. Frameworks can also include support software to facilitate data visualization and analysis tasks and the packaging of end-user applications that can be effectively used for decision making . At the core of all frameworks are standards for the transfer and exchange of information and data through the system. These standards represent the means by which disparate modeling components communicate.

There are a number of challenges from an IT perspective associated with interoperability. First, science components are not efficiently reusable and interoperable across frameworks. This is most important because of the need to utilize science models across disciplines and the desire to conduct research related to comparing the science across models. Secondly, the vast majority of software written for frameworks performs functions that are common to all frameworks, e.g. data exchange, model execution, data visualization, etc. These support functions often end up being custom designed and implemented for each framework system, thus, essentially wasting resources on redundant tasks.

Metadata is another important aspect of information standards. Metadata is information that accompanies a modeling component. This additional information describes attributes of the target data, for example, the name and contact information of the original developer of the data. As more components become available (i.e. data and models) it will be of great benefit to publish them along with their metadata to facilitate a user’s understanding of their genesis, pedigree, application history, etc. The development of ontologies potentially plays a role in facilitating the interoperability among data sources, including models. Ontology development exploits relationships among data to search for and retrieve information, in contrast to the methods used by text-based data search engines. Although potentially significant, the ontology development process is labor-intensive and can require retooling for each type of application.

Data Issues

While the database world is increasingly providing standardized means for accessing and retrieving data, issues related to data quality, pedigree and processing (i.e. preparing data for use in models) remain to be addressed. Modeling systems must integrate data from a myriad of sources, each with its own approach to data quality. It is necessary to understand this variability and specifically account for its impact, for example, on uncertainty. Pedigree, i.e., the history of a data set, is important and will require automated means to establish, document, and maintain it. Processing “raw” data into the form required for input to models can require sophisticated statistical analysis and modeling in its own right. Providing automated tools and methods to execute and document this processing is important.

Development of Decision Support Interfaces

Decision support systems represent the means by which to express the essence of the integrated science for the purpose of informing decisions. Decision support systems are designed to answer the myriad of “what if” questions related to decision options. These systems must achieve this end with clarity, efficiency, and with definitive statements regarding the limits of interpretation and uncertainties related to/ derived from the science-based information.

Mathematical Modeling and Scientific Computing research at DTU

Statistics and Data Analysis

The section is based on scientific competences within all sections at DTU Compute but has special emphasis on statistics, pattern recognition and software development. The following areas of research are of particular focus to this unit:

- Human perception data
- Industrial design of experiments
- Spatio-temporal statistics
- Computational statistics/data analysis and analysis of “Big Data”
- Applied probability

Algorithmics

Algorithmics is the part of computer science that deals with the design and analysis of algorithms and data structures and constitutes the scientific foundation for reasoning about resources used in computing such as time and space. This covers both the design and analysis of efficient algorithms solving concrete problems, and also with identifying common patterns of problems and associated algorithmic paradigms that can lead to efficient solutions for classes of problems.

The section’s research in this area includes: Approximation algorithms, stochastic search algorithms/heuristics, algorithms for statistics, data structures, and pattern matching.

Dynamical Systems

The mission of the section for dynamical systems at DTU Compute is to conduct fundamental, advanced, strategic and applied research in the area of dynamical systems. This involves both deterministic and stochastic systems, discrete and continuous systems, deductive and inductive model building, forecasting and descriptions, as well as control and optimization. Core competences comprise time series analysis and return maps, stochastic and nonlinear systems of differential equations, including partial differential equations, adaptive and stochastic control theory and parameter estimation.

Scientific Computing

Scientific Computing is the science of using computers and mathematics to solve problems from science and engineering. The section's expertise includes many of the aspects of Scientific Computing: from the modeling of physical phenomena to designing, analyzing, and implementing the methodology for the solution of real-life problems. The subfield of computational mathematics is of particular relevance in the context of risk as it enables advanced simulations based on numerical solution of complex differential equations, parallel and high-performance computing needed for optimization, control and uncertainty quantification.

2.2 Information, ICT and Cyber Security Risk

Concepts in IT Security Risk

The terms *information security, ICT security* and *cyber security* are often used interchangeably, and contain common core tenets of protecting and preserving the confidentiality, integrity and availability of information. 'Information security' focuses on data regardless of the form the data may take: electronic, print or other forms. 'Computer security' usually seeks to ensure the availability and correct operation of a computer system without concern for the information stored or processed by the computer. 'Information assurance' is a superset of information security, and deals with the underlying principles of assessing what information should be protected.

The globalization of the ICT marketplace and increasing reliance upon globally sourced ICT products and services can expose systems and networks to exploitation through counterfeit, malicious or untrustworthy ICT. And while not defined in diplomatic fora, the term 'ICT security' is often used to describe this concern. In general, ICT security is more directly associated with the technical origins of computer security, and is directly related to 'information security principles' including the confidentiality, integrity and availability of information resident on a particular computer system. ICT security, therefore, extends beyond devices that are connected to the internet to include computer systems that are not connected to any internet. At the same time, the use of the term 'ICT security' usually excludes all questions of illegal content, unless they directly damage the system in question, and includes the term 'supply chain security'.

There is no agreed definition of 'internet security'. Within a technical context, internet security 'is concerned with protecting internet-related services and related ICT systems and networks as an extension of network security in organizations and at home, to achieve the purpose of security. Internet security also ensures the availability and reliability of internet services.' However, in a political context, internet security is often equated with what is also known as 'internet safety'. In general, internet safety refers to 'legal internet content'. While this has sometimes been linked to government censorship in autocratic governments, restrictions on internet content are, in fact, common. Besides issues surrounding the exploitation of children, internet censorship can also include issues such as intellectual property rights as well as the prosecution of political or religious views. What internet security probably does not include is non-internet relevant technical issues, including those that address the various 'internets' which are not connected to the world wide web. These, however, are covered by the term 'network security'. Network security is particularly important for critical infrastructures that are often not directly connected to the internet. Consequently, for some, internet security implies a global government regime to deal with the stability of the internet code and hardware, as well as the agreements on the prosecution of illegal content.

The term 'cyber security' was widely adopted during the year 2000 with the 'clean-up' of the millennium software bug.[40] When the term 'cyber security' is used, it usually extends beyond information security and ICT security. ISO defined cyber security as the 'preservation of confidentiality, integrity and availability of information in the Cyberspace. (ISO/IEC 27032:2012, 'Information technology – Security techniques – Guidelines for cybersecurity')

Assurance Mechanisms: Information Security

A component of quality management, quality assurance, is 'focused on providing confidence that quality requirements will be fulfilled.' This is ensured through specific business processes, design principles and risk management criteria that ultimately form the bedrock of information security in general.

Information Security (which is often used interchangeably with the phrase information assurance, although the latter is a considerably wider concept) is often directly equated with cyber security, and forms the critical process-orientated assurance component in delivering cyber security for any organization.

Information Security is generally defined as the ability to protect information and information systems from unauthorized access, use, disclosure, disruption, modification, perusal, inspection, recording or destruction. This is accomplished through a process of Information Security Management that defines a 'security target' – such as a specific file, a computer, a system or an entire organization. This security target is then protected according to a specific protection requirement or protection profile, which will address basic information security principles of that target. The most basic of such security principles are confidentiality, integrity and availability (C-I-A) but further principles can be added as required.

Information Security Management is closely connected with a number of steps, in themselves related to the process of Risk Management. Using the ISO 27002 series structure as a point of departure, this includes:

Risk assessment: a thorough evaluation of the various 'attacks' (which includes intentional and unintentional acts of human and natural origin) that a system can be subjected to. Risk assessment (also known as risk analysis) is a very in-depth process that often is software-supported[566] due to the large number of attacks (often numbering in the thousands) and their cross-linkages that need to be considered.

Organisation of information security: this includes the specific assignment of roles (such as system administrator or auditor) and responsibilities (such as setting access privileges) for the organisation as whole. In particular, this also defines who will be responsible for ensuring that the Information Security Management process is adhered to.

Asset management: this includes inventory and classification of information assets – usually physical, such as in hardware or in computer peripheries. Asset Management often also connects to the critical issue of 'trusted supply chain' – the protection of hardware from intentional interference.

Communications and operations management: this is the 'heart' of much of cyber security, and includes defining the responsibility for the management of technical security controls in systems and networks including, for instance, firewalls and similar tools.

Access control: usually working in conjunction with human resources security, access settings are a critical in determining who has the right to access what part of a computer network, system, application or data. Traditionally, many of the most serious breaches of information security have come through errors in access control – particularly regarding expired accounts of former employees.

Information security incident management: this function includes the entire scope of 'cyber crisis management' (also known as business continuity management or as continuity of government), which itself encompasses a large set of procedures normally dealt with separately. This component also includes disaster recovery – usually meaning the separate storage and treatment of relevant data.

Compliance: this function details the roles and responsibilities of the monitoring process, as well as ensuring that other relevant standards and regulations are adhered to.

IT Security Risk Assessment

In the context of IT Security, risk assessment can be understood as the generation of a snapshot of current risks. More technically, it consists of the following phases:

- Threats identification: identify all relevant threats
- Threat characterization: determine the impact and likelihood of the relevant threats
- Exposure assessment: identify the vulnerability of the assets
- Risk characterization: determine the risks and evaluate their impacts on the business/organization

Figure 2 illustrates how IT security risk can be seen as a function of threat, vulnerability and assets value. It also shows that there are different ways to reduce the risks: countermeasures can either reduce the probability for a threat to become true. They can reduce vulnerability or they might help to reduce the impact caused if a threat is realized.

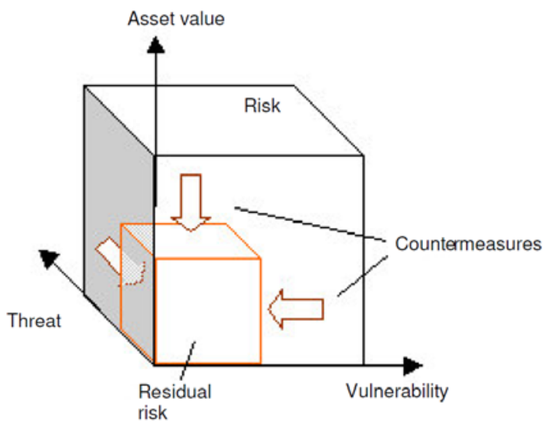

Fig. 2 Risk as a function of asset value, threat and vulnerability (ENISA 2006)

No certification or understanding of business/organization information characteristics can reduce risk to zero. There will always be an element of residual risk. To protect everything is very difficult to accomplish and, as high-profile attacks proliferate, there is a growing move towards an 'assumption of breach'. In other words, a public or private sector organization should design their cyber security systems in the implicit knowledge that targeted attacks are likely to successfully breach those systems. A key question is: which elements of its information inventory should an organization protect at all costs? This question will be difficult to answer, as the cost of maximizing the protection applied to information will likely result in it being less accessible for its original purpose.

IT Security Risk Management

In order to mitigate the identified IT security risks a risk management process should be implemented. For each assessed risk, the risk manager should propose security controls. In general, security standards propose security controls categorized in the following areas:

- Logical controls (e.g. protection of data, protection of network assets, protection of access to applications etc.)
- Physical controls (e.g. alarm systems, fire sensors, physical access control, surveillance etc.)
- Organizational controls (e.g. usage rules, administration procedures, process descriptions, definition of roles etc.)
- Personnel controls (e.g. sanctions, confidentiality clauses in contracts, training and awareness etc.)

The security controls should be selected, planned, implemented, communicated and monitored. IT Security Risk Management is a global approach to risk: on the basis of the assessed risks the process continues with the selection and implementation of security controls ("risk treatment"), the acceptance of risk that cannot or should not be treated further, the communication of risks and their monitoring.

More technically speaking, the process of Risk Management includes:

Risk assessment: find out which risks apply to your business and evaluate them. Management has to decide which risks will be treated or not.

Risk treatment: select and implement security controls to reduce risks. Controls can have different effects, like:

- mitigation
- transfer
- avoidance and
- retention of risks

Risk acceptance: Even when the risks have been treated, residual risks will generally remain, even after risk treatment has been performed or if controls are not feasible. The management has to accept the way risks have been treated. Thus, risk acceptance should always be a management decision. In our example, applying the four security controls mentioned above reduces the risk considerably, but there is still some residual risk: for example the unavailability of the notebook until it is replaced or the possibility that the encryption system used for disk encryption might be broken. Nevertheless, as in the first instance the possible impact is relatively small, and in the second one the probability that this happens (i.e. that the underlying encryption system is broken) is very small, the risks will probably be accepted.

Risk communication: consists of informing decision makers and involved stakeholders about potential risks and controls. This phase is of high importance and should be integral part of the risk management process. Depending on the involved stakeholders, this communications might be internal or external (e.g. internal units or external partners).

Figure 3 below shows the relation between the different phases of risk management.

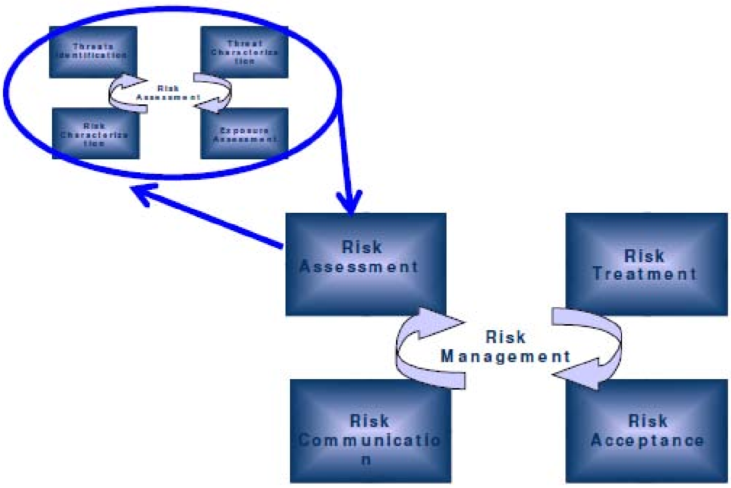

Fig. 3 Phases of IT Security Risk Management (ENISA 2006)

Information Security Research at DTU Compute

Language-Based Technology

In the Language Based Technology (LBT) section research is conducted on techniques and tools for ensuring the reliability of ICT powered systems of systems. Methods for the modelling, analysis and realisation of IT systems that facilitate the development of safe and secure IT systems with good performance are developed.

Basic research is taking place within two research centres: MT-LAB, a VKR Centre of Excellence on Modelling of Information Technology, and IDEA4CPS, a Basic Research centre on Foundations for Cyber-physical Systems.

Strategic research is mainly taking place within two EU projects with considerable industrial participation. The TREsPASS project is concerned with Technology-supported Risk Estimation by Predictive Assessment of Socio-technical Security. The FutureID project is concerned with developing trustworthy solutions for electronic identity systems.

Applied research is taking place within two European ARTEMIS projects with substantial industrial participation. The SESAMO project concerns Security and Safety Modelling and in particular issues related to the conflicting demands of security and safety. The PAPP project focuses on Portable and Predictable Performance of heterogeneous embedded many-cores.

Cryptology

Cryptology or cryptography is about secrecy and authentication. We are a world leading research group in the field of symmetric cryptography, and we concentrate our research efforts on the following disciplines:

- Symmetric encryption
- Cryptographic hashing
- Message authentication
- Boolean functions

3. Advisory Activities

DTU Compute has a long history of conducting statistical consultancy and participating in research and publication collaboration with other departments at DTU, other universities and external partners. The section aims at strengthening the connection to the statistics related activities in other departments at DTU and championing the use of high quality statistics within the Public Sector Consultancy activities at DTU. The department already hosts internal and external university consultancy services in statistics. One such unit is DTU Data Analysis, which is an interdisciplinary unit dedicated to supporting other DTU departments and external partners within software, statistics and data analysis.

The Statistical Consulting Center of DTU Statistics and Data Analysis mostly works with external clients (companies) and offers statistical consulting as well as development of web-interfaces and automatic reporting.

4. Educational Offerings

Table 2 lists all courses related to risk at DTU Compute, together with a brief outline of their content. This information was collected through DTU *Kursusbasen* by performing a search for the following keywords: *risk, security, safety, uncertainty, life cycle, sustainability, decision analysis*.

Course Nr./ Keyword	Title	Content	Type
02190 risk	IT Security (Health & IT)	Basic security concepts: confidentiality, integrity, authentication, availability etc. Threats, vulnerabilities and risks: Risk analysis for IT security. Security policies and security targets. Mechanisms for protection against significant security threats in individual computers and in computer networks, with special focus on the Internet. Administration of IT security. Legal and organizational aspects of IT security.	BSc
02228 risk	Fault-Tolerant Systems	Fault-tolerant systems: application areas. Fundamental concepts: fault, error, failure. Reliability analysis of software and hardware. Hazard and risk analysis. Fault tolerance: the concept of redundancy. Software, hardware, information and time redundancy; checkpointing; fault-tolerant networks. Developing safety-critical systems: the safety life-cycle; certification standards.	MSc
02233 risk	Network Security	Perform a risk analysis on a computer system, in order to determine the areas in which better counter-measures need to be introduced. Basic network security in LAN and WAN environments; Protocols for client-server communication in high risk environments; Secure communications to	MSc

		ensure confidentiality, authenticity and integrity. Security architecture: firewalls and DMZs, VLAN and VPN. Proxies, intrusion detection and protection systems (IDS/IPS), malware and malware detection, audit and analysis of attacks.	
02313 risk	Development methods for IT_Systems	Project management, project control, project plans, risk assessment, time estimate and role division. Requirement specification, Architectural models, design models, dynamic and static models. Programming. Documentation.	D.Ing
02431 risk	Risk Management	Introduction, terminology, asteroid impact (objective) risks, high reliability theory, risk tradeoffs and cost benefit, the safety factor concept and Petrosky's proposition on cyclic patterns of failure, Perrow's normal accident theory, Reason's barrier model, ammonia storage installation safety, What-If methodology, barrier diagram analysis, risk matrix assessment, risk acceptance criteria, disaster planning preceding Hurricane Katrina and emergency response, epistemology, accident precursor analysis, Wildavsky's views on anticipation and resilience, organizational learning disabilities, cases which cannot be explained by standard rational theory, accountability and blame, redundancy and reliability.	MSc
02435 risk	Decision-Making Under Uncertainty in Electricity Markets	Techniques of optimization under uncertainty: stochastic programming and robust optimization duality; here-and-now vs. recourse decisions; 1-stage, 2-stage and multi-stage decision-making processes; decision rules; robust and stochastic solutions; worst-case and expected-value optimization; risk aversion; scenario; value of stochastic solution, expected value of perfect information.	MSc PhD
02689 uncertainty	Advanced Numerical Methods for Differential Equations	Theory and practice in the use of advanced numerical computational methods for efficient solution of differential equation in science and engineering. Development, analysis and application of advanced numerical methods and algorithms for the solution of Partial Differential Equations (PDEs). Develop and generalize ideas from finite difference methods, Fourier methods and extend them to modern and powerful multi-domain methods such as Discontinuous Galerkin Finite Element Methods. The methods are also suitable for modern uncertainty quantification.	MSc PhD
02158 safety	Concurrent Programming	Concurrent programming: Processes, synchronization, communication. Process models, atomic actions. Safety and liveness properties. Deadlock.	BSc

		Verification techniques and tools. Critical regions, semaphores, monitors, synchronous and asynchronous message passing, call mechanisms, distributed objects, tupple spaces. Concurrent data structures. System design: Common communication patterns and algorithms. Client-server paradigm. Transactions and concurrency control.	
02223 safety	Fundamentals of Modern Embedded Systems	Basic concepts and characteristics of embedded systems. Design challenges. Systems engineering, modeling and simulation. Types of embedded systems: hard real-time safety critical systems (e.g., automotive, avionics), soft real-time multimedia systems (e.g., consumer electronics, smartphones), wireless sensor networks (e.g., for environment monitoring, localization), multicore field-programmable gate arrays (FPGAs), and labs-on-a-chip devices and bio-inspired systems.	MSc
02241 safety	Robust Software Systems	Understand and apply the robustness, safety and security formalisms for guaranteeing robustness of software systems.	MSc
02246 safety	Model Checking	Methods for modeling service oriented and embedded systems. Logical formalisms for expressing properties related to the safety, security and performance of systems. Validation and verification tools that determine the relationship between models and properties in order to establish strong guarantees related to safety, security, and performance.	MSc
01409 security	Lightwieght Cryptography	Efficient and low-cost solutions to security problems that arise in the field and practical ways to attack real-world systems. Recap on the basic notions of cryptology, implementation constraints in embedded systems, lightweight block ciphers, lightweight stream ciphers, lightweight authenticated encryption, public-key lightweight cryptography, lightweight security protocols, C programming for microcontrollers, elements of cryptanalysis, elements of signal processing, side-channel attacks.	MSc
01426 security	Cryptology 2	Rings and finite fields. The Advanced Encryption Standard. Message Authentication Codes. Discrete logarithm algorithms. Factorisation algorithms. Elliptic curves modulo a prime number. Ideas of provable security.	MSc
02141 security	Computer Science Modelling	(1) Regular languages and their relation to (deterministic and non-deterministic) finite automata, practical applications (searching in texts, lexical analysis, security automata, etc.) and some key theoretical properties (including closure and decidability properties).	BSc

		(2) Context free languages and their applications (in parsing and XML documents) together with a brief introduction to pushdown automata and their relationship to context free languages. (3) Transition systems and their applications in operational semantics for a variety of language constructs as well as formal techniques for reasoning about them.	
02142 security	Semantics and Inference Systems	Transition systems and their applications in operational semantics for a variety of language constructs including their use in specifying, e.g., reference monitors as well as formal techniques for comparing specifications. Inference systems and their applications in specifying simple type systems and simple security properties.	MSc
02159 security	Operating Systems	Operating systems: Processes, threads, scheduling. System calls. Support for synchronization and communication. Operating system organizations. Device drivers. Virtual memory. File systems. Virtualization. Security systems.	BSc
02165 security	Development of Software Products	To introduce product development from an industrial perspective, covering processes, phases, roles and aspects of the development of real products. To give students experience in product development from the following point of views: Product Management, Program Management, Development and Test.	MSc
02232 security	Applied Cryptography	Introduction to the practical design and analysis of cryptographic solutions.	MSc
02234 security	Current Topics in System Security	The topics considered in this course will change from year to year. Typical topics could include: Trust and reputation systems, Systematic design of secure IT systems, Security in pervasive systems, Privacy-enhancing techniques.	MSc
02238 security	Biometric Systems	Mechanisms in today's commercial biometric systems: Face recognition, iris recognition and fingerprint recognition. Sensors, biometric image processing, feature extraction and classification methods. Evaluation schemes for biometric systems, e.g. biometric performance testing and security testing. Data privacy principles to the biometric system design process.	MSc
02239 security	Data Security	Security concepts: confidentiality, integrity, authenticity, availability etc. Symmetric and asymmetric cryptography and their uses; key distribution and digital signatures; discretionary and mandatory access control policies for confidentiality and integrity. Communication protocols for authentication, confidentiality and message integrity; network security; system	MSc

		security, intrusion detection and malicious code. Security models and security evaluation. Administration of security. Legal aspects of computer security.	
02242 security	Program Analysis	Techniques for data flow analysis formulated using monotone frameworks and logical approaches. This includes the theoretical foundations within fixed point theory as well as algorithmic techniques for solving constraint systems.	MSc
02244 security	Language Based Security	Security protocols, their modeling and analysis, incl. techniques and tools that can be used to either detect confidentiality and authentication errors or to guarantee that no such errors can occur. Other techniques for language based security such as Information Flow, Access Control, and low-level support for security.	MSc
02267 security	Software Development of Web Services	Basic technologies for Web Services like XML, SOAP, WSDL, REST, etc. Problems and solutions in service oriented architectures, including orchestration and choreography of Web services, long living transactions, security, etc.	MSc
02325 security	Data Communication	Fundamental principles of communication in computer networks. Structure of the Internet and its protocols. Communication between two hosts on a computer network. Security aspect in Intra- and Internet.	D.Ing
02333 security	Parallel and Real-time Systems	Concurrent programming: The process concept and parallel programming models. Synchronization, race conditions, atomic actions. Critical regions, semaphores, monitors, message passing. Operating systems: Processes and threads, creation and execution, priorities, scheduling. Communication mechanisms, drivers, file system, resource administration and deadlocks, security.	D.Ing
02338 security	High Performance Application Development for Enterprise Mainframes	The purpose of the course is to teach students to program for, and work with the strongest commercial IT platform on the market - both in terms of speed, scalability, security and cost – the Mainframe. The Mainframes abilities makes it the preferred option for running a large part of the Danish critical infrastructure today, and there is a great need in the Danish business society, to train engineers with these skills. The main emphasis in the course will be on how you can develop applications for the z/OS platform, which can run 24x7x365 without downtime. The students will be trained in the architecture, and use of the various tools that are available on the platform.	BSc
02264 Life cycle	Requirements Engineering	Requirements Engineering (RE) is a key activity in software development (actually, in all kinds of	MSc

		product development). It is probably the single most complex part of software development as it comprises the "hard" technical issues as well as the "soft" social and organizational issues. RE is not just a phase, but covers the whole software life cycle.	
02257 Decision analysis	Applied functional programming	Database applications, resource planning, parallel gathering of information, Apps for mobile phones, domain specific languages, decision procedures, analysis tools, monadic programming, higher-order parsing.	MSc
02319 Decision analysis	Advanced programming for Diplom-E	Basic data types and calculations, choices and decisions, loops, arrays and strings, pointers and references, programming with functions and templates, program files and the pre-processor, structs and classes, class operations, operator overloading, inheritance, virtual functions and polymorphism, program errors and exception handling, class templates, input and output operations, and the standard template library (STL).	D.Ing
02450 Decision analysis	Introduction to Machine Learning and Data Mining	Structured data modelling. Data preprocessing. Feature extraction and dimensionality reduction including principal component analysis. Similarity measures and summary statistics. Visualization and interpretation of models. Overfitting and generalization. Classification (decision trees, nearest neighbor, naive Bayes, neural networks, and ensemble methods.) Linear regression. Clustering (k-means, hierarchical clustering, and mixture models.) Association rules. Density estimation and outlier detection. Applications in a broad range of engineering sciences.	BSc MSc
02457 Decision analysis	Non-Linear Signal Processing	Signal detection and pattern recognition. Bayesian decision theory and mathematical modelling of pattern recognition systems. Machine learning including neural networks. An introduction to the theory of machine learning is given. The theory will be illustrated by applications in the areas of digital media, bio-medicine, and data mining. Methods for recognition of speech, especially methods based on Hidden Markov Models.	MSc
02806 Decision analysis	Social Data Analysis and Visualization	Tools for analyzing data sets generated from online social interactions. Types of available on-line data for data visualization. Basic principles of displaying visual information. Apply Document Classification to categorize and analyze content in social data sets. Apply Decision Trees to retrieve underlying behavioral patterns in social data sets.	MSc

Table 2 Courses at DTU Compute explicitly and implicitly related to risk

5. Data Sources

Chen et al., Towards an integrated approach to natural hazards risk assessment using GIS: with reference to bushfires, Environmental Management, 2003, 31(4): 546-60

Integrated Modeling for Integrated Environmental Decision Making, Environmental Protection Agency, EPA 100/R-08/010 2008

Risk Assessment and Risk Management Methods: Information Packages for Small and Medium Sized Enterprises (SMEs), ENISA ad hoc working group on risk assessment and risk management, 2006

DTU Compute website

6. Glossary of terms related to Cyber Risk

Risk	A potential event that a threat will exploit vulnerability in an asset and thereby cause harm to the organization and its business. (ISO/IEC IS 13335-1) Potential for an unwanted outcome resulting from an incident, event, or occurrence, as determined by its likelihood and the associated consequences (DHS, 2008)
Threat	Any action or event with the potential to cause harm. Threats can be of different types: • Environmental (e.g. flood, lightening, storms, earthquakes, etc.) • Organizational deficits (ill-defined responsibilities, etc.) • Human errors (wrong e-mail address, missing critical dates, noting passwords on stickers, mistakenly deleting files, etc.) • Technical failures (hardware failure, short circuits, hard disk crash, etc.) • Deliberate acts (hacking, phishing, fraud, use of malicious code, theft, etc.) Sources of threats could be vandalism, espionage or just human mistakes and accidents. In the two first cases the strength of the threat can result from two major factors: the motivation of the threat and the attractiveness of the asset. (ISO/IEC IS 13335-1).) Natural or man-made occurrence, individual, entity, or action that has or indicates the potential to harm life, information, operations, the environment and/or property Note: Threat as defined refers to an individual, entity, action, or occurrence; however, for the purpose of calculating risk, the threat of an intentional hazard is generally estimated as the likelihood of an attack (that accounts for both the intent and capability of the adversary) being attempted by an adversary; for other hazards, threat is generally estimated as the likelihood that a hazard will manifest. (DHS, 2008) Any circumstance or event with the potential to adversely impact an asset through unauthorized access, destruction, disclosure, modification of data, and/or denial of service. (ENISA)
Hazard	Natural or man-made source or cause of harm or difficulty. A hazard differs from a threat in that a threat is directed at an entity, asset, system, network, or geographic

	area, while a hazard is not directed. A hazard can be actual or potential. (DHS, 2008)
Incident	Occurrence, caused by either human action or natural phenomena that may cause harm and that may require action. (DHS, 2008) Note 1: Homeland security incidents can include major disasters, emergencies, terrorist attacks, terrorist threats, wild and urban fires, floods, hazardous materials spills, nuclear accidents, aircraft accidents, earthquakes, hurricanes, tornadoes, tropical storms, war-related disasters, public health and medical emergencies, law enforcement encounters and other occurrences requiring a mitigating response. Note 2: Harm can include human casualties, destruction of property, adverse economic impact, and/or damage to natural resources. (DHS, 2008) An event that has been assessed as having an actual or potentially adverse effect on the security or performance of a system. (ENISA)
Vulnerability	A weakness of an asset that can be exploited by one or more threats. Vulnerabilities can exist in all parts of an IT system, e.g. in hardware or software, in organizational structures, in the infrastructure or in personnel. There are also different types of vulnerabilities: • Physical (no access control, no guards, etc.) • Logical (no security patch, no anti virus, etc.)☐ • Network (no network segmentation, no security gates, connection to mistrusted parties, etc.) Typical vulnerabilities resulting from the organizational deficits are, for example, ill-defined responsibilities for information security or the lack of audit trails. Unstable power grids or location in an area susceptible to flood are further examples of vulnerabilities of the environment and infrastructure. Physical feature or operational attribute that renders an entity open to exploitation or susceptible to a given hazard Extended definition: characteristic of design, location, security posture, operation, or any combination thereof, that renders an asset, system, network, or entity susceptible to disruption, destruction, or exploitation. Note: In calculating risk of an intentional hazard, the common measurement of vulnerability is the likelihood that an attack is successful, given that it is attempted. (DHS, 2008) The existence of a weakness, design, or implementation error that can lead to an unexpected, undesirable event compromising the security of the computer system, network, application, or protocol involved. (ITSEC)
Intent	Determination to achieve an objective. Note 1: Adversary intent is the desire or design to conduct a type of attack or to attack a type of target. Note 2: Adversary intent is one of two elements, along with adversary capability, that is commonly considered when estimating the likelihood of terrorist attacks and often refers to the likelihood that an adversary will execute a chosen course of action or attempt a particular type of attack. (DHS 2008)
Capability	Means to accomplish a mission, function, or objective

	Note: Adversary capability is one of two elements, the other being adversary intent, that is commonly considered when estimating the likelihood of terrorist attacks. Adversary capability is the ability of an adversary to attack with a particular attack method. Other communities of interest may use capability to refer to any organization's ability to perform its mission, activities, and functions. (DHS, 2008)
Consequence	Effect of an event, incident, or occurrence. Consequence is commonly measured in four ways: human, economic, mission, and psychological, but may also include other factors such as impact on the environment. (DHS, 2008)
Risk Assessment	Product or process which collects information and assigns values to risks for the purpose of informing priorities, developing or comparing courses of action, and informing decision making. (DHS 2008) Note 1: appraisal of the risks facing an entity, asset, system, network, geographic area or other grouping. Note 2: A risk assessment can be the resulting product created through analysis of the component parts of risk. (DHS 2008)
Risk Analysis	Systematic examination of the components and characteristics of risk. (DHS 2008) Note: In practice, risk analysis is generally conducted to produce a risk assessment. Risk analysis can also involve aggregation of the results of risk assessments to produce a valuation of risks for the purpose of informing decisions. In addition, risk analysis can be done on proposed alternative risk management strategies to determine the likely impact of the strategies on the overall risk.
Risk Matrix	Tool for ranking and displaying components of risk in an array. A risk matrix is typically displayed in a graphical format to show the relationship between risk components. (DHS 2008)
Risk Score	Numerical result of a semi-quantitative risk assessment methodology. (DHS 2008) Note 1: numerical representation that gauges the combination of threat, vulnerability, and consequence at a specific moment. Note 2: The application of risk management alternatives may result in a change of risk score.