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Cumulative Effects Assessment (CEA) Methodology: Theory and Practice

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Abstract

Cumulative Effects Assessment (CEA) is a subdiscipline of environmental assessment, specially targeting the collective effects resulting from diverse human activities and in combination with natural processes. CEA implementation in practice is slow, despite of the available framework and legal requirements. It is caused by the complexity of the cumulative effects issue, especially when quantifying the effect magnitude and analysing their significance.

The aim of this work was to suggest pragmatic improvements to straighten Swedish CEA practice. This was done by compiling CEA legal requirements, theoretical concepts and practical advices, followed by analyse of their use in selected practice-examples. Combining knowledge and information from diverse sources allowed me to identify the main implementation gaps and to propose means to advance CEA practice. Focus of the work are effects on the environment, but similar principles might be used to assess societal impacts.

The main finding is that there are CEA concepts and tools readily available, but they are rarely used in the practice. To enhance its implementation, CEA should be i) done independently from the conventional project-EIA, ii) implement system-perspective, iii) focus on protection of environmental functions, iv) target all pressures, not only project ones, v) assess alternative future scenarios and vi) relate to long-term sustainability goals. Further suggestions and recommended tools are stated later in the text. Relevant and credible CEA has the potential to promote sustainable development and optimal resource use.

Keywords: Environmental Assessment, Cumulative Effects, CEA, Magnitude, Significance

Reading Instruction: The chapter 5, Analysis, is the core of the text, targeting the main CEA principles and methods, including my suggestions for implementation improvements and what techniques to use in which CEA step. For readers wishing to find out the most about CEA with less reading, I recommend to start with this chapter.

In case of questions: contact me via e-mail a.kubart-at-gmail.com

Popular Summary

Human activities and development projects affect surrounding environment in multiple ways. These numerous impacts combine with each other, with other human-induced pressures as well as with natural processes. That might, and probably will, result in cumulative effects. The cumulative effects are usually larger compared to sum of the individual effects, with enhanced consequences both in space and time.

There are numerous ways how the effects can cumulate. It can be diverse effects from one activity, similar effects from several activities or different effects from the numerous activities. In any way, that are the possible consequences from all the effects altogether which would matter in the end. Therefore, these possible overall consequences should be forecasted and made clear to decision-makers. Cumulative effects assessment, CEA, is a standardized procedure how to do it.

As the effect will vary from activity to activity and from place to place, there cannot be any straightforward technique suitable for every assessment. In contrast, each CEA should be adapted to its specific context and needs, which makes it knowledge-demanding and challenging. It is also why CEA practical implementation progresses slowly, despite the 50 years of CEA development.

Aim of this work was therefore to overview available information and knowledge about CEA and to identify the main implementation gaps in Swedish practice. That helped me to provide recommendations how the practice might be improved in the most efficient way. Another output are suggestions of methods to be used in diverse CEA steps and how these methods can be combined to provide credible and meaningful assessment of the cumulative effects.

Preface

This thesis is written for my second master degree in more applied field than my original one, *i.e.* biology. In between, I also got PhD in geosciences and did postdoc in molecular ecology. In numerous contexts, I targeted relationships among vegetation, microorganisms and soil processes, studying how the changes in above-ground vegetation affect soil microclimate, fungal community composition and its functioning, which in turn affects soil properties, leading back to the plants, their composition, growth and litter production. I read numerous scientific articles and followed many presentations of fellow-researchers on multiple ecological and environmental topics. In that way, I became aware of the complex and inevitable links between all inseparable parts of ecosystems and learned to search for all system components.

Simultaneously, molecular-biology methods, which I used as laboratory tool to identify the microscopic fungi, developed very fast. The high-throughput (also called next-generation) sequencing successively allowed us ecologist to analyse hundreds of samples, resulting in millions of sequences to be joint into thousands of species clusters to deal with in further analyses. It brought me a need to steadily search for new methods how to prepare the samples and how to analyse the large amounts of data. I also discovered how time demanding the analyses can be and how crucial it is to use the proper technique in optimal way.

Then, I started this master program in Environmental Management and Physical Planning. Taking the EIA course, I observed that cumulative effect assessment is not properly achieved in practice. As a consequence of this finding and being convinced about cumulative effects importance, I decided to aim my thesis at them. The previous experience with analyses of large multivariate datasets gave me advantage to be able to evaluate the methods used in CEA and to suggest other techniques, used on similar data in ecology, but not introduced in CEA yet.

I desired the main part of the text (Analysis, chapter 5) to provide flowing information, based on huge amount of information from many sources, written in a different way than classical master thesis. By that, I aspired that it could be read independently, out of the context of the thesis, and be relevant for wider spectra of readers. I hope that the readers will understand, and possibly appreciate, this approach.

Contents

List of Tables and Figures

Abbreviations

CE – cumulative effects
CEA – cumulative effects assessment
CLD – causal loop diagram
EIA – environmental impact assessment
EIS – environmental impact statement
GIS – geographic information systems
N2000 – Natura 2000
SDM – system dynamics modelling
SEA – strategic environmental assessment
VEC - valued environmental component

Glossary

Activity – also called action, development or project, human-based; in this work, it includes both development projects (as a subset, for which conventional EIA is usually done) and activities such as transportation or forestry, which can also result in pressures
Causal loop diagram (CLD) – graphical visualisation of cause-effect relationships and feedback loops in system analysis
CEA – cumulative effects assessment, process of systematically analysing and assessing cumulative environmental change
Connectivity – the degree to which a landscape facilitates the movements of organisms and matter
Cumulative effects (CE) – changes in the environment caused by interactions among multiple pressures, both natural and manmade
Effect – any response of environment component to pressure's impact
Environmental impact statement (EIS) – document reporting EIA results
Impact - any aspect of a pressure that may cause an effect
Indicator – any variable used to measure condition of valued environmental component (VEC)
Indirect effects – secondary effects resulting from a primary activity
Magnitude – change of conditions in relation to past and present baseline
Natura 2000 – EU network of protected areas (Naturvårdsverket, 2019h)
Pressure – stressor leading to impact
Project-EIA – here EIA as usually done, i.e. for individual development projects
Scenarios – plausible, but structurally different descriptions of how the future might unfold
Scoping – identifying and reducing of items to be examined, not to put effort on trivial variables
Significance – substantial unacceptable change in component/variable, when compared to baseline
System approach – accounting for all relevant components of a system, with their interactions and interdependences
Threshold – limit of tolerance
Valued environmental component, VEC – any part of the environment that is considered to be important in the assessment, e.g. air, water, soils, terrain, vegetation, wildlife, resource use, habitat

1 Introduction

Cumulative Effects Assessment (CEA) is part of Environmental Assessment targeting the cumulative effects (CE), *i.e.* changes in the environment caused by interactions among multiple pressures, both natural and manmade. These pressures can originate from a single activity or, usually, from numerous ones. For conceptualised pathway from an activity to possible consequences, see Fig. 1. For indication how the effects from different activities and natural conditions can cumulate, see Fig. 2.

Human activity →	Pressure →	Impact →	Effect →	Consequence
Building a project	*Removing of habitat*	*Habitat fragmentation*	*Population decrease*	*Increase in pest*
Forestry	*Clear-cutting*	*Increased erosion*	*Increased run-off*	*Recipient pollution*

Figure 1. Activity – effects pathway in Environmental Assessment and possible examples. This pathway represents the core principle of the assessment. However, resolution among pressures, impacts, effects and consequences is rather gradual than distinct and can be defined in numerous ways (as also documented by the examples).

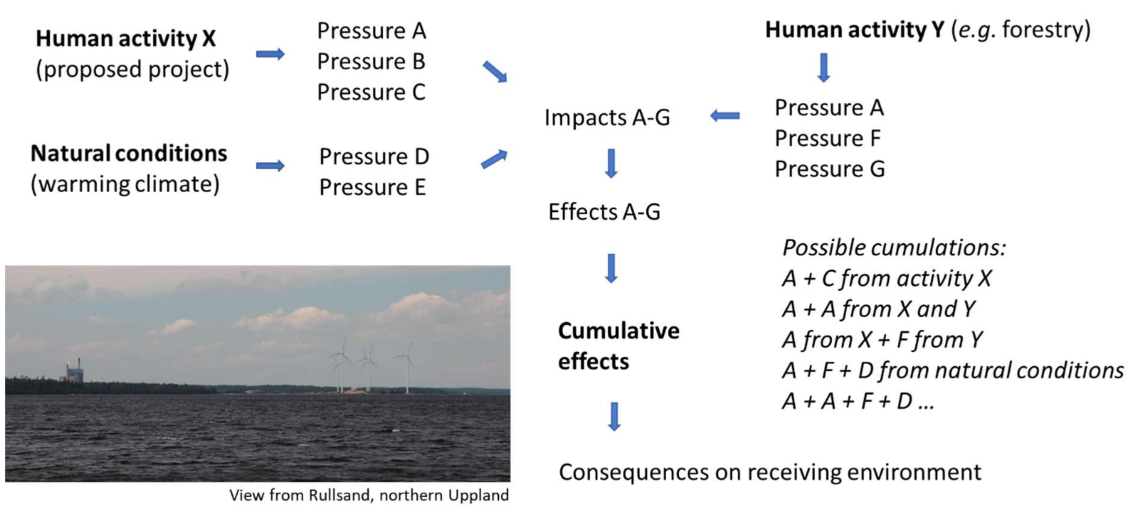

Figure 2. Possible cumulation of effects from different activities and natural variability. There are numerous combinations how the pressures might interact and CEA's goal is to forecast them. Photo: author.

Impacts from individually minor pressures can collectively result in significant CE (Sinclair, Doelle and Duinker, 2017; Schreier *et al.*, 2013; Gunn and Noble, 2011; Perdicoúlis and Piper, 2008). The impacts often accumulate in synergistic way, rather than in additive way only. Therefore, the CE may be greater (or in rare cases less) than the sum of individual effects (Hodgson and Halpern, 2019; Naturvårdsverket, 2019f; Foley *et al.*, 2017; Yang *et al.*, 2010). Moreover, the human-based pressures interact with seasonal and long-term variability in environmental conditions (such as succession or climate change). CE of such combined multiple impacts can be sudden and unanticipated, as being longtermly buffered until system exceeds a threshold. If it happens, even relatively small shifts in human-pressures or environmental conditions can result in large irreversible changes (Hodgson and Halpern, 2019; Foley *et al.*, 2017; Sinclair, Doelle and Duinker, 2017). One can therefore argue that it is only the total CE that truly matters to the environment and people relying on it. Hence, any assessment should focus on CE analysis rather than to assess impacts separately (Olagunju and Gunn, 2015; Senner, 2011; Therivel and Ross, 2007).

CEA had been introduced to consider all of the impacts on the receiving environment, not only impacts of the activity in question. It explores whether individually insignificant effects would result in significant CE when combined (Jones, 2016; Senner, 2011). CEA can be used to assess diverse impacts within single-project Environmental Impact Assessment (EIA) or interactions of such project with other projects in surroundings. Though, such project-EIA is limited in spatial and temporal scale and gives little attention to the broader context in which project impacts will occur (Joseph *et al.*, 2017; Bidstrup, Kørnøv and Partidário, 2016; Duinker *et al.*, 2012; Gunn and Noble, 2011). Hence, the main CEA strength comes in when evaluating multiple projects and activities in larger area. Strategic Environmental Assessment, SEA[1], and regional planning, may therefore be more appropriate framework to address CE and to support sustainability beyond the individual projects (Ball, Noble and Dubé, 2012; Johnson *et al.*, 2011; Seitz, Westbrook and Noble, 2011; Gunn and Noble, 2009). Proactive CEA at strategic level in the planning process may i) collectively address small actions not covered by EIA regulations, ii) provide early analysis of alternatives (Cooper, 2004) or iii) incorporate ecosystem integrity and sustainable goals in the planning. Further, SEA may be applied to a specific activity such as transportation or forestry (Connelly, 2011; Trafikverket, 2011).

CEA involves distinct consideration, compared to conventional project-EIA, as CEA should i) account for higher complexity, ii) assess enlarged spatial-temporal scale, iii) be based on ecological perspective and iv) initiate already in planning phase (i.e. not as late as in project-scoping). Therefore, CEA identified impacts will probably differ from those of the project-EIA (Baxter, Ross and Spaling, 2001). For more details about CEA, see works of e.g. (Willsteed *et al.*, 2018; Willsteed *et al.*, 2017; Jones, 2016; Connelly, 2011; Therivel and Ross, 2007b).

[1] SEA principles and approaches summarized in e.g. (Noble and Nwanekezie, 2017)

2 Background

2.1 Legislation

Legislation provides useful advices what an environmental assessment should include. Swedish laws and regulations are to a great extend based on EU legislation. At the EU level, CE consideration is required by following directives:

2001/42/EC, on the assessment of the effects of certain plans and programmes on the environment, i.e. the SEA Directive, which applies to public plans and programmes (European Commission, 2019a).

Annex I states (besides other; here mentioned what is relevant to CE) that:

- Environmental protection objectives should be taken into account
- Report should cover the likely significant effects on the environment, including biodiversity, fauna, flora, soil, water, air, climatic factors, landscape and the interrelationship between the above factors
- These effects should include secondary, cumulative, synergistic, short, medium and long-term permanent and temporary, positive and negative effects.
- Reasons for selecting the alternatives and a description of how the assessment was undertaken including any difficulties (such as technical deficiencies or lack of know-how) should be explained

Annex II provides criteria for determining the likely significance of effects, including:

- Degree to which the plan or programme sets a framework for projects and other activities and to which it influences other plans and programmes
- Cumulative nature of the effects
- Magnitude and spatial extent of the effects
- Value and vulnerability of the area likely to be affected

2014/52/EU amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment, i.e. the EIA Directive, which applies to defined public and private projects (European Commission, 2019b).

It states that:

- Environmental issues, such as resource efficiency and sustainability, biodiversity protection, climate change, and risks of accidents and disasters should constitute important elements in assessment
- Projects should consider and limit their impacts on land, particularly land take, and on soil, including organic matter, erosion, compacting and sealing
- Significant adverse effects of projects on biological diversity require assessment with a view to avoiding or minimising such effects, contributing to the target of halting biodiversity loss and the degradation of ecosystem services by 2020 and restoring them where feasible.
- It is appropriate to assess the impact of projects on climate (e.g. greenhouse gas emissions) and their vulnerability to climate change, as climate change will continue to cause damage to the environment and compromise economic development

- Precautionary actions need to be taken to ensure a high level of environmental protection
- Projects using or affecting valuable resources, projects proposed for environmentally sensitive locations, or projects with potentially hazardous or irreversible effects are often likely to have significant effects on the environment
- Description of any likely significant effects resulting from the use of natural resources, in particular soil, land, water and biodiversity, should be included
- Characteristics of projects must be considered, with particular regard to (besides others) cumulation with other existing and/or approved projects, and to the risk of major accidents and/or disasters, including those caused by climate change
- Environmental sensitivity must be considered, with particular regard to the relative abundance, availability, quality and regenerative capacity of the area and its underground, as well as paying particular attention to wetlands, riparian areas, river mouths, coastal zones, marine environment, mountain and forest areas, nature reserves and parks, protected areas, Natura 2000 sites and to areas in which there has already been a failure to meet the environmental quality standards

Similarly to SEA Directive, the EIA Directive requires to include CE, their magnitude, spatial extent and probability, description of the forecasting methods, difficulties, uncertainties, impact on climate and cumulation with the impact of other projects.

92/43/EEC on the conservation of natural habitats and of wild fauna and flora, i.e. the Habitats Directive. It ensures the conservation of over 1 000 animal and plant species, as well as 200 habitat types (European Commission, 2019c). An ‘appropriate assessment’ is required when any plan or project is likely to have a significant effect on a Natura 2000 site or on Annex IV species (which are under a strict protection regime even outside Natura 2000 network).

It is also worth to mention 2009/147/EC, the Birds Directive, though the species are included in the Natura 2000; Espoo convention on Environmental Impact Assessment in a Transboundary Context, which demands States to notify and consult each other on all major projects under consideration that are likely to have a significant adverse environmental impact across boundaries; Convention on Biological Diversity; Ramsar Convention on Wetlands and IUCN red-list.

In Sweden, the Environmental Code, Miljöbalken, integrates the EU Directives in Chapter 6 § 3-19 (SEA) and Chapter 6 § 20-45 (EIA). The Chapter 6 is supplemented with Environmental Assessment Ordinance, Miljöbedömningsförordningen (2017:966), defining the regulations. The CE are specifically named in Chapter 6 § 2 of Miljöbalken and in § 11 and § 13 of Miljöbedömningsförordningen. Chapter 7 of Miljöbalken describes diverse types of protected areas to take into account and embodies the Habitats Directive in § 27-29. Chapter 8 handles protected animal and plant species (including the Birds Directive), as well as the invasive ones, and is supplemented by Species Protection Ordinance, Artskyddsförordning (2007:845).

Other areas and limits that should be given special attention in environmental assessment, and therefore even in CEA, are:

- Sixteens Sweden’s Environmental Objectives, Miljömål, have to be considered in the assessment, according to Chapter 6 § 11 point d (Naturvårdsverket, 2019d)
- National interests, Riksintressen, defined by Chapters 3 and 4 MB

- Environmental quality norms, EQN, for sea, water, air and noise, regulated by Chapter 5 MB and specified by ordinances 2010:1341, 2010:477, 2004:660, 2001:554 and 2004:675
- Natura 2000 (N2000) sites, covered both by chapter 4 and 7 MB
- Regional and local environmental goals

2.2 Available Guidelines

There are numerous guideline documents (practitioner handbooks) about CEA concepts and how to perform CEA in practice (Canadian Environmental Assessment Agency, 2015; Natural England, 2014; IFC, 2013; Canter, 2012; ESMAP, 2012; English Nature, 2006; Cooper, 2004; European Commission, 1999; Hegmann *et al.*, 1999; CEQ, 1997).

These provide extensive introduction about CE and how impacts interact. Further, the handbooks include adequate information for scoping, i.e. about selection of environmental components to assess and about determining of baselines and boundaries. They usually mention causality and how to predict CE, followed by descriptions of methods to assess the magnitude and significance. However, these method descriptions are vague, repetitive, the tools are not interconnected and could not assist the assessment properly. Further, the majority of guidelines covers CEA on individual project-EIA level only, neglecting CEA in strategic environmental assessment or assessment of impacts from numerous projects. They also do not include important concepts and techniques. In addition, they do not cover CEA method development on scientific field neither technical advances, such as increasing computing and data-storage capacity, allowing for use of e.g. large databases, remote sensing or user-friendly software packages.

2.3 Implementation Challenges

Despite of the 50-years of method development, guideline availability, computational advances and legal requirements, CEA practice is not fully prosperous yet (Cronmiller and Noble, 2018; Dibo, Noble and Sánchez, 2018). CEA evolved both in the applied and academic field, increasingly addressing complexities and investigating even synergistic or antagonistic impacts, not only additive ones. However, science and practice did not align and the emphasis differed (Hodgson and Halpern, 2019; Jones, 2016). CEA science usually investigated species or ecosystem responses to pressures on large spatial scale (typically a watershed or a marine area), not always related to any project. Conversely, in practice is CEA usually part of an EIA process, demanded for a project approval and performed under limited resources. Thus, the research has developed distinct novel approaches, which are usually too complicated and demanding to conduct practical CEA.

When interviewing EIA professionals, Folkeson, Antonson and Helldin (2013) found out that effect evaluation was perceived as the most challenging part of the CEA process, and identified need of enhanced competence to assess the CE. The professionals said to lack state-of-the-art handbooks and novel working procedures for CEA. Common desire was that the procedures should be as stringent and practicable as possible (Folkeson, Antonson and Helldin, 2013).

Certain challenges are unavoidable though, based on CEA's complexity. Understanding of multiple variables, acting in combination within space and time, requires broad knowledge and experience, and, in ideal case, availability of large data-sets. Further, CEA will always involve multiple stakeholders with diverse responsibilities and interests. There are also practical limitations to apply too advanced methods, such as personnel or time shortage (Jones, 2016).

3 Objectives

It is required by law to assess CE in the environmental assessment. It is clearly stated what concepts and effects should be included in the EIS and even criteria to determine significance are provided. However, these standards are generally not fulfilled in reality. There might be numerous reasons for it, including lack of know-how and of good-practice examples. Therefore, the aim of this study was to consolidate up-to-date CEA knowledge from diverse sources and to compare it to reality, in order to answer the question:

How to perform realistic and credible CEA in practice?

Specific objectives were to:

1. Overview theoretical principles and concepts to assess CE, compiling information from CEA research, practical guidelines and legal requirements
2. Evaluate available tools with regard to their applicability in practical CEA and to emphasise techniques that are not included in the searched documents but which might improve/simplify CEA process
3. Analyse to what extend the concepts and tools are used in Swedish practice
4. Suggest proportionate improvements to straighten the practice

Focus of the work is on assessment of CE magnitude and significance (as this represents the most complicated and unclear step of the CEA process) and on environmental impacts (not social and economic ones). Scoping is briefly mentioned, as it is important for the following analyses. Though, it is not elaborated, because there are numerous detailed advices described in the handbooks.

4 Methods

This thesis is a theoretical study interpreting five sources of CEA knowledge to provide support for improved CEA implementation (Fig. 3). These sources were:

- Research papers published on the topic in impacted scientific journals
- Practitioner guidelines and handbooks from different countries
- Legislation on EIA and CEA on both EU and Swedish level
- Environmental impact statements (EIS) as examples of good-practice from Sweden
- Own experience from research in ecology and geosciences

In this way, I wanted to compile views of different origins (Snilstveit, Oliver and Vojtkova, 2012). More details how the particular searches were done are given below.

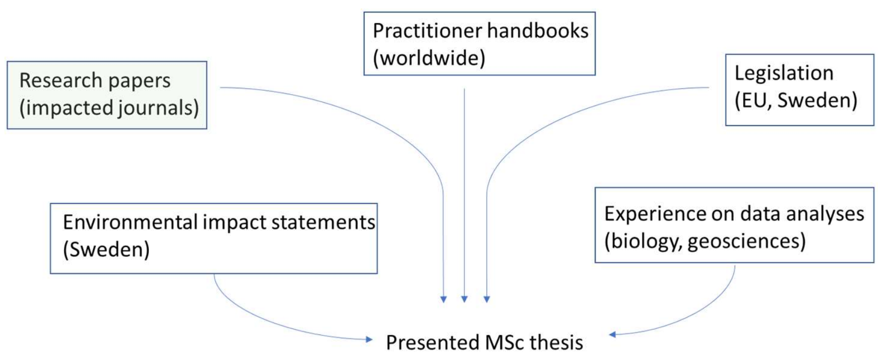

Figure 3. Sources of information and knowledge the thesis is based on.

Obviously, it is not possible to cover all the literature and information available. Similarly, the space of a master thesis is rather limited; the text is therefore written as a survey of the most considerable information, compressed from the sources named above. The idea was to write a concise but comprehensive text, helping the reader to get an overview of the CEA process and increase its understanding. To go deeper into any individual topic, one can start with the references cited.

I evaluated the techniques and their applicability in practical CEA based on my several-years of experience in ecological research, when I got evidence about time-demands of diverse methods (for more about my background and skills to perform such evaluation, see Preface). I also envisage that CEA would profit if trying ways of thinking and if testing wider range of methods than those highlighted in the handbooks. Therefore, I added ideas and tools which I find utilizable and available for CEA improvements. Although these are not common in the CEA papers and guidelines, they are applied in other branches dealing with environmental data.

4.1 Research Papers

First, I performed search for scientific papers in Web of Science (WoS) Core Collection, with search words: cumulative effects EIA; cumulative effects assessment; cumulative impacts assessment. I downloaded relevant papers going 15 years back, i.e. to 2004. Reading these papers, I picked out the important references that did not appeared in the primary WoS search. When writing about particular topics, I searched WoS again for the combination [topic, e.g. GIS] and CEA, as well as [topic, e.g. GIS] and EIA. Though, these further searches rarely provided any paper not yet covered by the primary search or not referred in the prior papers. In total, I skimmed 135 scientific papers, followed by more careful reading of those given by the References section.

4.2 CEA Guidelines

I used Google search with numerous search words to find the practical guidelines (handbooks) and online instructions, both in English and Swedish. It provided 28 guidelines in .pdf format. I did not find any detailed online guidance, even though general information about CE and CEA is often provided (e.g. by European Environmental Agency or by Naturvårdsverket). Several of the handbooks, especially the older ones, were often cited in the scientific papers as well. The compilation from the research papers and from the guidelines is combined in the Analysis section, where I tried to summarize the most important concepts, tools and recommendations that might help to improve the CEA practice.

4.3 Legislation Framework

The list of laws and regulations was combined from both the papers, guidelines, web search and EISs. The summary of legal requirements relevant to CE is given in Legislation chapter, 2.1. They are included as they conveniently state the expectations on environmental assessments and as they should be implemented in the process and resulting statement.

4.4 Environmental Impact Statements, EIS

The goal of this part of work was to identify good-practice examples to inspire further assessments. First, fifteen consultants from diverse consultancy firms[2] were asked if they could provide / recommend EIS including assessment of CE, as examples of good practice. Further, I searched Exempelbanken.se[3] for examples covering CE, which gave two EIS from the 100 included in the database. As I did not get any example of comprehensive plans from the consultants, I searched for them on web. Ideally, I wanted to target especially EIS written after implementation of changes in Chapter 6 of the Environmental Code in January 2018, specifying the importance of CE in the assessment. However, there were not many of such EIS available yet.

The original idea was to evaluate the EIS from the CEA standpoint, whether CEA was included and if there was a consistent approach to do it. I planned to use a checklist for the diverse concepts and variables, compiled from the other, above named sources of information. Though, it became evident soon that it was not possible, as CE were not assessed according to CEA basic principles in any of the statements. Thus, inclusion of CE in the EISs was examined on a scale 0 to 3, where 0 meant no mentioning of CE at all, 1 – CE were briefly mentioned, but not further described, 2 – certain information on CE was given and 3 – CE were targeted in a more prominent way, when compared to the other EISs. I also wanted to look after methods which were used for CE analyses, but as the evaluation were basically based on judgements only, I withdrew that idea.

[2] Contacts provided by my supervisor, Mari Kågström

[3] http://www.exempelbanken.se/Mkb, with 100 EIS examples

As proper evaluation of the CEA in the statements was not realistic, I looked instead if the concepts were used at least in assessment of the single impacts. If it would be the case, it could be faster to implicate them in CEA in future assessments. List of the concepts/variables is given in Table 1, displaying also the checklist for the EIS. Certain concepts were common in the EIS and/or in the legislation, but not in the research papers or the guidelines (such as Environmental quality norms, or Environmental objectives). These concepts were used in the checklist, even if they are not highlighted in the Analysis chapter (but all are mentioned there).

In total, I included 16 EIS, written by 11 different consultancy groups. The oldest EIS dated from 2012, three statements were written in 2018 under the new Chapter 6. The EIS were divided in four categories: i) railway related projects, ii) large scale projects, including two new roads, one transmission line project and one wind powerplant, iii) municipality comprehensive plans and iv) detailed development plans. The full list of EIS given in List of EIS, 9. The results from the EIS analysis are described in chapter 5.3, Swedish Practice from CEA Standpoint.

5 Analysis

The analysis part is divided into four subchapters according to the four specific objectives stated in Chapter 3.

The first subchapter 5.1 describes principles and concepts that are specific for CEA compared to project-EIA. They explain how to think to do systematic and consistent CEA and should be considered before taking up the CE magnitude and significance analyses themselves. Recommendations that I find the most important for the given concept are given in the green boxes following the concept-chapter in question.

The second subchapter 5.2 briefly mentions the methods to assess the CE and evaluates their applicability in CEA practice. Each method-chapter could be largely extended; in case of interest, see the given references and the handbooks (for the methods described in them).

The third subchapter 5.3 analyses the EIS examples from Swedish practice from the CE standpoint, points out examples of good practice and identifies implementation gaps.

Finally, the fourth subchapter 5.4 describes my suggestions how to advance CEA implementation as well as techniques I would recommend to use in particular CEA steps, relevant to magnitude and significance assessment.

5.1 Principles and Concepts to Assess Cumulative Effects

5.1.1 CEA Steps

There are different descriptions of the CEA process available in the literature, e.g. in Joseph *et al.* (2017), English Nature, pp. 19-21 (2006) or Sutherland *et al.* (2016). I identified following CEA steps:

1. Description of alternatives and future scenarios
2. Selection of valued environmental components (VECs, see below in 5.1.2) and their indicators
3. Setting of spatial and temporal boundaries, contextually for each VEC
4. Characterization of baselines, both past, present and future, including all pressures that might affect VECs
5. Identification of cause-effect relationships, direction of VEC responses to changes and of feedback loops
6. Identification of impacts and CE
7. Analysing CE magnitude and significance for defined alternatives and scenarios
8. Determining of mitigation measures
9. Evaluation of residual CE significance and uncertainty of predictions
10. Monitoring and adaptive management

As described in Objectives, this work further focuses on steps 5, 6, 7 and 9.

5.1.2 Valued Environmental Components and their Indicators

Land-use activities and development projects alter the environment in a complex way. CEA should focus on limited number of the most important variables, often called Valued Environmental Components, VECs[4] (i.e. receiving environment), which are defined during the scoping.

European Environmental Agency defines VEC as "an appraised, evaluated or estimated element or ingredient of a biological community and its non-living environmental surroundings" (European Environmental Agency, 2019). VEC approach helps to get holistic perspective and subsequently reduce complexity to focus on the most relevant components on appropriate scale, see e.g. Olagunju and Gunn (2015), and ref therein. VECs can be represented by physical objects (e.g. species population, habitat, soil, water, air, protected areas, noise), ecological processes (e.g., C sequestration, water retention), and even by abstract concepts (e.g. ecological integrity or ecosystem services). If VEC has no measurable value itself, it can be represented by indicators (see below); more VECs and indicators examples are given e.g. in Noble, Liu and Hackett (2017), Ball, Noble and Dubé (2012) or in Seitz, Westbrook and Noble (2011).

Only limited number of VECs should be examined (Ball, Noble and Dubé, 2012; Bérubé, 2007; English Nature, 2006). Hence, careful VEC selection from all possible parameters is crucial; it can be based on e.g. VEC abundance at the site, ecological importance, native/rare species, conservation status, exposure and sensitivity, data availability, public value or regulatory requirements. VECs usable for understanding CE at multiple scales and across projects are preferable.

CEA should be VEC-centric, i.e. done from VEC point of view. It should consider all possible pressures on the VEC, regardless of the source, i.e. including both human activities as well as changes in natural conditions (Willsteed *et al.*, 2017; Papadopoulou, Dikou and Papapanagiotou, 2014; Ball, Noble and Dubé, 2012; Trafikverket, 2011; Cooper, 2004). Canter and Atkinson (2011) recommend to think from the mindset that "I am the VEC or indicator, what are my historical and current conditions and how have I, or will I, be affected by multiple past, present, and future actions?" That is in contrast to project-EIA, when assessment is based on identifying project-induced pressures and their contribution to a change in present-baseline conditions.

VECs should not just be copied from project-EIA, as other VECs and impacts may be more important on larger scale and behave cumulatively (Hegmann *et al.*, 1999), compared to the EIA impacts. As VECs are already highly affected by human actions, it is important to identify both the past and present baseline in CEA scoping. The baselines will help to identify incremental CE and to rely them to original conditions (e.g. current population size of a species may represent only a fraction from the original one; Joseph *et al.*, 2017; Bérubé, 2007; English Nature, 2006; CEQ, 1997). Even future baseline should be defined, including other "existing, planned or reasonably foreseeable activities" and describing what changes would appear without the project. The estimate should account for range of natural variability, succession, climate changes etc. Foley *et al.* (2017) recommended to focus on slowly responding or frequently impacted VECs, ideally having regional importance (Bérubé, 2007). VEC identification can be (partly) based on analyses of similar projects, similar impacts and/or on similar VECs in prior EIS (Foley *et al.*, 2017).

[4] VEC concept emerged in Canada (Hegmann *et al.*, 1999); they are sometimes referred as Valued Ecosystem Components

Spatial scale should cover area large enough to assess a VEC properly, i.e. generally larger than just the project site. Optimally, it should go beyond jurisdiction borders, if necessary, covering e.g. whole watershed, planning region or species/habitat distribution area. Similarly, temporal scale should reach beyond project viability and account for total impact duration and for time needed for VEC to recover (Foley *et al.*, 2017). In such a long term, it is not needed to compare CE separately for construction and operational phase. The scales may differ for diverse VECs (Hegmann *et al.*, 1999).

VECs themselves are often not measurable. Quantifiable VEC indicators can be used instead to describe baseline conditions, assess CE and to interpret CEA outcomes (Sutherland *et al.*, 2016; Schreier *et al.*, 2013; Canter and Atkinson, 2011). Indicator examples are e.g. greenhouse gas emissions, population size, noise levels, habitat area, size of individuals of a species, concentration of pollutants, increase in pets, water level changes, waste production etc. Case studies using indicators and/or indices in EIA/CEA are presented in Larrey-Lassalle *et al.* (2018), Sutherland *et al.* (2016), Canter and Atkinson (2011) or Paukert *et al.* (2011).

In contrast to an indicator, an index is multi-metric value counted from several variables, with the purpose to summarize and simplify large quantity of data (Canter and Atkinson, 2011). Though, indices should be used carefully after proper consideration what they really express. Biodiversity indices, such as species richness, Shannon index or Simpson index can serve as examples; they may be over-interpreted, as they do not express rarity, phylogenetic diversity or ecological function of the species. To target single rare or indicator species may serve better in CEA.

Recommendations for indicator use:

- Each indicator should contribute unique information about the status of VEC; as they often have correlative structure (Sutherland *et al.*, 2016), potential redundancies among possible indicators should be tested (e.g. using PCA, chapter 5.2.1)
- Define suite of indicators linked to VEC that could be forecasted, rank magnitude if they are not possible to be quantified
- Do not use irrelevant indicators just because there are data available for them
- CE will often need different indicators than direct project-EIA effects
- Weighting of the indicators can specify the assessment
- Consistent use of common indicators across project assessments in a region would help to understand CE of numerous activities (Noble, Liu and Hackett, 2017)
- Illustrative example of indicators caused by diverse activities is available in English Nature (2006, p. 76).
- Numerous indicators and information about them are maintained by the European Environment Agency[5] or Water Information System for Europe[6]

[5] https://www.eea.europa.eu/data-and-maps/indicators/ and https://www.eea.europa.eu/data-and-maps/indicators/about

[6] https://water.europa.eu/

5.1.3 Cause-Effect Relationships and Prediction

With the VECs, scales and baselines defined in scoping, CEA proceeds with identification of impacts, causality relationships and resulting CE. The scoping and assessment are overlapping in this stage, prior to the analysis of CE magnitude and significance themselves.

Identification of cause-and-effect relationships reveals the activity-pressure-impact-effect pathways, which helps to define CE (Stelzenmüller *et al.*, 2018; Tamis *et al.*, 2016). Need of causality analysis was identified already in the primal CEA guidelines (Hegmann *et al.*, 1999; CEQ, 1997). It should define what all potential pressures (both of human and natural origin) will affect each selected VEC, how the pressures will be linked together and how the individual VEC will interact with each other.

Causality analysis at high aggregation level without details should start already in early scoping (Hegmann *et al.*, 1999). The causal chains should (ideally) target multiple activities in the given area and be identified in cooperation among multiple stakeholders (Sutherland *et al.*, 2016; EU Commission, 2013). More detailed causality analyses, performed separately for each VEC, should follow later in the process to make complex structures explicit and to identify all potential CE (European Commission, 1999; Hegmann *et al.*, 1999).

The analyses can be helped by network-, system- or causal loop diagrams (CLDs) as conceptual models. These diagrams help to visualise multiple projects, VECs, CE, interactions and directionality (Foley *et al.*, 2017; Cooper, 2010; Perdicoúlis and Piper, 2008). Whatever the diagram used, activities can be followed through the diagram to VEC or back to original pressure (Hegmann *et al.*, 1999), which can assist CE communication and help EIS readers. Preliminary diagrams from scoping can be refined to include more links and variables. Significance, probability and level of uncertainty can be highlighted by arrows of different thickness, colour or line pattern. Diagram description and linkage statements can be included in a supporting table or text.

The CLDs are the most powerful diagram tool, though not commonly recommended in CEA literature, with exception of EU Commission (2013) and of Perdicoúlis and Piper (2008). Compared to the other diagrams, the CLD method allows to describe reinforcing and balancing feedback loops, which improves overall understanding of the system behaviour. That can in turn help to identify effective mitigation measures to break the reinforcing loops and to straighten the balancing ones. Further, it can identify emerging properties[7] that would be missed in any search for impacts of individual pressures (Sinclair, Doelle and Duinker, 2017), but might results in unforeseen interactions and unexpected CE. It can also be extended to system-dynamics modelling, when desirable (chapter 5.2.7).

[7] Emergent properties arise from the collaborative functioning of a complex system, but are unexpected as they are not found in any of the individual items (e.g. neurons connected in brain, ants accomplishing complex tasks in ant-colony etc) or in any of the individual pressures (in CEA context).

When predicting CE, it should be considered that:

- The impacts on the VEC can interact in additive, synergistic or positive way
- There can be same kind of impact from several activities, causing increase in the impact (e.g. incremental noise from a number of developments), or diverse impacts can interact, resulting in a combined CE
- Minor insignificant impact from several activities may result in significant CE (European Commission, 1999)
- Spatial and/or temporal crowding becomes significant if too much happens within too small area or too short time period (before VEC can recover)
- CE can be of low intensity, but chronic, or appear as occasional dramatic events; irreversible damage can appear gradually or quickly, if thresholds become exceeded (Hegmann *et al.*, 1999)
- The responses will seldom be linear and effects can accumulate over time; account for temporal accumulation (in a continuous, periodic, or irregular manner), time crowding and time lags
- It is common with exponential relationships (i.e. x% decrease/increase yearly), characterized by slow discreet change in the beginning, followed by fast change later on
- There can be long delays between cause/impact and CE (Cooper, 2004)
- Impacts may appear away from source or be discontinuous (spatial lags; Cooper, 2004)
- Nibbling, i.e. gradual disturbance and loss of land/habitat, will cause successive small changes which CE can become significant during the time (typical case is habitat fragmentation caused by clearings for new housing or roads)
- Growth-inducing potential (also called spin-off activities or ancillary development) - each new action can induce further actions to occur, which will add to CE and create feedback effects (e.g. access roads, transmission lines, quarries; Lawrence, 2007). These actions should be considered as reasonably foreseeable action (future baseline), even if they may be dispersed and have different proponents, as they can together become significant (European Commission, 1999).
- Impact shift is situation when CE are caused by mitigation measures themselves
- Actions often considered in Europe include urban development, roads and transports, water supply, waste management, energy consumption, mining and quarrying (English Nature, 2006), with main types of targeted CE: habitat loss, fragmentation, degradation, pollution – chemical or biotic (invasive or ruderal species), disturbances – noise, vibrations, light, recreation. A checklist of the possible CE of development can be find in English Nature (2006), detailed description of CE prediction e.g. in Canter (2012).

5.1.4 Magnitude and Significance

CE magnitude can be defined as change relative to past (i.e. original state) and present baseline conditions. Magnitude can be equal to the sum of the individual effects (additive effects) or can be increased (synergistic effects) or decreased (antagonistic effects).

Determination of CE magnitude can be based on data of different origin, such as environmental monitoring, scientific literature, expert opinion, modelling, remote sensing and satellite images or from citizen science. Though, the data will often be incomplete or unavailable. Based on that, magnitude analysis can be entirely quantitative, mix of quantitative and qualitative for different variables, semi-quantitative using ordinal scale, or entirely qualitative (Foley *et al.*, 2017). An example of magnitude assessment on simple ordinal scale can be: low – minimal change in VEC; moderate – measurable change in VEC of short or medium duration, recovery possible, high – measurable change during project life and beyond, recovery hard.

CE significance says if CE leads to unacceptable VEC changes (Ehrlich and Ross, 2015). The changes can be considered unacceptable even if not exceeding a threshold of irreversible change. Significance criteria can be also developed from existing policy or objectives. In any case, the criteria should be always considered in the proper VEC context, based on VEC characteristics and on knowledge available (Joseph *et al.*, 2017; ESMAP, 2012; Bérubé, 2007; Lawrence, 2007; English Nature, 2006). CE significant in one situation will not necessarily be significant in another one.

Following criteria are to be considered when assessing CE significance:

- CE magnitude - the higher the magnitude, the potentially more significant CE. Future baseline and distance of change to the targets and thresholds are also important – significance will be high if threshold would be exceeded (Foley *et al.*, 2017; Hegmann *et al.*, 1999). Synergistic CE may be more significant than the additive CE. Even positive effects should be considered (and enhances by mitigation measures).
- CE geographical extend
- CE frequency and duration, if CE will happen once, sporadically, often or be continuous and permanent
- VEC sensitivity (also called vulnerability to pressure) - the higher the sensitivity, the less resistant VEC is (González Del Campo, 2017) and can sustain less CE before irreversible changes would appear. VEC resilience (reversibility, recovery potential) is also important, even if not exceeding threshold – would the recovery/restoration be complete, partial or none, how much time it would take?
- VEC value, given by presence of rare and indicator species or habitats, important ES or high quality / protected / N2000 sites. Even a large magnitude CE may not be significant if the affected VEC is common, widely distributed and readily able to recover, but a small magnitude CE may be highly significant to a sensitive / valuable VEC.
- Existing VEC disturbance (Hegmann *et al.*, 1999) and relative contribution of diverse pressures (ESMAP, 2012); local insignificant effect can contribute to significant CE (Cooper, 2004), but the significance will be lower if VEC is already highly disturbed. Significance increases also with number of induced actions (e.g. access roads, transmission lines, new housing; Canter, Chawla and Swor, 2014)
- CE likelihood (probability) - even an unlikely impact may be significant and unacceptable if it is severe (Ehrlich and Ross, 2015) and as such should be counted in as a worst-case scenario
- Significance shall be estimated based on precautionary principle

As CEA is on large-scale and long-term basis, there will always be lack of sufficient information about future baselines, pressures and efficiency of mitigation measures. Hence, significance assessment will always be connected to high uncertainty (see next chapter 5.1.5). Therefore, it needs to be contextual, robust, explained and defensible. Use of categorial scales for the criteria is useful and sufficient, even for significance evaluation itself (Hegmann *et al.*, 1999). Matrices and matrix operations can help when defining both criteria values and significance.

Some works recommend to assess significance only for CE with residual effects after mitigation (Dibo, Noble and Sánchez, 2018; Hegmann *et al.*, 1999) or to focus only on negative effects. This would save resources, but add on uncertainty. Others, including IFC (2013), Lawrence (2007), Cooper

(2004) and this text, recommend the opposite. Determining significance for all CE prior mitigation measures can point out the most severe CE to focus mitigation effort on. Further, it reveals what would happen if the mitigations fail or are less efficient than expected. The residual CE significant after mitigation measures will be those to be monitored preferentially (Cronmiller and Noble, 2018). Expected mitigation effectiveness should be stated and can be included in scenarios (IFC, 2013). Similarly, benefits of the most significant positive CE can be maximized by mitigation measures, if they are recognised.

5.1.5 Dealing with Uncertainty

Uncertainty is the degree to which knowledge is limited. Uncertainty in CEA is thus higher compared to EIA, as result of CEA's complexity. There are diverse sources of uncertainty, such as i) randomness, ii) variation and spatial differences in natural systems, iii) lack of information, knowledge and data, iv) unknown causality, v) non-linear responses to pressures, vi) model limitations or vii) subjectivity of expert evaluations (Stelzenmüller *et al.*, 2018; Judd, Backhaus and Goodsir, 2015; Canter and Atkinson, 2011). The longer timeframe, the less certain analysis is. Thus, uncertainty is unavoidable and should be acknowledged.

It is needed to state:

- Uncertainty assessment principles
- Level of uncertainty (or confidence) in significance judgments, on ordinal scale
- Which values are based on calculated data, on expert evaluation and on assumptions
- Record of assumptions, data gaps, and tool limits

Explicit uncertainty tests exist, often based on Bayesian methods (Melbourne-Thomas *et al.*, 2012) or on Monte-Carlo methods (Stock and Micheli, 2016). Though, their use would be too complicated in practical CEA, where expert judgements remain a suitable option. Otherwise, Monte-Carlo would be reasonable comprehensible technique. In case of high uncertainty, conservative conclusions, integrating of precautionary principle and possibility to adaptive management are crucial (Canter and Atkinson, 2010; Lawrence, 2007; Hegmann *et al.*, 1999).

5.1.6 Scenarios

As high complexity and considerable uncertainty are intrinsic in CEA, scenario analysis should be CEA's fundamental component. However, use of scenarios was not mentioned at all in the primary guidelines, but became recognised in the newer ones, e.g. by Canadian Environmental Assessment Agency (2015) or IFC (2013). CEA science adopted scenarios somewhat earlier (Amer, Daim and Jetter, 2013; Schreier *et al.*, 2013; Weber, Krogman and Antoniuk, 2012; Seitz, Westbrook and Noble, 2011; Duinker and Greig, 2007). Scenarios are best applicable in long-term studies to account for a range of future conditions, to explore alternatives and to predict outcomes of various mitigation measures (Sutherland *et al.*, 2016; Duinker and Greig, 2007).

Recommendations for scenario use:

- Future activities may be certain, reasonably foreseeable or hypothetical (Hegmann *et al.*, 1999)
- Land-use scenarios may be business-as-usual, enhanced conservation or enhanced development (IFC, 2013)
- Most likely future scenarios should be considered at least, but including even other scenarios might improve understanding in case of uncertainty, including both worst-case and best- case scenarios
- Using two to five scenarios is considered optimal (Amer, Daim and Jetter, 2013; Duinker and Greig, 2007, and references therein)
- Each scenario should provide significant contrast from the others
- Do not become attached to a single scenario, viewing others as hypothetical (Duinker and Greig, 2007); the greatest insight might be gained by understanding the contrasts among the scenarios
- Same scenarios should be simulated for all defined alternatives, including the zero one
- Include climate change as well as extreme weather conditions (Kim *et al.*, 2018; EU Commission, 2013)
- Scenario building can be time-consuming; take pragmatic approach not to extend the CEA process
- Verbal description and comparison between scenarios can be reasonable, or use of a summarizing matrix

5.1.7 Thresholds, Carrying Capacity and Trend Analysis

Thresholds and carrying capacity are diverse concepts of sustainability, based on similar idea. A threshold is limits beyond which an impact becomes a concern. Thresholds are sometimes given by regulations, e.g. for contaminants affecting human health and constituents in air and water, such as emission limit values covered by IPPC directive. In other situations, thresholds may be unknown, especially in case of biological variables. Practitioner may determine own thresholds or acknowledge that there are no thresholds, make trade-offs clear and determine CE significance anyway (IFC, 2013; Halpern *et al.*, 2008; Hegmann *et al.*, 1999). Exceeded threshold results in severe damage when VEC recovery will take long time or become impossible[8]. That can happen suddenly and unexpectedly, usually in situation when thresholds are not clearly identified until they are crossed (Bérubé, 2007). Therefore, precautionary principle should be applied, especially when threshold values are lacking and uncertainty is high.

Carrying capacity is ability of an ecosystem to support continued activity (such as population growth, tourism, clear-cutting etc.) without excessive degradation, i.e. without reaching the threshold. It can be expressed e.g. as maximal concentration of nutrient or pollutant, maximum daily loads, maximal amount of linear infrastructure, minimal area of habitat to support a viable population or an ecological function, population decrease before viability is threatened etc.

Theoretically, if CE of all activities within targeted area do not exceed a threshold, the CE might be considered insignificant and therefore acceptable (ESMAP, 2012). Though, limits of acceptable change, e.g. given by policies[9], should be more ambitious and stimulate innovations. In the Swedish

[8] E.g. mortality rate will become larger compared to recovery rate, i.e. population will disappear
[9] E.g. overview of EU policy targets for climate change and biodiversity (EU Commission, 2013)

context, Environmental Objectives are to be included in the assessment (Naturvårdsverket, 2019d) and might be used as thresholds.

Trend analysis is a way to estimate thresholds and carrying capacity by quantifying impacts of past actions over time. Assuming that the phenomena is likely to persist, the past data can be projected into the future. The analysis reveals if the trends are continuing, changing, or levelling out, and if thresholds are to be / has already been reached. Though, credible data are needed and the analysis is most relevant when applied to a short time horizon, i.e. considerably shorter than CEA timescale should be (Canter, Chawla and Swor, 2014; European Commission, 1999).

5.1.8 Biodiversity and Ecosystem Services

Biodiversity mirrors all the ecosystem variables and their complex interactions; as such, biodiversity is CE issue by its nature (CEQ, 1997). All kinds of activities inevitably result in habitat fragmentation, reduction of landscape connectivity (Larrey-Lassalle *et al.*, 2018) and in species disturbance (Bigard, Pioch and Thompson, 2017). Thus, each CEA will probably deal with ecological variables (Mitchell *et al.*, 2015; Wagg *et al.*, 2014; EU Commission, 2013; English Nature, 2006). Their assessment should i) focus on scales relevant for ecological functions (Dibo, Noble and Sánchez, 2018), ii) capture spatial heterogeneity (Halpern *et al.*, 2008) and temporal dynamics (such as seasonality of e.g. nesting, vegetation season, seasonal tourism) and iii) include both human and natural drivers of CE.

The EIA concept of "no net loss" requires that any land or water body disturbed by an activity should be replaced with an area of equivalent capability to support VEC (Bigard, Pioch and Thompson, 2017; Bull *et al.*, 2016; Maron *et al.*, 2016; ESMAP, 2012). It can be done by off-setting or by compensatory restoration. Though, habitat which can become of sufficient quality within a reasonable timescale must be available (English Nature, 2006). Moreover, a restored habitat will never more reach ecological complexity of a climax (Maron *et al.*, 2016; Calvet, Napoléone and Salles, 2015). It is therefore preferable to avoid CE on well-preserved ecosystems, e.g. by choosing different alternative, than to compensate.

Recommendations for using ecosystem services as CEA framework:

- To learn more about the concept of ecosystem services and its diverse pros and cons, one can look at work of (Gunton *et al.*, 2017)
- Information on trends in supply and demand of ecosystem services in the area may do CEA more accessible and acceptable compared to natural conservation approach
- An approach is to identify thresholds, when demand will exceed supply and when the ecosystem services will disappear (Maron *et al.*, 2017)
- Another option is to assess CE on areas providing key ecosystem services and describe consequences to their supply (Mitchell *et al.*, 2015)
- Ecosystem services can be connected with Environmental Objectives (Miljömålen)
- Guidance can be found at Naturvårdsverket's website (Naturvårdsverket, 2019b)
- Ecosystem services view gives possibility to protect even man-made ecosystems, such as pastures and agriculture land, not only natural habitats as the conservation approach

Recommendations for assessing ecological variables:

- It can be beneficial to define CEA objectives to base the assessment on (e.g. to avoid/reduce further CE on key biodiversity sites (Cooper, 2004), no net loss or no habitat loss)
- Ideally, both taxonomic, phylogenetic and functional biodiversity (Craven *et al.*, 2018) would be targeted, which is unrealistic in practical CEA; though, it is possible to consider these biodiversity facets when selecting representative species to assess (i.e. select highly different species to focus on)
- Include rare, threatened or indicator species, not trivial ones
- Screen for protected areas and Natura 2000[10] sites to assess CE on them (Naturvårdsverket, 2019g); though, there may be valuable habitats and species outside protected areas as well, which should not be neglected (Duarte *et al.*, 2016; English Nature, 2006)
- For possible inspiration, Duarte *et al.* (2016) provided Relevance index for N2000 habitats, based on their geographic range, local abundance and ecological rarity; the index can be considered if dealing with N2000 sites
- Migration corridors are important for ecological processes and metapopulation dynamics (Larrey-Lassalle *et al.*, 2018), CEA should therefore aim also on CE on the network of green and blue infrastructure
- Habitat fragmentation is practical VEC for CEA; though, habitat quality, not only area, should be assessed, as the quality affect resistance and resilience[11] to CE (Roche and Campagne, 2017)
- Exact data will probably not be available and are possibly not needed; ecological knowledge about the species and ecosystem might be sufficient for CEA relevant assessment
- Initial data and information can be obtained from diverse sources, e.g. Artdatabanken[12] and its fauna and flora inventories, county boards' information about natural reserves, N2000 Network Viewer, Naturvårdverket sites[13], scientific literature etc.

Ecosystem services are a concept to quantify diverse ways in which humans benefit from nature (Gunton *et al.*, 2017; Helfenstein and Kienast, 2014; Villamagna, Angermeier and Bennett, 2013). Critique points that it is an anthropogenic view that facilitates the monetisation of nature (Roche and Campagne, 2017). Though, the concept acknowledges people's reliance on ecosystems and biodiversity and can help to explain their importance to decision-makers and public. In contrast, explanation based on ecological processes can be too abstract for non-professionals.

5.1.9 Climate Change

Whatever spatial scale defined, human activities and VECs will be inevitably affected by processes from outside (Halpern *et al.*, 2008). The most prominent example is the climate change, which may progressively become the dominant pressure (Naturvårdsverket, 2019e; Clarke Murray, Agbayani and Ban, 2015; EU Commission, 2013). Other external factors are not on climate change scale, but might be important anyway (e.g. migratory populations or airborne pollutions).

[10] Natura 2000 is network of protected areas, set up to ensure the survival of Europe's most valuable species and habitats, based on the 1979 Birds Directive and the 1992 Habitats Directive; https://www.eea.europa.eu/data-and-maps/data/natura-9

[11] resistance as ecosystem ability to remain unchanged under disturbance, resilience as it capacity to quickly recover from a damage

[12] https://www.artdatabanken.se/sok-art-och-miljodata/

[13] http://natura2000.eea.europa.eu/, http://skyddadnatur.naturvardsverket.se/

As CEA targets long timescales, implementing climate change impacts on the future baseline and on CE in inevitable. Increased temperature and precipitation as well as extreme weather events, such as i) windstorms, ii) heavy rainfalls increasing flood risk, iii) decreased water supply due to drought or iv) rising of sea level and coastal erosion, are to be accounted for. CEA should deal both with the ways to reduce greenhouse-gas emissions, caused by CE, as well as with the ways for climate change adaptations (EU Commission, 2013). As climate change extend cannot be exactly forecasted, it brings uncertainty to CE predictions (Willsteed *et al.*, 2017 and references therein). Therefore, several climate change scenarios shall be used in CEA (at least the best- and the worst-case). They can be found at SMHI or IPCC webpages [14].

Climate change will also increasingly induce changes in biodiversity. Species ranges will shift and species that cannot adapt or migrate will extinct at a locality in question (García-Palacios *et al.*, 2018; Foley *et al.*, 2017; Thuiller, 2007). It might be followed by increase in pathogenic and invasive species, which will further transform natural habitats and disrupt native species. Not surprisingly, climate change interacts with other factors, such as land-use changes and habitat fragmentation. Altogether, these factors are likely to promote changes of dominant species and biotic homogenization. It might result in unpredictable interactions between plants, animals and microorganisms (Thuiller, 2007), with consequences to ecological processes and ecosystem services.

Therefore, CE on landscape connectivity and green-corridors (Naturvårdsverket, 2019a; Naturvårdsverket, 2019c), as well as on habitats of high quality (such as ancient woodlands or not-eutrophicated wetlands and water-bodies), will be highly significant and should be avoided. Forecasted vegetation shifts[15], spreading of invasive species and possible functional changes should be acknowledged, when assessing the future baselines, CE significance and uncertainty.

5.2 Assessment Tools

CE should be assessed for each alternative under all scenarios for each of the selected VEC and identified impacts, as defined in scoping (Sinclair, Doelle and Duinker, 2017). For each CE, magnitude (level of change, 5.1.4) and significance (if changes are deemed acceptable, 5.1.4) should be predicted. Adequate mitigation measures should be defined for the significant CE and residual significance assessed again.

There are numerous methods and tools described in different sources. However, methods used in scientific literature are usually too complicated to be applicable in CEA practice, while the lists of tools in the guidelines are general and not much to help the CEA practitioner. Below, I evaluate the most prominent tools and emphasise other useful, though less supported ones.

5.2.1 Multivariate Statistics

Multivariate analysis reveals statistical associations between numerous variables; those can be pressures, VECs and indicators, species, environmental conditions or even alternatives and scenarios. It can help to i) reduce number of variables by choosing the most relevant ones, ii) identify potential redundancies and thus avoid analysing of correlated indicators (Sutherland *et al.*, 2016) as well as iii) visualise distances among alternatives and scenarios, which might simplify communication of the assessment results.

[14] http://www.smhi.se/klimat/framtidens-klimat/klimatscenarier and https://www.ipcc.ch/data/

[15] E.g. using future distribution maps for dominant species or species-distribution models

Widely used multivariate technique is principal component analysis, PCA. It reduces multiple data to a small number of uncorrelated variables, called principle components, without much loss of information, and visualises the maximum variability in the dataset. Visualisation of PCA results in scatterplots can enhance discussion of alternatives under different scenarios (Kamijo and Huang, 2017). Redundancy analysis, RDA, represents a multivariate analogue of regression and thus allows to identify the most significant variables (by Monte-Carlo permutation test). Both PCA and RDA are highly explanative and easy to use. Surprisingly enough, they are not exploited in CEA works.

Random forests are another extension of regression to multivariate ordination methods. This method splits response variables by creating a decision tree (so called recursive partitioning), identifying indicators that well describe the VEC. In CEA research, random forests were applied by e.g. Jones *et al.* (2017) for a watershed or by Large *et al.* (2015) for a marine ecosystem. Though, this technique is already too complicated for practical CEA and more straightforward multivariate methods would be more suitable.

5.2.2 Matrices

Matrices are commonly mentioned in CEA guidelines, as they are easy to adapt for assessment in task. Though, their main strength is not to assess CE magnitude itself. Preferably, they can be used to identify CE, to consistently summarize results and to compare alternatives and scenarios. Another use might be to report numerous underlying values in matrix format in Appendices.

Structured use of matrices to detect activity impacts on VEC can ensure that potential effects are not overlooked. Then, impacts can be cross-referred against each other (individually for each VEC) to identify and quantify CE. Matrix cells will show only pairwise interactions, but patterns in the finished matrix may strike and suggest even higher level of cumulativeness; the cumulativeness itself can be further considered in a separate column.

Variables in matrices can be assigned qualitative values or ordinal scores e.g., low, medium, and high, or scales from -x to x. Links between variables can be defined in interaction matrix (ESMAP, 2012; Weber, Krogman and Antoniuk, 2012) and variables further analysed using matrix manipulations (Hodgson and Halpern, 2019; CEQ, 1997), e.g. to get sum of scores for each VEC or alternative (Hegmann *et al.*, 1999). It is also possible to rank impacts and VECs by relative weighting, when sum of weights is 100%. Weighting criteria must be clearly set out; advantage is that they can be provided by numerous stakeholders and averaged.

For deeper analyses, one has to count to work with multiple matrices. A premise is to select an appropriate matrix with proper cross-referencing of pressures / VEC / impacts on adequate levels. As consequence, matrices can easily become too big to grasp and cumbersome to use (European Commission, 1999), especially in CEA.

5.2.3 Multicriteria Analysis

Comparison of alternatives under different scenarios can be done by multicriteria analysis (MCA). MCA is also matrix-based, evaluating each alternative in regard to each criterion (Walby, Armstrong and Strid, 2012; Balasubramaniam and Voulvoulis, 2005). Its use can be appropriate in case of conflict resolution between multiple participants, as it is transparent and can consider different perspectives (Kamijo and Huang, 2017; Moretto *et al.*, 2017; Li, Xie and Hao, 2014).

In the MCA area, the Rapid Impact Assessment Matrix (RIAM) was developed specially for EIA by (Pastakia and Jensen, 1998). In RIAM, scores in the matrix describe the degrees of positive and negative effects ascribed to the alternatives (Kuitunen, Jalava and Hirvonen, 2008), followed by determination of impact significance (Ijäs, Kuitunen and Jalava, 2010). Originally, five evaluation criteria were included - importance, magnitude, permanence, reversibility and cumulativeness. Ijäs, Kuitunen and Jalava (2010) then added a sixth criterion. susceptibility (vulnerability) of the VEC. Li, Xie and Hao (2014) suggested assigning weights to the indicators and included sensitivity analysis (by adjusting weights values), to better use of RIAM in SEA. Shakib-Manesh *et al.* (2014) emphasized cumulativeness more strongly. However, RIAM cannot assess causality and CE from multiple pressures accurately for CEA.

Next MCA tool is QUAlitative Structural Approach for Ranking (QUASAR), based on the interference between plans and environmental objectives and recently proposed for SEA by (Galassi and Levarlet, 2017). Other interesting approaches are criteria aggregation in a decision tree according to defined rules, performed by IF-THEN-ELSE functions (Craheix *et al.*, 2016) and CEA based on landscape vulnerability evaluation (Pavlickova and Vyskupova, 2015; Toro *et al.*, 2013; Toro *et al.*, 2012). These MCA techniques can be modified and simplified for practical CEA and are therefore referred here as source of inspiration. In general, MCA can increase objectivity and transparency, but attention to false sense of accuracy is necessary, due to all aggregations and assumptions on the way to provide final scores (Janssen, 2001).

5.2.4 Geographic Information Systems, GIS

Use of GIS is well covered both in the guidelines (mainly for visualisation) and in the scientific literature (even GIS modelling). Both spatial and temporal analyses are possible in different resolution, depending on data availability and quality for GIS cells. The visualisation can help to i) determine alternative with the least impact on sensitive areas, ii) summarize CE in an overview map and iii) display CE hotspots.

For each cell, topographic features, activities, pressures, ecosystem components and their indicators etc. can be overlapped. This information can be complemented by vulnerability weights, likelihood, past changes and trends[16]. The overlay analysis will identify the most vulnerable / valuable areas and their extend, as well as VEC affected by several impacts and check for spatial and temporal overlaps (Hodgson and Halpern, 2019; Tamis et al., 2016; (European Commission, 1999). That reveals areas with increased CE risks, especially if the actions occur at the same time, originate in the same location or impacts spread to other locations (Stelzenmüller *et al.*, 2018; Hegmann *et al.*, 1999).

GIS is thus highly useful tool in CEA, but needs descriptive data in spatial format, compatible with other data from various sources (Stelzenmüller *et al.*, 2018). In practice, visualisation by GIS is recommended option, while deeper analyses and modelling would easily become to extensive. Thus, GIS suits best in combination with other CE quantification tools; for examples, see e.g. Bigard, Pioch and Thompson (2017), Fernandes *et al.* (2017) and Nogueira Terra and Ferreira dos Santos (2012). Swedish Agency for Marine and water management provides SYMPHONY[17] method for CE mapping in ecosystem-based marine spatial planning; it includes 32 ecosystem components, impacts and sensitivity (Havs- och vattenmyndigheten, 2018).

[16] E.g. analysed from remote sensing pictures
[17] https://www.havochvatten.se/hav/samordning--fakta/havsplanering/om-havsplanering/vad-ar-havsplanering/symphony---ett-planeringsverktyg-for-havsplanering.html

5.2.5 Environmental Risk Assessment Approach

Certain recent works suggest to incorporate risk assessment approach into CEA (Stelzenmüller *et al.*, 2018; Tamis *et al.*, 2016; Judd, Backhaus and Goodsir, 2015; Chen, Fath and Chen, 2011). Risk is defined as "the likelihood and severity of an adverse effect occurring to ecosystem component(s) following exposure to pressure(s)" (Stelzenmüller *et al.*, 2018). The approach is then based on risk identification, analysis and evaluation, using standardized terminology and procedures defined by ISO norms (ISO 31000[18]). The assessment targets risk sources, events, causes, consequences, likelihood of occurrence, presence and effectiveness of control measures and acceptable risk level, similarly to CEA, but using another point of view and terminology. Thus, the methods overlap and the risk approach might further complicate indistinct CEA in practice.

5.2.6 Qualitative and Quantitative Modelling

Qualitative numerical modelling is conditioned by data availability and by sufficient understanding of the simulated processes. Numerical models are developed and readily available for noise, air dispersion, hydrologic regimes or soil erosion (European Commission, 1999; CEQ, 1997). In contrast, ecological models about organisms, habitats and their interactions are challenged by complexity and limited knowledge about ecosystem functioning, which results in high uncertainty. Their use needs many assumptions and can give fictitious precision while not increasing the objectivity (English Nature, 2006).

So called end-to end ecosystem models attempt to represent the entire ecological system, including all the major relevant processes, abiotic conditions, nutrient cycling and dynamic two-way interactions (Fulton, 2010). An end-to-end approach used in (scientific) CEA is Ecopath[19]. It can e.g. identify the keystone species according to their relative impact on the food web, assess their conservation status and trends for future abundance. The software can assess CE, perform sensitivity analysis and test different scenarios, given that the data is available. It can be suitable for a detailed analysis of N2000 sites as in the case study of Fretzer (2016), since local authorities monitor the N2000 sites and report to the European Commission every six years[20]. For marine ecosystems, OSMOSE[21] and Atlantis[22] are available. Though, such detail models are not suitable for practical CEA, where less time-consuming, more robust and less complicated tools are preferable.

Quantitative models represent an alternative to the numerical modelling. They are based on pairwise interactions of system variables, both biotic and abiotic, denoted by +, −, 0 signs (Carey *et al.*, 2014). They predict system responses to external pressures, without need to measure the variables. There are multiple approaches, summarized in Hordoir *et al.* (2018). One of the most common is network analysis, used e.g. by Reum *et al.* (2015), evaluating ocean acidification to shellfish community, by Chen, Chen and Fath (2015) for food web investigations in a river or by Cooper (2010) to assess ecosystem services. Second used technique is loop analysis, assessing food-web responses to pressures (Carey *et al.*, 2014; Justus, 2006). Even these techniques will usually be to detailed, complicated and time consuming for use in non-scientific CEA. In that context, system-dynamics modelling (following chapter 5.2.7) is more flexible, as it can include broader range of variables, feedbacks and scales. To assess community composition and species links to environmental variables, multivariate methods would reveal them by ordination, without subjective definition by user.

[18] https://www.iso.org/iso-31000-risk-management.html
[19] http://ecopath.org/
[20] https://www.eea.europa.eu/data-and-maps/data/natura-9
[21] https://github.com/osmose-model/osmose
[22] https://research.csiro.au/atlantis/

5.2.7 System Dynamics Modelling

System dynamics models (SDM) has numerous advantages for use in CEA, especially for dealing with causality and scenarios. Though, it is neither recommended, except in Duinker and Greig (2007) or used in the CEA context. This work advocates for its enhanced application in future assessments.

Cumulative effects on VEC are unavoidably dynamic (i.e. non-linearly changing in time, especially in long-term in CEA), complex and highly interlinked. That is why SDM fits well to assess them. A central SDM principle is that parts of any system can be related to each other through cause-effect relationships. Such causality chains form feedback loops; reinforcing (positive) loops tend to amplify any change and to produce exponential growth, while balancing (negative) loops tend to counteract any change and to move the system towards an equilibrium (Tedeschi, Nicholson and Rich, 2011). SDM are made up of several feedback loops linked together, which gives them capacity to target virtually all complex behaviour patterns. As consequence, the models can represent complicated systems relatively accurately and provide holistic view better than other tools.

Systems are constantly changing and feedback processes usually do not operate instantly, but create inertia or delays. Similarly, cause and effects can be distant in space (Tan *et al.*, 2010; Sterman, 2002). A conceptual model (in form of causal-loop diagram) is useful as the first step to reveal system components, causal relationships and feedback loops in transparent way (Perdicoúlis and Piper, 2008). However, behaviour of the systems is best understood by simulation modelling (Tedeschi, Nicholson and Rich, 2011). SDM do not aim to forecast exact values of system variables at a given time. Instead, they display trends, comparisons and conditions under which the system is oscillating, growing, declining or in equilibrium. A system-dynamic model is formulated as systems of differential equations that are solved by a relevant software. Advantages of system-dynamics modelling include:

- Variables and data can be broadly defined, in different units and include both qualitative and quantitative measures (Hordoir *et al.*, 2018; Karami *et al.*, 2017; Tedeschi, Nicholson and Rich, 2011)
- Relationships among variables and temporal changes can be exactly defined by user (e.g. decreasing or increasing efficiency of mitigation measures, changing VEC resistance, succession, climate changes, impacts of policy interventions or technological development)
- The model simulates time development of the related variables; their initial values can be specified based on data
- Models can be built robust if explicit data is not available or uncertainty is high
- Feedback loops properly address even higher-order impacts, CE and unforeseen interactions (emerging properties)
- The loops can also reveal whether the same pressure has different CE in the short- and long run as result of long-term cumulative changes
- Loops, functions or parts of a model can be easily changed or switched on/off; therefore, it is easy to compare alternatives and scenarios once the model is built
- Simulated variables and their time development can be visualised in plots for comparisons
- The models can be built iteratively, on diverse aggregation levels and combine insights from multiple stakeholders
- Models can be carried out using a variety of user-friendly computer packages (Vensim provides even a free version[23]); hence, SD modelling is (relatively) easy to learn, as it does not demand deep mathematical and modelling knowledge from the user

[23] Another free option is deSolve R package, though more complicated to use; see

5.3 Swedish Practice from CEA Standpoint

Sixteen EIS [24] as examples of good practice were analysed from CEA standpoint, as summarized in Table 1. The majority of the statements mentioned and/or described CE, especially in the infrastructure projects. The CE parts ranged from a single sentence: “No indirect or cumulative effects are estimated to arise...” (EIS 1, p. 68) to several pages. CE were usually not quantified, neither on an ordinal scale, with exception of EIS 6 (Road 288, Table 19). Instead, they were described in the text and based on judgements, not on data or using some indicators. They were not described from VEC-centric perspective either. The only example of VEC-centric approach was Chapter 21 in EIS 4, Varbergstunneln, studying diverse pressures to N2000 site Getteröns nature reserve. This chapter was also the only one mentioning trends, both for bird species and for habitats. Moreover, this project had clearly defined environmental goal, stating that: “natural values of the N2000 site Getteröns reserve should not be decreased by the project” (page 18 of the EIS).

Table 1. Analysis of the 16 EIS from the CEA standpoint, showing if the concepts from previous chapters were included. As the real CEA was not performed in any of the examples, use of the concepts was assessed on single EIA effects only. Certain concepts were prominent in the EIS, but not in the handbooks.

	Railway projects					Large-scale projects					Comprehensive plans					Detailed plans				
Project/plan	Ombenning	Vretaån	Tulgarn	Varbergstunneln		Road E45	Road 288	Wind power	Power line		Södra staden	Svedala	Vallentuna	Sollentuna		Säbyviken	Fullerö	Brogård	Börjetull	
Consulting firm	VR Infrapro, Calluna	AquaBiota	Ekologigruppen	Tyrens		ÅF	Ramböll	Enetjärn natur	Ekologigruppen		Sweco	WSP	Vallentuna kommun	Ekologigruppen		Tyrens	Structor	Ekologigruppen	Ramböll	Sum
EIS number	1	2	3	4		5	6	7	8		9	10	11	12		13	14	15	16	
Year of publication	2018	2014	2014	2015		2017	2012	2016	2014		2016	2017	2017	2017		2014	2018	2016	2018	
Cummulative effects	1	2	2	3		0	3	3	2		1	0	2	0		1	3	0	0	11
VEC	x	x	x	x		x	x	x	x		x	x	x	x		x	x	x	x	16
PPF baselines							x										x			2
Time scale	2040	?	2030	2030		2040	2040	?	?		2050	2045	2040	2030		?	2030	?	2030	11
Contextual spatial boundaries	x		x	x		x	x									x				6
Causality																				0
Magnitude	x	x	x	x		x	x	x	x		x	x	x	x		x	x	x	x	16
Significance	x	x												x						3
Probability		x		x		x	x						x	x		x		x		8
Weighting	x			x		x														3
Uncertainty			x	x			x	x			x	x		x				x		8
Alternatives	x		x				x	x	x		x					x	x	x	x	10
Scenarios							x						x	x			x			4
Thresholds																				0
Trends				x																1
Biodiversity	x	x	x	x		x	x	x	x		x	x	x	x		x		x		14
Project goals	x			x		x	x	x	x					x		x				8
Environmental quality norms	x			x		x	x	x			x	x		x		x			x	10
Environmental objectives	x		x	x		x	x	x			x	x	x	x		x		x	x	13
Ecosystem services								x				x	x	x				x		5
Green infrastructure														x				x	x	3
Climate change	x			x		x	x	x			x		x	x		x				9

https://api.rpubs.com/rsmard05/sysDynR, http://cran.r-project.org/web/packages/deSolve/ and (Duggan, 2016)

[24] As listed in List of EIS, chapter 9.

As the proper CEA approach was not used in any of the EIS, use of the concepts the Table 1 was considered for the individual EIA variables, not for CE. Even in this way it could be reviewed if the concepts were used in the practice and to identify the largest implementation gaps. If already used in EIA, these concepts might gradually infiltrate to CEA practice.

Effect magnitude on receptors (let's call them VEC even in this EIA context) was always evaluated. However, it was based on estimates and judgements, not on data analyses, and was expressed on (most often) three grade scale, from small to medium and large effect. In few cases, magnitude was combined with weighting, but it was never used further for significance assessment. Several EIS recognized and explicitly mentioned the need of contextual spatial boundaries for individual VECs. Five of the 16 EIS did not clearly stated time scale and those where it was given, it was short, not covering whole project life-time. The latest year was 2050 in EIS 9 (comprehensive plan Uppsala Södra Staden). Even this time, ca 35 years ahead, would be too short for a proper CEA, which should consider CE accumulating during time and beyond projects life-time (Jones 2016).

Past and future baselines were rarely included, not surprisingly for EIA. Similarly, possible future scenarios were rarely mentioned and never assessed. More than half of the EIS analysed more alternatives than the main and zero alternative. Uncertainty of the results was mentioned, usually shortly, in half of the EIS, comparably to probability and/or risk discussion. Biodiversity was commonly included while ecosystem services assessment was not prevalent, with exception of comprehensive plans. Green infrastructure was rarely considered, despite its increasing importance when habitats are lost and degraded as consequences of human activities. Neither climate change consideration was regular practice, mentioned in about half of the EIS. When CC was included, it usually targeted project effects to GHG production, and seldom project adaptation to CC (but see e.g. EIS 4, Varbergstunnel).

Sweden Environmental Objectives and project effects on them were usually targeted while Environmental Quality Norms were assessed less often. Important CEA concepts of cause-effect relationships, trends, thresholds and carrying capacity are so far missing in the practice. The effects were always estimated, never quantified. Deeper evaluation of few representative uncorrelated variables might identify unseen consequences and/or long-term trends, if considered.

CE were mostly neglected in the comprehensive plans. As these plans are part of early strategic planning, cover large areas and long-term pressures with irreversible land-use changes and consequences, CE should become important part of their assessment. Moreover, as they usually suggest additional activities in already highly developed areas, cumulation of effects and their high significance due to reaching thresholds can be expected. For example, building of new housing will necessarily be connected with habitat loss, both in case of town densification and sprawl. It will also lead to increase production of GHG, air pollution, noise, waste-water etc., which all will interact together and with the pressures from already existing development. Importance of remaining habitats and their quality in the city-close nature will increase even more, together with the pressures on them. All these variables should therefore be properly assessed in the comprehensive plans, optimally using system-thinking.

Large- and long scale CEA is also needed for the infrastructure projects. As documented by the examples of both railway and road EIS in this text, the assessment usually covers only a short part of the railway or road, where it can be very detailed. Similarly to city development, CEA should display the overall effects on landscape-level, prevent nibbling and ensure sustainability of the whole infrastructure projects.

Ecosystems, habitats and connected variables[25] are generally those receiving the most negative consequences from the human activities (as also documented by the EIS). Part of them disappears due to the construction, which leads to habitat fragmentation. Remaining parts can be degraded by the project, e.g. by pollution spread, hydrological changes and other interacting pressures, leading to CE. The project EIS usually conclude that even if the consequences are negative, they are not significant. As already mentioned, insignificant effects from numerous small projects can lead to severe unanticipated changes on larger scale. For example, even if a species will not (immediately) disappear from the place, the gene-flow between populations can be disturbed and the species will not survive in long-term at the locality. A species extinction can be followed by changes in food-chain and further extinctions. The locality conditions will also successively change due to climate change (5.1.9) and species populations will need to migrate. CEA could ensure habitat connectivity and migration corridors in the landscape to prevent the extinctions/biodiversity loss.

In summary, a consistent CEA approach was not used in either of the included EIS, although they were provided as the best cases of the practice. The majority of the best examples date several years back, before implementing of the new version of the Chapter 6 in Miljöbalken. The EIS 14 was an exception, representing a good example of CEA on a detailed development plan level. Certain concepts were not included in the EIS, even if required by legislation, such as significance, uncertainty or relationship with other relevant plans and programmes. Use of these concepts would improve not only CEA, but even EIA practice.

There are many parameters to be covered in the assessment: environmental objectives, quality standards, ecosystem services, green infrastructure, VECs etc. The EIS text could easily become very extensive if including them all and discussing them separately (as it is usually done). That is where holistic perspective and systematic approach might help, analysing them together, as the concepts overlap. System thinking, causality, CEA mindset with VEC-centric perspective would considerably improve CEA in the practice.

Problems with CEA implementation are common worldwide, despite the consensus that CEA is a good idea (Willsteed et al., 2018; Jones, 2016; Judd, Backhaus and Goodsir, 2015; Olagunju and Gunn, 2015, and references therein).

Interviews with planners and EIA practitioners revealed diverse struggles, such as:

- Lack of systems perspective, even on project level (Noble, Liu and Hackett, 2017; Gunn and Noble, 2011)
- Strategy for identifying and analysing CE is indistinct from the approach for EIA-project effects (Baxter, Ross and Spaling, 2001)
- Lack of knowledge how to include CE and a lack of clear regulations how this should be done (Folkeson, Antonson and Helldin, 2013; Wärnbäck and Hilding-Rydevik, 2009)
- Spatial and temporal scales chosen with little concern of CE (Folkeson, Antonson and Helldin, 2013)
- Correct analysis of CE and inclusion of an ecological network scale (Bigard, Pioch and Thompson, 2017)

[25] Often referred as ”natural values” in the EIS

- CE are left unexamined as project impacts were determined to be insignificant (Baxter, Ross and Spaling, 2001)

Even the Swedish consults I was in contact with acknowledged it[26]:

"CE has not been handled in that extent they should in previous EIAs."
"It is (CE) a matter difficult to handle and we in the practice have not found any good way to deal with them."
"I do not have any really good example."

However, the analysis of EIS showed that CEA principles are slowly coming to the practice. To speed up the process, it is necessary to realize that CEA and single-project EIA involve distinct considerations and therefore require different approaches, as discussed below.

[26] I keep the citations anonymous

5.4 Suggestions for Improvements and Tools Recommended

CEA implementation into the Swedish practice is still in its initial phase and experience how to do it is largely lacking. The new version of Chapter 6 of the Environmental Code (Miljöbalken), asking more specifically for CE assessment (compared to the previous version) might help to fasten the implementation process. It is not realistic to expect use of numerous concepts and combinations of methods immediately. Rather, it will be a continuous procedure with growing know-how through the time. Below are my suggestions how to start with in the most efficient way. In any case, use of limited number of selected concepts and methods to perform a simply CEA would be much better than to neglect CE completely because of the challenges with their assessment.

5.4.1 Enhanced CEA Implementation

As two the most important step of successful CEA implementation in Swedish practice, I suggest to:

- Switch mindset to VEC-centric perspective (*i.e.* refocus from the individual project impacts to the environment concerned)
- Adopt system-approach in defining impact relationships, feedbacks and CE

Further prominent aspects to take into account are:

- CEA should preferably be a separate section of EIS or a stand-alone document, not integrated at the end of each impact section (as usually done)
- CEA section should have its own methodology, scales and baselines
- Small projects shall be put in the broader context, as many small actions would probably result in nibbling effects and become significant
- EIA usually states that the project will cause negative consequences, which will still be acceptable – CEA should be done in any case, using trend analysis and carrying capacity/thresholds to confirm or disprove the acceptability
- National EIS database would provide inspiration of good-practice examples and of similar projects and VECs
- At least certain VECs/indicators should be quantified, not all of them only judged by expert opinions
- Regulators should require properly done CEA both on strategic and project level
- Use of concepts and recommendations highlighted in this text

5.4.2 Recommended Tools

Coming back to the CEA steps (chapter 5.1.1), these are my recommendations of tools:

Step 2. Selection of valued environmental components (VEC) and their indicators

- GIS to visualize different variables in the area
- system approach on highly aggregated level
- multivariate statistics to select uncorrelated VEC

Step 5. Identification of cause-effect relationships, VEC responses to changes and feedback-loops and
Step 6. Identification of impacts and CE

- system approach on more detail level, increasingly elaborated CLDs
- plotting of impacts against each other in a matrix (for each VEC)

Step 7. Analysing CE magnitude and significance for defined alternatives and scenarios and
Step 9. Evaluation of residual CE significance and uncertainty of predictions

- GIS localisation and quantification of spatial variables (e.g. habitat loss, land-use change)
- SDM simulations, plotting of time-trajectories in graphs
- Other modelling for variables where data available
- Expert judgements

All steps

- Consultations among stakeholders, data mining and literature search to get the knowledge and information

Outputs to communicate the results

- GIS map to overview the CE
- Summarizing matrices (for magnitude, significance, probability, uncertainty etc.)
- MCA, if requested to support decision-making, with CE weights provided by different stakeholders to include conflicting perspectives
- Multivariate statistics to plot the alternatives
- Explicative CLD adapted for communication purposes
- Verbal description

Ideally, the tools would be combined and used flexibly in the context of the given assessment.

Combination of techniques for any deeper evaluation of numerous variables might require several software packages. Their price and lack of usage know-how may represent additional challenges. Another option is to use R programming language. Its open-source format allows to use codes written by others for any thinkable analyse of environmental data, including SDM (Duggan, 2016) or GIS. Though it may be complicated for a beginner, many online discussions on code and analyse use provide help and R is definitely an option to consider.

6 Discussion

Discussion aims to set the text into a broader context. First, it compares the different sources of information about CEA concepts and tools, followed by discussion of the tool-use in the second part. The third section targets links between CEA science, practice and regulators, while the last part outlines CEA contribution to ensure long-term sustainability. In contrast, the individual concept and methods are discussed in the Analysis part (chapter 5) in the corresponding subchapters, in order to give the text better flow and the reader possibility to read the Analysis only without browsing into the Discussion.

6.1 Sources of CEA Information

This work aimed to consolidate relevant knowledge about CEA from research, handbooks, legislation and practice, and to suggest new ways to improve CEA practice. I tried to summarize and evaluate the most relevant information from all the above sources, in order to deliver over the core knowledge about the CE identification and quantification to readers who do not have possibility to read such extended information sources.

Altogether, combining the papers and handbooks gave me the knowledge about CEA principles and concepts, needed to create the checklist for analysing the EIS. Further, they elicited which methods are and are not suggested to conduct CEA, which in turn facilitated to create the list of recommended tools (5.4.2). Reading the Directives and the Environmental Code documented that the assessment principles had made their way into the legislation. They provided surprisingly elaborated information and requirements, especially those on EU-level. Evaluating the EIS confirmed that CE are not assessed sufficiently and the legal requirements are not fulfilled in the practice examples. Consequently, I could identify the most crucial steps to start with in CEA implementation (5.4.1).

The research papers and handbooks widely differed both in concept and in information provided. The scientific papers could be divided to two groups; the first one describing complex CEA examples on large spatial scales, often not connected to any project and too advanced to be applicable in practice (see 5.2). The second group of papers targeted CEA process quality and flows and/or practitioners' views (not aim of the thesis, but see 5.3). The handbooks often overlapped and seemed to take over information from each other, the newer ones seldom bringing in new ideas (though this is a generalisation). Further, they focused on scoping, while the parts about magnitude and significance assessments were incomplete and would not provide guidance needed to perform it.

Even the guidelines available in Swedish (Folkeson, 2010) were based on the Canadian and US handbooks, *i.e.* Hegmann *et al.* (1999) and CEQ (1997). The main strength of this document was to take in Swedish nomenclature and glossary for the CEA expressions from English. Even that document highlighted the VEC-centric perspective and importance of the total CE on the VEC; though, this was never employed in the Swedish practice, as the EIS analysis revealed. Similarly, the second Swedish handbook (Trafikverket, 2011) recommended to focus on VECs and states that the road planning should consider landscape in a holistic perspective, including CE such as habitat loss, impacted hydrology and land-use changes, not only road corridors. Again, this was not fulfilled either in the road or railway connected EIS.

6.2 CEA Tools

Several methods to quantify CE are described in the papers and handbooks. Besides of briefly evaluating their applicability in practice, I proposed enhanced use of techniques not common in CEA literature and practice, especially of multivariate statistics and system dynamics modelling. These might help to uncover unseen trends, correlations and causality relationships and thus improve CE predictions (5.1.3, 5.2.1 and 5.2.7). I also tried to identify the most relevant tool in individual CEA steps (5.4.2), to obtain the most knowledge and for optimal communication of the results.

In the handbooks, tools are usually described as individual approaches, but their combination is needed to offer the most complete picture (e.g. expert judgement and / or checklists to set causality to identify CE and to visualise them in GIS etc.). Even in survey done by Dibo, Noble and Sánchez (2018) the majority of respondents indicated that there are no 'best tools' that can be recommended for assessing potential CE on biodiversity. Instead, the choice of tools was said to depend on the project context and location, on VEC being assessed and on availability of data and information. Similarly, Hodgson and Halpern (2019) reviewed 6 categories of methods and found that no single method assessed all impacts. Interesting examples of method combinations were presented e.g. by Pradhan et al. (2015), combining GIS, remote sensing, loop analysis and RIAM, or by Papadopoulou, Dikou and Papapanagiotou (2014), using system diagrams, GIS and checklists.

Complex quantitative modelling is neither realistic or needed in practical CEA. The quantitative approach is important to understand the mechanisms that contribute to cumulative change and should be the science contribution (see below, 6.3). Priority of practical CEA is to capture the complexity and to understand the drivers of cumulative change, not the precise CE quantification (Ball, Noble and Dubé, 2012; Therivel and Ross, 2007; Justus, 2006). Semi-quantitative assessment can represent a pragmatic option instead. They have more reasonable data requirement, but adequate knowledge of relationships is needed anyway. If used, the models should be robust enough in order not to increase biases and lead to overpredictions. Qualitative methods represent solution when data is limited and detailed relationships unknown (Justus, 2006) or future activities largely unsure (as e.g. in case of SEA for comprehensive plans).

Even simple description of CE, fitting for purpose and getting predictions that are "good enough" can reveal the appropriate management measures (Jones, 2016; Therivel and Ross, 2007). However, it should not be used for all of the effects and VEC, at least certain indicators should be quantified. That is not the case in practice, where CE are usually assessed by expert judgment only. That may be sufficient option for small projects (e.g. mini-CEA), but not for substantial assessments. The judgement will always rely on subjective inputs, with among-expert differences in perceptions of the problems and CE pathways (Stier et al., 2017). Besides replication problems, the judgement might also overlook subtle but cumulatively significant effects (Therivel and Ross 2007), especially in case of larger activities. Thus, trends analysis, use of thresholds and cause-effects based modelling should be substantial part of properly done CEA. Reference cases from comparable VECs and / or activities, and ideally results from their monitoring, would help the assessment.

6.3 Role of Science and Regulators in CEA Practice

In a recent study, Willsteed *et al.* (2018) described that there still was dissonance between CEA science and practice. Moreover, they observed variability in CEA quality between assessments. They argued for CEA driven by best available science; that can be unrealistic though, at least in case of the advanced demanding techniques. Foley *et al.* (2017) proposed opportunity to align CEA practice more closely with science through the use of monitoring data. Jones (2016) claimed that numerical methods for assessing CE are largely available, meaning that CEA's biggest problems are not scientific. Instead, the challenge was that each CEA step requires practitioners to make analytical decisions and objective rules for how to approach those decisions are lacking. Duinker *et al.* (2012) were the most realistic, identifying contributions from science to CEA practice as follows: i) investigative protocols, ii) basic ecological knowledge and grounds for threshold establishment, iii) cause-effects knowledge, iv) tools and methods and v) education of analytically competent practitioners. Hence, the expertise demand represents more compelling issue than method availability, as a wide range of knowledge is needed. Further, establishing of right team is fundamental, including well-functioning cooperation, communication and coordination (Folkeson, Antonson and Helldin, 2013), besides the analytical skills.

Responsibility for CEA quality is another issue. Individual project proponents might not consider CE as their concern. Moreover, their level of effort could be limited by available time, money and personnel. Therefore, CEA quality is rather regulator task. Folkeson, Antonson and Helldin (2013) founded EIA reviewer at the County Administrative Board (or another review authority) to have a crucial role, even though it is the proponent (project developer) or the municipality (in case of Comprehensive- and Detailed Development Plans) who has the main responsibility for managing the assessment process. In any case, CE issues should be introduced early in the planning process, ideally during SEA (European Commission, 1999). CE should be assessed stepwise in collaboration among diverse stakeholders and between infrastructure- and spatial planning (Folkeson, Antonson and Helldin, 2013; Trafikverket, 2011). At the project level, CEA would provide broader perspective of the numerous pressures, both from the project itself and from other activities. Regulator should coordinate the project-level assessments, in order to understand CE of multiple activities (Noble, Liu and Hackett, 2017) and to best support CE management (Joseph et al., 2017).

6.4 CEA Contribution to Sustainability

As the development continues, species and ecosystems indisputably disappear. Indeed, habitat loss, fragmentation and degradation were often estimated as the most significant and irreversible consequences in the EIS. Large-scale modifications of ecological processes, potentially caused by CE, might subsequently impact human communities relying on ecosystem services (Griffith et al. 2011), affecting well-being and quality of life. The set of VECs chosen for the assessment should therefore include at least one, but preferably several, ecological variable(s) and try to quantify (at least some of) them.

CEA's main goal is to ensure long-term sustainability and avoid postponing on adverse effects into the future (unless all other options are worse). As such, it has to cover time segment lasting long enough to underpin even slowly accumulating, but consequently significant CE. On the other hand, CEA uncertainty will increase with the time included as a consequence of challenges to predict future. However, certain long-term forecasting is possible; one might not predict when a CE will appear and when threshold will be passed, but it can be forecasted that it would happen if people keep to remove or alter the environment in question. Hence, if something will happen is more important to know than when (Hegmann and Yarranton, 2011).

Reliable evaluation of what may happen is important information for decision makers who will have to decide whether it is acceptable or not. Precautionary principle plays important role in the decision, based on the unavoidable uncertainty. Best available technologies should be prioritized for optimal resource use (Jones, 2016; Hegmann and Yarranton, 2011). Further, all stakeholders should have realistic expectations what is possible in CEA given the current knowledge, available data and level of effort and resources. Although CEA can never be perfect, it is always better to accept its challenges than to completely omit CE from decision-making.

7 Conclusions

CEA is both a tool to provide information for informed decision-making as well as a strategy for long-term thinking, trying to define which trade-off of human activities are still acceptable and not compromising the sustainable development. Dealing with numerous pressures, issues and values, CEA can never be simple and straightforward. On the other side, it should not be too complicated or detailed, in order to be feasible and communicable to non-experts. Thus, any CEA should be adapted to the context of the particular assessment and focus on structured comparisons among alternatives, rather than on precise effect quantifications. CEA complexity, flexibility and need to combine diverse tools require both expertise and clear requirements. The most important steps to take in the near future is to see the whole picture of the problematics, start to think from system-perspective and start to apply relevant methods. In any case, CEA implementation is a continuing process where the practice itself will determine the realistic extent and ways to carry the assessment out. I hope that this text might partly contribute to it.

8 References

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9 List of EIS

List of Environmental Impact Statements used for the analysis:

1. Ny mötesstation Ombenning, Sträcka Snyten – Fagersta, Godsstråket genom Bergslagen, Fagersta kommun, Västmanlands Län, VR Infrapro & Calluna, 2018
2. Ostlänkens påverkan på Natura 2000 området Kilaån – Vretaån, SE0220304, Nyköpings kommun, Södermanlands län, AquaBiota, 2014
3. Tulgarn Natura 2000 – passage av ny järnväg, Ekologigruppen, 2014
4. Varbergstunneln, Västkustbanan, Varberg-Hamra, Varbergs kommun, Hallands län, Järnvägsplan, Tyréns, 2015
5. E45 Vattnäs – Trunna, Orsa och Mora kommuner, Dalarnas län, ÅF, 2017
6. Vägutredning Väg 288, delen Gimo-Börstil, Östhammars kommun, Uppsala län, Ramböll, 2012
7. Vindkraftanläggning vid Finnåberget, Sollefteå och Ragunda kommuner, Västernorrlands och Jämtlands län, Enetjärn Natur, 2016
8. Ny 400 kv-ledning mellan Råsten och Östfora, Ekologigruppen, 2014
9. MKB tillhörande Fördjupad Översiktsplan för Södra Staden, Uppsala kommun, Sweco, 2016
10. Hållbarhetsbedömning, Översiktsplan Svedala 2018, Svedala kommun, 2017
11. Översiktsplan 2040 Vallentuna, Vallentuna kommun, 2017
12. Miljökonsekvensbeskrivning av Översiktsplan 2018 för Sollentuna kommun, Ekologigruppen, 2017
13. Miljökonsekvensbeskrivning för detaljplan Säbyvikens Marina i Österåkers kommun Samt tänkbara miljökonsekvenser av en naturpark, Tyréns, 2014
14. Detaljplan Fullerö Företagspark, Urbanica AB och Uppsala kommun, Structor, 2018
15. Detaljplan för Brogård 1:84 m.fl . (Husbytorp - Tegelhagen) nr 1402, Upplands-Bro kommun, Ekologigruppen, 2016
16. MKB till detaljplan Börjetull, Uppsala kommun, Ramböll, 2018