Beiträge zum Stuttgarter Maschinenbau

Michaela Keßelring

Sustainable Test Site Decision-Making

Decision-making under technological-social-ecological considerations

stuttgarter maschinenbau
interdisziplinär und vielfältig

University of Stuttgart
Institute of Human Factors and Technology Management IAT

University of Stuttgart
Germany

Beiträge zum Stuttgarter Maschinenbau **Vol. 12**

Editors: Prof. Dr. Katharina Hölzle, MBA
Prof. Dr.-Ing. Oliver Riedel

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Fraunhofer Verlag

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Cover illustration: Michaela Keßelring

Bibliographic information of the German National Library:
The German National Library has listed this publication in its Deutsche Nationalbibliografie; detailed bibliographic data is available on the internet at www.dnb.de.

ISSN: 2750-655X
ISBN: 978-3-8396-1875-2

D 93

Zugl.: Stuttgart, Univ., Diss., 2022

Print and finishing:
Fraunhofer Verlag, Mediendienstleistungen

The book was printed with chlorine- and acid-free paper.

Nobelstraße 12
70569 Stuttgart
verlag@fraunhofer.de
www.verlag.fraunhofer.de

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Preface

The German economy is well-known throughout the world for its plant and mechanical engineering. With its two mechanical engineering faculties housing 42 institutes, the University of Stuttgart is the largest university institution for mechanical engineering in Germany. Our scientific excellence in this field is based on our numerous doctoral students and their outstanding dissertations. Many of these dissertations arise out of local, national and international collaborations with renowned universities and non-university research institutions, such as the German Aerospace Center, the Fraunhofer-Gesellschaft and the Max Planck Society. The fields covered by the dissertations range from Bio-Engineering, Energy Engineering, Automotive Engineering, Cybernetics and System Engineering, Product Development and Design, and Production Engineering to Process Engineering, and are based on the six main research areas of Advanced Systems Engineering, Autonomous Production, Software-Defined Manufacturing, Resilient Supply, Biointelligence and Decarbonization of Industry. The research findings from the dissertations aim to develop customer-specific, product-, process- and employee-oriented technologies in a targeted and timely manner.

Many of the dissertations written within the framework of the research work at the institutes are published in this series »Beiträge zum Stuttgarter Maschinenbau«. Our wish for the doctoral candidates at the two faculties of Stuttgarter Maschinenbau is that their dissertations in the field of mechanical engineering will be recognized by the wider professional community as authoritative contributions and thus contribute to establishing a new standard of knowledge.

For Stuttgarter Maschinenbau

Stefan Weihe
Vice Dean Faculty 4

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Foreword by the editors

Innovation is the basis for social, economic and scientific progress. It is created through the interaction of technology, market, and human needs. Considering these three factors requires transdisciplinary collaboration and integration of different perspectives and capabilities.

Research at the Institute of Human Factors and Technology Management (IAT) at the University of Stuttgart and the associated Fraunhofer Institute for Industrial Engineering IAO is characterized by this transdisciplinary and integrating perspective. Here, research is conducted with the conviction of finding scientific solutions for practical issues and bringing them into application. Based on a common understanding with the human being in the center, the change of organizations and societies is systemically examined and empirically founded models and solutions are derived.

The doctoral students at the IAT and IAO institutes haven taken up this challenge and report their findings in the present »Beiträge zum Stuttgarter Maschinenbau«. This current series continues the work of the former institute directors at IAT and IAO, Hans-Jörg Bullinger and Dieter Spath, together with Wilhelm Bauer, and focuses on the future. We, the editors, wish the authors that their dissertations in the fields of work science, technology and innovation management will be perceived as important and authoritative contributions in the wider professional world and thus establish a new level of knowledge.

Univ.-Prof. Dr. Katharina Hölzle, MBA

Univ.-Prof. Dr.-Ing. Oliver Riedel

Sustainable Test Site Decision-Making
Decision-making under technological-social-ecological considerations

Von der Fakultät Konstruktions-, Produktions- und Fahrzeugtechnik
der Universität Stuttgart
zur Erlangung der Würde einer Doktor-Ingenieurin (Dr.-Ing.) genehmigte Abhandlung

Vorgelegt von

Michaela Keßelring M.Sc.

aus Starnberg

Hauptberichter:	Prof. Dr.-Ing. Oliver Riedel
Mitberichter:	Prof. Dr. rer. pol. Dipl.-Ing. Meike Tilebein
Tag der mündlichen Prüfung:	26.07.2022

Institut für Arbeitswissenschaft und Technologiemanagement (IAT) der Universität Stuttgart

2022

Abstract

The advent of sustainable technology development led to many invigorating initiatives, development methods, and sustainability assessments. The advent meant an increasing focus on how technologies contribute to current and future sustainable development. However, the connection between sustainable technologies and sustainable development at test sites is barely considered in this discourse. Today, test sites often fall in the jurisdiction of technology development. A compartmentalization that impedes the exploitation of sustainability considerations at the first intersection between real-world applicability and technology assessment.

Merging sustainable technology development and sustainable development at test sites received little scholarly attention. One reason is the challenge of encouraging interdisciplinary discourse where technology as the preserves of engineers and the role and influence of social science for sustainable technology management interconnect. Where sustainable test sites are concerned, this becomes evident through the functions of associated parties. Technology developers aim to assess or realize their test case, while sustainability advocates require testing operations not to disturb the social and physical environment. Two sometimes competing objectives. Sustainability analysis of test sites requires methods to assess new or even reevaluate existing test sites under technology, social, and ecological aspects that bring the perspectives of technology developers and sustainability advocates. For independent interface assessments, cross-disciplinary evaluations require replicable decision procedures. Procedures that current theoretical and practical approaches fall short on providing.

Under the notion of sustainable test site decision-making, the thesis aims to close this research gap and develop an integrated decision framework for sustainable test site assessment and follow-up selection. The thesis focuses on technology-centered decision-making, social and ecological impact determination, and disclosure requirements for technology testing in natural environments.

Qualitative and quantitative research build the basis for developing the sustainable test site decision framework. The resulting framework guides the (I) computation, (II) execution, and (III) application of sustainable test site decision-making. Thus, it provides the means to research the viability of test sites for a range of innovative technologies under social and ecological perspectives. In addition, the framework may set the criteria for public reporting of technology activities, ecological impact communication, and capacity assessment of test sites.

The thesis complements the literature on sustainable technology development in natural environments and introduces practical requirements for responsible technology development and decision-making under uncertainty. Finally, the thesis is the first to balance testing requirements and sustainable development principles in a decision approach for physical test sites. Procedures that current theoretical and practical approaches fall short on providing.

Zusammenfassung

Mit dem Einzug der Nachhaltigkeitsdebatte in die Technologieentwicklung und das Technologiemanagement rückte die Frage in den Vordergrund, wie man Technologieentwicklung nachhaltiger gestaltet und wie Technologien zu einer nachhaltigen Entwicklung im Allgemeinen beitragen können. Im Übergang zwischen nachhaltiger Technologieentwicklung und Technologieanwendung können reale Testgebiete für explorative Geophysik genutzt werden, um Analysen und Bewertungen in natürlichen Umgebungen durchzuführen.

In diesem Diskurs wird die Nachhaltigkeit von Testgebieten selbst jedoch kaum berücksichtigt. Ein Grund dafür ist die Herausforderung, die Technologie, oftmals eine Domäne der Ingenieure und die Rolle sowie den Einfluss der Sozialwissenschaften für ein nachhaltiges Technologiemanagement zu verbinden. In Bezug auf nachhaltige Testgebiete wird dies durch die Rollen der beteiligten Parteien deutlich. Technologieentwickler wollen beispielsweise ihren Testfall bewerten oder realisieren, während Nachhaltigkeitsadvokaten fordern, dass der Testbetrieb die soziale und physische Umwelt nicht stören darf. Dies sind zwei manchmal konkurrierende Ansätze. Folglich erfordert die Nachhaltigkeitsanalyse von Testgebieten Methoden zur Bewertung neuer oder auch zur Neubewertung bestehender Testgebiete unter technischen, sozialen und ökologischen Aspekten, welche die Perspektiven von Technologieentwicklern und Nachhaltigkeitsadvokaten zusammenbringen.

Fachübergreifende Evaluierungen bedürfen unabhängiger Schnittstellenbewertungen und replizierbarer Entscheidungsverfahren. Beides sind Ansätze, welche die derzeitigen theoretischen und praktischen Arbeiten nur unzureichend behandeln. Die vorliegende Dissertation zielt darauf ab, diese Forschungslücke zu schließen und einen integrierten Entscheidungsrahmen für die Bewertung und Auswahl nachhaltiger Testgebiete zu entwickeln. Dabei konzentriert sie sich auf die technologiezentrierte Entscheidungsfindung, die Bestimmung der sozialen und ökologischen Auswirkungen und die Offenlegungsanforderungen für Technologietests in natürlichen Umgebungen.

Qualitative und quantitative Forschung bildet die Grundlage für die Entwicklung des Entscheidungsrahmens für nachhaltige Testgebiete. Der resultierende Entscheidungsrahmen beinhaltet die (I) Berechnung, (II) ein prozessuales Vorgehen für und (III) die Anwendung von nachhaltigkeitszentrierten Entscheidungen für Testgebiete. Er bietet somit die Möglichkeit, die Tragfähigkeit von Testgebieten für eine Reihe innovativer Technologien unter sozialen und ökologischen Gesichtspunkten zu untersuchen.

Darüber hinaus kann der Entscheidungsrahmen die Kriterien für die öffentliche Berichterstattung über Technologieaktivitäten, die Kommunikation ökologischer Auswirkungen und die Kapazitätsbewertung von Testgebieten festlegen. Die Arbeit ergänzt die Literatur zur nachhaltigen Technologieentwicklung in natürlichen Umgebungen und stellt praktische Anforderungen an eine verantwortungsvolle Technologieentwicklung und Entscheidungsfindung unter Unsicherheit vor. Schließlich ist die Arbeit eine der ersten, die Analyseanforderungen und Prinzipien der nachhaltigen Entwicklung in einem Entscheidungsansatz für reale Testgebiete in Einklang bringen.

Thank you notice

I am deeply indebted to my supervisor Prof. Dr.-Ing. Oliver Riedel. His infectiously inspiring and inquiring mind made me challenge my work every day and had a lasting impact on my thinking.

I would like to express my deepest appreciation to Prof. Dr. rer. pol. Dipl.-Ing. Meike Tilebein, who offered her expertise, and experience and made me identify the connections of interdisciplinarity. For his time and generous support I also want to thank the chair of my defense committee Prof. Dr.-Ing. Thomas Maier.

My journey would have never started without Prof. Dr.-Ing. Frank Wagner. Had it not been for his empowerment, vision, and initiative my path would not have been that clear.

My appreciations go out to Prof. Dr.-Ing. Peter Ohlhausen, who offered his keen eye and sharp mind. Thanks, should also go to Dr.-Ing. Manfred Dangelmaier, who encouraged and hosted the exchange among Ph.D. students at the Fraunhofer IAO / University of Stuttgart IAT.

This endeavor would not have been possible without the study participants, research assistants, and my peers from the INFACT project which impacted and inspired me. With that, I am beyond grateful to the colleagues from the Helmholtz Institute Freiberg for Resource Technology. A truly inspiring group of researchers, that opened their doors and minds to me.

To Hernan Ugalde Ph.D., Dr.-Ing. Jonathan Masior, and Anne Keßelring M.A. I am forever indebted. Their late-night feedback sessions and moral support lifted me up and carried me through the years.

I would be remiss in not mentioning my husband. His patience kept me levelled and his love kept me sane. My heart goes out to my parents, who put their all into their two children.

Finally, to all who dream about doing their Ph.D. – go for it. It is the journey of a lifetime.

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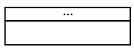
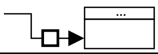
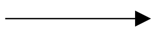
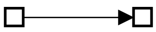
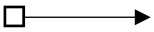
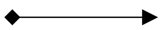
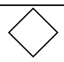
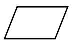
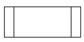
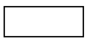
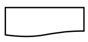
Abbreviations

aAHP	advanced Analytic Hierarchy Process
AEM	Airborne Electromagnetic
AHP	Analytic Hierarchy Process
AIC	Akaike-Information-Criterion
AIIP	Airborne Inductively Induced Polarization
AIP	Airborne Induced Polarization
AMT	Audiomegnetotellurics
ANP	Analytic Network Process
CATREG	Categorical Regression
CEF	Continuous Ecological Functionality
CI	Consistency Index
CMMI	Capability Maturity Model Integration
CR	Consistency Ratio
CSR	Corporate Social Responsibility
CTA	Constructive Technology Assessment
dB	Decibel
DEMATEL	Decision Making Trial and Evaluation Laboratory
DOAI	Disturbance-Oriented-Adjustment and Information Approach
ED	Ecological Disclosure
ELECTRE	ELimination Et Choix Traduisant la REalité (engl. Elimination And Choices Translating Reality)
EM	Electromagnetic
ERS	European Reference Sites
ESG	Environmental, Social, and Corporate Governance
FN	False Negative
FP	False Positive
FTMG	Full Tensor Magnetic Gradiometry
GFEM	Ground-Floor Electromagnetic
GIS	Geographic Information Systems
INFACT	Innovative Non-Invasive but Fully Acceptable Exploration Technologies
IP	Induced Polarization
IPTH	Leibniz Institute of Photonic Technologies
ISO	International Organization for Standardization
kNN	k-Nearest Neighbors
LCA	Life Cycle Assessment
MAUT	Multi-attribute Utility Theory
MAVT	Multi-attribute Value Theory
MCDM	Multi-criteria Decision Making
MNE	Multinational Enterprise
MODM	Multi-Objective Decision Making
MPST	Multi-level Perspective on Socio-Technical Transitions
MT	Magnetotellurics
NIMBY	Not-in-my-backyard
OECD	Organisation for Economic Co-operation and Development
OLS	Ordinary Least Squares
PROMETHEE	Preference Ranking Organization Method for Enrichment of Evaluations
PROSA	Sustainability Assessment to Solve Sustainability-Centered Decision Making
RMT	Radio Magnetollurics
RI	Random Index Values
R&D	Research and Development
SCOT	Social Construction of Technology
SDSS	Spatial Decision Support System

SLO	Social License to Operate
SME	Small and Medium-Sized Enterprises
SQUID	Superconducting Quantum Interference Devices
SR	Social Responsibility
STD	Sustainable Technology Development
STSDF	Sustainability-Oriented Test Site Decision Framework
TAM	Technology Acceptance Model
TD	Technology Development
TEM	Time-Domain Electromagnetics
TMI	Total Magnetic Field Intensity
TN	True Negative
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TP	True Positive
TRL	Technology Readiness Level
UAS	Unmanned Aerial Systems
UTAUT	Unified Theory of Acceptance and Use of Technology
UXO	Unexploded Ordnances
VDI	Verein Deutscher Ingenieure
VHMS	Volcanogenic Host Massive Sulfide
VIKOR	Visekriterijumsko Kompromisno Rangiranje (engl. High-Criteria Compromise Ranking)
VMS	Volcanogenic Massive Sulfide
VTEM	Versatile Time Domain Electromagnetic
V&V	Verification and Validation
WoS	Web of Science

Symbol Directory

Symbol	Meaning
«component»	Stereotype
	Block with values and parts, i.e. an object with properties and objects
	Interface to the outside of a model
	Flow (neutral)
	Activities with interfaces
	Aggregation, partial elements also have a meaningful meaning in the connected context
	Inheritance, takes over properties
	Composition, associated dependencies
	Decision
	Input / Output component step
	Predefined process
	Process step
	Artefact

1 Sustainable Technology Tests in Real Environments

Sustainability would likely appear on the first page of a list of concepts troubling the twenty-first century. Humanity has been using resources at breakneck speed and must acknowledge that the current business-as-usual resource consumption has outgrown planetary boundaries (Li et al., 2021). And while there is agreement that action needs to be taken (e.g., United Nations Sustainable Development Goals), there is often a lack of established strategies to turn piecewise activity into replicable concepts (Pichler et al., 2017). To develop such concepts, there is a need to investigate sustainability backlogs throughout technology development (TD).

Sustainable technology development (STD) is praised for integrating the goals of innovation and growth, an engaged society, and decreased impacts on the environment (Loiseau et al., 2016). Recent technological innovations in sensing, automation, and computerization may increase the sustainability of industries (Butts-Wilmsmeyer et al., 2020). The proof factor is one bottleneck for the market entry of highly innovative and often high-risk developments (Azoulay et al., 2019). A proof of concept provides regulatory, scientific, engineering, or investment communities with evidence about technical performances (Bradley et al., 2013; Jobin et al., 2020). The requirement for proof of concept implies that despite profound improvements in laboratory, simulations, and pre-trial processes, the value of a technology is not fully marketable until there is credible evidence of its applicability in the real world (Fenn et al., 2003). Real-world applicability can be tested in natural areas that resemble the end-user setting. So-called test sites offer a semi-controlled environment to aid the development of the proof factor (Kirincich et al., 2018). While this is hardly novel, the required capabilities to launch and maintain test sites commonly exceed those of a single actor or entire sector (Schuurman et al., 2015). Stakeholder needs and perceived suitability differ depending on the decision structure for test site development and test site usage (Proctor & MacCallum, 2019). From the perspective of the technology developer, the focus may lie on the technical suitability of the test site. For the technology manager, the situation is more complex. As test sites are designated natural environments, sometimes located near populated areas, test site creation requires the balancing of three dimensions: the technical, physical- (ecological), and social environment (Emami et al., 2020).

1.1 Sustainable Test Site Controversy and Research Gap

One major issue in sustainable technology research is the lack of knowledge in how sustainability development and sustainable technology usage connect. In the literature on testing for sustainability, the relative importance of social, ecological, and technical suitability is debated (Vacchi et al., 2021). Questions have been raised about the sustainability of using and recycling technologies (Imoniana et al., 2021). But little is known as to the paradoxical lack of operations and resources midway between sustainable technologies and the sustainability of using technologies. Test sites are embedded in that nexus concerning technical performance assessment and ecological and social embeddedness (Oudinot et al., 2018). Per this nexus, three aspects are relevant: (I) Abounding technical considerations may deem a testing endeavor futile. (II) Lack of ecological understanding of a test site area can lead to invasive behavior to fauna, flora, water, atmosphere, and soil. (III) Where invasiveness targets protected species and livelihood is concerned, community structure and functions become critical to the operability of testing. And what is more, stakeholders beyond the regional level may preempt testing or cause uprising (MacCallum et al., 2020). So to bridge the gap between performance and compatibility, test sites need to be technically relevant and compatible with the social and physical environment. Adding to this challenge is the dynamic of decision structures that, where sustainability is concerned, span between different branches of expertise (Gehl Sampath, 2019). And where testing and test execution investment is concerned, deciding factors span between ponderable and measurable decisions (Bach et al., 2018; Dirim & Sozer, 2020).

Between decision-makers, information asymmetries may lead to decision-making processes that wrongly favor one aspect over another (Bergh et al., 2019). To date, little research that brings together the technical, ecological, and social dimensions exists. The research gap points to a need to study sustainability-oriented test site decision factors and build a springboard for integrated TD. Thus, the research target is to:

Develop an integrated sustainable decision framework for technology test site selection.

1.2 Test Sites in Mineral Exploration

To approach the research target, technology management and sustainability principles will be applied to sustainable test site selection of the Horizon 2020 project for **I**nnovative **N**on-invasive but **F**ully **AC**ceptable exploration **T**echnologies (INFACT). A project that aims for the development of acceptable test sites that aid a transformation towards inclusive mineral discovery, and exploration. Per the project approach and the characteristics of the mineral exploration industry, the project is understood to serve the purpose of the research target. Considering the project approach, the INFACT project recognizes stakeholder engagement, with technology specialists, mineral, and mining sector professionals, sustainability experts, as well as communities affected by test sites and wider society as a key element of technological success. (Grant agreement ID: 776487, 2017)

Characteristics of mineral exploration are representative of current and future challenges of macro-level sustainability[1] as the industry (I) employs its technologies in natural end-settings, (II) has seen rising political and social pressure to reduce impact, and (III) has encountered an increase in the development of highly innovative technologies (Jürgens et al., 2020). In addition, mineral exploration test sites have the potential to recognize transferability possibilities of the developed framework when technological and non-technological challenge similarity is involved for distinguishing transferability (Jürgens et al., 2020; Ridder et al., 2018). Hence, mineral-exploration-centered concepts are expected to be transferable into related industries. This dissertation analyzes transfer technologies in the field of geophysics, such as Full Tensor Magnetic Gradiometry (FTMG) or Airborne Induced Polarization (AIP). Applied to mineral exploration as an industry, sustainable test sites would enable advanced sensor development and demonstration with limited interference with the social and ecological environment.

1.3 Research Approach

Concepts to realize advanced and sustainable decision-making require sound measurement procedures, cost-effective decision execution processes, and replicable approaches that enable operational tracking of the decisions made. To develop a technically thorough concept, the dissertation (I) analyzes technical test site requirements, (II) explores the dimensions of ecological sustainability through ecosystem goods and services for disturbance assessments, (III) considers social sustainability by evaluating stakeholder macro-level decision factors and communication strategies, and (IV) reviews structural decision approaches.

The outcomes of the research are (I) a structural decision-making approach, (II) a process model that identifies the most effective and efficient way to make sustainable test site decisions, and (III) a content model, which is a factor-based account of the relevant decision factors for technical, ecological, and social test site perspectives.

[1] Macro-level sustainability focuses on the link between novel technologies, and the social, economic, and physical environment at the community, national, regional or international level, Gouvea et al. (2018).

As resource-effective location decision methods remain scarce in technology management, the dissertation includes perspectives from economic, ecological, and social sciences. As a result, the thesis is the first to explore how to utilize economic decision models for STD in natural environments. Furthermore, it is among the first to analyze different stakeholder needs for test site development. Previous work focused primarily on one decision factor concerned with testing, thus favoring one aspect over another. Understanding the connections could support the communication between technical experts and potentially non-technical decision-makers. To further improve sustainable TD, this approach can be leveraged in academic research, in particular for elaboration on interfaces between different disciplines and hierarchy levels.

1.4 Thesis Structure

The structure of the thesis encompasses eight chapters. After the introduction, chapter two examines the existing literature. Chapter three plans, specifies, generates, and analyzes the sustainability-oriented test site decision framework (STSDF). Chapter four presents the design and the results of the quantitative and qualitative research methods used to collect data for the STSDF. Chapter five presents the final STSDF. The sixth chapter is concerned with the STSDF validation for mineral exploration and the transferability of the STSDF to investigate its generalization. Finally, the thesis closes with a discussion of the results and an analysis of research contribution and output in chapters seven and eight. Figure 1 displays the topics covered for each chapter, excluding the introduction. For readability reasons, chapter and sub-chapter titles displayed in the figure are abbreviated / synthesized. As per the figure, TEC-SOC-ECO stands for technological, social, and ecological.

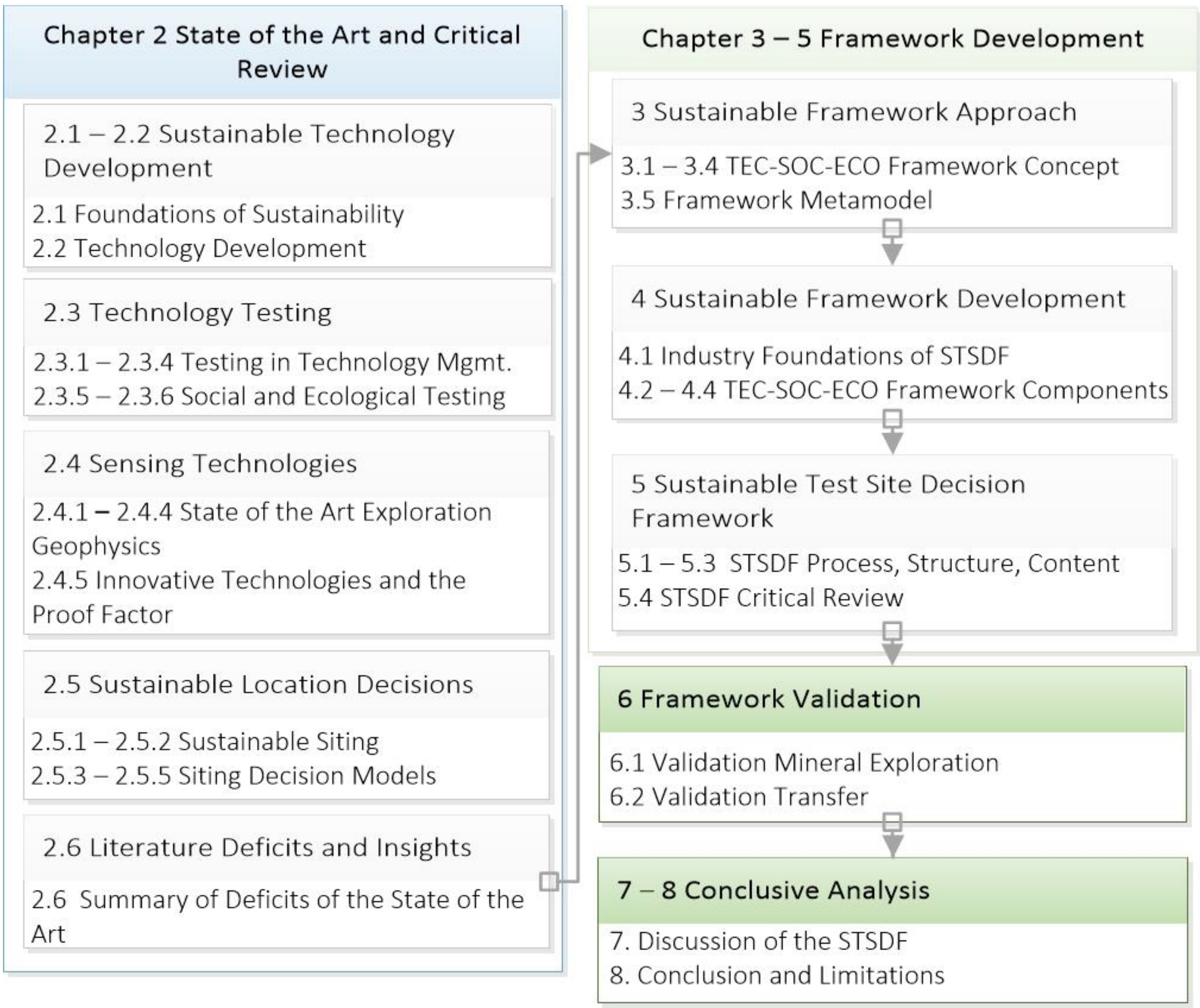


Figure 1 Structure of the Dissertation

Throughout the dissertation, the core contribution lies in building the connection between the known aspects of TD, its relation to testing geophysical methods in the natural world environment, and the application under technological, ecological, and social aspects. The aim is to draw on the requirements by each of these fields to develop a framework that gives a comprehensive view of test site areas.

2 State of the Art and Critical Review

Chapter two deals with the concept of sustainability as it applies to the research question, the definition of TD, and the principles of testing technical solutions. Furthermore, the chapter introduces the state of research and state of practice in sustainable sensing technologies. The chapter continues with location decision procedures, sustainable test site decision concepts, and theoretical decision procedures thereof. Figure 2 illustrates the items discussed in the chapter.

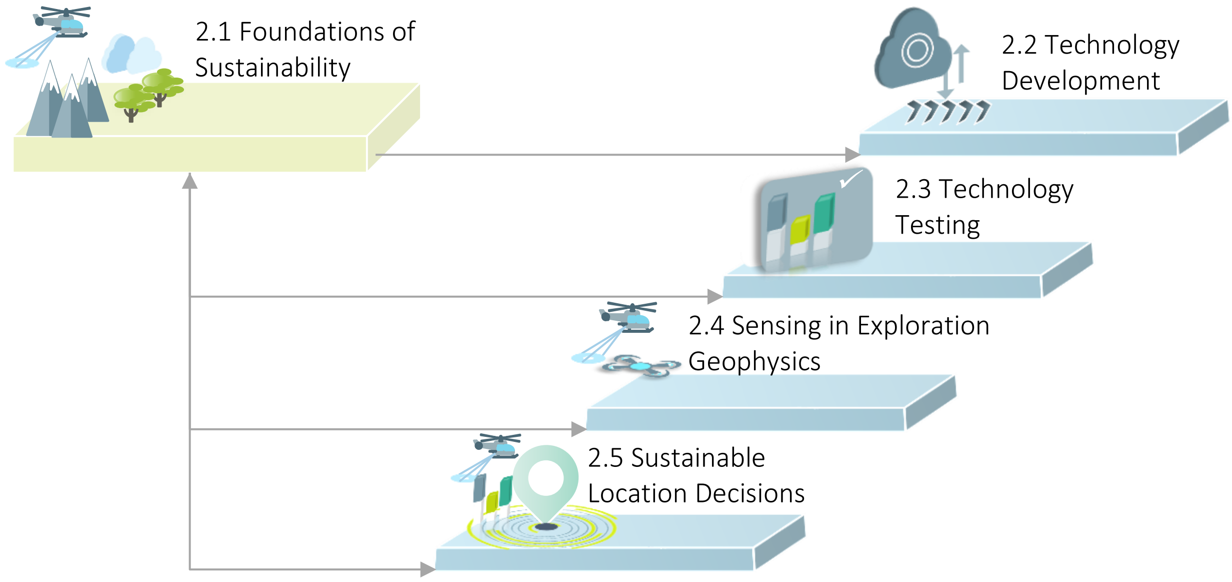


Figure 2 Schematic Relation between the Objects of the State of the Art and Critical Review

The chapter closes with a discussion of the implications of the state of the art.

2.1 Foundations of Sustainability

In "Our Common Future", the World Commission coins sustainability as the one that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, 1997, p. 16). Corporate, political, and scientific bodies attempt to implement future-oriented sustainability definitions (e.g., Sustainable Development Goals of the United Nations) (United Nations, 2015). And while there is an understanding of the perspective of sustainability, no final definition is agreed upon. Among the existing definitions, the most adopted terms see sustainable development as integrating economic activity with ecological integrity, including anthropogenic concerns, and an effective / transparent governance system (Biloslavo et al., 2018; Eigner et al., 2013; Gbededo et al., 2018). Per this definition, sustainability includes economic, ecological, and social perspectives (econ-eco-soc), each defined in the following.

Lorek and Spangenberg (2014) define economic sustainability as the economic welfare attained from externalized ecological and social costs of doing business. Less outcome-oriented definitions stem from Doane and MacGillivray (2001), who argue that economic sustainability is the process of securing long-term business value without jeopardizing future generations' welfare. Along the same vein, Common and Perrings (1992, p. 7) argue "that the allocation of economic resources should not result in the instability of the economy / environment system as a whole."

Ecological sustainability and economic sustainability are inherently intertwined. Ecological concerns occur at spatial, temporal, and convolution levels – far from what individuals can recognize, let alone tackle (Salafsky, 2010). According to Fath (2015) and Borland and Lindgreen (2013), ecological sustainability is bound to the producer / consumer loop and limited by the constraints of the physical world.

Authors such as Porritt (2007) extend the sustainable view by adding maintenance and restoration as a principle to ensure the biophysical capacity required for the long-term future. Ecological sustainability is therefore the conservation and restoration of the physical environment.

Social sustainability is the least understood sustainability perspective (Eizenberg & Jabareen, 2017). Scholars identify three reasons: (I) indicators associated with social sustainability are not fully described, (II) correlation among social sustainability indicators is often subjective, (III) the interconnectedness between indicators and the scope of social sustainability creates a fuzzy front (Yunna Wu et al., 2017). Sustainability science often addresses two distinct functions of social sustainability, namely contextual and procedural sustainability. Suopajärvi et al. (2016) define contextual social sustainability as the normative function of social coherence. The contextual social sustainability includes the creation of social capital, preservation of socio-cultural characteristics (Vallance et al., 2011), valued and protected local cultures (Jensen et al., 2011), as well as quality of life (Littig & Griessler, 2005). Procedural social sustainability refers to political participation, participatory processes, equity, justice, inclusion, access, and a sense of shared ownership (Boström et al., 2015). Vital in adopting a holistic approach and understanding the dynamic interactions between nature and society is an understanding of vulnerabilities and resilience of complex social-technical systems (Ruiz-Ben, 2020). However, Boström et al. (2015) argue that perception of social sustainability differs depending on the context. The authors suggest that expectations and needs, rather than tangible impacts, influence the perception of future welfare (Suopajärvi et al., 2016). Trust in public regulations, media coverage, and corporate social sustainability of individual companies govern the perception of expected impacts. Related publications, such as Naderpajouh et al. (2014) find that sentiment, credibility, transparency, and amount of information, shape a projects' social sustainability.

2.1.1 Effects of Technology on the Integrated Sustainability Triangle

The connection between technology, social, ecological, and economic sustainability is often referred to as the integrative sustainable triangle (Barile et al., 2017). Several authors argue that TD can turn existing situations into preferable states (A. P. Davis, 2005; Hall et al., 2019). The individual characteristics and instances of preferred situations include technologies providing the means for resource procurement, the transformation of resources, and their applicability for socio-economic systems (J. Wang et al., 2018).

Throughout the TD process, the sustainable impact of technology advancements depends on end-user behavior (Klotz et al., 2018). Ehrlich and Kennedy (2005) introduce a simplified equation[2] to describe the relationship between end-user behavior and technology specification. However, Chrysoulakis et al. (2015) and Sadeh et al. (2021) argue that impact is a relative measure and follow the impact description of Cabezas et al. (2004). Per Cabezas et al. (2004) the total sustainability improvement is the sum of the improvements in dependence on the degree of usage. Figure 3 displays the usage-dependent perspective, where the composition arrow depicts the dependency between impact, adoption, and usage.

Sustainability research must identify and link measures of ecosystem functioning to reinforce the persistence of the structures and operation of economic, social, and ecological components (Cabezas et al., 2004). Only then can coordination and advancement of TD for sustainable systems become possible. The following section outlines existing theories that aim to describe sustainable linkages.

[2] The authors state that the sustainability impact (I) is the product of the technological specification (T), the adoption (A), and the usage (U) of a technology ($I = A * U * T$).

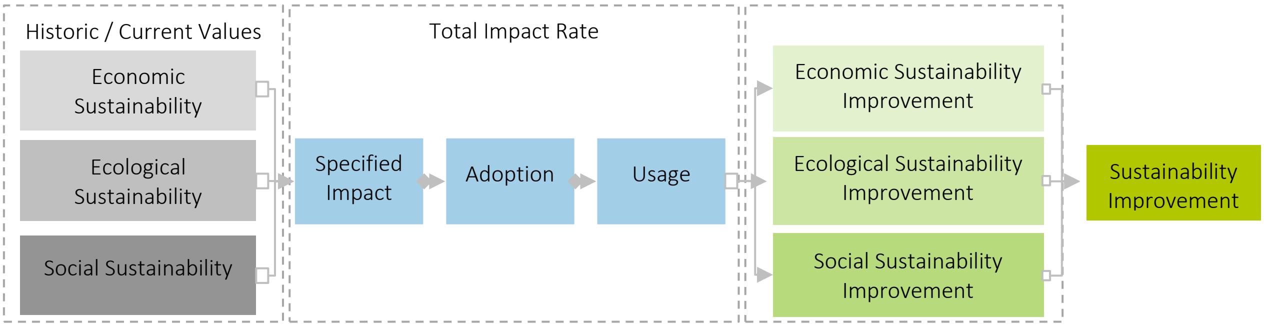


Figure 3 Moderators of Social, Ecological, and Economic Factors
Source Own Representation

2.1.2 Sustainability Technology Theories

Among others, the promotion and governance of sustainable technologies and their consumption receives attention from political (Kergroach et al., 2018) and social-science research (Avelino et al., 2016). Several authors frame and assess the dynamics between technology, society- and ecology- and economics (Andersen & Wicken, 2021; Yun & Liu, 2019). The studies vary by their (I) technological focus, (II) the variables, and (III) the context supporting the consideration baseline. Table 1 illustrates several papers and theories that advance the discourse for socio-technical, technical-economic, and technical-ecological strategies. The column title scope indicates whether the authors considered technical (TEC), social (SOC), ecological (ECO), and / or economic (ECON) dimensions. The abbreviations are not continuous but applied for readability.

Table 1 Sustainability Theories and Concepts

Standard	Description	Scope	Origin
Sustainability sciences	The authors demand for sustainability science to (I) start a scientific discussion about appropriate methods and requirements. (II) Put sustainability on the political agenda. (III) Focus on the interactions between technology, nature, and society to promote social learning, and navigate sustainability. (Kates et al., 2001)	TEC ECON SOC ECO	Science
Ecological modernization	Ecological modernization is an analytical approach that analyzes the economic benefits of environmentalism. The basic assumption is that enlightened self-interest together with ecological and economic growth can benefit industrial development. (Mol, 2000)	ECON SOC ECO	ECON
Voluntary Self-Disclosure	The mechanism of voluntary self-disclosure publicizes initiatives for sustainable development (Lindgreen & Swaen, 2010). Voluntary self-disclosure plays a central role for many sustainability mechanisms for companies' disclosure (e.g., Corporate Social Responsibility (CSR); voluntary disclosure), or entire industries (e.g., Model Mining Development Agreement; Natural Resource Charter). (Mudd, 2010)	TEC ECON SOC ECO	Industry
Green management	At the core of the green management paradigm is the idea that companies allocate and improve ecological performance through flexible (substitutive, extractive, symbiosis etc.) and discounted resource management. (Rugman & Verbeke, 1998)	TEC ECON SOC ECO	Company
Industrial ecology	Industrial ecological researches material and energy streams in systems. It views the economy from a network perspective wherein the earth is the input and commodities are the output factor. The quantification of flows is driven by the assessment of ecological impacts and antecedents of industrial activities. (Ehrenfeld, 2004)	TEC ECO	Industry
Eco-innovation	Eco-innovation illustrates the shift from linear to circular products, consumption processes and sustainable system innovation. (Kemp, 2010)	TEC ECON SOC ECO	Product/ Service Systems

Table 1 indicates that usage, industry image, and operations, including complementary technologies, shape the perception of sustainability. Arguably, challenges of STD are coupled with and enforced by path-dependencies and lock-in effects (Åhman & Nilsson, 2008; Safarzyńska & van den Bergh, 2010). That is why the perception of sustainability in socio-technical, technical-economic, and technical-ecological systems changes incrementally and is context-dependent (McKenna, 2020).

To this point, sustainability is mostly discussed as a feature of single system components (Fath, 2015). The question of how to enhance the entire system remains challenging. And while there is a plentitude of scholarly work on the systems perspective of the integrative sustainability triangle, little practical approach seems to exist. Research results often see differences in simulated and real-world measurement (Tsai et al., 2021), thus challenging the specification, adoption, and usage of technological advancements (Truffer et al., 2008). TD may add to this challenge and is recognized as a reinforcing factor. It can unlock new capabilities and counteract obstacles faced with sustainability in what has been termed the Anthropocene – the era shaped by mankind (National Geographic; Sotoudeh, 2005).

2.2 Technology Development

The following lays out the basic terminology of TD and its features. The sub-chapter lays the theoretical foundation of the thesis. Figure 4 illustrates the structure of 2.2. The aim of 2.2 is to depict influencing factors, impacts, and challenges of sustainability on TD.

Figure 4 Chapter Structure of Technology Development

2.2.1 Classification Concerning Technologies

Especially when different fields interact (e.g., sustainability management), precise wording can minimize inaccuracies. Schöggl et al. (2017) or Arnette et al. (2014) argue that while a specification that uses temporal logic may be helpful, indecisive definitions confuse interactions. Minimizing indecisiveness, Table 2 defines technologies, techniques, and systems aligned to the thesis.

Table 2 Definitory Outlines of Technology, Technique, and System

Notion	Previous Definitions
Technology	Per Verein Deutscher Ingenieure (VDI) 3459, technology "is the intangible application of particular methods, principles or laws of nature, singly or in combination, to achieve particular effects, as well as the study of technical methods and procedures used and applicable in technology without the use of the means themselves". Depending on the objective of the scholarly outlines, the scope of the definition varies. In engineering, several authors define technologies as the sum of activities and processes employed to produce goods and services or achieve intended effects (e.g., scientific investigations) (Bullinger, 1994; Gochermann, 2020). By contrast to the German speaking literature, Maskus (2004) applies an output-oriented definition. The author focuses on the market perspective and defines technology as the transformation of specialized knowledge into practical purpose. As this study sets out to analyze technology tests and demonstrations in natural environments, technology relates to the purpose of its end-setting.
Technique	VDI provides two definitions for techniques. VDI 6226 defines techniques as the way of creating and using artefacts through knowledge and skills. VDI 3459 specifies techniques as the application of specific means and principles of nature, to accomplishing a desired aim or performing a development activity. By contrast, English-speaking scholars, Groen and Walsh (2013), understand a technique to be a physical modality employed to transform inputs into output. Summing up these definitions, the present work understands techniques to be a specific application of technologies. So only when it is applied in a specific context does a technology become a technique.

Table continues on the next page

Table 2 continued

System	Definitions of systems abound, but no standardized definition is adhered to across the disciplines covered in this dissertation. To define systems, the VDI provides a different viewpoint. Most recent is the systems definition of the VDI 2206. Derived from the systems engineering perspective, the guideline understands systems as cross-disciplinary, interrelated, technical constructs. Other VDI definitions stem from creativity management and simulation (VDI 4003; VDI 4521) or construction (VDI 3633). Disciplinary distinctions might be outdated in forthcoming work as system lines often blur for sustainable systems. Unclear structural dependencies between system impact, system environment, and system behavior across the structural dependencies are but one result (Schlör et al., 2015). The present study acknowledges that systems may be society, ecological, economic or technology-related. Consequently, a system is a group of interacting, interrelated entities that form a unified whole.

This sub-chapter cautioned precise notation and introduced terminology for the pages to follow. Next, the thesis discusses the development and marketability of technologies, techniques, and systems.

2.2.2 Definition of Technology Development

Definitions of TD vary by (I) scope, (II) process design, and (III) system orientation. Table 3 discusses the state of the art in TD.

Table 3 Definitory Outlines of Technology Development

No.	Description
Scope	Various authors discussed and shaped TD (Aristodemou et al., 2019; Klappert et al., 2011; Schimpf et al., 2016). The broadest definition considers all task-oriented processes that serve to explore and exploit knowledge (Klappert et al., 2011). The objective of the research affects the scope of the definition. While some authors focus on research and development, they hardly incorporate the product perspective (Aristodemou et al., 2019; Nobelius, 2002). The literature shows that innovation-centered or test and quality-centered studies tend to include the prototyping and commercialization phases (Rodgers et al., 2021).
Process structure	Though definitions come in varieties, most start with an idea and end with a technology, as a result. Among others, information technology profoundly changed the linear view of the development process (Masior et al., 2020). Furthermore, rearranged development models create value by facilitating interactions between external and internal development steps. Thus, the emphasis shifted from dictating processes to development governance (Graessler & Hentze, 2020).
System orientation	More recent literature reports that TD is system-oriented (Masior et al., 2020). Following a logical sequence of tasks, systems engineering is a structured multidisciplinary approach (Graessler & Hentze, 2020). Systems engineering aims for a cross-disciplinary optimum (VDI 2206). Per Graessler (2015), model orientation and virtual development support interlinking disciplines. According to Kaiser et al. (2017, p. 682), employing virtual development methods optimizes "productivity, flexibility, and innovativeness during the development phase."

Given the focus of the dissertation, the thesis considers (I) the scope from requirement definition to commercialization, (II) adopting an iterative development process for (III) technologies. Hence the thesis understands TD as the iterative modelling and analysis of interrelated elements, with continuous requirements, technology development, verification[3], and validation[4] (V&V).

2.2.3 Sustainable Technology Development

STD refers to achieving sustainability "through science and technology" (Anastas & Zimmerman, 2003, p. 96). Sustainability sciences represent a fundamental change in how development push and pull factors dictate the minimization of negatives associated with technologies (Sethi et al., 2018). Information, knowledge, and perceptions concerning social, ecological, and economic problems and solutions build the foundation of STD (Weaver, 2017). The main STD tasks include (I) defining and

[3] Evidence of the truth of statements (VDI 2221).

[4] "Check as to whether the test results really show what is to be determined by the test" (VDI 2221).

ranking sustainability objectives, (II) generating sustainability requirements and identifying sensitivities between the sustainability triangle, (III) validation of sustainability performance against the objectives and requirements, and (IV) creating a verification strategy (Ahmad et al., 2018).

However, sustainability in TD is not limited to transitions to new technologies. Adaptability of technical systems, societal adoption, and usage are necessary (Sethi et al., 2018). Hence, sustainable developments build on the TD specifications (see 2.2.3.1) and the conformity of technologies with the context they are set out to operate in (see 2.2.3.2).

2.2.3.1 Technology-Centered Sustainability Specifications

Addressing sustainability in TD is an exhaustive branch of science. Scholarly work follows three lines of STD. Namely, (I) principles of sustainability enhancement, (II) sustainable assessment methods, and (III) sustainability development methods and tools.

Principles of sustainability enhancement: Principles to enhance technologies emerge on different levels in the physical and economic environment (Weaver, 2017). Initially tracing back to 1995, the main STD enhancement principles are four-fold (Hanssen, 1995) and relate to: (I) the substitution of system parts (components, subassemblies etc.) (Ringen & Welo, 2021), (II) the enhancement of the interaction between system units (Saputri & Lee, 2020), (III) reformulating requirements beyond existing systems (Watz & Hallstedt, 2020) and performance improvement, concerning user requirements (Saputri & Lee, 2020), and (IV) reduction or addition (D'Amato et al., 2017).

Figure 5 illustrates these principles.

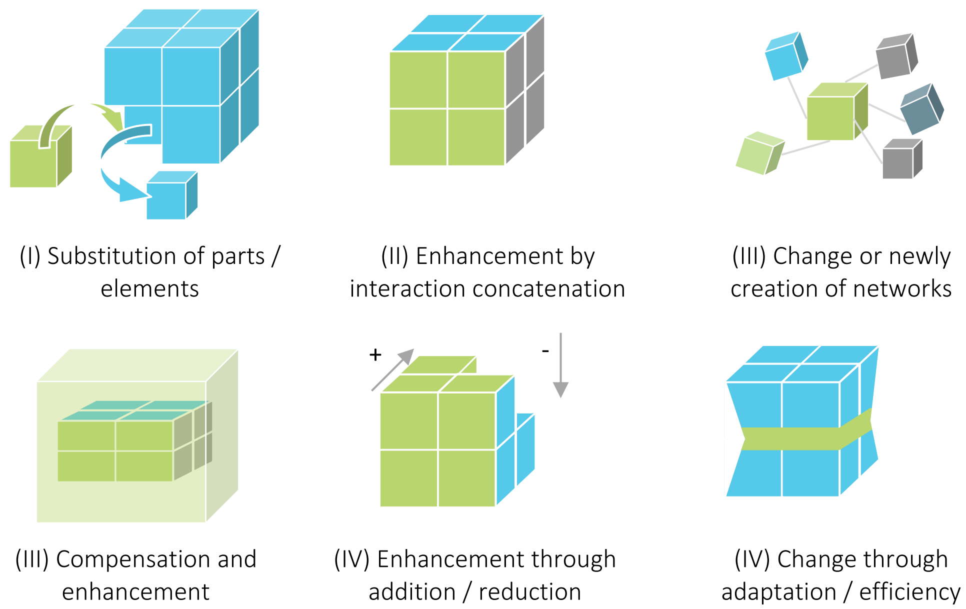


Figure 5 Principles of Sustainable Technology Development
Source Own Representation aligned to Kornwachs (2018)

Despite the broad and non-engineering-focused illustration, the STD principles of Figure 5 trace back to engineering research (see section above), thus justifying its representation. Scholars suspect a hierarchy within the four sustainability enhancement principles (Ahmad et al., 2018). To date, no definite ranking has been found. In addition, principles hardly occur within the same research paper.

From the literature, it occurs that balancing requirements, architectures, functions, and designs can improve sustainability (P. Zhang et al., 2021). The theoretical perspective mostly misses the discussion on how to integrate conflicting objectives. Also, the macro-level perspective mostly lacks.

Sustainability assessment methods: At best, sustainability performance measurements (I) focus on accurate indicators, (II) represent at least one angle of the sustainable triangle, (III) consider the life cycle, and (IV) allow flexibility to integrate missing data (Ahmad et al., 2018). Scholars critique the overarching focus on one-dimensional methods and question the usage of historical databases to assess novel approaches (Bertoni et al., 2020). Measurements must be tracked and fed back into data sets (Al Assadi et al., 2021). In addition, connecting measures can increase transparency and deliver current information (Pförtner et al., 2016). Sub-chapter 2.3.6 provides a detailed account of sustainability assessment methods.

STD methods and tools target the management, modelling, and simulation of technologies. Studies suggest eco-design tools (e.g., Design for Environment Guidelines, The Ten Golden Rules, etc.) (Maccioni et al., 2021) or focused eco-guidelines (e.g., Design for Assembly) to improve sustainability performances (Russo et al., 2015). Prerequisites of sustainable methods include data availability, capability management, integrating workflow, modular design of product and service development, and collaborative design models (Bertoni et al., 2020). Given the complexity of integrating social, ecological, and economic considerations into developments, computerized tools for modelling, analysis, and visualization of engineering problems spur (St Flour & Bokhoree, 2021). Critics argue that current methods often fail to account for the balance between tangible and intangible values (Tukker, 2015), as well as quantitative and qualitative tools (van Schoubroeck et al., 2021).

Critical review of the literature shows that questions on which to consider scope (e.g., production sustainability; business models) in methods and tools now and in the future are not fully answered.

2.2.3.2 Operability of Sustainable Developments

Interaction between STD and end-setting is subject to sustainability improvement (Gasde et al., 2020). Scholars observe that technical equipment can cause direct and indirect sustainable impacts (Foley et al., 2017). Most accounted for direct impacts include ecological impacts (e.g., through air pollution or noise pollution) and societal impact (e.g., air pollution and noise pollution) (Cecchin et al., 2020). Indirect impacts may arise later or at a different spatial, temporal, or geographical instances (Almeida et al., 2021).

According to Andersson et al. (2021), indirect or perceived impacts often outweigh direct, measurable impacts of activities (Andersson et al., 2021). Therefore "(e)mbedded entropy and complexity must be viewed as an investment when making design choices on recycling, reuse, or beneficial disposition." (Anastas & Zimmerman, 2003, 23).

Considering sustainability early in the TD process can lower the change effort or market risk (Schöggl et al., 2017). From the perspective of STD, comprehensive technology assessment becomes crucial to creating and sustaining society / nature relations (Ajjabou et al., 2019; Pichler et al., 2017).

Sustainability awareness has accelerated but has not come to a conclusion or milestone. For example, standards for sustainability reporting (e.g., Global Reporting Initiatives; International Organization for Standardization (ISO) 1400 family) are mostly company-centered (Ikram et al., 2021) – TD standards lack.

Moreover, the dynamic nature of the operations (different areas of application, various forms of use) requires context and environment-dependent development and evaluation procedures (Pichler et al., 2017). The outlines may lead to the conclusion that despite the wide scholarly coverage, STD remains rather unspecified. Reasons may include the interaction of different disciplines (social, ecological, economic, technical sciences) that work with varying concepts of value, wording, and evaluation methods.

2.3 Technology Testing

Sub-chapter 2.3 is composed of (I) the foundation of technology testing, (II) maturity models, (III) virtual testing, (IV) physical testing, and (V) social and (IV) ecological testing. Figure 6 illustrates the structure of sub-chapter 2.3. This review supports the development of a technology-centered STSDF.

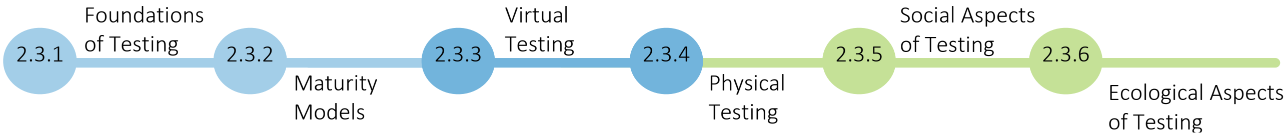


Figure 6 Chapter Structure, Technology Testing

2.3.1 Foundations of Testing

Tests are critical for deploying technologies (Czichos, 2018; Gühmann et al., 2016). Testing refers to the "ascertainment of the extent to which the item being examined fulfils a requirement" (VDI / VDE 2645). Testing aims to make decisions concerning the development, utilization, or exploitation of technologies (Bahill & Henderson, 2005; Belt et al., 2008). Often, fixed procedures "determine one or more characteristics of a product, process or service" (VDI 4220). Defining one or more reference characteristics (VDI 2710; VDI 4220) and assessing causes and effects of system behavior build the basis of such procedures (Malkowsky, 2019).

Neurohr et al. (2020) exemplary describes the testing procedure through three steps. (I) The test derivation defines the requirements of testing. (II) Subsequent test execution uses an appropriate testing method, e.g., virtually, physically or in a combination. (III) Test evaluation then assesses the requirements in comparison to the test data. Finally, the technical and economic criteria (e.g., cost-ing), and increased ecological, social, legislative, and political criteria suitability of technologies are defined (Kurnianingtyas et al., 2020). The results of the test procedure are used for performance statements. Figure 7 depicts the described testing process.

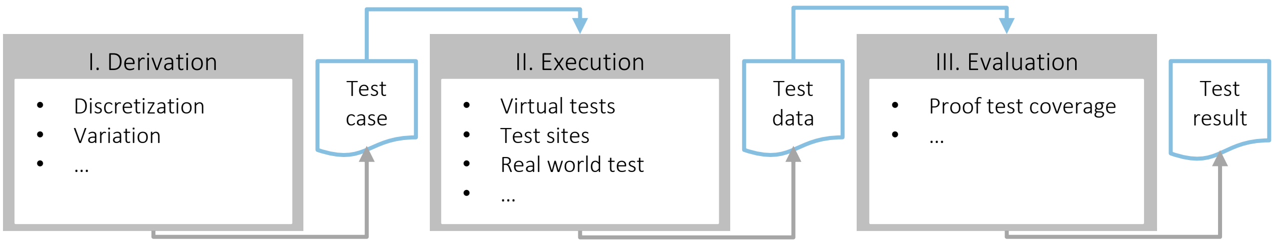


Figure 7 Simplified Testing Framework
Source Own Representation aligned to Neurohr et al. (2020)

Comparisons and references may have a micro-level and macro-level assessment function (Jobin et al., 2020). While satisfying the constraints imposed by technical and physical limitations (Acosta & Falcone, 2021), the macro-level assessment may refer to the confirmation of feasibility by providing impartial evidence that the requirements for an planned use close to an end-settings have been met (e.g., audits) (Jobin et al., 2020).

Macro-level testing may introduce uncertainty into test results. Occluded objects and single events are named as reasons (Neurohr et al., 2021). To overcome, related risks physical testing is applied, which compared to virtual tests and depending on the perspective is more resource intense (Böde et al., 2018). Past years have given rise to unprecedented growth in the system's complexity and thus testing (Collier et al., 2018). Combined with resource restrictions, such expansion requires accurate splitting of virtual and physical tests (Böde et al., 2018). Two aspects are subject to discussion in the following.

2.3.2 Maturity Models as Tools in Assessing Test Timing

Assessment methods exist to monitor and codify performance at different intermediate or transitional development stages. Existing methods include the functional analysis (Malkowsky, 2019), technology portfolio analysis (Peter et al., 2019), and the utility analysis (Behdad & Thurston, 2011). The methods introduce different stages of analysis and vary by application context.[5]

Testing methods and measures depend on the maturity, the technical specifications as well as the testing mission (Tahera, 2014). "Maturity"[6] helps to differentiate between different stages during the TD (Inków, 2019; Pschybilla et al., 2019). Maturity models exist to assess maturity in different contexts. For each maturity stage, maturity models describe the typical activities a company performs. By codifying the activities, best practice scenarios can be derived (Fraser et al., 2002). Existing scenarios include quality management (Agrawal, 2020; Crosby, 1979; Sabtiana et al., 2018), software development (Hidayati et al., 2018; Paulk, 2009), innovation, collaboration (Cukier & Kon, 2018), digitalization (Weber et al., 2017), as well as the effectiveness of research and development (R&D) (Berg et al., 2002), product development (Schuh et al., 2017; Sinnwell et al., 2019), product reliability (Helgesson et al., 2012), design of product-service systems (Exner et al., 2017), and sustainability in new product development (Hynds et al., 2014).

The most prominent instruments identified for this research objective are the technology S-curve, the V-model, the Technology Readiness Level (TRL), and Capability Maturity Model Integration (CMMI). The S-curve graphically illustrates the performance potential of a technology as a function of the R&D expenditures and the technology life cycle representation (Christensen, 1992). Iteratively modelling and analyzing developments increase the maturity in the V-model (Graessler, 2015). Traditionally, the V-model does not count as a maturity model. Literature yet highlights its maturity-enhancing capabilities and classifies it as a maturity-supported development model (Petrasch et al., 2008). TRL describes the testing behavior of companies alongside nine readiness levels (Mankins, 2009). CMMI supports the maturity-oriented development of products and services (Chaudhary & Chopra, 2016). Scholars argue for the role of CMMI in quality assurance (Liberato et al., 2017). Appendix 1 provides a critical discussion of the instruments.

In an effort to cut innovation risk, companies increasingly combine technology management methods such as agile development, lean startup, and user-centered design with the illustrated maturity models (Zorzetti et al., 2021). In 2021, Zorzetti et al. reviewed the maturity model literature. The authors challenge the widely held view that specific contexts require ever more adaptations to existing models. If the authors are right, the novel approaches are premature and existing maturity models remain relevant (Zorzetti et al., 2021).

Following the presented studies, it is evident that TD links to the test program. It emerges that (I) testing is an iterative process, (II) technology maturity hints at the degree of innovativeness of a product (see S-curve), (III) marketability and technology maturity are intertwined, (IV) depending on the readiness phase and industry in question testing behavior varies (see TRL 7), and (V) maturity assessments can hint at the quality of processes and be implemented in commercial products. For the present work, these insights indicate that market and technological perspectives are critical to the scope of testing and the occupancy of public test areas. The following sub-chapter introduces the structure and functions of testing behavior.

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[5] The thesis recognizes that testing and assessment are distinct. Given the focus of this thesis assessment, methods such as quality function deployment, value engineering, strategic planning, and investment calculus will not be paid any further attention.

[6] Quality level of capability on an ordinal scale (VDI 5702).

2.3.3 Virtual Testing

As per the World Quality Report 2019-2020, the average percentage of test case automation has increased from 28% to 45% (Natarajan & Sinha, 2021). The respective literature reports on three critical drivers for test program automation: (I) increased speed and frequency of release cycles and reduced market entry timeframes, (II) a need for fast, cost-effective, first-time-right testing in an increasingly complex ecosystem, and (III) increased requirements regarding traceability, responsiveness, and compliance, with real-time analytics dashboards (Nass et al., 2021).

In recent years, various authors argued for the benefits of virtual tests[7] (Nass et al., 2021; Tahera et al., 2019). Authors suggested that digitized engineering increases the confidence and effectiveness of handling complex products and systems and enhances the problem-solving capacity (Gorskii et al., 2020). Various authors extended this view by demonstrating how digital representations within the development process support traceability (Nass et al., 2021; Stavesand et al., 2017) and aid in closing loops (Y. Chen et al., 2018) in the product usage.

Tools such as computer-aided engineering, software for physics modelling, or design exploration software support the successful combination of mechatronic systems (Alaei et al., 2019). Beyond the TD perspective, such systems also cover procurement, assembly, and end-of-life stages (Mandić & Ćosić, 2011). Authors such as Lemu (2014) divide the scope of respective tools into (I) virtual systems employed for development, and (II) virtual products used to simulate a product in a virtual (constructed world), and (III) exchange product or design data (Assad et al., 2021).

Within the virtual space, the performance and behavior of technologies can be manipulated and studied (Ng et al., 2008). Lemu (2014) argues that the tools applied in virtual testing enable experimentation and virtual prototyping with system and product models. Associated benefits include the reduction of development times (Stavesand et al., 2017), decision support for engineering, and the management of sensitivities (Sivertsen & Haugen, 2018).

From a TD perspective, virtual testing can back the verification of requirements between virtual products and systems (see V-model), enable the validation of the virtual product before the physical implementation, and support problem solving (Seider, 2013).

Virtual testing is not isolated from the physical world (Filip et al., 2021). The virtual model may integrate, simulate or reproduce field failures in small scale environments (Nybacka, 2010). Continuous problem solving and issue resolution accompanies the virtual testing process. As a result, virtual models realize the reduction of costly offline tests, reproduction of testing outputs, and increasing the response time (Böde et al., 2018).

In addition, data reduction from offline tests can increase the understanding of the behavior of single parts and elements (Mrosik, 2018). Virtual test outcomes may facilitate communication and demonstration of behavior between different disciplines and across locations compared with solely physical tests (Scurati et al., 2021). The demonstration is especially relevant for highly complex projects where poor communication distorts engineering skills and customer experience. Here, visualization of capabilities may add to increased outcome accuracy (Degen et al., 2021).

Several authors bring up limitations of virtual testing. C. G. Lee and Park (2014) suggest that digitally transforming the development process to enable virtual testing is a complex endeavor because of its demand for cooperation between different engineering and computer-aided systems.

[7] The thesis recognizes that "virtual" easily links to "simulation". Both notions are hardly interchangeable. For discussion of the differences, see Bonetti et al. (2021).

Nybacka et al. (2014) state that virtual systems rely on interpreting measurements, often leading to normalized results. Developing virtual environments that accurately represent natural conditions and increasing social and ecological requirements may consequently be flawed. Authors such as Yang et al. (2011) add to the explanation and state that flaws occur because of the complexity of natural environments, as well as the limited quantifiability of social and ecological requirements (Iwanaga et al., 2021). Reasons include the availability of data (Scholtes et al., 2021), and the measurability of unprecedented impact human interaction (e.g., human pilots or drivers) (Neurohr et al., 2020), or the unique impact of technical and occluded socio-ecological dynamics (Neurohr et al., 2021). As a consequence, it can be argued that physical tests remain relevant despite virtual advances. What follows is an account of physical tests with a focus on field tests.

2.3.4 Physical Tests

Depending on the customer segment in question, physical tests have different purposes. Ballon et al. (2005, p. 2)[8] distinguish six types of physical test platforms: "(I) prototyping platforms (including usability labs, software development environments), (II) testbeds, (III) field trials, (IV) living labs, (V) market pilots, and (VI) societal pilots."

I. Per Ballon et al. (2005), a physical prototyping platform is a development space employed for mass-produced goods. It has the objective to establish the first proof of concept of a new technology, product, or service.
II. Testbeds are controlled environments (e.g., laboratories). According to Ballon et al. (2005), testbeds do not aim for full exposure to end-setting conditions but host tests in a protected environment.
III. Field trials are tests in a restricted, but natural environment (Ballon et al., 2005).
IV. Living labs are experimentation environments especially targeting business-to-consumer markets and strive for the integration and validation of products and services in real-life contexts (Ballon & Schuurman, 2015). An increasing number of literature reports explore the value of living labs to information and communication technology (Eriksson et al., 2006; Følstad, 2008).
V. Finally, both the market pilot and
VI. Societal pilots release a product or service to a limited amount of end-users and either aim to generate data for marketing purposes or the creation of societal innovation (Ballon et al., 2018; Ballon & Schuurman, 2015).

Additional testing grounds introduce the proof of concept centers (Jobin et al., 2020), and Franquesa et al. (2020) report on reference sites dedicated to performance tests. Considering the scope of the two testing grounds, pinning either one concept to the six types of test platform is hardly feasible. Hitherto definitory lines blur, making a definite categorization fraudulent. Indeed, technological advancements and test design form the core of current literature. Technology management is so far to catch up to the outcome-oriented test-citing literature.

2.3.4.1 Foundations of Field Trials

As the thesis focuses on field trials, the following discusses the respective literature in detail. The literature uses field trials, physical tests, and testing in real-life or testing in real-world environments synonymously.

[8] The thesis recognizes the age of the source. Among the reviewed sources it is the most comprehensive and actual, original review of physical test facilities.

In the course of a TD process, scholars propose field trials starting from TRL 5 (Mankins, 2009). Such suggestions, however, differ in accordance with the nature of the test object and its complexity (Emami et al., 2020). Notwithstanding type- and object related variations, field trials analyze different possible situations a system under test may encounter. The analysis determines the degree to which system requirements are fulfilled (Winner et al., 2015). Field trial data enables the validation of a surrogate model of reality (Emami et al., 2020). This model of reality can in turn be utilized for the verification of a system (Böde et al., 2018). Hence, field trials offer developers the opportunity (I) to sample performance data about components, systems, or the endurance of both in end-user settings and (II) optimize their virtual models (Neurohr et al., 2020; Wallmark et al., 2014). In turn, more precise statements about the ruggedness, flexibility, stability, or usability of technology can be made (Böde et al., 2018). So-called test sites provide a physical place of reference where reality can be observed via measurements. Mostly driven by public-private partnerships, test sites validate performance (and generate re-usable models), calibrate instruments, and generate proof of concept (Carini et al., 2019; Shelbourn et al., 2006). Test sites are of particular relevance in industries with high safety standards, high ambiguity of system performance, and complexity (e.g., Emami et al., 2020; Hu et al., 2020). However, while various initiatives for physical tests exist, the scale of literature covering physical test sites and respective reference model descriptions remains modest in relation to the size of the practical application (R. Brown, 2018).

Existing research focuses on the automotive industry (Neurohr et al., 2021), space (Ximenes et al., 2020), military (Joiner et al., 2018), various fields of geophysics (Ajjabou et al., 2019), and utilities (Blavette et al., 2021). Considering the objective of the thesis, the following outlines first depict the scope of field trials, and secondly discuss the characteristics of field trials in geophysics.

2.3.4.2 Field Trial Scope in Geophysics

Execution of field trials varies by the physical or technological principle, and different testing agendas / targets (Foged et al., 2013; Witherly, Irvine, & Godbout, 2004). Identified targets include (I) general performance analysis, (II) calibration, and (III) proof of concept. The following explains the target scope.

General performance tests: Technical system components as well as the entire technical system, should yield robust performance in natural conditions (Starr et al., 2017; Zillmer et al., 2020). Witherly et al., (2004) illustrate, that comparing technologies with different maturity levels can improve subsurface imaging. At the same test area, Witherly and Irvine (2006) found that repetitive benchmarking of new components of a system against the previous system composition enables performance improvements. Armenta et al. (2015) also support the positive relationship between field trials and performance improvement. Hence, performance tests in natural environments are not limited to the purpose of gaining momentum but are a prerequisite for market entry. Until recently, geophysics paid limited attention to the macro-level of test sites. By analyzing social factors of mineral exploration in conjunction with the technical performance of a non-invasive exploration system, Ajjabou et al. (2019) illustrate an approach for introducing sustainability-centered testing. Despite the publication, efforts into macro-level testing remain limited. Reasons may include the often remote application areas and the limited occlusion potential.

Calibration: Regarding measurement technologies and specifically sensors, calibration refers to the process of (I) comparing a measured value with a (II) reference response through forward modeling (Foged et al., 2013). For the reference model the primary parameters must be representative of key variables of the actual measurements. Forward (or data-based) regression of the reference model represents the system behavior and builds the reference response. Regression coefficients can be modelled by confronting reference responses with actual measurements (Sanft & Walter, 2020).

The variance between the reference response and the measured data provides insights on required adjustments to improve the performance (Boyd, 2000; Danielsen et al., 2003). In a strict sense, calibration does not include adjustment activities such as corrections and alterations to reduce potential deviations (Minsley et al., 2012). There are different types of calibration. Regularly, the type of calibration is associated with the physical response of a sensor or system targets. Common calibration types are voltage, physical artefacts (e.g., electromagnetic (EM), gravity), spectral, and thermal calibration. Figure 8 illustrates the process of calibration as proposed by Foged et al. (2013). The process displayed is a reference for EM calibration.

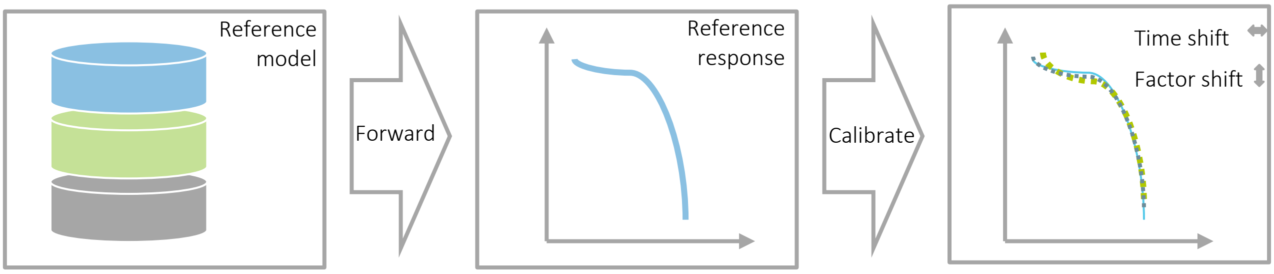


Figure 8 Calibration Process
Source Own representation aligned to Foged et al. (2013)

Proof of concept: Regarding proof of concept, the proof principle is often defined from a performance testing perspective. The proof factor is among the biggest challenge for technology adoption and overall development (Passarelli et al., 2021). High investment and highly uncertain technologies come may come with severe risks (Pilecki, 2017). Developing a robust body of evidence can reduce regulatory, scientific, engineering, investment, and social adoption barriers. Jobin et al. (2020) therefore argue that a proof of concept refers to the available validation of efficacy, impact, or alignment with regulatory standards. Proof of concepts "require an open and evolving infrastructure that allows benchmarked data sets to test and evaluate sensors, improved systems modelling, and analysis by neutral, disinterested parties." (Kirincich et al., 2018, p. 1). This notion is supported by aeronautical sciences, which find that robust benchmarks can reduce the adoption barriers proof of concept require (Rana & Chudoba, 2020).

As a consequence field trials are either employed for performance improvements, or to demonstrate technologies' performance to third parties. Particularly in cases where third parties evaluate the performance, the reliability of the technology increases, and so does visibility and the ability to reach potential customers (Hendry et al., 2010).

Whenever field trials are concerned, critics suggest that the ambiguity of the natural environment (limited control over test parameters) (Pilecki, 2017) and the single point perspective (often measurements are conducted during a limited period only) challenge the explanatory value of field trials (Böde et al., 2018). For calibration, the term field trial might be misleading and is thus omitted from further investigation.

2.3.4.3 Industry Background in Geophysics

Harnessing the potential of innovative technologies in natural sciences is growing (Capello et al., 2021; Chang, 2021). Particularly for substantial investments, accurate knowledge about the performance of technologies is required. Where measurement targets are physically remote (e.g., geology), instruments and installations have a high degree of performance uncertainty (Kirincich et al., 2018). Controllability of the environment (e.g., weather changes) and unclear target signatures add to the challenge and drive uncertainty (Pilecki, 2017). Actions that can reduce the described uncertainty and provide information about the technical performance as close to the designated target environment as possible can add value (McLean et al., 2020).

Authors such as Borisov and Pochukaeva (2017) define the added value as a function of investment risk and efficiency associated with technology gains (see 2.1.1). Ajjabou et al. (2019) suggest that standardized and open validation procedures are required to overcome innovation roadblocks. The authors indicate that a benchmarking procedure to move the state of research into the state of practice is required (Ajjabou et al., 2019).

Similar statements come from Senior et al. (2004). The authors illustrate that comparing technologies with different maturity levels can improve sub-surface imaging (Senior et al., 2004). Armenta et al. (2015) also support the positive relationship between field trials and performance improvement. Hence, performance tests in natural environments are not limited to the purpose of gaining momentum but are a prerequisite for market entry.

Technologies often encounter regulatory requirements with different stakeholders. Requirements include considerations such as risk exposure to the social and physical environment (MacCallum et al., 2020). Sound preliminary data collection and demonstration are imminent requirements (Viezzoli, Roffey, et al., 2018). For comparative technology tests, scholars critique that the industrial value of a field trial is only as relevant as is the timeliness and relevance of the benchmark (Lonjarret et al., 2020).

2.3.4.4 Requirements for Field Trials in Geophysics

Test requirements dictate test site requirements (Hannon et al., 2004). Four common requirement categories exist, namely (I) physical environment, (II) benchmark data (site model), (III) ecological environment, and (IV) social environment. The following outlines these requirements after Hannon et al. (2004).

Physical environments refers to the area where individuals test or calibrate their technologies. Hence, the physical environment is the test target area. Test target areas that are fit, or fit for purpose, are influenced by the industry, the opportunities to cease, and the challenges the system foresees to overcome. For military applications, F. Gomez (2014) introduces target requirements that cover the different climate zones of the earth. In Gomez report, test sites development happens in areas as diverse as the desert and tropical land areas. Measurement-oriented scholars report on test target requirements concerning mineralization (Witherly & Irvine, 2006), wave energy (Atan et al., 2018), or wind speed (Simley et al., 2020). Common to the approaches is that the test target is the foremost requirement named.

Benchmark data (site model) is crucial for evaluating the functionality and performance of a specific technology, "both for application users and developers, and for the database developers themselves" (Ray et al., 2011, p. 1139). The scope and quality of benchmarks vary. Standard measures to assess existing benchmarks are (I) age, (II) scope, and (III) verification status (e.g., official verification by state or experts) (Ajjabou et al., 2019; Nevalainen et al., 2021). (I) Using outdated data challenges the ability to prove enhancements beyond the status quo (Lonjarret et al., 2020). Outperforming the status-quo may also be a negative to regulatory approval, as performance deviations from the data set may generate regulatory hurdles. (II) Concerning the scope of the available benchmark data, F. Gomez (2014) indicates that previous knowledge about the interaction between fields such as biology and geology can help extrapolate data and confirm outperformance within a given scope. Witherly and Irvine (2006) support this notion and argue that the more context the data provides, the better the benchmark. The context is a function of physical and chemical properties included in the benchmark (Dentith & Mudge, 2014). Comprehensive benchmark analysis in geophysics is yet limited. Trade-offs between assessment measures (e.g., age vs. scope), and assessment focus (e.g., deep targets vs. surface targets) are hardly assessed.

Per the ecological environment, Vagiona and Kamilakis (2018) argue that the impact estimation of projects on the natural environment is a critical determinant of sustainability. Similar outlines stem from Senior et al. (2004). In their work, the impact of operations and the reciprocal impact of the environment on control devices may negatively affect externalities (Senior et al., 2004). Hence, ambient environmental test site conditions may affect the robustness of the results. Atan et al. (2018) stress the instability of the environmental conditions to simulate exposure. Viezzoli et al. (2017) illustrate opposing requirements (stability of ecological conditions). Stability of the environment is especially true for sensitive measurement devices, whose performance value differs by condition. The stability of test site conditions and signatures can change by season (Hillers et al., 2015). Changing conditions can impact the effectiveness and accuracy of the performance analysis, calibration, or demonstration (Foged et al., 2013; Melin et al., 2018; Salzmann et al., 2007). This suggests that benchmarks collected during one conditional spectrum may no longer hold for alternating conditions.

Social environment and technology execution are interlinked. Manifestation of the linkage includes (I) the dependency between TD and (local) economic development (Irtyshcheva, 2021), and (II) the dependency between TD and acceptance (Masimba et al., 2019). Hence, for technological advancements to succeed, addressing compatibility with the social environment is critical (Heeks Richard, 2020). Aside from the socio-technical connection, societal challenges often end up at the top of project risks. Grudens-Schuck and Sirajuddin (2019) suggest to resolve associated risks and increase the longevity of test sites stakeholder knowledge and community involvement is suitable (Grudens-Schuck & Sirajuddin, 2019). Availability of information about the stakeholders and the provision of project data for perception formation can minimize associated risks (K. Davis, 2017; Oliveira & Rabechini, 2019), but data is often limited.

Despite the mapped requirements and challenges, little work about establishing effective prioritization of physical and social science research and information sharing efforts exists. The following subchapter details the social and ecological aspects of testing.

2.3.5 Social Aspects of Testing

Most testing measures associate with technical, ecological, and economic performance criteria (MacCallum et al., 2020). To pave the way for transformative approaches, such performance criteria may not suffice. The inclusion of social measures requires macro and micro-level perspectives alike. Measures to assess social sustainability do not necessarily pre-exist but are often subject to future-oriented abstractions (Bender & Rovira, 2021).

For example, the viewshed[9] is a well-recognized topic of social sustainability (N. Ahmed et al., 2019). It refers to the disturbance of the familiar landscape aesthetics. Permanently installed technologies such as wind farms, power lines, pipelines, or even skyscrapers report and analyze visual impacts (Bender & Rovira, 2021). Evidence from the literature suggests the relevance of visual pollution to the acceptance of projects (N. Ahmed et al., 2019). However, the literature also argues that perception of pollution level is context-dependent. Scholars such as Fontes et al. (2018) therefore state that socio-technical dependencies must be assessed prior to judging the impact of technical systems. Socio-technological assessments may guide, structure, clarify, and sometimes legitimize generative abstractions (Fontes et al., 2018). Table 4 displays a set of assessments for socio-technical and socio-economic technology considerations. A comparison of the different assessments reveals that assessments vary by their technological focus, institutional perspective, and scope (both time-wise and actor-related). A review of the methods is provided below the table.

[9] A viewshed is the area that one can see at any time, Fisher (1993).

Table 4 Social Aspects of Testing

Type	Description
Technology acceptance model (TAM)	TAM is a widely applied system to model "usage intentions usage intentions and behavior as a function of perceived usefulness and perceived ease of use." (F. D. Davis & Venkatesh, 1996, p. 19). The scales are applied to predict and draw conclusions about the user acceptance of information technologies.
Unified Theory of Acceptance and Use of Technology (UTAUT)	The UTAUT predicts the behavioral intention of information technology users. The theory originates from organizational contexts. UTAUT empirically proved to explain the variance in technology usage in new contexts, novel user populations, and cultural settings. (Venkatesh & Zhang, 2010)
Multi-level perspective on socio-technical transitions (MPST)	MPST describes and analyzes complex socio-technical sustainability transitions (Geels, 2004). Building on innovation studies, sociology of technology, and institutional theory, the approach explores ontologies of transition behavior to sustainable technologies (Geels, 2002), infra-structures, social practices, institutions, and markets (Geels, 2004).
Social construction of technology (SCOT)	SCOT advocates that anthropogenic activities shape technology applications (Bijker et al., 1987). It analyzes structural concepts to study the design, development, and transformation of technology (Klein & Kleinman, 2002).
Constructive technology assessment (CTA)	CTA assesses the dynamics of technology and society to anticipate societal transitions into technologies (see Rip et al. (1995) for an analytical overview). CTA translates insights from so-cio-technical scenarios into TD approaches. By integrating stakeholder insights into the dy-namics of a specific technology field it allows a social environment oriented assessment of dif-ferent conceptual and contextual perspectives from science and technology (Konrad et al., 2017).
Technological innovation systems	Technological innovation systems assessment studies the emergence and growth of sustaina-ble innovation systems, including emerging industries and the analysis of socio-technical tran-sition (Markard et al., 2015).
Long waves	The long waves theory stems from Schumpeter's economic perspective. The assumption is that technology evolution and its social acceptance form the basis for future innovation adap-tation. The memory, and thereby the acceptance, of society is far-reaching and a sum of indi-vidual developments. (Groot & Franses, 2005)
Technology future studies	Technology future studies discounts and contextual and behavioral stakeholder requirements in relation to specific technology applications (Truffer et al., 2008).
Social license to operate (SLO)	Refers to the ongoing acceptance of operations by stakeholders. SLO is often used to analyze the legitimacy of extractive operations. Only recently, it has been applied to assess technology test operations and their acceptance by local communities. (Proctor & MacCallum, 2019)
Reflexive governance	Reflexive governance examines conditions for STD. It assumes that technological systems are embedded in an interplay of social-ecological vulnerabilities, agent-based conceptualizations, and distributed governance structures (Bauknecht et al., 2006; Beiki et al., 2012). The concept relates to procedural sustainability and addresses actor networks at different levels of govern-ance (Feindt & Weiland, 2018).
Sociology of expectations	The sociology of expectations merges the technology of future studies and the theory of long waves. The connection builds on the assumption that historical expectations influence future expectations. The theory introduces metrics to analyze the success of pre-market applications with stakeholder integration. Here pre-market applications are defined as systems in which practical utility and value are yet to be demonstrated. (N. Brown & Michael, 2003)

TAM and UTAUT are often applied for information technology and focus on consumer products. The scope considered are different situations (e.g., time and culture), control factors (e.g., gender, organ-izational type, and size), and study subjects (e.g., undergraduate and researcher). Studies associated with the governance and analysis of transition management include theories including the multi-level perspective on socio-technical transitions, the social construction of technology, and CTA (Truffer et al., 2017). The premise of theories varies by the direction of action. In this context, human action is either regarded as a determinant of technological change, or technology is recognized as a determi-nant of social change (Konrad et al., 2017). Hence, society / technology relations impact one another (Rip, 2018). For the work, these interdependencies imply that sustainability transformations in soci-ety / technology relations may reinforce sustainability (Pichler et al., 2017).

Other studies break up this linear way of looking at socially-centered technology assessment through technological innovation systems (Fontes et al., 2018). According to the theories, cyclic interdependencies of different actors and objects are reinforcing by nature. Both historical events and expected future states influence technological value (Grunwald, 2018). More recent studies stress the inclusion of stakeholders to understand the sociology of expectations and the ensuing process of reflexive governance (You Wu & Su, 2020). Here the preciseness of research methodology is important, as the subject does not naturally lend itself to unbiased, quantifiable indicators. Metrics to assess the social and natural phenomenon affected by technology are as important to understand as identifying stakeholders affected, however limited (Maier et al., 2018). Considering the evidence, it seems that systems enforce the complexity of societal systems (Lindblad-Gidlund, 2009; Mazé et al., 2011). Hence, test sites must consider increasingly complex and often heterogeneous drivers during their development (Kirincich et al., 2018). Feedback loops between historical, future, contextual, and adaptive feedback loops (both damping and amplifying) reinforce the value of a technology (Maier et al., 2018). Limitations and conditions that influence the accountability of theories root in public perception. This interdependency is why stakeholder analysis becomes increasingly important and provides means to combine socio-economic aspects and socio-technical characteristics of TD.

2.3.6 Ecological Aspects of Testing

Depending on the test requirements, the ecological impact of technologies is either assessed on the indicator level (e.g., monetary, or product-related) or from a holistic perspective. The latter includes the macro environment (area), biophysical, and habitat conditions (Beemsterboer & Kemp, 2016).

Concerning the holistic perspective, scholars argue that sustainability measures benefit from acknowledging the context a technology is placed in (Watz & Hallstedt, 2020). Contextual determinants of technology impact include the physical and social environment (Bond & Morrison-Saunders, 2013). Table 5 illustrates macro-level assessments.

Table 5 Macro-Level Ecological Assessment Methods

Method	Description
Life Cycle Assessment (LCA)	LCA consists of four stages: definition of objective and scope, inventory analysis, impact calculation, and analysis of results (Pelletier et al., 2019). The assessment provides measurements about the flows of "air pollutants, emissions to water, resources, wastes, and byproducts in metric units" (Beemsterboer & Kemp, 2016, p. 76).
Multi-criteria analysis	Multi-criteria measurement refers to benchmarking the performance of STD. Criteria differ depending on the objective of the assessment. The calculation method often builds on pair-wise comparison or other additive weighing measures. (Korol & Shushunova, 2019; Linkov et al., 2007)
Ecological impact assessment	Ecological impact assessment reviews ecological regulations and documents the materials, weights, hazardous substances, and impacts on protected specimens during the utilization and disposal phase of products. (Anthonissen et al., 2016; Şengül & Theis, 2011)
Data-driven ecological simulation	In his work on simulation-driven ecological assessments, Acevedo (2016), illustrates the importance of interdisciplinary work in sustainability. By simulating the behavior of products in their end-setting, sensitivities can be captured and visualized (Acevedo, 2016). Product and service impact on earth systems (Arbault et al., 2014), the environment (Mani et al., 2013), ecology, and human-nature interactions (Bisilkas et al., 2012) are but few examples.

There exist plenty observations, measurements, and analysis concepts. The specifics of each method depend on the design, materials used, production, usage, and end-of life cycle processes (Mani et al., 2013).

The complexity of optimization and assessment potential and the lack of standardized assessment processes challenges the reliability of the impact assessments across the life-cycle. Holistic systems approaches to predict and verify ecological technologies are hardly established. (Mihelcic & Zimmerman, 2021)

The previous outlines of the dissertations have alluded to the methods presented in the table. Since few specifics exist, the procedures are subject to transfer across disciplines. Hence, the research will introduce a more detailed view on the content of macro-level assessment methods.

2.3.6.1 Ecological Macro-level Impact

The focus of this literature review is derived from the existing body of literature. Previous work puts macro-level measurement focus on disturbance factors to flora, fauna, and atmosphere (García-Quintero & Palencia, 2021; Smith et al., 2018). The following introduces common disturbance sources to analyze the macro-level impact on fauna, flora, atmosphere, water, and soil. The outline focuses on the ecological impacts of technology tests in natural sciences. The focus includes assessments of platforms (helicopter, unmanned aerial systems (UAS) etc.) and sensory equipment.

Flora: Different types of platforms can influence plantlets and rootstocks, generate erosion or inhibit future growth vegetation conditions (R. Jones et al., 2000). Technology impacts on the flora are often carried via the atmosphere (Donnadieu et al., 2009). Global and local temperatures, precipitation levels, topography, and biodiversity challenge the analysis of dependencies and impacts (Beemsterboer & Kemp, 2016).

Fauna: Pervasive and impairing symptoms of reaction through platforms disturb wildlife (Pepper et al., 2003). Numerous studies exist that quantify linkages of UAS's (Vas et al., 2015), fixed-wing (Hillman et al., 2015), and helicopters (Harris, 2005) with wildlife. Regardless of the platform type or the generated impact, disturbances are the most thoroughly researched interventions to ecological sustainability. Common types of disturbance include light pollution, noise pollution, and changes in the magnetic field. Table 6 illustrates the sources of potential disturbance to wildlife.

Table 6 Sources of Disturbance to Fauna

Pollution	Definition and discussion
Light Pollution	Reported by nighttime satellite images since 1970 (Elsahragty & Kim, 2015). Light pollution is well recognized. Current regulations have already introduced measures to minimize the presence of light pollution from infrastructure. In Germany, new demand-based lighting systems are mandatory since 2020 (BMWE, 2020). Such systems only light up once a low flying aircraft is in the vicinity.
Noise Pollution	Noise pollution is a hazard to health and productivity, as well as a subject of public discourse (Santini et al., 2008). Noise pollution may stem from the platforms (e.g., UAS, fixed-wing). Noise is traditionally measured in decibel (dB). dB alone does not cover the impact of noise pollution (Hainge, 2013). Authors such as Hainge (2013) and Ma et al. (2018) find that different power spectra of noise signals (colors of noise) influence humans in varying ways. In addition, the location in which the noise is experienced influences the perception of the noise exposure (Ma et al., 2018).
Visual Pollution	Visual pollution is the presence of objects (e.g., fog, airwill, aircraft, transmission wires) in the landscape that changes the visual landscape (Brinkmann, 2020a). Analysis methods include trade-off analysis, impact simulation, or air particle density measurement (N. Ahmed et al., 2019). In mineral exploration, aircrafts, or groundworker, as well as airwill can cause obstructions (Peach, 2000). Visual pollution has fairly small disturbance potential on fauna but may have reputational significance for a project. Especially in delicate eco systems, which require safeguarding to avert impairment to sites of sensitivity, minimizing (visual) pollution and upholding communication is critical (Brinkmann, 2020a). A critical review of the literature indicates that limited knowledge on the behavior of fauna exists (Watkins et al., 2020). The trade-off between acceptance of communities and impact on fauna is however reported on (Choi-Fitzpatrick, 2019; Devlin, 2005).
Changes in the magnetic field	Change in the magnetic field may occur through technical equipment. Besides mineral exploration (Sharlov et al., 2017), industries such as geothermal exploration (Gasperikova & Cumming, 2020), hydrogeology (Danielsen et al., 2003; Fitterman & Stewart, 1986), and environmental survey (Sorensen & Auken, 2004) employ such equipment. One example is the time-domain electromagntic (TEM). TEM builds on the principle of inducing electric and magnetic fields by transient pulses of an electric current into the subsurface and the subsequent measurement of the decay response. Slight changes in the earth's magnetic field may occur in the process (Genovesi et al., 2006).

Atmosphere: Several authors reported adverse atmospheric impact of flying platforms (Henderson et al., 2012; Linares et al., 2013). Related empirical studies and research reviews measure and process combustions of platforms (e.g., CO2 emissions, NOx) (Czyz & Siadkowska, 2020; Mendes et al., 2020). Studies in engineering or earth science helped identify the number of excavating factors adversely affecting the environment (D. S. Lee et al., 2010). Optimization tasks include platform geometry, engine constraints, and flight patterns (D. S. Lee et al., 2010). Per asymmetric atmospheric conditions, optimization problems often require multidisciplinary measurements and simplifying the system-level problems. As a result, Chittick and Martins (2009) criticize that limits of such advances start at the core of the research objective. The lack of a clear understanding of the correspondence between atmospheric conditions, soil, habitat, space, and time leads to a disconnection between the definition of the research scope and its explanatory power (Andersen & Wicken, 2021). While fauna and flora delineate their jurisdictions, atmospheric conditions upset such jurisdictions (Hauschild et al., 2020). Atmospheric conditions lack a clear juridical framework. Hence ever more compartmentalized studies are emerging that address different challenges of (quantitative) impact assessments (Green, 2017; D. S. Lee et al., 2010) or conceptual product design procedures (Henderson et al., 2012)

Water: Water is a sophisticated time-space complex. Observing capturing and analyzing the different dimensions (river, lake, sea, groundwater) has a long-standing history (Hurtubise et al., 1977). Evolving assessments include the simulation of water impacts, installations to monitor erosion, and pollution (Luengo Frades et al., 2019). According to Mosleh et al. (2017) and Fasanella et al. (2005) indoor laboratories and exterior field studies are the most prominent product assessment approaches. Scholars such as White et al. (2017) highlight the dependencies between air or surface impacts on the water systems. Examples build on water recovery and condensation. Intensification of the impact of human activities is ongoing (Quadra et al., 2019). Despite an increasing focus on water system impact assessment (e.g., ongoing development of standard creation by bodies such as the World Wide Fund for Nature or ISO research on technology water impact accounting appears limited (Fasanella et al., 2005; Quadra et al., 2019).

Soil: Soil consists of different layers, the so-called soil horizons. Soil testing traces, analyzes, and compares the impact of natural phenomena (e.g., rain, drought, plant roots) on soil organisms (Cai et al., 2019; ISO, 2012). Most technology tests focus on technology-induced impact (Minasny et al., 2020). Non-invasive impact modelling (Fasanella, 2008; Tiruta-Barna et al., 2007) and the comparison of analytical and laboratory studies (ISO, 2014b) build the core of such tests. Controversy exists on impact testing with real-life data. One argument is that the extraction of soil for testing purposes impacts the soil horizons (Garrigues et al., 2012). Hence, ex-ante analysis of soil pollution shall be limited (T. Wu et al., 2017). Besides the invasiveness of physical tests, critics argue that the scope of such observations is rather piecemeal. Limited long-term evaluation exists and dependencies with other macro-levels are hardly considered (F. Liu et al., 2021).

Arguably, the outlines focus on direct impacts. Indirect impacts caused by influences between the critical earth zones may also apply. For example, air pollution and changes to vegetation diversity could have ripple-through effects on a system. Concerning ecological aspects of testing, it must be understood that all three pillars of ecology, technical performance, and social equity must be viewed from a context perspective (Brinkmann, 2020b). Context may include historical (e.g., dynamic of change in a region, may lower perceived disturbance), and geographic (e.g., dessert increases airwill potential) perspectives (Brinkmann, 2020a; Peach, 2000).

Reference points as identified in the Brundtland Report are key for accurate assessments (Brundtland, 1985). And while there is an increasing amount of reference data and computing capacity to integrate context and technical behavior, the complexity of nature challenges the accuracy of impact predictions (Obade & Gaya, 2021).

In this context, noise has been shown to be connected to the majority of harm to fauna and a variety of ecosystems. Animals, in particular, are reported to show physical reactions to noise (e.g., change in behavior and range) (Parris & McCauley, 2019). The ecosystem centrality of noise disturbance justifies the need to elaborate on noise disturbance.

2.3.6.2 Ecological Disturbance Measurement

Among the introduced disturbance sources, noise pollution is the best-covered topic in literature. Authors report about alert behavior of different species. Authors such as Bateman and Fleming (2014) analyze different platforms – UAS and helicopter – but list similar criteria for disturbing other species. Determinants of disturbance are engine type and the friction of vehicle and air, including vibration and rattle. The disturbance level, often described in meter, then determines the emitted noise to the target and flight pattern (vertical approach, horizontal approach, acceleration) (Mulero-Pázmány et al., 2017).

Noise levels caused by airborne systems spike during takeoffs and landing. Topography, meteorological conditions, and background levels determine the propagation of noise. As a general rule, the larger and heavier the platform, the more noise it emits (Pepper et al., 2003). In consequence, disturbance predictions build on the types of platforms, their flight patterns, takeoff and landing distance / duration, and the atmospheric conditions. A corresponding measure is sound intensity (Simons et al., 2015). Sound intensity is often subjective as it is closely related to soundwave frequencies, which species respond to differently. Measuring the impact of the different platforms on the environment is challenging. Reasons include the multitude of factors that impact the noise level and its propagation (Simons et al., 2015). Most publications dealing with noise neglect the factors of movement (Mulero-Pázmány et al., 2017). What follows is the measurement of disturbance to a species at the vertical elevation between species and platform. Noise affects the different forms of wildlife differently Mediating factors are species, source, and situations (Diener & Mudu, 2021).

The effects of noise vary from serious to negligible and are clustered in alert classes. Alert classes cluster effects on wildlife. The most common alert classes are no visible change (1), alert standing / vigilance / heads-up (2), alert running / flushing / flight (3), and alert aggressive behavior / abandonment of nest (4). Composite studies that cover variables of disturbance sources and levels relevant to natural sciences are scarce. Existing meta-studies focus on the general activity in response to different sources, and disturbance monitoring for urban exploiters (Bateman & Fleming, 2014) or the disturbance of humans on artic wildlife (Coetzee & Chown, 2016). Except for natural parks (Jotikapukkana et al., 2010), guidelines, and procedures for fieldwork build on aviation regulation rather than on wildlife disturbance. In some cases, aviation regulation procedures omit impact minimization. For example, Mulero-Pázmány et al. (2017) see increased elevation as a mitigator of disturbance. Yet, European legislation requires UAS to fly no higher than 120 m and upon request 135 m, whereby German legislation allows for a maximum height of 50 m (DFS Deutsche Flugsicherung, 2020). Such legislations may tilt or override technology considerations. For example, Abou Chakra et al. (2020) test the resolution of surveys' independence of survey heights. They find that the lowest distance to target observed (50 m) yields a 10.5 times higher resolution than at 500 m (highest distance observed) (Abou Chakra et al., 2020).

2.4 Sensing Technologies in Exploration Geophysics

Sensing devices are instruments that help scientists record variables about a system in question (Han & Wang, 2008). Associated technologies and techniques observe surface patterns such as the signature of mineralization (Heincke et al., 2019), or subsurface patterns and the physical signature of a rock (Kuras et al., 2018). The exploration of the natural phenomenon with sensing is illustrated to understand the practice and the underlying principles that determine field trials.

Sub-chapter 2.4 consists of five parts. Figure 9 illustrates the sub-chapter structure.

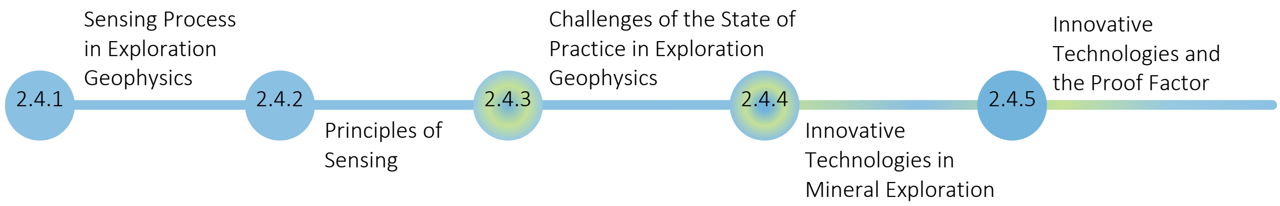


Figure 9 Chapter Structure, Sensing Technologies in Geophysics

This review supports the development of a strategically relevant STSDF.

2.4.1 Sensing Process in Exploration Geophysics

The sensing procedure consists of five steps. These are (I) the definition of survey object, (II) data acquisition, (III) data processing, (IV) data display, and (V) data interpretation.

Figure 10 displays the principal stages of natural phenomena characterization, from identifying the objectives of the survey to providing an interpretation, and the properties at each stage.

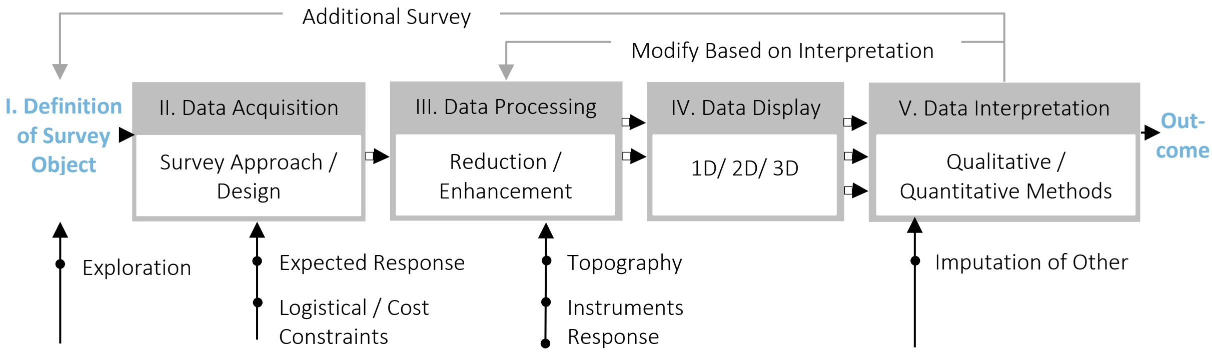


Figure 10 Sensing Measurement and Data Utilization Process in Exploration Geophysics
Source Own representation aligned to Dentith and Mudge (2014); Number of arrows indicates increasing products

The survey objectives determine which instruments are employed. Depending on the expected physical signature, the instrument applicability can vary. The survey objective and the surrounding environment can dictate which technologies and methods to use (Viezzoli, Roffey, et al., 2018). For the sensing planned duration, funding and terrain set the tone (Amaro et al., 2021; Wood & Hedenquist, 2019). Among other funding, the methodology employed and exploration stage determine which platform operates and whether to take relative or absolute measures.

Data acquisition designs the survey depending on the physical target. While most methods allow for relative statements, few employ "absolute" measures that may gauge the total extent of a physical parameter (Milsom & Eriksen, 2013). Comparable measures meter the difference in physical properties between two points. This approach only allows estimates since the information gained enables the interpretation to make statements about the difference between two points. Relative measures are more cost-effective to obtain (Dentith & Mudge, 2014). The same applies to the collection platform (ground vs. airborne).

Data processing entails the correction and reduction of raw field data (e.g., removing noise from external sources or minimizing systematic patterns in the data that are not linked to the target) and enhancing the measurements in the data space (Pinet et al., 2019; Sun et al., 2018). The transformation (interpolation) of data into a regularly spaced numerical distribution of measurement points is crucial to this. The data processing sets the tone for merging or comparing data. Joining data sets with existing measurements for the area in question is part of data processing (Haldar, 2018).

Data display or visualization of processed data happens next. Different visualization options exist for 1D (e.g., profile plots) and 2D (e.g., series of profiles with similar scale and direction in a contour plot) data. 3D displays (voxel display) also work when data points are distributed through space. Typical 3D models consist of petrophysical values, vector measurements, geochemical, geological, hydrological, and geographical information (Dentith & Mudge, 2014). The more relevant and accurate data points are collected, the less ambiguous is the follow-up data interpretation.

Data interpretation analyzes the collected data and derives plausible argumentation for the characteristics of an anomaly (Sun et al., 2018). Interpretation is an iterative process and evolves through applying different concepts and approximations until the most accurate presentation of the physical or chemical occurrences is obtained. Data interpretation is conditionally based on the calibration of the equipment and the existing geological, petrophysical, hydrological, or geochemical data. This situation is what Dentith and Mudge (2014) call the geophysical paradox. The authors argue that to make statements on the character of physical responses, one has to know the nature of a physical response. The more parameters the data set entails, the lower the ambiguity of the interpretation. The majority of statements remain approximations until a project fully uncovers the subsurface. Therefore the merging of data sets and physical evidence can lower the ambiguity of interpretation (Pinet et al., 2019), meaning that the sum of relevant data points increases the context and reduces the opacity. Yet, physical evidence (e.g., through drilling), can only verify assumptions.

The requirement for standardized procedures and the interdependency of acquisition, processing, display, and interpretation is illustrated in Figure 11.

Here, the typical characteristics of a physical response (excluding seismic and hyperspectral) are illustrated. Figure 11 a) shows that variations such as a negative contrast of the same size and at the same depth produces an inverted image of the positive contrast. Amplitudes (A) and wavelength (λ) depend on the depth and size of the anomaly and physical contrast (ΔP). This relation allows for two statements. First the closer the proximity between sensor and source of signal, the higher the amplitude of the signal. Hence survey design must be aligned to the project objective. Second, anomalies that have different ΔP might be located at different depth Figure 11b), or have different shapes can have the same A and λ Figure 11 c-d). (Dentith & Mudge, 2014)

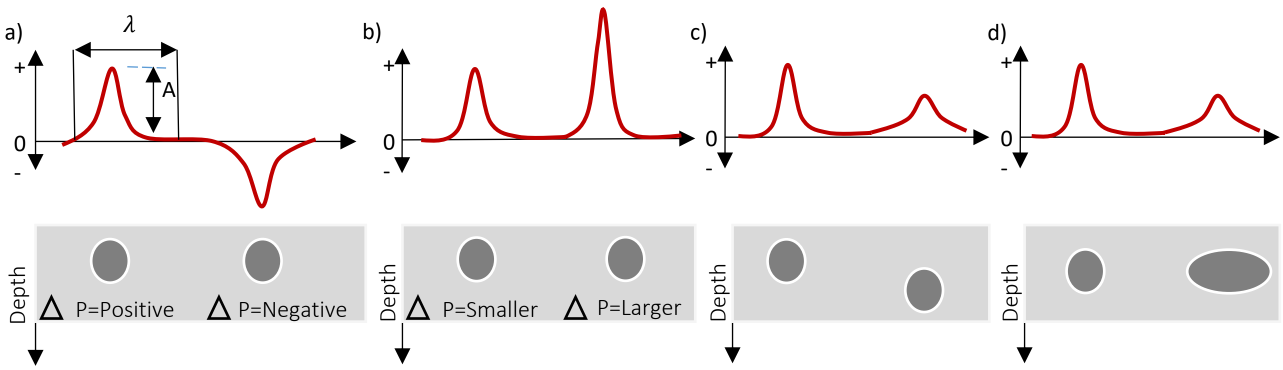


Figure 11 Geophysical Response
Source Own representation aligned to Dentith and Mudge (2014)

Given the context dependency and to ensure robust interpretation, standardized procedures are crucial (Dentith & Mudge, 2014).

Having identified the procedure of sensing and the cross-lateral connections, Table 7 sums up the quality-defining criteria of a survey.

Table 7 Quality Criteria for Survey Design and Execution

Stage	Quality Measures
Definition of survey target	Objective clarification enhances the effectiveness of the survey
Data acquisition	• The better the understanding of the survey area (topography and culture with buildings, power lines, towns), the higher the effectiveness of the data acquisition • Suitability of instruments and survey procedures determines the acquisition success
Data processing	• Accuracy and preciseness of instruments • Noise levels • Follow standardized procedures for compatibility with different data sets
Data display	Appropriate and data-sensitive display: e.g., proper equalization (data to colors), adding isolines, multiple useful transformations of the data
Data interpretation	Sum and diversity of data points; experienced professional conducted the interpretation Physical evidence from soil or rock extraction enhances the validity of interpretations

As discussed, the sum and quality of sensing data can provide an accurate view of the surface and subsurface. However, all interpretation is context-based (Pinet et al., 2019). Drilling offers the most reliable source of information about an area. However, drilling is primarily stationary, destructive, and costly, and it still gives point estimates of the underlying data area. That is, a significant number of boreholes would be required to test an interpretation thoroughly. Dentith and Mudge (2014) compare the cost for sensing and the cost for drilling about the area covered and compelling the sensing technologies. While their work mainly focuses on economic aspects, the destructiveness of soil or rock destruction is established.

Despite the rapid advancements of sensing technology in recent years, ongoing drilling TD investments (PDAC, 2020) could suggest that drilling remains superior concerning reducing ambiguity in interpretation. One way to decrease the dependency on drilling is to improve the innovative capacity of natural sciences. Nascent efforts and public funds aim for the reduction of invasive procedures (Ajjabou et al., 2019). Advancements spun across industrial barriers and aim on bringing novel technologies to the market or recognizing technology transfer between industries as diverse as medical and mineral exploration (Kergroach et al., 2018).

The following sub-chapter first introduces the principles on which sensing technologies build. In a second step, the most innovative non-invasive technologies are presented. Understanding principles and technologies contribute to the purpose of this dissertation, as it provides context to the requirements a test site has to fulfil.

2.4.2 Principles of Sensing

Sensing methods record or respond to differences in physical properties. Recorded changes imply changes in the local geology, the vegetation, or the hydrology trigger sensing methods to indicate a signal response (Dong et al., 2010). Changes can arise from mineralization, objects, materials, or process changes (e.g., contacts between different geological units). Although different sensing methods are sensitive to different physical properties, the general characteristics of a physical response remain similar. Detecting the physical features of an area requires one or more physical measures (Clauser, 2014, 2018).

Geophysical measurements and hyperspectral sensing have applications in several fields throughout the natural sciences. The methods vary by the physical property they are targeting. Seeing that not every physical phenomenon will respond to a method in a given area, understanding the methods employed during the investigation is valuable for determining the requirements that technologies pose to real-life testing (e.g., availability of a specific physical property in the subsurface) (Dentith & Mudge, 2014).

At present, geophysics distinguishes between five classes of subsurface physical sensing devices, namely (Dentith & Mudge, 2014; Haldar, 2018), (I) gravimetric, (II) magnetics, (III) radiometric, (IV) electrical, and (V) seismic. In addition, surface feature detection regularly employs hyperspectral technologies. Table 8 illustrates the physical measurement principles.

Table 8 Physical Measurement Principles

Method	Explanation
Gravimetric	Gravimetric responds to changes in the earth gravity field and allows for density measurement. The method is based on Newton's Law of Gravitation: $F = Gm_1m_2/r^2$, with G = Gravity, F = force, m_1, m_2 = masses and r = separation distance between the masses. Due to the small dynamic range of the expected density variations, gravity lacks the sensitivity of other methods Gravity is rarely employed as a single method but is often accompanied by magnetic or electrical methods. (Dentith & Mudge, 2014; Essa & Munschy, 2019)
Magnetic	Magnetic surveys analyze potential fields as gravity. More precisely, magnetic methods are sensitive to changes in the magnetic field of the earth or other research objects, allowing for statements about the magnetic potential in an area (Dentith & Mudge, 2014). Magnetics is among the oldest survey methods in geophysics and the easiest to perform, yet the hardest to interpret, with interpretation being mostly subjective (Pinet et al., 2019). Additionally, magnetics is comparatively more sensitive to external fields of magnetism (also referred to as noise) causing artefacts in the data (Milsom & Eriksen, 2013; Valenta, 2015).
Radiometric	Via radiometric methods, the radioelement content of a rock is measured. This method detects variations in radioactivity by measuring gamma rays (high-energy EM waves). Radiometric surveys were initially developed for uranium search and take on the smallest in part in the geophysical literature for mineral exploration (Milsom & Eriksen, 2013).
Electrical	Electrical methods, induce an EM field into the subsurface of the earth and a detector (sensor) measures the ground response. Electrical methods are mostly based on the deliberate induction of current into the ground. Thereby the electrical conductivity and resistivity of a rock volume are measured (Auken et al., 2017). These methods are mostly limited to ground application as the controlled induction of energy at height is limited. Yet, the controllability of energy enables more precise targeting. The costs for performing electrical methods are higher, as method require external production of some source of energy. (Baum, 2019)
Seismic	Seismic methods are active methods that work with the propagation of sound waves. By inducing elastic waves into the ground, the wave propagates through the subsurface. The propagation is recorded by a sensing device that measures the deformation of the ground as a function of time. This method allows to draw statements about the elastic properties and is most effective for analyzing layered stratigraphy. Therefore, it is mostly applied in the oil and gas industry. (Mondol, 2010)
Hyperspectral	Hyperspectral imaging acquires multiple spatial images in spectrally contiguous bands. Each acquired image entails the reconstruction of reflectance spectrum for each pixel of the image and contains a complete spectrum. Concurrently, spatial and spectral data about an object or act under study can be obtained. (Shukla & Kot, 2016)

Summing up, the employed methods respond to different physical properties and vary in their applicability for different exploration scenarios.

The dissertation will discuss the advantages and disadvantages of the methods to provide an overview of where innovation is of high value.

2.4.3 Challenges of the State of Practice in Exploration Geophysics

Analyzing drivers for innovation in geophysics, the sub-chapter is informed by technical reports and the work performed during the INFACT project (Nevalainen et al., 2021; Viezzoli, Roffey, et al., 2018).

Preliminary work co-authored by the thesis authors indicates growth in publication and patent intensity on sensing technologies see Ruiz-Coupeau, Kesselring, et al. (2020).

Growth drivers including innovation are (I) openness, (II) social pressure towards becoming less destructive, (III) economic considerations, and (IV) physical challenges, which Table 9 discusses.

Table 9 Drivers of Innovation in Exploration Geophysics

Driver	Description & Critical Review
Openness	According to Carayannis et al. (2020), an open exchange may enable spillover across natural sciences. The authors suggest that determinants of spillovers across different branches in natural sciences are (I) the common use of a technology, (II) the specific nature of the target, (III) the time-horizon for investigation, and (IV) the technological proximity (Dumont & Meeusen, 2000).
Social and regulatory pressure	In recent years, regulatory pressure has led to an increased focus on less-invasive sensing devices. Being less invasive is of course relative to previous practice. In the context of natural sciences, the degree of destructiveness compares different attributes of technology and sets them in context with extractive methods (e.g., drilling). (Ajjabou et al., 2019) Current research and practice are often the comparison points. An established unit of measurement does not exist. However, energy consumption, invasiveness (Ruiz-Coupeau, Jürgens, et al., 2020), or whether the method is active or passive may serve as a proxy.
Economic considerations	Waye et al. (2009) and Mwitwa et al. (2011) argue that innovation investment is an optimization problem, which is increasingly considering social and ecological externalities. Levidow et al. (2016) argue that such externalities relate to the impact on the social and physical environment. Several authors investigate methods for analyzing priorities among economic, ecological, and social objectives. Examples are LCA (Pelletier et al., 2019), ecological management accounting (Latan et al., 2018), and eco-efficiency of circular economy (X. Liu et al., 2019). When costs of technology change exceed benefits, public entities can provide funding or increase the market pressure to regulate welfare. Coccia (2019) argues that the national interest of institutions and the population's well-being add to the evaluation of public benefits. In this regard, two main national interests drive sensing equipment innovation: (I) resource availability and supply chain security, and (II) sustainability and social justice of resources. Hence, moderated or non-moderated economic benefits drive innovation.
Physical challenges	The resolution and accuracy at a different depth, cover (e.g., vegetation), and soil are important for advancing the predictive quality of operations. Depth is particularly challenging (Nevalainen et al., 2021). The range of the depth targeted is highly variable. In an open pit, crater, or other areas where human or natural activity has altered the distance to sea level, research can reach deeper targets. Depths between 200 m to 2000 m are within the scope of current development (Lin et al., 2015). Conversely, Greenfields in the mineral exploration or archaeological and agricultural operations focus on more shallow, near-surface exploration. In both contexts, natural signals that mask, mingle, and create false positives are common challenges (Deckert et al., 2018). The reasons are the formational interference and the depth effect on the signal-noise ratio. Innovative geophysical solutions are required to meet these challenges.
Ecological challenges	Two aspects stand out for ecological impact. Firstly, detection and mapping often involve the extraction of physical soil parts. The better sensing technologies become, the lower the destruction through invasive extraction (e.g., drilling) (Ajjabou et al., 2019). In addition, platforms for sensor mobility (e.g., groundworker; helicopter) may cause pollution of physical spaces. A shift towards minimizing the environmental impact that brought about UAS as sources of exploration mobility is reported on (Booysen et al., 2021).

Besides the conceptual aspects of innovation, miniaturization is among the top technology enablers for innovation. Miniaturization allows employing UAS's rather than a helicopter and enables the merging of various sensors on one platform (Niedzielski, 2018).

State of the industry, innovative instruments merge multiple sensors, whereby the Helmholtz Institute for Resources in Freiberg is among the top players (Heincke et al., 2019; Thiele et al., 2021). In this context, technology takes in a cross-cutting function.

Besides the technological possibilities, UAS's may be positively perceived by the public, the decrease of the target to sensor ratio and the ability to access increasingly remote areas (B. Jones & Mendieta, 2021).

This sub-chapter described the four drivers of innovation associated with exploration geophysics. The thesis goes on to illustrate innovative instruments in geophysics, focusing on mineral exploration.

2.4.4 Innovative Technologies in Mineral Exploration

The following outlines present innovative examples that link to the collaboration, economic, political / environmental / social, and physical drivers. The selection builds on a patent and publication analysis on less-invasive exploration technologies.

The analysis is a preparatory study to this thesis (Ruiz-Coupeau, Jürgens, et al., 2020). To verify the relevance of the technologies, the author contacted the consortium of the INFACT project to assess the relevance of the technologies. Relevancy criteria were (I) the applicability of the technology and (II) the degree of innovativeness. Identified technologies are: Ground-Floor Electromagnetic (GFEM); Magnetotellurics (MT); UAS based magnetic survey; AIP; FTMG. Drawings presented in this sub-chapter are not in scale. The content structure is aligned to INFACT deliverable D5.4.

2.4.4.1 Ground-Floor Electromagnetic

Starting with GFEM, Table 10 provides a summary of the GFEM and provides information about the technological features and their status-quo.

Table 10 Ground-Floor Electromagnetic Report

TRL	8
Short Description	GFEM allows interpreting conductors below conductive over-burden and deep conductors. An airborne transmitter generates a signal and ground sensors, positioned near target locations, measure low-frequency EM responses.
Innovativeness	Observes non-decaying anomalies in the system on-time; detection and discrimination of extremely high conductivity targets; high-frequency range; exploration depth exceeding 2000 m (Driver: Physical Challenges)
Application Scope	Mineral exploration, groundwater exploration, charting contamination (trails and fracture systems), and engineering (e.g., mapping of collective properties for construction, pipeline route mapping)
Test Site Requirements	Flying permit, accessibility, well-mapped subsurface

GFEM employs a series of fixed receivers on the surface and an airborne transmitter. The fixed receiver and transmitter are spatially separated (see Figure 12).

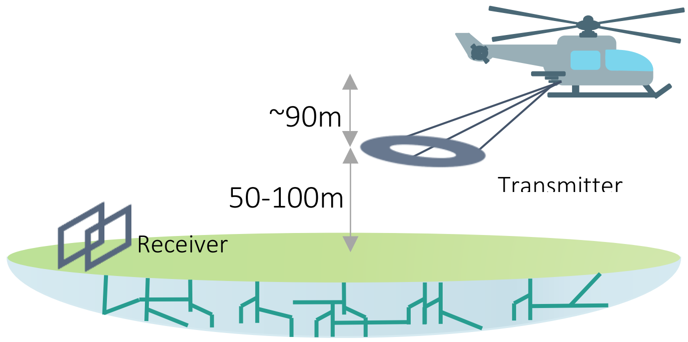


Figure 12 Ground-Floor Electromagnetic Campaign Set-up
Source Own representation informed by INFACT (2018)

The separation enables the computation of the received signal from the transmitted signal with sufficient accuracy. In addition, the separation allows to detect and discriminate highly conductive targets (Bengert et al., 2020). Compared to purely ground-based methods, topographic challenges such as accessibility of the field or elevation corrections are minimized (Viezzoli, Roffey, et al., 2018). The combination increases the robustness of the collected data and reduces the follow-up survey requirements (Bengert et al., 2020). According to the INFACT Grant Agreement, the patent for this application is pending. Triangulation with the company data of Geotech verifies the patent status. GFEM was demonstrated during the INFACT project and is therefore at a TRL 7.

Berardelli et al. (2018) and Bengert et al. (2020) are key scholars in GFEM research.

2.4.4.2 Magnetotellurics

After identifying the key features of GFEM, the following introduces MT. Table 11 provides a summary of the technology and provides information about the technological features and their status-quo.

Table 11 Magnetotellurics Technology Report

TRL	8
Short Description	MT builds on passive EM. In orthogonal directions on the earth surface, MT infers resistivity structure from the measurements of the electric field E and the magnetic B fields. Data inversion enables the determination of subsurface structures from as little as ten meters to > 100 km. (Zorin et al., 2020)
Innovativeness	Resolution of features at greater depths than other geophysical methods (Driver: Physical Challenges), passive method (Driver: Social and Regulatory)
Application Scope	Mineral exploration, groundwater exploration, buried waste, archaeological sites, agricultural drainage, and geothermal
Reference Requirements	EM noise, aeromagnetic, shallow and deep subsurface data, geological / petrophysical data or, if not available, assumptions of in-situ conductivity are taken.

MT is a passive exploration method analyzing natural time-varying magnetic and electronic fields of the earth. It measures the geomagnetic field and identifies electrical conductivity / resistivity at great depth (A. Jones, 2018). The MT methods measure both horizontal and vertical induction of the EM field. In the data space, this produces 2D inversions, forward modelling and inversion with other data sets may result in 3D models of the conductivity distribution of the subsurface (Kirsch, 2019). Appendix 2 provides a distinction of three principal types of MT. For 70 years, MT has been an active research field in natural sciences. However, only within the last 10 to 15 years, MT has been applied to measure an entire mineral system (e.g., brines, fluids, clays, melts, graphite or metallic mineralization) rather than a single ore body. The status-quo is referred to as pre-competitive data collection, and there is room for improving the inversion time (e.g., via airborne solutions). (Heinson et al., 2018) Following the line of argumentation, MT is at TRL 8 (existing technology system completed and qualified for test and demonstration.

Key literature on the subject includes Pedersen and Rasmussen (1990), Chave et al. (2012), Heinson et al. (2018), Unsworth (2018), and Borah and Patro (2019).

2.4.4.3 Unmanned Aerial Vehicle-based Magnetic Survey

Table 12 provides a summary of the UAS-based magnetic survey and provides information about the technological features and their status quo.

Table 12 UAS-based Magnetic Survey Report

TRL	8
Short Description	UAS-borne magnetics identify accumulations of susceptible minerals by detecting anomalies in the total magnetic field intensity (TMI).
Innovativeness	Flight flexibility and robustness for direct targeting, 30 m above ground, accessibility of geologically and logistically challenging areas (Driver: Physical Challenges), low-cost UAS-mounted systems for wide-area high-resolution magnetic surveys (Driver: Economic Considerations).
Application Scope	Mineral exploration, environmental analysis, forestry, agriculture, UXO (unexploded ordinances), civil engineering, archaeology, military
Test Site Requirements	Well-mapped EM noise; range of line combinations possible

Magnetic surveying measures the strength and relative change of a magnetic field at a location. Magnetometers measure TMI in the direction of the sensor. Magnetometer sensors build on quantum-mechanical properties of atoms.

Magnetometers are sensitive to the geomagnetic field and measure anomalies resulting from the magnetic properties of the subsurface (magnetic susceptibility and remanence) (Macharet et al., 2016; Nevalainen et al., 2021). Advances in (I) payload preciseness, (II) locating ability of the UAS, (III) microprocessors, (IV) miniaturized sensors, and (V) actuator efficiency enable drone-based magnetic surveys (Salman, 2017). The drone-based approach bridges the gap between a helicopter or fixed-wing efficiency and the detailed targeting of ground-based magnetic surveys. Lower survey heights may be essential to detect weak responses < 1nT (Jackisch et al., 2019). Figure 13 illustrates the campaign setup.

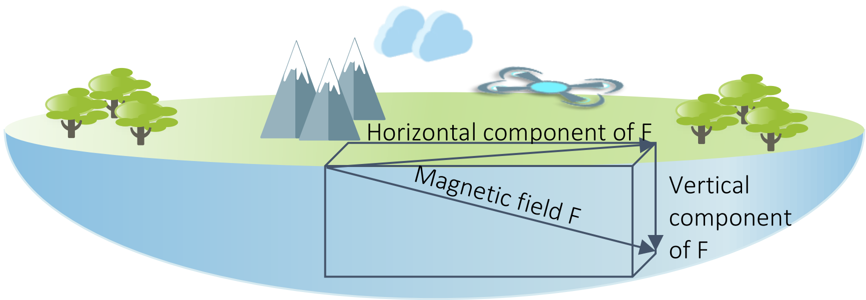


Figure 13 UAS Magnetics Campaign Set-up
Source Own representation informed by INFACT (2018)

Publications on UAS and magnetometer first emerged in 2008 (Web of Science (WoS)). Since then, the survey landscape has seen a growing trend in publication, and disciplines such as aerospace, engineering electronics, computer science, and remote sensing dominate.

As magnetometers traditionally stem from military applications, there may be a distortion in the amount of research performed (Norris, 2008). A reason for the underrepresentation may be the confidentially on which this industry works (S. Howell et al., 2021). However, geophysics-related publications are limited (eight relevant publications) with two case studies for UAS-based magnetic surveys (Funaki et al., 2014; Thiele et al., 2021). Thus UAS-based magnetic surveys are at a TRL 7.

Further literature is by Funaki et al. (2014), Malehmir et al. (2017), Parshin et al. (2018), Jackisch et al. (2019), and Thiele et al. (2021).

2.4.4.4 Airborne Induced Polarization

Moving to AIP, Table 13 provides a summary of AIP and provides information about the technological features of AIP and its maturity.

Table 13 Airborne Induced Polarization Report

TRL	7
Short Description	AIP is a modelling method that extracts chargeability models from airborne EM responses. In doing so, it extrapolates the geological information for processing and extracting AIP data to detect geological control(s).
Innovativeness	Develops chargeability and resistivity models. Better prediction of depth to resistive basement below shallow conductive and chargeable cover complementary chargeability models (Driver: Economic Considerations).
Application Scope	Mineral exploration, environmental analysis (incl. temperature analysis, contamination)
Test Site Requirements	Ancillary information in the inversion of lateral constraints as well as prior information. Properly sampled starting parameters (e.g., sensitivity range).

AIP uses Airborne Electromagnetic (AEM) survey data and extracts information about the polarization effect from the AEM data. Differentiating polarization and electrical measurements is challenging. Reasons are limited bandwidth and, compared to ground methods, the shorter sample time. Macnae (2016) Argue that measuring parameters other than a minimum chargeability is almost impossible.

"Modelling further suggests that AIP effects in double-dipole AEM systems can only be reliably detected from polarizable material in the top few tens of meters" (Macnae, 2016, p. 495). Improvements in this area consequently happened in the past six years. In 2015, companies introduced the first industrial applications. To do so, Geotech flew their Versatile Time-Domain Electromagnetic (VTEM) system over Colorado and introduced their own AIP processing software (Kwan et al., 2015). This extraction of chargeability models is possible through a processing method for extracting apparent chargeability called Airborne Inductively Induced Polarization (AIIP) with statistical parametric mapping from EM data (Geotech, 2016).

Critics may question whether a software can single out the best-suited model, while equally suitable variations may exist. Viezzoli and Manca (2020) refuted the statements and argued that the depth of AIP anomalies does not necessarily result in fainter chargeability models.

As AIP is airborne, the approach is less costly (Dentith & Mudge, 2014). The interpretable data is more diverse and allows for a less ambiguous data interpretation and more precise delineation of geological horizons than AEM data alone. Chargeability models may differentiate between conductors (e.g., clays versus salty aquifers) and correlate with alteration and disseminated sulfides (Gurin et al., 2018; Kang et al., 2017; Wey, 2015).

Kratzer and Macnae (2012), Viezzoli and Kaminski (2016), Kaminski and Viezzoli (2017), Di Massa et al. (2018), Viezzoli, Menghini, et al. (2018), and Viezzoli and Manca (2020) are key for AIP research.

2.4.4.5 Full Tensor Magnetic Gradiometry

Turning now to FTMG, Table 14 provides a summary of the FTMG and provides information about the technological features of FTMG and its maturity.

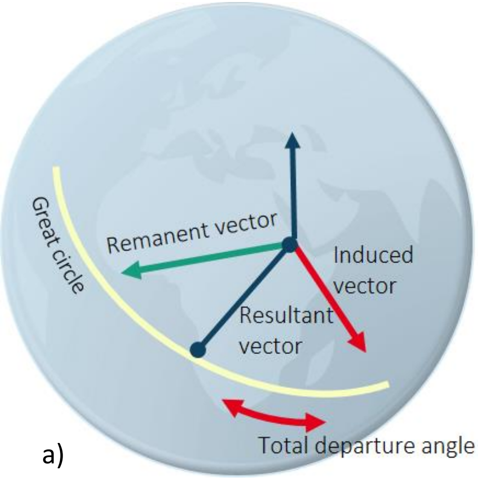
Table 14 Full Tensor Magnetic Gradiometry Report

TRL	8
Short Description	FTMG measures the magnetic field intensity. FTMG builds on a low-temperature superconducting planar airborne Superconducting Quantum Interference Device (SQUID). All properties of the magnetic field gradient are measured with this method.
Innovativeness	Simultaneous measurement of gradients and curvature of the magnetic field, detailed 3D information, and fewer measurements improved decisions on drill hole targeting, detection of minute magnetic sources (Driver: Economic Considerations).
Application Scope	Mineral exploration, environmental analysis, waste deposits, UXO, archaeology, security, civil engineering
Test Site Requirements	Detailed information about noise, safe logistics for helium transport, magnetic anomaly

FTMG systems build on SQUIDs, providing measurements of the total magnetic gradient tensor of the Earth's magnetic field. The gradient tensor is the mathematical description of the changes in the magnetic field. The tensor describes three non-diagonal and two diagonal elements of the tensor matrix. Measuring the five components of the tensor matrix yields information about the total directional sensitivity (Queitsch et al., 2019). By specifying changes in the magnetic field into transitions or gradients of the magnetic field vectors, Queitsch et al. (2019) model the full magnetization vector (permanent, resultant, remanent, induced vector). Thus, the method unites the physical occurrence of flux quantization and Josephson tunneling (Clarke & Braginski, 2006; Fagaly, 2015).

According to supracon AG (2014), six gradiometers and three oriented magnetic field sensors can compensate for motion noise. Moreover, the gradient measurements suppress geological noise and thus enhance surface-near features (supracon AG, 2014). With that, it delivers unparalleled sensitivity levels and novel dimensions in physical property measurement. In the field, the measuring system can be operated in-ground and from fixed-wing or helicopter platforms.

The measuring arrangement is installed in a cooling unit to keep the sensors at working temperature (down to -269° Celsius) (Leibniz Institute of Photonic Technologies (IPTH), 2010). The range of separately taken measurements allows reconstructing a complete magnetization vector. All aspects can be separated from the data if ancillary information from susceptibility, geometry, and remanence exists. Thus, the ambiguity of interpretation decreases and inversion control increases (Nevalainen et al., 2021). The commercialization of FTMG SQUID started through an industry research cooperation between Anglo America, De Beers, IPTH and a spin-off of IPTH – supracon AG. The collaboration began in 2007 (Chwala et al., 2012), since then several reports on application scenarios have appeared (Fagaly, 2015; Stolz et al., 2021). Press releases of DIAS state that the system is fully commercial. Similar notions exist on the supracon AG website (supracon AG, 2014). Jessy Star system, can be employed for fixed-wing and helicopter exploration (Stolz et al., 2021; supracon AG, 2014). Figure 14 a) illustrates the direction of target signal measures, b) illustrates the FTMG campaign design.



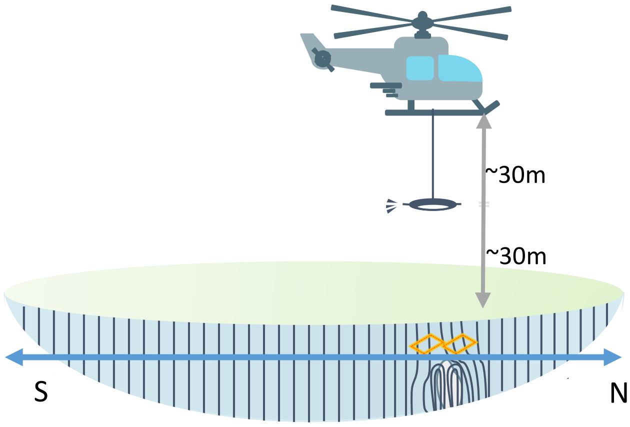


Figure 14 Full Tensor Magnetic Gradiometry Campaign Set-up
Source Own representation aligned to a) supracon AG (2014) and b) INFACT (2018)

FTMG system, processing, and interpretation outlines can be found in Pedersen and Rasmussen (1990), Stolz et al. (2006), Schiffler et al. (2012), Queitsch et al. (2019), and Stolz et al. (2021).

2.4.4.6 Review of Innovative Technologies

Summing up the innovative technologies, it emerges that each system poses different requirements to a test site. The main findings of this section can be summarized in four points: (I) The long development cycles indicate that the appropriateness of test sites is crucial to market entry. (II) There is a particular focus on data processing. Critics question the ability of technologies to expand the depth, resolution, and accuracy of measurements. Machine Learning and Artificial Intelligence may improve the data processing stage going forward. (III) The size and background of the company are crucial for determining the level of information and support required to identify a suitable test site. (IV) The importance of data fusion from different measurements is increasing. To ensure the current and future applicability of a test site, it is crucial to serve not only the needs of one system. Consequently, an ideal decision framework to be developed would consider all methods.

2.4.5 Innovative Technologies and the Proof Factor

Advances in resource characterization can succeed commercially if they are able to provide a proof factor to industry counterparts. Validation in open and standardized procedures is commonly requested. Several projects in natural sciences study and generate proof of concept (Kirincich et al., 2018). Partly because of the increased funding and the clear visual impact, renewable energies such as wind farms are the most recognized topic in test site development.

However, dividends in the industry are more often than not associated with technology advances, social, and ecological compatibility.

Technological advancements visible to the public conscience are caught in between technological gains and public impact minimization (Proctor & MacCallum, 2019). This implies that advances estimating the atmospheric boundary layer, remote sensing, monitoring wildlife, and geophysical remote sensing must interfere as little as possible with the environment while maintaining high-performance levels (Komac et al., 2018; Viezzoli, Roffey, et al., 2018). Less-invasive technologies should perform better with the same or less impact or show similar performance levels than existing technologies. Shepherding the transfer of existing research-grade technologies into the state of practice requires a benchmarking process. Benchmarks consist of robust, precise, and accurate data sets (Schoukens & Noël, 2017). Benchmarks allow comparing the state of the practice and state of research, thus giving the technology developer the ability to prove the efficacy of a "given technology against known conditions, encouraging a more rapid regulatory and industry acceptance" (Kirincich et al., 2018, p.16). Two factors add to the discussion on benchmarks. Firstly, the benchmark alone does not suffice. Beyond the benchmark, the natural environment a technology is tested in dictates the performance scope and picture the proof factor, meaning that a proof of concept is only as relevant for a particular case as is the environment it was proven to work in (Sapia et al., 2015). A proof of concept that stems from an arid area is comparably less powerful when the industry requires the technology to work in arctic conditions (Schoukens & Noël, 2017). Similarly, flat topography test sites have little predictive value for mountainous end settings. The second factor relates to the social and physical environment in which a test site is embedded. Improved understanding of where tests operate may streamline development advancements, reduce time-to-market, and minimize ecological impacts. Efforts to better understand, map, and characterize social and physical environments are numerous (Ghamisi et al., 2019). The pictured conditions directly add to the economic calculus of activities that occur at test sites. In many ways, working in a stable physical and social environment can provide a regulatory basis on which development can be fostered (Kesselring, Wagner, et al., 2020)[10].

Simultaneously, public acceptance and physical compatibility may reduce risks and allow for the creation of projects that are valuable to native societies and the fauna and flora. Social scientists report various examples for social compatibility. Stakeholder engagement research targets integrated, informed approaches that analyze the impact of developmental activities on ecosystem participants (social and physical environment stakeholders) (Proctor & MacCallum, 2019). Concerning physical environment protection, areas and exclusion distances for developments and activities exist. Characterization lacks efficacy and is expensive to undertake. The initial report of impacts and identifying disturbance potential may support the protection of species and either guide or completely exclude certain areas for test site operations. In summary, the previous section shows that there are three distinct factors to consider for advantageous test site location, namely, (I) technological suitability with regard to the physical area and the data space for benchmarking, (II) social compatibility, and (III) ecological monitoring and protection.

Site characterization and selection is a process that often exceeds the resources of single companies up to entire industries (West et al., 2018). A significant component of the resource factor is the uncertainties associated with identifying sustainably relevant and sustainably operational test areas. Uncertainties may be associated with one or all of the three factors listed initially. Estimates of suitability and design characteristics amplify project risks and, in turn, project costs.

[10] Preliminary work on the development of sustainable test sites that presents the state of the art; limited related research exists.

The opportunity lies in developing a test site selection framework that considers reliable scientific data on the test site to reduce regulatory overheads. Analyzing the required technological, social, and ecological conditions for site characterization may provide substantial innovations of three factors:

I. Resource-efficient and market-oriented site characterization

II. Inclusion of a regional sustainability focus developed in institutionalized industry and public decision-making

III. Provision of proof of concept areas to boost technological change

Considering the three factors, the question on how to compose and evaluate them in an integrated way arises. Thus, allowing for a targeted sustainable test siting procedure. The following sub-chapter will henceforth discuss decision-mechanism for site characterization.

2.5 Sustainable Location Decisions

Site selection refers to the identification and evaluation of location alternatives. Manufacturing companies were the first to develop sophisticated processes to identify best-suited sites. Since then, the practice has expanded from the view of a single manufacturer to site selection for projects as complex as start-up cluster development. Depending on the selection objective, a variety of static and interactive measures are used. The categorization of these measures falls into five segments, namely logistics, economic, environment, social / political situation, and legal. Appendix 3 shows an overview of traditional measures. Figure 15 illustrates the sub-chapters that build the structure of 2.5.

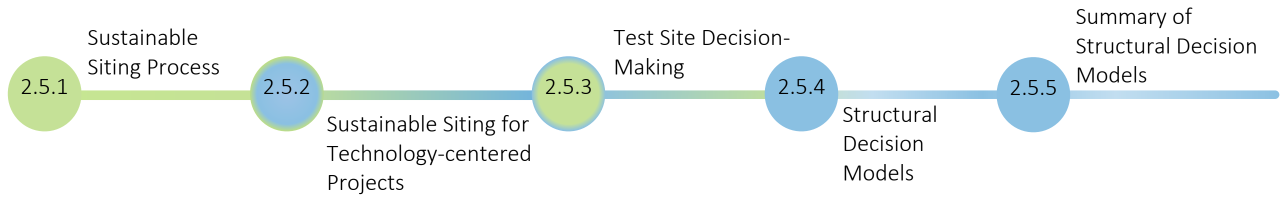


Figure 15 Chapter Structure, Location Decision-Making

This review supports the development of a structurally accurate STSDF.

2.5.1 Sustainable Siting Processes

The impact of a location decision is never purely economic, ecological, or social. Interdependencies between economic factors, ecological stewardship, and perceived value for society increase the complexity of decision-making. Different theories exist in the literature regarding the importance of each factor. Vagiona and Kamilakis (2018) conclude that social and ecological concerns may outweigh economic considerations. The following shall discuss the two.

2.5.1.1 Social Siting Considerations

Despite calls for resource conservation, a certain amount of construction and development is necessary and desired in a functioning modern society (Al Garni & Awasthi, 2018; Sonesson et al., 2016). Decision reality is accompanied by challenging relationships between communities and developers. Drawing on global databases, authors such as Andrews et al. (2001) point to a sharp rise of conflict between communities and companies. Similar notions reached common industry understanding. For example, Ernest and Young single out social acceptance as the most significant market risk to the extraction sector (Mitchell, 2020). To address concerns, Lamelas et al. (2008) and Sumathi et al. (2008) developed spatial models to assess social impacts in land use decisions. Due to the contextual dimensions of social sustainability, such models remain limited. Governance of decision-making increasingly recognizes stakeholder involvement as a factor for the informed analysis.

Proctor and MacCallum (2019) state that stakeholders can bring a shared vision of sustainability, though that may be an idealized scenario. The authors depict that the study of social barriers can lead the charge of stakeholder inclusion. Whether a site is socially sustainable or not, communities respond to or are influenced by the positive or negative risks involved in the placement (MacCallum et al., 2020). The degree to which and how communities "respond" or are "influenced by" are formative elements of social location decisions. From the literature review, five aspects appear likely to impact social favorability. These include (I) procedural sustainability, (II) context, (III) intergenerational equity, (IV) risks, and (V) social acceptance. Table 15 displays the five aspects. From Table 15, it appears that natural asset value and its contested use are driven and supported by the embeddedness of meaning, symbols, experiences, and livelihoods of the surroundings.

Table 15 Social Siting Regimes

Aspect	Conducted Research
Procedural Sustainability	Procedural social sustainability refers to political participation, participatory processes, equity, justice, inclusion, access, and a sense of shared ownership (Partridge, 2005).
Contextual Assessment	Suopajärvi and Kantola (2020), refers to contextual social sustainability as the condition within communities, including social coherence (Littig & Griessler, 2005), social capital, preservation of sociocultural characteristics (Vallance et al., 2011), or valued and protected local cultures and quality of life (Littig & Griessler, 2005; Partridge, 2005). In other words, social sustainability depends on the mitigation of negatives and the perceived value of compensational measures to communities. Assessment includes personal characteristics, perceived side effects, technological, and spatial objectives and operational factors (Langer et al., 2016).
Inter-generational Equity	The intergenerational dimension of the location decision can be viewed from the social responsibility perspective (see ISO, 2010). According to L. Chen et al. (2014, p. 155), “Cultural difference and ethical values should [..] be taken into consideration” for location decision-making. Examples of cultural analysis concepts are Hofstedes’ work on cultural traits across countries (Hofstede, 2009). As county-level characteristics differ, extending such concepts to the scope of the current research is challenged by the pre-dominant country perspective.
Risks	Conceptual work and empirical research in risk governance stem from authors such as Ortwin Renn (Kasperson et al., 1988; Renn, 2008). Research in this field includes studies that address risk perception, risk communication, or applying the precautionary principle for specific risk fields. In addition, some studies are primarily concerned with making the integrative risk governance approach applicable for selected risk fields such as location decision literature. (Tasdemir et al., 2020)
Social Acceptance	For location decisions, social acceptance considers citizens' sentiment towards the incorporation of structures in proximity to their homes or workplaces (Barragán et al., 2017). Acceptance is determined by (I) physical, (II) psycho-social, (III) social, and (IV) institutional factors. Identifiers of acceptability differ per the proximity of the project. The "proximity hypothesis" is one of the most cited concepts to analyze the spatial distribution of acceptance. Empirical research by C. E. Mueller et al. (2017) states that acceptance is likely to decrease with the proximity of planned installations. Proximity measures are not absolute, which means that single numbers or threshold calculations do not hold across regions. Geography influences proximity and thereby acceptability (Chowdhury, 2020). Seemingly unrelated factors such as mountains, valleys, rivers and seas impact perception and acceptability (Lesser et al., 2021). Moreover, intergenerational equity, especially in indigenous habitats, shows vocal differences about the considered scope of influence (Puaschunder, 2020). Recent legislations incorporate social acceptance as a legislative measure for development planning. In consequence, measures to capture acceptance are often resourced intensively. One of the most well-known methods is the stated-preference survey, used to assess the views of individuals towards sustainable energy installations. Clean Growth Strategy / Outcomes of Bonn COP23, HC 596/597 considers softening the stance of structural planning favoring communities and regions that accept and thereby allow the development of projects (House of Commons, 2017).

The nexus between competing concepts of space, cultures, corporate, financial, and geography causes current approaches to resemble "Black Boxes" rather than analytical tools. Unlike the processes of ecological compliance, engineering, and cost analysis of production, social sustainability analysis remains largely anecdotal.

2.5.1.2 Ecological Siting Considerations

According to the Simthsonian Institution (2021), extinction threatens about 15,000 of the eight million species on Earth. Most animal and plant species suffer from the loss or destruction of their habitats through direct (e.g., intensification of land use, biocides and fertilizers) or indirect (e.g., nitrogen emissions) human impacts.

There is hardly a strategy to effectively protect nature and its biodiversity in location-siting decisions (Hauck & Weisser, 2015). Existing analysis is mainly concerned with the study of species protection for construction projects. However, the transfer of species protection concepts can be a guideline for protecting (endangered) species and protecting the critical habitats of animals and plants. Legal frameworks such as the Habitats Directive, which proposes CEF (Continuous Ecological Functionality), establish the need for protection and stakeholder preferences during siting-decisions (Stotzem, 2017). Each decision-making process asks at least four questions. Table 16 depicts the questions.

Table 16 Ecological Considerations towards Location Decision-Making

Question	Scope	Definition
WHAT is protected	Target species and individual species in specific biotopes	The protection of individual target species (umbrella species) can co-protect other animal and plant species with overlapping requirements (Lambeck, 1997).
WHY is it protected	Legally prescribed protection status, stakeholder requirements, endangerment status, ecological requirements of a species	Legal frameworks provide the basic concept for ecologically informed location decision-making. However, depending on the project, the involvement of different stakeholders is necessary and / or value-adding. (Hauck & Weisser, 2015)
HOW is it protected	Type of protection measures	Knowledge about the protection of fauna is mostly limited to larger mammals. Yet, research efforts increase per the effect of mobility platforms on species. (Hauck & Weisser, 2015)
WHEN is it protected	Limited by the lifecycle of species (e.g., breeding, nesting)	The life cycle of a species is the key to successful ecological design. Only if the specific needs of the animal are met can it occur at the planning site. (Stotzem, 2017)

Other concepts such as Animal-Aided Design have emerged only recently. Animal-Aided Design studies the existence of faunas as share of the design of environments (Hauck and Weisser, 2015).

Authors such as Hauck and Weisser (2015) argue that Animal-Aided Design uses existing knowledge about the species and creates something new through design. According to the authors, the validity of such concepts only becomes apparent by developing new ideas and checking their acceptance across industries.

2.5.2 Sustainable Siting for Technology-Centered Projects

Data from several sources show that measures for sustainable technology project siting differ from traditional siting (Spyridonidou et al., 2021; Vagiona & Kamilakis, 2018). Technology-centered measures include proximity to noise sources such as electricity grids and distance to local communities and critical infrastructure (non-interpretable or unwanted component of signals) (Roddis et al., 2018; Swofford & Slattery, 2010) as well as social acceptability (Moradi et al., 2020). Among such measures, decision hierarchies exist.

For the American Wind Energy Association, first decision measures include proper technological operation and compatibility of land / area, secondary measures are ecological impacts, including risk to fauna and communities (American Wind Energy Association, 2019). Bonetto et al. (2017) set out three criteria: (I) suitability of the areas (geological restrictions, visual and acoustic noise, safety and environmental conditions), (II) ecological impact on fauna, and (III) natural assets, including wind speed (Bonetto et al., 2017).

According to these data, sustainability is a widely recognized decision-making factor for technology-centered installation siting. Ismaeel (2019) supports this by arguing that sustainable site selection is a critical step in the decision-making process with progressive effects on the rest of a project. Comparing technology-centered and facility or cluster-centered approaches reveals three distinct differences: (I) Traditional approaches put political, economic, social, and legal factors at the core of their decision-making process. (II) By contrast, technological, social, and ecological considerations dominate the technical installation perspective. This finding, while preliminary, suggests that (III) test site location decision also differs from traditional approaches and warrants caution in the use of standard measures, as they may not apply.

While scarce, the following presents the literature on test site location decision-making.

2.5.3 Test Site Decision-Making

Test site suitability relates to the effective and efficient analysis of intended performance. One of the main aspects for the suitability of a test site is the significance of the area for the intended test derivation (i.e., demonstration, calibration) (Kirincich et al., 2018; Nybacka et al., 2010). Several studies introduced test site characteristics as means to investigate the suitability of an area. Examples are from nuclear tests (Kersting et al., 1999), groundwater exchange in coastal environments, TEM methods (Foged et al., 2013; Sapia et al., 2015), and other airborne geophysical methods (Witherly et al., 2004). Few researchers cover the selection process of the test area in detail. Exceptions are by Kirincich et al. (2018), who investigate ocean testbed characterization, and King et al. (1998) for army testing. Nybacka et al. (2014) cover automotive winter testing and analyze wireless technologies in mobile railroad environments. Despite the different industries, previous literature appears to show consistency across the selection process. The most detailed outlines stem from Hannon et al. (2004). The authors build on King et al. (1998). Table 17 illustrates the selection process.

Table 17 Test Site Selection Process

Process Objective	Study Activity
Test mission definition	Testing community defines mission requirements in quantifiable environmental criteria.
Environmental requirements definition	Select the key climate, physical, and biologic characteristics of the environment necessary to achieve a test mission.
Selection for hierarchy analysis	Determine the importance of environmental parameters of interest
Selection of geographic regions	Apply screening tools to a regional analysis.
Selection of ecological parameters	Analyze the test mission to identify the ecological parameters that apply to the specific mission needs.
Selection of sites	Scientific and practical considerations used to obtain candidate sites from a selected region.
Rank sites for criteria compliance	Conduct a comparative evaluation of the local environment at each candidate site.
Rank sites according to testing mission	Use critical criteria to grade each site against each component of the test mission to make a rating of testing capability.

Source Hannon et al. (2004)

Test site requirements and test site decision criteria show similarities. (I) Climate, (II) physical location, (III) test requirements, (IV) benchmarks, (V) socio-economic background, and (VI) environmental condition are decision criteria that authors such as Hendry et al. (2010) and K. Y. Huang et al. (2021) Consider in test site performance reports. The following outlines introduce each decision criteria individually.[11]

[11] Limited research on test site decision criteria exists. Preliminary work of the author shaped the state of the art.

Climate can influence the stability of the testing conditions. For example, climatic variations may affect water bodies and total dissolved solids, which are directly related to the expression of electrical conductivity. K. Y. Huang et al. (2021) show that climatic conditions can hint at the relevance for testing. K. Y. Huang et al. (2021) argue that climate contributes to the scalar variance budgets. Similar outlines in the automotive industry show that when testing mobile conditions in extreme climates, stability or variability of the states is critical (Nybacka, 2009; Nybacka et al., 2014; Wallmark et al., 2014). Thus, and depending on the test mission, climatic conditions are important for the test robustness and may support the relevance of the test environment.

The primary concern for the **physical location** is that the area must allow equally valid data generation compared to the end-setting and other environments. The physical requirements are bound to the testing mission as well as the industry background. Challenges facing current technologies require testing in the most realistic and often challenging conditions (Kesselring, Wagner, et al., 2020). The demonstration does not always intend to show the most demanding environments. Often, demonstration bias may lead to choosing well-controlled areas.

Test requirements link to the testing or **benchmarking process** (Kesselring, Gloaguen, & Ajjabou, 2020). There is no universally adopted benchmarking process. However, most authors agree with three steps: (I) subject and process definition, (II) the identification of parameters and data sources, and (III) the determination of the difference in their adjustment and referencing (Kütz, 2022). Benchmarking can be a single measurement action or a continuous process (Witherly & Irvine, 2006). Often, companies use the same reference data to prove incremental innovations along with their portfolio (Witherly et al., 2004; Witherly & Irvine, 2006). Benchmark evaluation features the representation of the physics (e.g., geophysical formations or propagation of fluids) (Viezzoli, Roffey, et al., 2018). The higher the complexity of the background, the more spatial resolutions, variations, spatial location, illumination, and time are required. Numeric measures (e.g., accuracy, computational speed), the functionality or context of the data in the model space (e.g., physical interaction) and model interfaces (e.g., coupling dimensions of measurements) are defining factors (Zhou et al., 2018). Feeding back varying test site measurements and the cross-disciplinary evaluation of data may increase the validity of the benchmark (Ghamisi et al., 2018).

Limits of benchmark integration include the data type (Zhou et al., 2018), differences in measurement processes and times, timeliness (reusing outdated data) (Ghamisi et al., 2018), and the availability or access to data (P. K. Ahmed & Rafiq, 1998). Standardized measurement reporting (Ghamisi et al., 2019), timestamping (Zhao et al., 2017), continuous review (Das Antar et al., 2019), and the establishment of minimum disclosure marks (P. K. Ahmed & Rafiq, 1998) can minimize the limitations. Tough adaptations require test site users' willingness to adopt the benchmarking quality aspects.

Social governance risk is well-publicized, with financers and investors requiring due diligence to incorporate associated risks in project profiling. Social governance is also an area that garners interest with investment brokers who develop social and economic profiling tools (Lo & Kwan, 2017; Wei, 2021). Social and economic dimensions are a significant risk to the test site operations. Acceptance of communities links intrinsically to a project or company's social performance (Proctor & MacCallum, 2019). The test site decision literature proposes a series of indicators of socio-economic dimensions (Loukogeorgaki et al., 2018). The evaluation models focus on three broad social performance parameters: (I) existing context, (II) stakeholder engagement and relations, and (III) local content and shared value.

Considering the **ecological dimension**, the invasiveness or disturbance of technical systems is often assumed (Ajjabou et al., 2019). Maximizing domain awareness to minimize impacts on habitats and endangered species is a topic named by most test site decision scholars (Kirincich et al., 2018).

Area profiling entails multiple observations during intense site activities. Avoidance of perceived, high impact periods (e.g., nesting) is but one practical implication. Alternative methods utilizing advanced sensing of protected species are suggested, but not implemented in the profiling decision (Vagiona & Kamilakis, 2018). Existing outlines are descriptive and stop at explaining that regulations meant to protect the fauna are highly uncertain. Table 18 illustrates the categories, the scope of criteria covered for each category, and introduces the references recognizing these categories.

While the literature on windfarm selection introduces structural models for site selection, test site selection procedures are scarce. Sources depicting respective approaches use a finite set of alternatives (see Table 18), and may omit matters considering reusability, efficiency, transferability, replicability, and ease of use. In addition, existing approaches fail to acknowledge that selection of procedures should be independent. Efficient and easy to control sample procedures, including the use of new adaptive decision rules, are required.

Table 18 Categories of Test Site Selection

Category	Scope	Hannon et al. (2004)	Kirincich et al. (2018)	K. Y. Huang et al. (2021)	King et al. (1998)
Climate	Temperature	✓		✓	✓
	Rainfall	✓		✓	✓
	Humidity	✓			✓
	Atmospheric variability		✓		
Physical Location	Area size	✓			✓
	Slopes	✓			
	Relief	✓			
	Surface stream	✓			✓
	Understory	✓			
	Relief and landform	✓			
	Geology		✓		
Socio-Economic	Land use / Ownership	✓		✓	
	Cultural-historical background	✓		✓	
	Surrounding land use	✓			
	Capability to continue missions	✓		✓	
	Community integration		✓		
	Public data sharing		✓	✓	
Test Require-ments	Acceptable testing capability	✓	✓	✓	
	Quality of benchmark		✓	✓	
	Scope of context data		✓	✓	✓
	Coordinated data		✓		
	Integrated data (models)		✓		
	Logistical infrastructures			✓	
	Resource variability		✓	✓	✓
	Expressiveness of test target / resource		✓		✓
Ecological	Vegetation	✓			
	Ocean streams		✓		
	ecosystem models		✓		
	Endangered and threatened species	✓	✓		

Checkmarks indicate when a factor was considered

The analysis of multiple decision categories often requires entangled modes to evaluate and often quantify a decision category in relation to another. The following sub-chapter introduces the structural perspective on decision-making.

2.5.4 Structural Decision Models

Decision support models are techniques that transfer real-life conditions into assessable, often quantitative measures (Cozzani & Salzano, 2016). The following introduces the most used decision support tools, namely multi-criteria decision making (MCDM), Geographic Information Systems (GIS), the Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and the index methodology.

2.5.4.1 Geographical Information Systems

GIS store and visualizes station and satellite-based geographical information (Mohammed et al., 2019). GIS include "importing digital terrain data, interpolating between station data, and overlaying gridded satellite data" (Myers, 2012, p. 220). By exploiting geographical information, GIS are suitable for complex terrain and factor analysis. Various authors support the efficacy of GIS for site selection (Das & Gupta, 2021; Myers, 2012). One study by Das and Gupta (2021) examines the relationship between terrain complexity and decision support. The authors demonstrate the use of GIS to visualize comprehensive datasets and situations and show that digitally imaged findings reduce the distortion of information perception (Das & Gupta, 2021). Similarly, Dibs et al. (2018) note in their paper on surface modelling that GIS outperforms the traditional selection approaches by generating interactive information accessible to cross-disciplinary teams. Adding to this perspective, Kuznichenko et al. (2019) draw a picture of the benefits generated. The authors illustrate three main benefits: (I) provision of a coordinated view, (II) comparability of alternatives, and (III) determination of strategic short and long-term solutions (Kuznichenko et al., 2019). Authors such as Z. Liu and Cheng (2020) report on similar benefits. Data models (spread between spatial data and location markers; age of data), limited academic foundation (Rürup, 2017), and the intensity of resources required to purchase or generate GIS limit the applicability of GIS (Pettit et al., 2020).

2.5.4.2 Multi-criteria Decision Methods

The purpose of MCDM is to evaluate relative advantages and disadvantages. Outcomes are insights about the suitability or favorability of different situations. Renewable energy planning (Pohekar & Ramachandran, 2004), evaluation (C.-N. Wang et al., 2018), and policy (Kaya et al., 2019), sustainable location decision (Abdel-Basset et al., 2021), project evaluation (Khalili & Duecker, 2013), and environmental impact analysis (Cohen et al., 2019) are but few areas that apply MCDM. Table 19 displays the main steps in MCDM.

Table 19 Multi-Criteria Decision Procedure

Step	Task	Description
1	Criteria Definition	Define system evaluation criteria, in line with analysis goal
2	Generation of Alternatives	Generate alternatives to depict acceptable deviations from an optimum
3	Scoring	Score the criteria and analyses
4	Evaluation	Apply one of the normative MCDM methods (e.g., TOPSIS, AHP)
5	Identification	Identify the best alternative
6	Iteration	In case the alternatives are ill-suited, iterate.

Source Hwang and Yoon (2015)

Since late 1960, MCDM has gained recognition, with several sub-methods spinning off. Spun off research methods build on the (I) pairwise comparison, (II) scoring, or (III) outranking criteria (Ilbahar et al., 2019). AHP, analytic network process (ANP), and decision-making trial and evaluation laboratory (DEMATEL) are examples for pairwise comparison (Ocampo et al., 2019). Scoring-based methods are multi-attribute utility theory (MAUT), multi-attribute value theory (MAVT), multi-objective decision making (MODM), and TOPSIS (I. B. Huang et al., 2011).

Outranking of alternatives is performed with methods such as ELimination Et Choix Traduisant la REalité (ELECTRE), preference ranking organization method for enrichment of evaluations (PROMETHEE), and visekriterijumsko compromise rangiranje (VIKOR) (J.-P. Brans & Smet, 2016). Recently published works increasingly use PROMETHEE for sustainability assessment to solve sustainability centered decision making (PROSA) (Ziemba et al., 2017).

The classification is not exclusive. A critical review of Ilbahar et al. (2019) and Penadés-Plà et al. (2016) shows that some ranking based methods also employ pairwise comparison (e.g., PROMETHEE). Still, it provides a first classification of the methods by using the dominant logic of the method in question. The methods vary concerning their applicability for sustainable as well as technology-centered location decision-making (C.-N. Wang et al., 2018).

Papers that employ one or more MCDM build on the narrative that technological performance associates with systems' geographical location (Rikalovic et al., 2014). Factors affecting the suitability of MCDM for technology-centered siting decisions are hardly examined. Despite the lack of literature, the reviewed scholarly work indicates that AHP, TOPSIS, MAUT, PROMETHEE, and PROSA are most applied for technology-centered location citing.

Table 20 provides an overview of the methods and their siting context.

Table 20 Multi-Criteria Decision Making in Technology-Centered References

Method	Description	Place Selection	Advantages / Disadvantages
AHP	Breaks down the criteria into a weighted hierarchy	Hydropower (Supriyasilp et al., 2009), wind farm (Al-Yahyai et al., 2012), solar farms (Tahri et al., 2015)	• Robust results as it calculates decision-maker's inconsistency • Ability to reproduce results • Traceability of calculation failures
TOPSIS	Analyzes the shortest distance between ideal solutions and alternatives	Thermal power plant (Choudhary & Shankar, 2012); solar farm (Nazari et al., 2018); wind power (Solangi et al., 2018); vehicle charging stations (S. Guo & Zhao, 2015)	• Allows for precise analysis of differences • Highly complex • Impreciseness in real-world problems (Salih et al., 2019)
PROME-THEE	Outranks alternatives by pair-wise comparison	Offshore wind farm (Yunna Wu et al., 2020); vehicle charging station (Yunna Wu et al., 2016); Solar power (Yunna Wu et al., 2019)	• Ease of use and • Completeness of ranking • Highly advanced analytical tools (i.e., sensitivity analysis and visualization
ELECTRE	Analyzes relations and exploitation notions of concordance	Solar power, wind farms (Erdin & Ozkaya, 2019); Off-shore wind farm site selection (Abdel-Basset et al., 2021)	• Handling discrete criteria • Both quantitative and qualitative • Complete ordering of the alternatives • Robust results as it provides a judgment on degree of credibility for outranking relations
PROSA	Interval based outranking which further integrates sustainability measures	Offshore wind farms (Ziemba et al., 2017)	• Transparency • Ease of use • Compatible with analytical tools available in PROMETHEE • Limits linear compensation of criteria • Little evidence for applicability
MAUT	Defines a utility function to decide over a set of attributes	Wind farms (Shakirov et al., 2019)	• Allows a high number of independent criteria / alternatives • Purely normative / no concept behind item weighting

The table builds on a systematic literature review. Search terms used are the “respective method” (e.g., AHP) AND “location siting” AND “technology”. In case the title includes the respective method, the paper was scanned and if applicable, considered.

Given the long history of the approach, several reviews on the general applicability (Yap et al., 2019), or industry-specific analysis (Shao et al., 2020) exist. According to the reviews, the most common tools for MCDM are AHP and TOPSIS (Yap et al., 2019). Despite positive reviews, critics argue that MCDM is flawed by incomplete information and utilization of respective data in the decision-making process and a poor representation of interacting entities (Odu, 2019). Appendix 4 provides a detailed account on AHP, TOPSIS, and PROMETHEE. The three methods are well proven for technology-centered decision-making, are most recognized by the analyzed literature, and represent each of the MDCM methods (pairwise comparison, scoring, and outranking).

2.5.4.3 Index Method

An index is an aggregated representation of a situation. Situations are aggregated until one final descriptive value is generated. The index aggregates complex conditions, which necessitates considering entire index systems rather than single measurement (Eichhorn et al., 2017). Besides economics, indices are a well-known tool in social sciences (Häder, 2015) to support the understandability of multidimensional phenomena (Organisation for Economic Co-operation and Development (OECD), 2008). Indices can be composed of sub-indices or be a standalone index. Like indices, sub-indices build on a certain number of dimensions (or pillars).

Such measurements can manifest in political, economic (Hickel, 2020), social, legal (Singh et al., 2021), technological (Gründler & Krieger, 2018; Jovanović et al., 2018), biological (Ruaro et al., 2020), or other categories. Within a dimension, different factors describe the elements influencing the phenomenon in question. Factors within a sub-index can work as standalone representations of a situation or an aggregated view on circumstances. Due to the granularity, the OECD (2008) refers to indices as “composite indicators”. According to the institutions, indices built the foundation for interdisciplinary discourse about the index-related topic (OECD, 2008). Therefore, Häder (2015) and the OECD (2008) claim that usability determines the operability of an index.

2.5.4.4 Combination of Structural Decision Models

Several studies examined the extent to which the different decision approaches can complement each other. Various studies assessed the efficacy of GIS and MCDM compatibility for new energy resources. Examples come from Villacreses et al. (2017), who considered solar farm locations with a combination of GIS, MCDM methods, including AHP and TOPSIS. Reported benefits are improved insights for policymakers to enhance and better understand selection between options in sometimes conflicting criteria fields. Other examples include the combination of GIS, TOPSIS, and indices to obtain a siting suitability index. Examples include Al-Yahyai et al. (2012), Seyedmohammadi et al. (2018), and Aydin et al. (2010), who used GIS and ordinal weighting for wind farm siting.

Collectively, these studies show that mostly supplementary methods are combined, which means that practices either stem from pairwise comparison, scoring or outranking of criteria. Two methods for pairwise comparison are hardly ever combined.

2.5.5 Summary of Structural Decision Models

Previous studies dealt with location decision-making for sustainable technology installations and test site location decisions. Existing test site approaches fail to deliver assessments concerning the benchmark quality and notes on how to perform tests with high social acceptance and little ecological impact. Moreover, a structural site assessment is a powerful but complex and resource-intensive task.

As sustainability awareness increases, the amount of stakeholder requirements added to decision-making complicates the process. In consequence, a model to support preliminary decision options is required. Process and resource costs may be reduced if decision-making can be streamlined with the framework.

2.6 Summary of Deficits and Insights from the State of the Art

The main goal of the current study is to develop an STSDF for highly innovative sensing technologies. To do so, the investigation reviewed state of the art in literature and technologies. The literature reveals that STD focuses on economic and ecologically sustainable design of functions, products, and intralogistics. However, even though ecological, and social risks rank top on the sustainable agenda, researchers have not treated the sustainability of the application of the product in much detail.

Moving to technology testing, virtual testing is a fast-emerging research field. However, the demonstration and audit part of testing continues to require physical tests. With a high degree of uncertainty and investment risk, this is especially the case for sensing systems. Previous studies showed that the suitability of physical test areas is bound to the fit of the target area and robust benchmarks. In the current literature, benchmarks are loosely defined.

Most studies refer to the requirement for solid benchmarks and the resource intensity associated with their development. However, the appropriateness of context-dependent data varies depending on the scope, scale, timeliness, and quality of data significantly. Closing this research gap is important for technical decision-making. The sustainability of technical operations further builds on social and ecological impacts.

Existing research pays little attention to social and ecological stewardship in conjunction with technical performance. Regarding sensing technologies, both publication and patent analysis showed a robust research intensity. The research intensity is partly accounted for by the cross-disciplinary applicability of measurement technologies. Innovation drivers of sensing development are economic, social, ecological, and technological. Due to the ambiguity of physically distant or covered research targets, such technologies are highly uncertain. Technologies such as the FTMG (helium-cooled, magnetic system) pose logistical challenges to often cross-disciplinary industry players.

Physical testing, which often exceeds the capacity of entire industries, is a substantial obstacle to market entry. An originating requirement is unified, resource-effective, decision-making support systems for physical tests. As far as location decision-making is concerned, traditional siting approaches appear unfit for technological systems. A comparison between renewable energy siting and manufacturing-centered approaches provides evidence. By construction, renewable energy technologies are sustainable. Public discourse on siting intensifies the consciousness.

Selection criteria such as fit for technical purpose, distance to human settlements, or acceptance of installations and fauna observation were proposed. The test site selection literature follows similar selection criteria. Different from the literature on permanent structures, few papers address this topic.

Among the reviewed literature, only two scholars coined their approach sustainable. Social compatibility has received only limited attention to date. Previous studies focus on favorable ecological conditions. Stewardship of ecological health (e.g., fauna protection or mitigation considerations) and social sustainability are hardly recognized. Siting criteria evaluation employs a combination of GIS, MCDM's or indices. No standardized procedure for recurring decision processes is available. For multi-purpose sensing systems, iteration of test site selection is important, meaning that as system performance or targets change, so does the suitability of a test site. The appropriateness of exhaustive, static, and single-use decision frameworks is therefore questionable.

Together the thesis analyzed STD, technological testing, state of the art sensing technologies, systems, and sustainable location decision-making. Figure 16 summarizes the literature review and builds connections to existing gaps in the literature, as discussed henceforth.

The figure illustrates the theoretical content analyzed so far on the left side. The right side of the figure is a representation of the insights gained from the theoretical review. The figure intends to represent relationships between abstract theoretical objects and the identified insights. It is noted that there is no uniquely correct solution to the knowledge gaps identified.

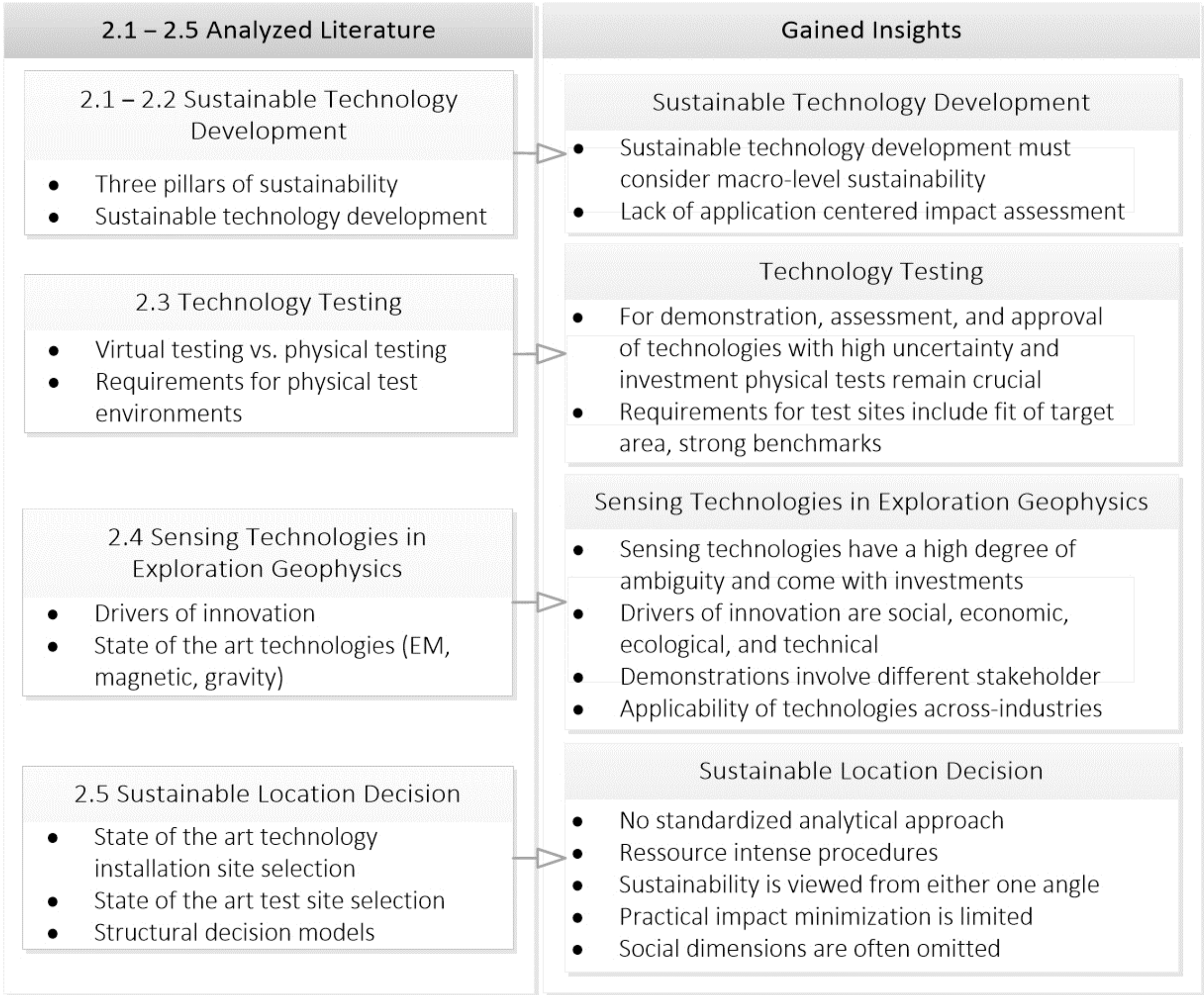


Figure 16 Overview on State of the Art and Gained Insights

Overall, the state of the art analysis strengthens the need for a dynamic test site decision framework. Drawing upon the research goal, the following attempts to establish a sustainable test site decision framework that meets stakeholder requirements and contributes to closing the research gaps.

3 Sustainable Test Site Development Framework Approach

Chapter three sets the conceptual frame for the STSDF. It elaborates on requirements clarifies the underlying assumptions, and justifies the methodological decisions taken for developing the STSDF. The chapter provides a founded argument on whether to consider a specific decision factor for the STSDF.

Chapter three is structured into five sub-chapters. It starts with an analysis of general research needs and stakeholder requirements[12], the STSDF must meet (3.1). The second sub-chapter is devoted to technical limitations. Here, technology-centered location decision-making and industry limitations are illustrated and their relevance for the STSDF is discussed. 3.2 concludes with a detailed account of technology test site conditions in mineral exploration. The third sub-chapter (3.3) introduces the scope of ecological sustainability considered. 3.4 considers the social framework scope.

Building on these insights, 3.5 introduces the metamodel of the STSDF.

3.1 Requirements for the Sustainable Test Site Development Framework

The STSDF aims to provide a decision-making tool for identifying and developing global test sites. The STSDF is meant to determine the favorability of test sites for technological performance improvement and demonstration purposes under technical, social, and ecological considerations. From the literature review and the analysis of deficits and insights (see 2.6) a set of STSDF development requirements emerge.

The requirements include stakeholder requirements and research requirements. Stakeholder requirements build on the idea that innovation, knowledge, and growth must be facilitated through company and industry specific decision-tools. In addition, and to invigorate sustainable test sites, social and ecological dialogue and research are required to improve test site systems.

Figure 17 illustrates the insights derived. It clusters the stakeholder requirements into sustainability- and technology-centered requirements. The rectangular items indicate the parts that are required and depict the sub-chapter where the insight was derived from.

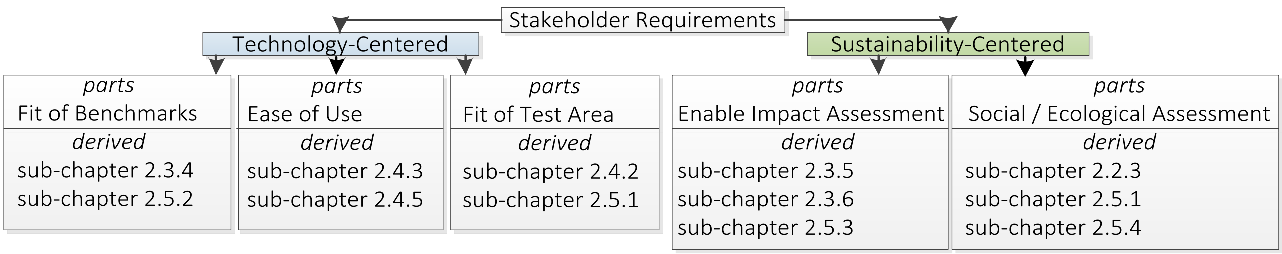


Figure 17 Stakeholder Requirements for Sustainable Test Site Decision-Making

Emerging from the theoretical and stakeholder perspective, research needs exist. Research is required to drive technology development while improving the sustainability of test sites in terms of ecological impact and social acceptability.

Per technology performance, research into the verification of out-performance of the respected state of the art is required. Considering social and ecological aspects, the thesis must analyze how a range of societal relationships and ecological challenges can be introduced into an integrated decision-framework.

[12] The expression requirement, is used to depict a condition or an ability which the STSDF *needs* to possess.

Figure 18 illustrates the insights derived. It clusters the research needs into sustainability- and technology-centered requirements. The rectangular items indicate the research gaps that require overcoming and depict the sub-chapter where the insight was derived from.

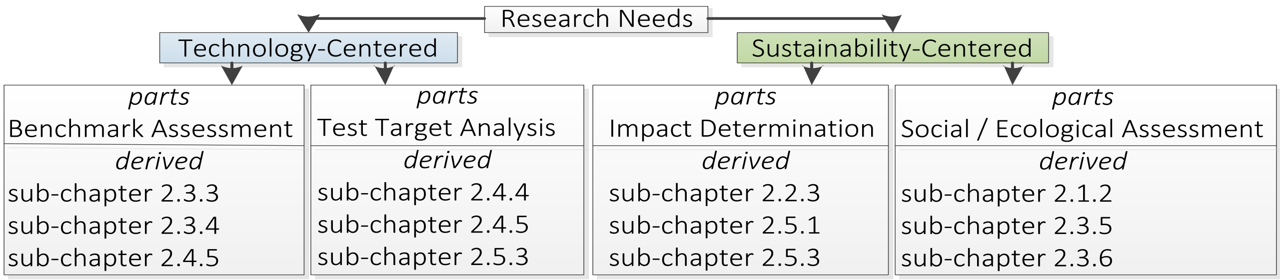


Figure 18 Research Needs Derived from the State of the Art

Together, Figure 16, Figure 17, and Figure 18 illustrate the transition from state of the art, state of required research to the STSDF. These visualizations offer a classification of process views on sustainable test site decision-making studies. Distinctions between stakeholder and research needs provide a distinctive view on the entities to be conceptualized in test site analysis.

From this point the thesis explores the stakeholder requirements in detail and closes the research gaps, finally integrating both perspectives. Prior to the research flow and framework development process the context for the development must be set. The context is embedded in the research and stakeholder requirements and shall set the frame for what is to follow. The context is extracted from the literature and formulated as assumptions[13]. The assumptions are as follows:

I. Technology developers and stakeholders of a test site have an interest in testing and demonstrating the performance of technologies (derived; sub-chapter 2.2)
II. Sustainable technologies have to adhere to macro-level conditions (derived; sub-chapter 2.3)
III. Technology test sites are embedded in a socio-ecological context (derived; sub-chapter 2.4)
IV. Differences in natural settings and benchmarks influence the suitability of test sites (derived; sub-chapter 2.4)
V. Test site decision-making lies in the nexus between technical progress and investment decisions. Managers and technology developers require different degrees of information granularity (derived; sub-chapter 2.5)

From the assumptions and the stakeholder requirements and the review on decision-making by Greco et al. (2019), STSDF design criteria emerge. Design criteria can guide in the selection of methodologies for process, structural, and content data (Greco et al., 2019).

For the thesis the design criteria shall incorporate the assumptions, to stipulate and guide the STSDF development. From these considerations, five design criteria for the STSDF are identified. Hence, the STSDF shall:

I. be relevant
II. be easy to understand
III. provide multidimensional information
IV. ensure comparability between test sites
V. be replicable.

[13] Assumptions recognize that there are factors beyond the STSDF control that are necessary to realize the research objective. The assumptions build on the literature review.

Relevance refers to the fit of the framework for industry and research. Like other technical investments, test sites advance TD-related knowledge as well as physical, biological, and atmospheric conditions of natural phenomena.

Depending on the technical equipment to be tested, and the regulations in place, the contribution to innovation differ. Hence, the relevance of test sites can differ. Relevance criteria are the scale and scope of decision-making factors.

The second criterion roots in the need to include different stakeholder interests in the decision-making process. Traditionally, TD builds on micro-level requirements that make a technology fit for purpose. Sustainability approaches bring additional dimensions into this discussion as they widen what is considered part of the environment (micro vs. macro).

Increasing scope requires the provision of an interface between technical requirements and social and ecological aspects. In addition, technical and managerial staff require different depths of information levels to come to a decision.

Together, it is therefore of value to achieve a shared understanding of both technology developers who are familiar with the technical requirements and those who are familiar with the economic investment decisions and the social and ecological perspective of a natural area.

The multidimensional nature of test site environments is the third requirement. Multi-dimensionality is required as decision factors vary in importance and the complexity of sustainability cannot be expressed in a single equation.

The fourth design criterion stems from the target group definition of the test sites. The target group are technology developers and test site developers. Both parties must compare the suitability of one site over another. In this way, an informed investment (e.g., test time) emerges.

Finally, the fifth design criterion relates to the transferability of the STSDF. To ensure long-term scientific contribution of the framework, the STSDF must be replicable. In this way, researchers or practitioners may adapt the STSDF replicate, improve, and extend it.

3.2 Technical Sustainability Framework Design Considerations

The following sub-chapters discuss location decision-making, limitations, and industry context.

3.2.1 Location Decision Considerations

The economic, technological, and social and physical environment influence the technical fit and degree of sustainability of the STSDF. Table 21 discusses the relevance of the aspects for the STSDF. From the analysis of the aspects, all four remain relevant for the STSDF.

The analysis of the economic perspective reveals a close link between strategic technical investments, future trends, and challenges. For demonstration and technical progress, the technical and physical / ecological aspects are closely linked.

Given the relevance for the technology developer rather than the public space, the technical and physical target environment are henceforth combined, and the ecological environment becomes a decision criterion.

Technical and physical target environment will further be referred to as the requirement space for the technology developer (technical requirements). The social environment will be part of the social sustainability discussion.

Table 21 Aspects of Test Site Evaluation

Factor	Explanation	
Economic	Economic considerations differ from those made in traditional site selection. Authors associate economic aspects with the strategic value of the test site for the market (Neurohr et al., 2021). Hence, favorable economic requirements relate to the environment in questions depicting strategically relevant challenges. In mineral exploration, targets may lie at a certain depth, or in remote areas (e.g., arctic). Costs of deeper exploration are comparatively higher and the uncertainty in test data increases (Dentith & Mudge, 2014). Here physical tests that are representative of such challenges are required. Whether an area captures the strategic relevance for future trends and challenges is essential for the decision-making process. Economic aspects including the creation of jobs or increases in local income (e.g., tourism) are omitted. This is the case as occupation rates of test sites are limited (Kesselring et al., 2021), and operations are expert-driven rather than requiring local labor.[14] As of the misleading term, economic, this aspect is further referred to as strategic space relevance for future trends and challenges.	✓
Technological	Technological considerations refer to the quality of the reference data set. Technology developer that focus on advancing the sensing of protected species, a geological property or a plant want to prove that they perform better than the status quo. Therefore, applicability of technology refers to how well reference data sets may be employed for comparison. Applicability is a main factor determining the attractiveness of the test site. Hence, the decision-making model considers reference data sets.	✓
Social Environment	At the local level, testing activities would direct feedback into the regional industry and public via stakeholder engagement and involvement activities (Proctor & MacCallum, 2019). At the national level, aspects related to the exploration and exploitation of test site were analyzed by Kesselring et al. (2021). The authors show that engaged communities may support the development of test sites. Stakeholder and community engagement are relevant subjects once a selection process has narrowed down options. The social environment through social acceptance is therefore out of the decision-making scope. Please note that social sustainability remains relevant and will be subject to section 4.3.	✓
Ecological Environment	The applicability of an environment is a pre-condition for test missions. Applicability refers to aspects concerning the physical target area. Take the case of airborne sensing as an example. If a target area has just the scope of the target itself, it may be questionable whether helicopter-borne sensing devices are suitable to test (Dentith & Mudge, 2014). In addition, sustainability is the focus of this thesis, and the previous literature review showed the relevance for ecological monitoring and compatibility. Consequently, the physical target area is an assessment criterion.	✓

Checkmarks affirm the relevance; crosses indicate non-applicability for the STSDF

3.2.2 Industry Framework Considerations

Even though the initial research interest extends to the whole range of technology testing in natural environments, the scope of the present dissertation is limited to sensing technologies.

To ensure the fit of the model and advance the scientific discourse, the application scenario is further limited. To evaluate which technical field might offer sufficient data and potential transferability, two papers have been published over the course of the work of this dissertation.

The first paper is a joint research paper with Ruiz-Coupeau, Jürgens, et al. (2020) on patent analysis for sustainable sensing technologies. In the second paper, Kesselring et al. (2021) analyze how technology and knowledge are transferred across natural sciences.

The sciences in question were analyzed regarding the following criteria:

[14] One might argue that helicopter services may be hired locally. Given the specific industry knowledge of such services, local expertise development beyond commercial flights is necessary.

I. Degree of coverage of physical parameters
II. High absorptive capacity indicating heightened testing and demonstration requirements
III. Connectedness and transferability of technologies and players in the field
IV. The cumulative number of existing test site facilities
V. The degree of risk imposed through social and ecological challenges

Mineral exploration as a use case matches these criteria.

3.2.3 Case Study – Mineral Exploration

Mineral exploration refers to the search, identification, and often the analysis of a quantifiable grade of ore deposits. The grade is a measurement for determining the number of metals and minerals in a rock body. Discoveries are either referred to as reserves, classified as a profitable exploitation occurrence or as a resource, or defined as a resource that is not immediately profitable or extractable.

As circumstances change, many discoveries classified as uneconomic can become profitable and vice versa. These circumstances can be (I) economic, (II) ecological, (III) legal / political, or (IV) social. For example, if progress lowers the marginal cost of extraction or environmental erosion and infrastructure development, this may tip the scale towards exploitation. (Dentith & Mudge, 2014)

Mineral exploration plays a pivotal role in natural sciences. Evidence from a patent analysis by the author, published in cooperation with Ruiz-Coupeau, Jürgens and Herrero (Ruiz-Coupeau, Kesselring, et al., 2020), reveals that mineral exploration has a high network centrality in natural sciences and fulfils the industry requirements illustrated in 3.2.2.

Appendix 5 discusses each industry criterion individually. Considering the objective of this thesis, (I) technological, (II) social, (III) ecological, and (IV) economic aspects to testing is discussed in the following.

Technical aspects: As shown, systems employed in mineral exploration target different physical properties of mineralization or an area of interest. The detectability or presence of physical properties varies. Consequently, existing test sites often focus on a specific range of equipment. Exemplary for calibration, and physical tests are the test sites in Denmark (Foged et al., 2013), Australia (Australian Society of Exploration Geophysicists, 2016), Canada (Witherly & Irvine, 2006), and Italy (Sapia et al., 2015) that serve to study TEM. Other test sites, such as the Canadian Reid Mahaffy, specialize in technologies related particularly to airborne geophysical methods (Witherly et al., 2004). In addition to the specialized testing grounds, efforts to develop test sites that serve several sectors in parallel exist (Kesselring et al., 2021). Table 22 displays an account of existing test sites and their scope.

Regarding social and ecological factors, social acceptance is named the highest risk of an exploration project, while ecological compatibility (especially concerning platforms and invasive technologies) is among the top drivers of technological change. Despite the numerous test sites available, little progress concerning their sustainability exist. None of the existing areas considers social and ecological factors when testing a technology. The absence leaves room for interpretability of their sustainability and leaves aside efforts to improve awareness of social and ecological risks in mineral exploration. In this regard, increased efforts could enhance the value of test sites.

Economic necessities result from the ambiguity of test results. Credible verification of performance is hoped to reduce technical adoption barriers and confidence to exploration decision-makers, and stakeholders, and civil society.

Table 22 Test Sites in Mineral Exploration – Overview

	Technical Suitability							Area Markers										Tests	
Test Sites	Magnetics	Radiometric	Hyperspectral	Gravity	EM	Hydrogeology	Earth Observation	Remining	Airborne Testing	Ground-data	Surface Targets	Shallow Targets	Deep Targets	AIP benchmarks	Close economic Orebodies	Accessibility	Well-developed Logistics	Calibration	Tests and Demonstration
Alexandria, US				✓					✓	✓					✓	✓	✓	✓	
Breckenridge, US		✓							✓						✓	✓	✓	✓	✓
Reid Mahaffy, CA	✓				✓	✓			✓	✓		✓		✓	✓	✓	✓	✓	✓
Caber, CA					✓				✓				✓	✓	✓		✓	✓	
RJ Smith, AUS	✓			✓					✓	✓	✓	✓			✓	✓	✓		✓
Forrestania, AUS					✓				✓	✓		✓			✓	✓	✓		
Nepean, AUS					✓				✓	✓		✓	✓	✓	✓				
Carmanah, AUS					✓		✓	✓	✓	✓		✓			✓	✓			✓
Sensys Sensorik, DE	✓									✓	✓	✓			✓	✓			✓
Leicester, UK										✓		✓			✓	✓			
Nantes Lab, FR										✓	✓	✓			✓	✓			
Lingby, UK					✓		✓		✓			✓			✓	✓	✓		✓
San Rossore, IT					✓		✓			✓		✓			✓	✓	✓		
Vredefort, SA	✓				✓		✓		✓	✓		✓	✓		✓	✓	✓	✓	✓

Checkmarks and green coloring indicate when a factor is applicable / is considered
Source Own Representation aligned to Grant agreement ID: 776487, 2017

Summing up section 3.2, the primary challenges and future lines of research lie in reducing destructiveness and analyzing the social sustainability of current mineral activities, and achieving sustainable technologies already during the development of new mineral activities.

3.3 Ecological Sustainability Framework Design Considerations

Turning to the scope of ecological sustainability considered in the STSDF, test sites often come with different degrees of ecological impacts. They can be direct or indirect and affect (I) fauna, (II) flora, (III) water, (IV) air, and (V) soil. Table 23 presents the breakdown of the direct and indirect effects on the ecology through test sites.

The table discusses the integrability of these effects into the decision frameworks. Checkmarks affirm the relevance, crosses indicate non-applicability for the STSDF. Non-applicable aspects will not be considered in the STSDF. The impacts discussed in the table depend on the attributes of the local environment and the type of testing activities. The need to reduce operational stress drives current innovation activities in natural sciences and especially mineral exploration.

As Ruiz-Coupeau, Jürgens, et al. (2020, p. 9761) state, "stressors of mineral exploration may be bound to the platform (e.g., helicopter vs. drones) or the exploration technique (e.g., extraction or sensing)". As innovation moves in a less-invasive direction and given the background of the current thesis, only those technologies are considered which do not extract the rock.

Admittedly, innovation in mineral exploration is not limited to geophysical exploration (non-extracting methods). It is however beyond the scope of this study to examine later stages of mineral exploration. This is partly because extractive methods are distinct for mineral exploration, but less representative of other natural sciences. Another reason is that the extraction does not fall in the scope of sustainable test sites. Based on Table 23, disturbance to fauna, and flora will be included as decision-making factors.

Table 23 Ecological Assessment Limitations

Factor	Explanation	
Fauna	Disturbance of different platforms to fauna are well-documented and included in the STSDF.	✓
Atmosphere	The climate impact of exploration methods may among others be tied to the platform and related logistics. Technical reports hardly list the causes of climate stress. The INFACT project calculates the emission by fuel consumption (kg/hour or liters/km). Logistical considerations are quantifiable but lie outside the test site jurisdiction (INFACT, 2018). However, the proximity of logistical infrastructure is a factor that is favorable in itself. Consequently, the framework integrates logistical emissions as a measure of closeness to logistical infrastructure (see 5.3). Testing related impacts emerge from the platforms employed (UAS, helicopter, fixed-wing). According to INFACT experts, atmospheric impacts may vary across platforms (INFACT, 2018). Hence, emissions that occur during the campaign depend on third party disclosure. And as systems that are designed for specific purposes may account for fixed aspects of testing, the circumstance warrants exclusion. The exclusion shall not encourage to omit scope two and three emissions in future research.	×
Flora	Sources of flora alteration include soil extraction and trampling. Ground-work may cause punctual alterations on flora and crops. Regularly, governmental institutions forbid trampling in areas where protectable plants grow or limit trampling to post-harvest season. (see INFACT D6.1.) From the test site perspective, seasonal requirements may cause limits in testing times. Vegetation protection is yet a factor that may cause a decline in attractiveness. In consequence, it is a critical decision factor. *(Included as means of accessibility in technical evaluation).*	✓
Water	The work is limited to land-borne, non-invasive methods. Considerations towards water quality are therefore omitted. The thesis recognizes dependencies between air, soil, and fauna, but argues with the limited accessibility of testing data and probing grounds.	×
Soil	The work is limited to land-borne, non-invasive methods. Considerations towards soil horizons may occur through airwill or heavy machinery. As no deeper horizon effects are reported on, this factor is neglect able. The thesis recognizes dependencies between the factors, providing non-invasiveness no destructive analysis shall be considered.	×

Checkmarks affirm the relevance; crosses indicate non-applicability for the STSDF

3.4 Social Sustainability Framework Design Considerations

Mineral exploration provides products and services integral to lifestyle expectations Western society has grown accustomed to. However, negative public perception is caused by land use conflicts and a lack of knowledge about the benefits of mineral exploration for daily consumption patterns (Proctor & MacCallum, 2019). For example, mineral exploration is a precursor to mining and a potential 'blot' on the landscape. And while society may benefit from mining, local communities carry the negative impact. In economics, this has been termed a `NIMBY' good, the abbreviation standing for not-in-my-backyard (Dear, 1992; McGurty, 1997). Yet it is the social sciences, not the natural sciences that are concerned with the matter despite the interdependencies with the ability to develop technology efficiently and effectively (Badera, 2014). For test sites, consistent social consideration starting from the outset of exploration can help maximize the site's potential. Social considerations require an accessible and responsive assessment mechanism. While social concerns may be broad and fall within the initial research question, the technical considerations towards quantifiability and ease of use place limits on the scope for the purpose of this work. Table 24 presents the breakdown of the topics which define social sustainability as introduced in section 2.3.5. Checkmarks represent those factors considered relevant for location decision-making. Crosses mark non-applicable factors. The STSDF will not consider those factors.

Table 24 contents show that impacts on the living environment and contextual social sustainability (associated interdependencies) are relevant for the STSDF. The thesis recognizes that transparent and reliable information sharing is a feature of social sustainability. Effective communications and information (and continuous consent) is an ongoing process and may act as a tool to integrate the concepts of the tables into the STSDF.

Table 24 Social Sustainability Components Evaluation

Concepts	Explanation	
Contextual social sustainability	Acceptability and perceived importance of test sites vary by community and are highly contextual. Especially for industries associated with destructive operations, contextual aspects greatly influence the sustainability of the process. Consequently, the degree to which different factors or indicators mirror the contextual relationship is critical.	✓
Economic and employment from a social perspective	Preliminary work of the present author analyzed the potential to integrate economic measures into test site decisions. By analyzing the expected occupation rate of test sites for mineral exploration, though desired it emerges that single test sites have a limited impact on the economic structure. Therefore the thesis excludes economic and employment perspectives from further investigation. (Kesselring et al., 2021)	✗
Impacts on the living environment	Test sites in mineral exploration cause impacts on the viewshed via (I) airwill, (II) platforms, and (III) a heightened amount of people. Concerning heightened occupation, the literature on business models for mineral exploration test sites (Kesselring, Wagner, et al., 2020)[15], suggest that the frequency of test site usage correlates with the frequency of innovations within an industry. Demonstrations in mineral exploration mostly allow one demonstration at a time, test teams rarely exceed ten people[16]. Demonstration time-span in mineral exploration may be up to two weeks (see campaign planning in Grant agreement ID: 776487, 2017). Depending on the test area, the frequency and scale of test site occupation suggest no significant change in the viewshed. Thus, the thesis excludes infrastructural aspects from further study. Airwill and platforms may impact the viewshed. Communication, collaboration, and monitoring can mitigate or minimized distress. Analyzing the pollutants associated with testing can mitigate social impacts. Given the potential of pollution through platforms such as UAS's, or helicopters the thesis considers impacts on the living environment.	✓
Procedural social sustainability	The perception of projects (test-sites) varies by county. Local communities set their own standards. To ensure a high ease of use across counties, the thesis excludes country-specific (procedural) social sustainability assessments from further analysis.	✗
Regulation & CSR	Regulation can secure better participation rights for the stakeholders and different kinds of mandatory impact assessments. Establishing rules for accepted standards at test sites creates a baseline for responsible practice. Regulatory requirements can impact the operations at a test site. In contrast, weak regulatory systems may allow industry players to exert more control and flexibility over the practices to operate at test sites. Regulatory frameworks are subject to improving the social sustainability of the operation rather than assessing their status quo. Therefore, the STSDF will exclude regulation and CSR considerations. Yet, regulatory setups require early reflection.	✗
Sociology of expectations	Much of the concepts within social testing (Table 4) either focus on the design (e.g., TAM, UTAUT), ex-post TD or future markets. Only the sociology of expectations is connected to demonstrations of technological behavior with socio-technical and technical-economic (e.g., demonstration and investment). Data about the efficacy of expectations are limited. The connection between ecology, economy, sociology, and technology remains understudied. The impact on the living environment is thus analyzed.	✓
Intergenerational equity	Challenge for intergenerational equity may occur for an exploitative project where today's set-up may influence future generations. For non-permanent testing grounds, remediation may be omitted.	✗

Checkmarks affirm the relevance; crosses indicate non-applicability for the STSDF

Despite excluding the initial decision-making strategies, the discussed concepts may be relevant to consider in future research. A reasonable approach to maintain the integrity of the STSDF is to monitor advances in social sustainability and integrate new insights into the framework.

[15] Reference from preliminary work that present the state of the art. The reference is the single one identified reference on sustainable business models in mineral exploration.

[16] Ten people was hardly exceeded for industry field work during the INFACT test operations.

3.5 Metamodel of the Sustainable Test Site Decision Framework

The previous sections set the scope of the STSDF. Figure 19 summarizes the considered topics and limitations. Bold lettered concepts were included. Notice that the feasibility of STSDF is discussed in the following.

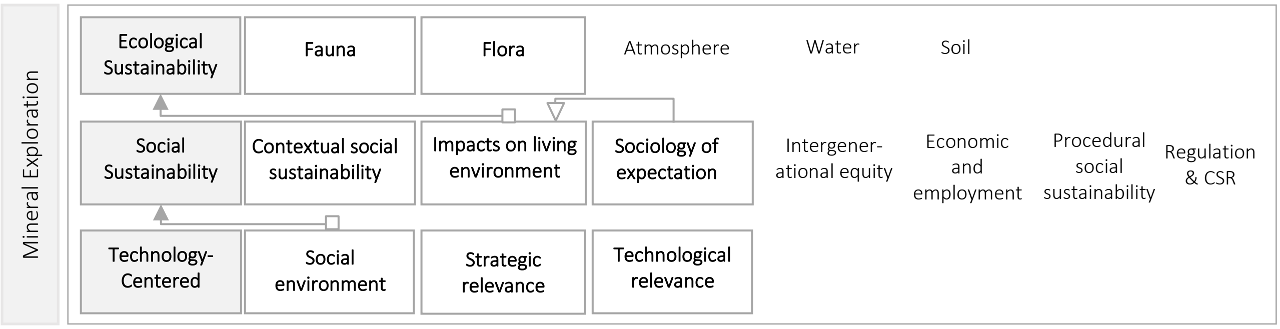


Figure 19 Overview Limitation Decision

Building on these insights, the research enables the derivation of a first metamodel. The metamodel uses the remaining topics to produce a model of the connection between social, ecological and technical decision aspects in the STSDF.

The metamodel serves as a deliberate way to rationalize the decision spaces and their connections. The metamodel concept proposes a solution to address test site decision problems and facilitate the development and communication of the STSDF. Figure 20 displays the metamodel.

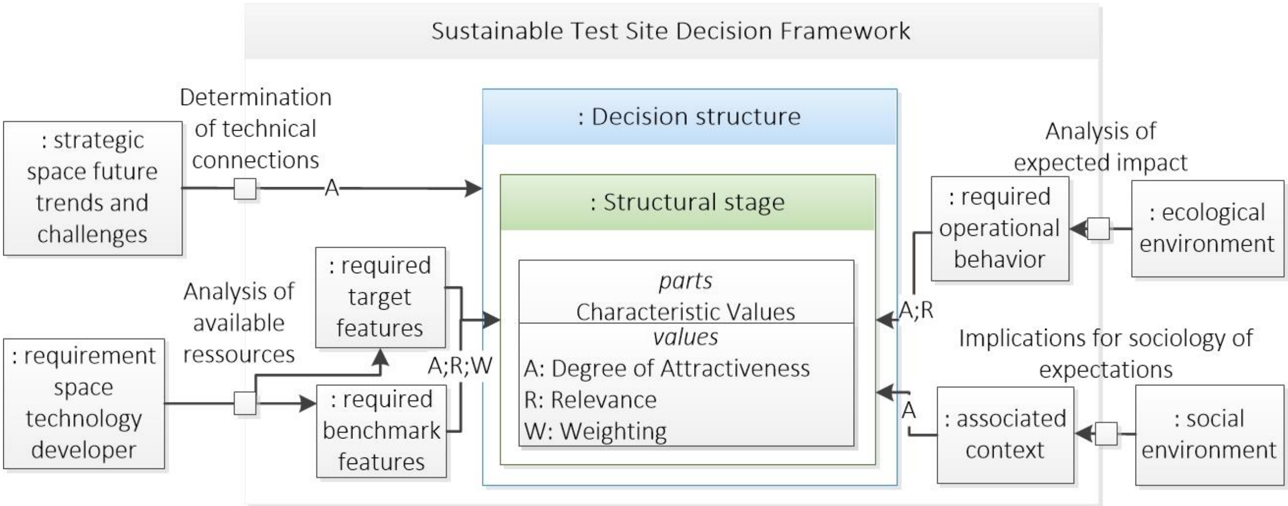


Figure 20 Metamodel of the Sustainable Test Site Decision Framework

The developed metamodel includes (I) the strategic space, future opportunities and challenges; (II) the requirement space of technology developer; (III) ecological sustainability of fauna and flora conditions; (IV) the social environment concerning impacts on the living environment and contextual social sustainability. It connects each of these decision components to the context there are embedded in, and the role they play in assessing the sustainable test sites. (I) The metamodel systematizes the strategic space, by defining the initial and future technical solution and the required reference structure. Technical solutions, test parameters of interest, and the technology strategy influence the decision structure. Considering the plentitude variance in test sites incongruities between the strategic space and technical requirements are possible. Reasons include that technical structures are defined according to different strategies during development. The definition of the technical maturity level at which a solution is tested is fundamental for the assessment of test areas. The same applies to potential changes that may need to be addressed in the future. The results are critical markers that define the attractiveness of a structural element.

(II) The technology developer defines the target assessment. Differentiated, technological interests are evaluated considering the test site resources (available data, target features, social, logistical, ecological properties). The structured evaluation weighs the relevance of the resources to the required properties. The weighting matrix, which compares the higher-level structure items in pairs, indicates the technology-strategic relevance of individual structure items. The attractiveness of a test site provides for the development of comparative evaluations of the structural elements. The relevance of an element contributes to the degree of attractiveness of a structural position. Through the product of weight and attractiveness, a prioritization for structural revision can be determined. The metamodel allows for individualization of the different weightings and structuring possibilities. The ecological, social weighting systematizes the sustainability-centered problem-solving process.

(III) Based on dynamic influences of different testing methods on the ecological environment, new requirements that lead to possible changes in the testing behavior are identified. The criticality of changes in relation to the relevance of a structural position impact the attractiveness of the test site. Their criticality is determined by the probability of disturbance, and community feedback. The effort of testing change reflects the contribution to the commonality of a structure item.

(IV) The sustainability assessment depends on the social perception of the disturbance. Design options for test campaigns are extensive. Clear determination of adaptations concerning minimizing disturbance perception is mostly limited to low complexity tasks. Quantification of test relevance, for example the adaptation of the flight altitude, in relation to the quantifiable significance of a test is difficult. Also, the existing, methodical approaches deliver relative results. To optimize social sustainability, the structural element focusses on sociological expectation.

(V) Finally the structural perspective evaluates the decomposed structural positions. The dependencies of the structuring are so complex that a mathematically unambiguous solution is hardly feasible. Through the product of attractiveness and relevance, a prioritization for structural revision can be determined. Consequently, the method suggests an approach for technical, ecological, and social structuring.

The structured metamodel for the STSDF and its implementation ensures the flexibility of the STSDF for further research.

The following chapter leads the operationalization of the metamodel into a decision framework.

4 Framework Development

The framework development process leans on Ulrich et al. (2020). It starts with the framework generation, framework component selection, and is followed by the validation.

Public databases, qualitative and quantitative assessments informed the generation, selection, and validation of the STSDF. Technical, social, and ecological data were first collected separately. Later, the information was integrated into the STSDF. The dissertation chooses the separated approach for two reasons. Firstly, in-depth information is required. Experts in one field may lack in-depth knowledge about another field. Secondly, different fields use similar terms for different entities. Without curation, this may introduce misleading information. Figure 21 illustrates the methodological framework development.

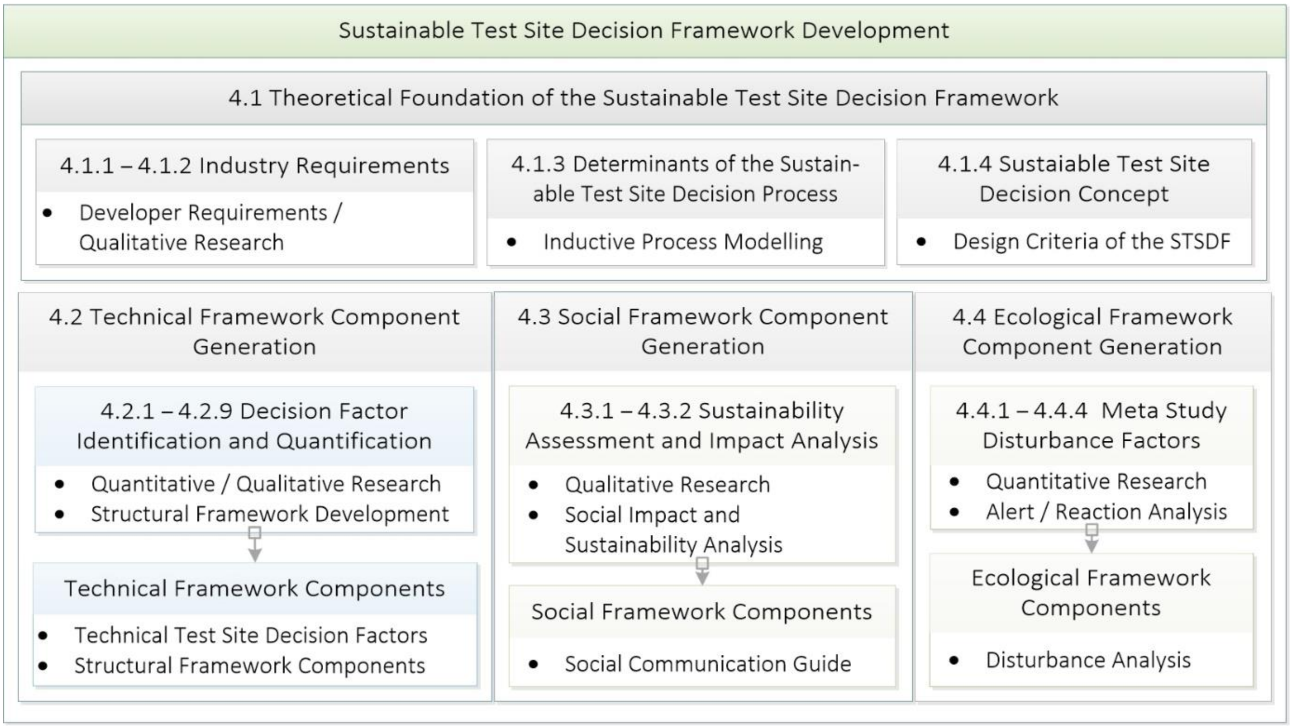


Figure 21 Data Collection Approach

The figure shows that each analysis group (technical, social, ecological) consists of original research. If not stated otherwise, all values are rounded to two decimals. Each section follows the same four steps: (I) data collection, (II) data evaluation and analysis, (III) combination of data and concept improvement, and (IV) reflection of the results and scoring.

Statistical analysis and calculations were conducted with the help of R Studio and Python.

4.1 Foundation of the Sustainable Test Site Decision Framework

Framework development starts with the theoretical analysis of the problem and the refinement of the situation through expert interviews. The data collection follows a two-step approach:

I. Revision of state of the art location decision factors

II. Interviews with test site users from industry

The following sub-chapter 4.1.1 illustrates the data collection process, 4.1.2 evaluates and analyzes the collected data, 4.1.3 combines and integrates the data, 4.1.4 closes the sub-chapter by introducing a first process and content model for the STSDF.

4.1.1 Industrial Requirement Analysis – Data Collection

The relevance of the STSDF is determined by its fit for different user groups. The dissertation suggests that the STSDF can be used by technology developers, technology managers and test site decision-makers alike. The study acknowledges that different preferences in STSDF computation exist across these groups. Differences may be attributed to company size, technological know-how, specialization, and the expertise of the decision-maker. Such differences are often used to mark out small and medium-sized enterprises (SME's) and multinational enterprises (MNE's) and academia.

Literature by Gembarski and Lachmayer (2017), Steen et al. (2011), Unger and Eppinger (2011) argues that customer understanding is needed for establishing a concept that responds to the users and needs. The dissertation employs a customer journey to address this. Table 25 depicts the customer journey approach, the sample selection, and the data collection.

Table 25 Study Approach to the Industry Requirement Derivation

Step	Description
Customer Journey Method	The customer journey aims to analyze the technology developers' and researchers point of view and gain insights into typical behavior when testing technologies in natural environments (Holmlid & Evenson, 2008). The findings clarify which decision-making processes and decision criteria are considered across user groups.
Sample Selection	Appropriate sample selection is important for identifying the needs and traits of real STSDF users (Chism et al., 2008). Therefore, the study sample consists of (I) a business development manager from a globally operating mining and minerals MNE, (II) a technology developer from a physics-centered SME, and (III) research experts from a research institute that have already tested their technologies in natural environments. The participants were contacted via the INFACT project.
Data Collection	The study design builds on Halvorsrud et al. (2016), who divide the customer journey approach into four steps. (I) Company view, (II) acquisition, (III) execution, and (IV) service.

Table 26 aligns the Halvorsrud et al. (2016) journey steps to the test site usage approach. Within the number column, the table employs the classification of Halvorsrud et al. (2016), within the step column of Table 26 the notation of the steps is adjusted to the use case.

Table 26 Customer Journey Questionnaire

No.	Step	Research topics
I	Company View	• Size and specialization • R&D strategy and R&D budget
II	Pre-testing Stage	• Definition of the initial situation when considering tests • Degree of technology maturity • Audience for test results • Pre-conditions for test site suitability
III	Testing Stage	• Knowledge and assistance required during the test initiation and execution
IV	Post-testing Stage	• Data processing and benchmarking

The initial contact with participants happened via Mail. Each participant was free to choose whether to respond to the questions via Mail or during an interview. For cases where the email response was selected, the researcher reserved the right to call the participants and ask for clarification. Two out of three participants answered via Mail.

4.1.2 Data Evaluation and Analysis

Adopted from Halvorsrud et al. (2016), the customer journey evaluation follows a company-specific decision property analysis to determine the test site requirements. The answers of each participant were analyzed, and similar notions were synthesized through deductive coding. Table 27 displays the test site decision steps that take place for each participant. The different steps, foci, and requirements point to the significance of introducing a flexible assessment tool. Especially in terms of the services required, differences exist.

The study indicates that the SME is concerned with the technical suitability and the demonstrative power of test sites. In comparison, the MNE recognizes the social and ecological challenges and demands for them to be assessable. Academic perspectives enhance the analysis by indicating the power of networks for testing and cooperation in research processes. The findings show that the STSDF must be adaptable to the requirements of each industry actor. A test site might appear suitable by presenting expected technical, ecological, or social benefits using weights that reflect the importance.

Table 27 Customer Journey Research Results

S	Object	MNE	SME	Academia
I	TD structure	Own R&D departments	Often externally funded with partners from specific industries holding stakes	Own R&D departments
II	Logistics	Own logistics and campaign planning	No logistics and campaign planning	Network of logistics and planning activities exist
	Testing	Business development and R&D decide on tests	Testing decisions are made in cooperation between industry partner, research manager / business owner	
	TRL	Test site for incremental and radical innovations (TRL 5-9)	Test externally funded mostly radical innovations (TRL 8-9)	Project dependent (TRL 5-9)
III	Physical tests	Initial testing takes place in known areas close by ("backyard")		
	Test aim	Benchmarking is crucial for proofing the performance		Project dependent
	Strategic space	Applicability (target type, depth, signature)		Project dependent
	Technical decision space	Availability for testing; logistic processes; benchmarks	Availability for testing; logistic processes; physical space information	Availability for testing; logistic processes; benchmarks; relationship to local institutions
IV	Required support	Stakeholder engagement	Data processing	Political / legal support
	Required services	External geophysicist to verify the measurement		n.a.

Green coloring indicates similarities

The small sample size limits the external validity of the customer journey. However, given the small community that publishes on test site development, the sample is nonetheless deemed suitable for a preliminary inventory.

4.1.3 Determinants of the Sustainable Test Site Decision Process

The insights from the customer journey reveal that some criteria are of more importance than others and that distinctive criterion might pre-empt further test site characterization. This is interpreted to imply that there is a hierarchy in factor importance.

Hence, no matter how favorable lower-ranked factors are, they will not matter if higher-ranked factors score poorly. Consequently, the thesis proposes a hierarchical decision order. The decision order builds on a three-step process: (I) Step one is the so-called exclusion stage. The exclusion stage aims to sort out non-applicable sites promptly in the site selection process to decrease efforts for continuation analysis. (II) The evaluation phase is detail-oriented and only entered once a prior exclusion assessment is successfully conducted. (III) The analysis of ecological and social conditions concludes the third step.

The following section will discuss the implementation of the technical, social, and ecological factors and the industry requirements.

Given the possible interactions between concurrent technical factors and the social and ecological system, a formal specification on the sequence of factor analysis is helpful. The dissertation, therefore, introduces a sequenced decision-making process, which reduces run-time.

The sequence specification builds on the assumption that first and second-order factors exist. First-order factors constitute a test site's first and foremost goal (exclusion criteria). Second-order factors are amendable or at least are not the top priority (evaluation criteria). Figure 22 illustrates these considerations.

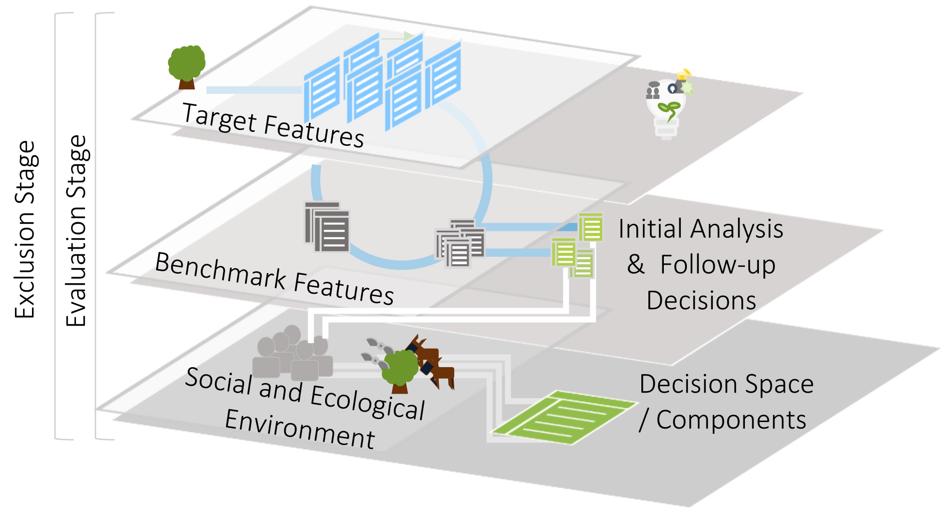


Figure 22 Decision-Making Process

Exclusion criteria: The decision-making process starts with ruling out test sites that do not surpass a specified threshold value. In the exclusion stage, binary decision-making is applied. Here factors that must be present at a site are checked. Those sites that do not meet the required settings are deemed incompatible and ruled out for further decision-making.

To illustrate this mathematically, the following rule applies. The exclusion criteria b under consideration may either be equal to the requirement level or exceed the requirements and will be zero below the degree of requirement fulfillment. Which applies to the decision with Q questions, q = {1, 2, ..., Q} as follows:

$$B = \sum_{q=1}^{Q} b_q \qquad b_q = \begin{cases} 1\ if\ e \geq \underline{e} \\ 0\ if\ e < \underline{e} \end{cases} \qquad (1)$$

Whereby, B is assumed to be best, the higher it is.

This narrows the follow-up evaluation and reduces run-time at an early stage.

Evaluation criteria: Factor expression differs between test sites. Evaluation factors determine the most attractive and relevant site from a (I) technical perspective as well as the (II) ecological, and (III) socio-economic perspective[17]. The evaluation consists of multiple factors in the categories of technical target features, benchmark features, social features, and ecological features. As some factors and categories are more relevant a scoring and weighting process is required. Hence the evaluation stage combines the structural representation of factor and category assessments.

Ecological and social structuring take the form of social expectation management, impact assessment, and impact communication. The process of evaluation is iterative. It alternates between strategic and technical decision space, ecological disturbance, and expectation management until a satisfactory test site is identified. Together the requirement for efficient decision-making and the avoidance of a final number in favor of a set of interdependent decision criteria require a structural model (see 4.2.4 – 4.2.9).

[17] Later the categories were further detailed.

4.1.4 Sustainable Test Site Decision Concept

The thesis has thus far developed an initial STSDF process. The framework sets out to be in line with the design criteria. To ensure that none of the design criteria is violated so far and to identify additional research needs, Table 28 gives a preliminary overview of the design criteria fulfillment of subchapter 4.1.

After the initial scoring and the process definition the framework content and its structural computation require definition. To define the content, variables that describe the decision space must be defined and analyzed. Following the content creation, the functional form of the relationship must be established.

Table 28 shows that variables are of different importance. Hence a mechanism to weigh and aggregate variables must be defined.

Table 28 Scoring of Framework Design Criteria

Design criteria	Explanation
Relevant	The approach follows a test site decision-making process until the first interest for test site usage / development. The process considers the piloting and application of sensing technologies. While not making the testing and future TD direction sustainable, the process can provide time and space to develop and nurture a sustainable test site and facilitate more socially and ecological sensitive test sites. In addition, sustainability supports, builds, and maintains a solid foundation of social and ecological acceptability, which is among the most significant project risks and of particular importance should a test site develop into a fixed institution.
Be easy to understand	The approach so far builds on desk research. The information that must be gathered is clearly structured and inclusively framed. For some purposes, it can still make sense to rename and adapt individual steps. The data computation must consider the transferability through robust mathematical models, which support the entire process.
Multi-dimensional information	During the decision-making process, the framework proposes that some factors are more relevant than others. The framework suggests that good practice is equal to technical factors from the outset of test site development and at crucial decision points through the testing and TD phase. Incorporating multiple dimensions applies to both the overall strategy of the STSDF and the selection / exclusion of specific testing methods. This advances earlier approaches as ecological and social aspects are now thoroughly assessed before launch.
Ensure comparability between test sites	Considerations include integrating additional data and keeping the number of different sources within one dimension small. The adaptability reduces potential data lacks, albeit at the expense of potentially limiting the scope. The sequenced, yet comprehensive approach, may obtain an objective picture across other sites.
Replicability	To examine whether the model is replicable, outliers or unrealistic trend continuations are eliminated. Case-based replicability requires the comparison of average trends with every time series data set that contains imputed data.

For composite indices Greco et al. (2019) suggest that each selection must be driven by the assortment of methodologies for data selection, normalization, weighting, and aggregation. The thesis follows this suggestion and extends the view by the imputation of missing variables and data analysis. The decision was made to ensure the replicability of the entire process.

Together five steps emerge. These steps are (I) selection of factors (including the deduction, induction of categories), (II) weighting and aggregation, (III) data analysis, (IV) data normalization, and (V) imputation of missing data. Different methods exist to compute these steps. Though there is no one methods that fits all aspects, the STSDF will compose different methods. Table 29 sums up the potential methods for each stage. The introduced methods will be analyzed and evaluated for their suitability.

The evaluation builds on the test site design criteria. The evaluation reviews the methods for each of the five steps, tests the most appropriate method, and verifies its applicability. The sum of selected methods constitutes the measurement logic behind the framework and extends the literature.

Table 29 Development Steps for Practical and Theoretical Test Site Decision Approach

Step	Potential methodologies
Selecting factors	Expert Interviews, public databases, trusted organization Statistical methods – factor scores, statistical methods – factor score estimates
Imputation of missing data	Mean imputation, Least observation carried out forward Cold deck, non-negative factorization, multiple imputations
Data analysis	Component analysis, multivariate analysis
Normalization	z-score normalization, min-max normalization, relative value normalization
Category weighting and aggregation	Arithmetic mean, geometric mean, harmonic mean, pairwise comparison (e.g., AHP), scoring (e.g., TOPSIS), outranking of criteria (e.g., PROMETHEE)

4.2 Technical Framework Component Generation

The technical framework component generation aims to (I) select variables that describe and measure different aspects of sustainable test sites, and (II) integrate them into a mathematical decision structure. Sub-chapter 4.2 therefore and aims to answer two questions:

Which factors enable sound performance at test sites and how do they influence the effectiveness of decision-making?

How can an integrated replicable decision-making process be computed?

Figure 23 illustrates the structure of sub-chapter 4.2. Figure 23 indicates the objective of each step, the nature and process of the research, and the value to the overall model.

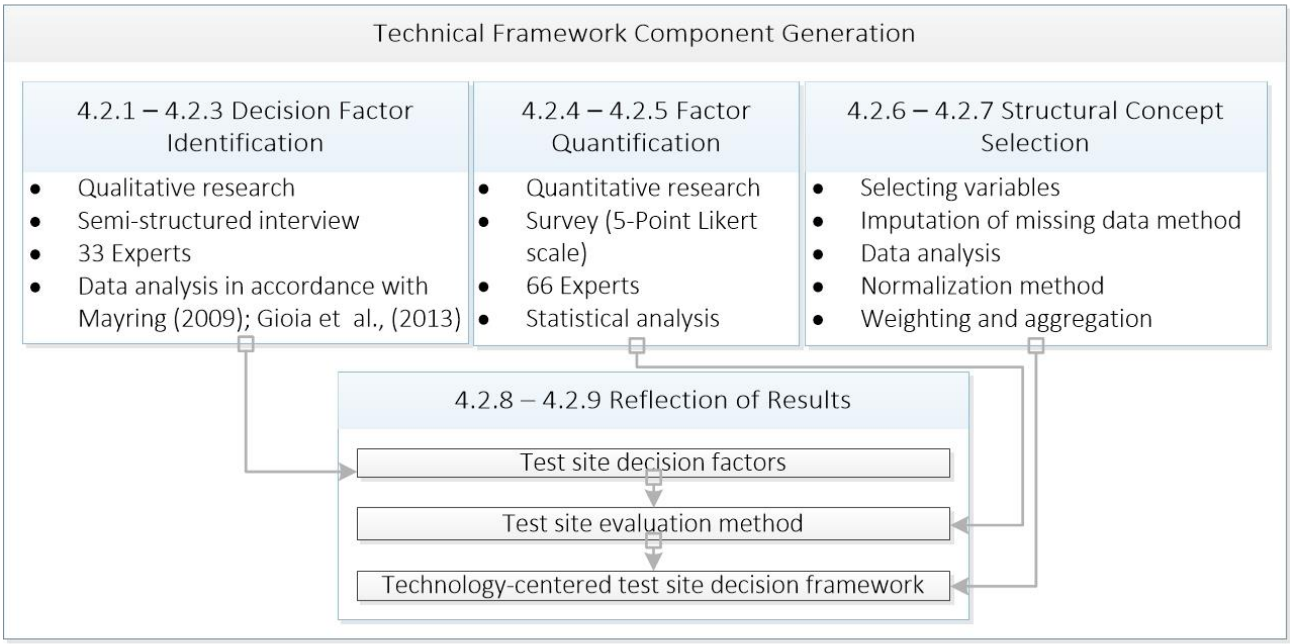


Figure 23 Technical Concept Generation

First, the thesis selects variables through expert interviews from established organizations to answer the questions. Triangulation with public databases verifies data quality and completeness (H. Noble & Heale, 2019).

Next, the identified factors are grouped into categories, followed by the quantification of factors through statistical factor scores. Component analysis checks the factor scores. The decision of why each step is taken and how the variable selection contributes to the overall STSDF is outlined.

As stated earlier, categories receive different weights. There exist various ways to compute weights. The section analyzes weighing and normalization schemes. Based on the analysis, the best fitted mathematical constructs are selected.

4.2.1 Data Collection for Technical Sustainability Framework Components (qualitative)

The factor selection builds on semi-structured, in-depth interviews conducted with experts from industry and research. Semi-structured expert interviews balance structured data collection and openness (Flick, 2017).

Answers are not limited to the interview frame but allow new and unexpected topics to emerge. For the data collection, interviews were conducted with 33 experts[18] from international business, research, and industry practice.

The interviews happened between August 2019 and February 2020. Table 30 illustrates the data sample and the data collection process.

Table 30 Technical Framework Components – Sampling and Data Collection Process

Stage	Description
Sample Selection	Experts were chosen based on their proven expertise. Expertise is present when the participant has either (I) published on the topic of testing technologies, or benchmarking, (II) participated in the European Union funded project INFACT, or (III) was referred to by an expert that fulfilled either one of the criteria. Closely related to the general characteristics of mineral exploration, the sample consists of 16 experts from North America, ten experts from Australia, six experts from Europe and one expert from South Africa. The heterogeneity in the model allows for generalization and reduces sample distortion. For confidentiality, the sample was anonymized. Appendix 6 depicts the expert characteristics and their backgrounds.
Sampling Details	The researcher analyzed the mailed responses carefully to check whether the participants thoroughly understood the context. After reviewing the answers, one of the manual answering experts was asked to re-send the questionnaire to amend very short responses and address the inclusion of counter questions rather than answers. After providing the expert with additional information on context and objective, the re-sent questionnaire fulfilled the comprehensiveness and context alignment criteria. The interviews were audio-recorded and transcribed.
Data Collection	Contact with experts was initiated via email or LinkedIn. Due to time differences, the interviewees could either participate in an interview via Skype or WebEx or answer the questionnaire independently. In sum, 27 of the interviews were conducted online, while six interviewees sent their answers via mail. The interviews lasted between 38 and 75 min, and the interview language was English.

4.2.2 Data Evaluation and Analysis for Technical Sustainability Framework Components

In line with Mayring (2020) deductive coding was applied to select the test site decision factors. The coding led to an initial amount of 130 factors. In a second instance, the thesis reviewed the factors, and synonymous elements were aggregated.

After aggregating and filtering, a total of 64 factors remained. For reasons of validity and comprehensiveness, the factors were validated via triangulation. The triangulation identified two missing factors, leading to a sum of 66 factors. The factors were then grouped into categories.

The metamodel informed the category building. Inductive coding identified Table 31, shows the factors identified for each category. Additional material is provided in Appendix 7. The appendix first describes each factor (Table 70-Table 72) and then assigns each factor to interview statements (Table 73). The appendix provides an in-depth view and verification for the deductions provided hereinafter.

[18] An expert is an individual with special knowledge representing mastery in testing and test site management / selection.

Table 31 Technical Decision Space – Test Target Features

Category	Factor
Test Target Features	Type of commodity; grade of mineralization; depth of targets; ore-body geometry; size of the area; type of host rock; physical property of the target signature; petrophysical property of the host rock; geological complexity; structural complexity; area is representative for current and future challenges; climate; topography; cultural and atmospheric noise
Benchmark Features	Coverage of physical parameter; availability of drill hole data; availability of ground-based database; coverage of airborne surveys; availability of a geological model; depth the database covers (depth of recorded data); availability of structural data; availability of geochemical data; availability of petro-physical model; availability of ore-reserve models; availability of geophysical model; availability of lithological model; statistically representative amount of data; age of existing data; type of drill hole; types of techniques and technologies employed to generate the benchmark; resolution / pixel size of database; accuracy and preciseness of database; preciseness of database; data formats are industry-standard; data collection was performed by suitably qualified professionals
Socio-Economic Environment	Stability of government; government support for TD; clear landownership; level of bureaucracy; availability or easiness to obtain flying permits; ability to publish data; duration of license; strong intellectual property rights; acceptance of local community; image of mineral exploration and related activities
Logistical Environment	Proximity to airborne landing and take-off facilities; proximity to platform maintenance; accessibility by road; proximity to hotels; proximity to airport; availability of business services (e.g., consulting)
Ecological Environment	Environmental condition (fauna, flora); safety standards

It is apparent that despite the initial separation of technical, social, and ecological assessment criteria, initial factors for all three were identified. Considering the expert selection, this is of little surprise. Closer inspection shows a tendency for general assessment factors rather than specified insights into ecological and social decisions. As for a balanced sustainability assessment, an in-depth analysis of social and ecological assessment dimensions remains relevant.

4.2.3 Combination of Data and Technical Components Framework Integration

To this point, the technical framework component development is performed. For the selection of factors, the process indicates that expert interviews and triangulation are suitable. Table 32 illustrates the suitability and provides an indication of the topics that require analysis.

Table 32 Theoretical Framework Scoring

Activity	Alternatives	
Selecting variables	Expert interviews with parties from trusted organization	✓
	Triangulation with public databases	✓

Checkmarks affirm the relevance; crosses indicate non-applicability for the STSDF

In addition, the framework components build on the notion that the factors themselves are of different importance. For this thesis, the most suitable way for factor-based weight assignment is discussed next.

4.2.4 Data Collection Technical Framework Components (quantitative)

The STSDF uses three decision-steps, five categories and 72 factors to determine the attractiveness of a test site. Following the recommendation of the OECD (2008) as well as the example of decision frameworks such as Dutta et al. (2018) or Schwab (2019), assigning importance to the factors and categories may ease the evaluation of test sites. Three procedures are regularly applied to assign importance to the different factors. Authors such as Ramana et al. (2013) employ:

I. literacy deduced weights as so-called factor estimates
II. weights based on the frequency a topic or factor is mentioned
III. quantitative questionnaires to receive an importance ranking for the factors.

Factor score estimates are imperfect representations of the factors and do not perfectly correlate with the factors themselves. Statistical deduction of factor scores can estimate the stipulations of the theoretical model precisely (Nesta, 2016). Applied factor analysis frequently uses statistical deduction. Therefore the importance of the identified factors was analyzed using quantitative questionnaires to achieve a high relevance and applicability for both industry and research (Walsh & Holmes, 2019).

The questionnaire queried the identified factors. The survey was structured into four parts and hosted on lime survey. English language was used as the survey language. Before the activation of the survey, the researcher performed four pre-tests, and a native speaker checked the study. The pre-tests followed the procedures described by Vannette and Krosnick (2017) for reflective models. The pre-test intends to improve the comprehensibility of the survey, check the relevance, timeliness, accessibility, interpretability, and coherence (OECD, 2008).

Relevant factors should fit the overall concept and dimension. Timeliness referred to the factors representing current and future developments. Whereby the future was defined by a length of ten years. The TD cycles of natural sciences determine the timespan.

The availability of data concerning the factor in question determined the accessibility. Interpretability of the factors should be as low as possible to reduce ambiguity. Coherence is the self-consistency of a factor across the assessment.

After completing the tests, inconsistencies and room for improvement regarding the survey timing, its electronic functionality, structure, language, understandability, and obsolete or missing question were identified, and minor changes were made. In addition, two composite factors were identified, namely geological model and physical parameters. Table 33 depicts and justifies their inclusion.

Table 33 Composite Factors for Decision Framework

Factor	Background
Geological model	**Description:** The geological model is a composite factor of the sum of various models. **Coherence intrusion:** The sum of factors represents the diversity of the geological model. The diversity of input data is one of the quality criteria of a geological model. **Justification:** The geological model is a composite of other physical parameters. There are input variables that are more or less important. Moreover, some methods such as EM may only require the geophysical model. Consequently, the composite, as well as the single factors, remain in the survey.
Physical parameters covered	**Description:** Physical parameters constitute various models (e.g., geophysical or hydrological model). **Coherence intrusion:** The amount of physical parameters covered by a data set increases the application range of different technologies (e.g., gravity and magnetics) **Justification:** Despite physical parameters being an input factor for the entirety of models, it serves as a quality proxy for the models. The more physical parameters covered, the higher the application range for benchmarking. However, in some cases, the sheer absence of one parameter might render a test site unsuitable. Consequently, the moderating quality variable remains in the survey block.

Table 34 illustrates the final survey structure. The survey launched in April 2020 and closed in July 2020. The distribution took place via LinkedIn of the researcher as well as the head of a renowned exploration research institute, thus increasing the quality of reached experts. In addition, the thesis contacted 50 people via mail.

This path was followed to increase the reach and contact relevant experts. Due to dual-distribution (LinkedIn; email), the research cannot identify a response rate. 66 respondents started the survey, 53 participants completed it and on average 43 answers per question were given.

The drop-outs appeared especially with more sensitive topics such as socio-economic aspects, or right at the beginning.

Table 34 Technical Concept – Survey Structure

Part	Description
I	Firstly, the study gave an introduction about the background and the objective. The opening provided statements about the confidentiality of the data and the anonymous nature of the questionnaire.
II	Secondly, the factors were queried. Participants were able to assign importance levels to the factors presented to them. A limitation to the importance assignment is that the identified factors are context-dependent, which means that 500 ill-spaced drill holes may be worse than 100 well-spaced drill holes. Consequently, questions to obtain importance levels must be as open as possible while maintaining a specific focus on target information gains. The researcher identified the asymmetric 5-Point Likert scale including a "not applicable" option as appropriate. The method proved suitable in comparative research (Joshi et al., 2015). Appendix 8 details the decision to choose the 5-Point Likert scale and highlights how missing variables were treated. The order in which the categories and factors were presented builds on the outline of Malhorta (2006). In line with the authors, the survey started with the introduction of topics with higher familiarity. In this manner, higher retention rates are expected. Hence, the study started with test target features (incl. geology), followed by benchmark features, and ended with more sensitive or ambiguous dimensions, such as ecological, and socio-economic ones.
III	Part three of the study intended to weigh the overall categories from 1 (most important) to 5 (least important). Two aspects justify this approach. First, to validate the initial assumption of exclusion and evaluation criteria. Second, to provide a weighting scheme of the categories that allows refinement of the overall accuracy of the decision framework and identifies aggregation potential.
IV	Part four anonymously analyzed the demographics of the respondents. These questions asked for age, gender, and experience, such as the number of occupation years and the technological field of expertise. Demographics were gathered to analyze the representativeness of the sample. After completing the survey, respondents were provided with the contact details of the researcher.

4.2.5 Data Evaluation and Analysis of the Test Site Survey

The analysis follows the OECD framework for component analysis (OECD, 2008). Other methods such as multivariate analysis may fit but increase the complexity and ease of use of the analysis (Dutta et al., 2018; Nesta, 2016). Moreover, the study disconnects the demographics from the answers to ensure data privacy, thus limiting the applicability of multivariate analysis. Thirteen minutes was the average duration time for completing the survey. Appendix 9 depicts the demographics of the survey, while Figure 24 illustrates the occupational background by absolute measures (count).

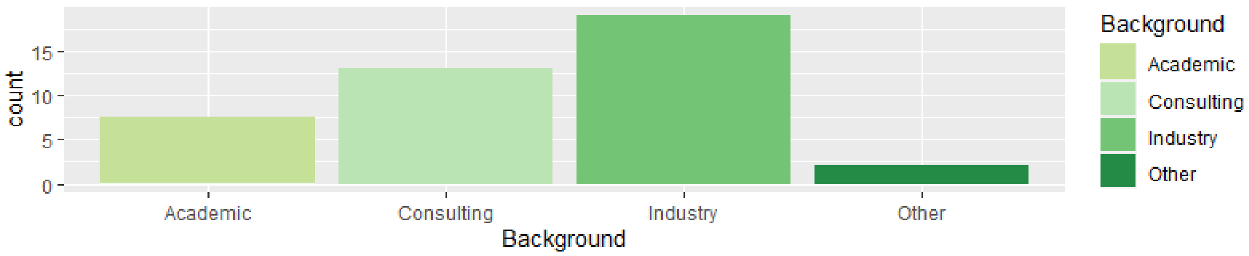


Figure 24 Occupational Background

The occupational background reveals that the majority of respondents have an industry background, which corresponds with the target group of the decision framework.

Male respondents make up the majority of the sample. The majority of survey respondents are between 36 and 55 years old (see Figure 25).

Appendix 10 displays the results of the component analysis factor. The appendix includes information about the number of observations per question, the calculated mean, standard deviation, the 25th and 75th percentile as well as the minimum and maximum, skewness, kurtosis, range, central tendency.

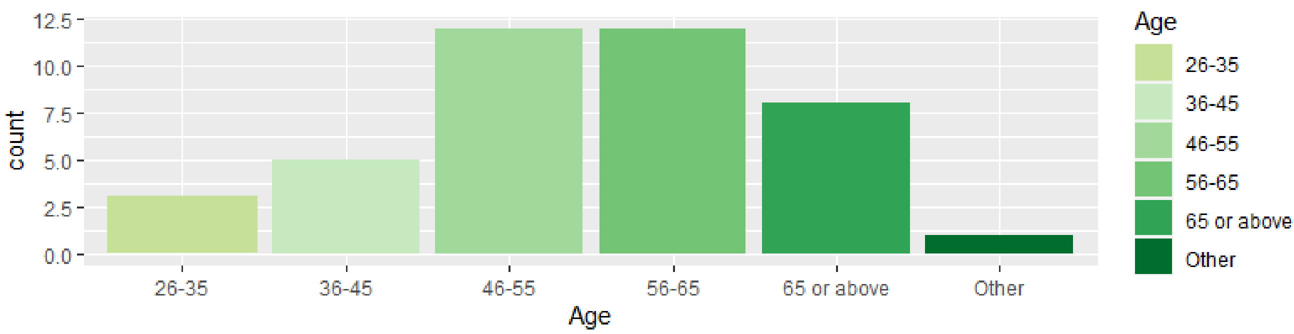


Figure 25 Demographics of the Survey Participants

The data was computed using Rstudio a programming language with open-access in provision (Schumacker and Tomek, 2013). For categories classified more sensitive, most of misses happened ("I don't know"). The discrepancy may hint at a gap between geoscientific and socio-economic and socio-ecological understanding. Standard deviation further spiked with technology-specific factors such as vegetation. Supporting, the differentiation between technology developer and academia, factors indicating the ability to share or protect the testing operation show high deviations (e.g., ability to publish data, strong intellectual property rights. Adding to the support, government support for technology development, according to the customer journey is critical for academia also indicates higher standard deviation. Most scores are ≥3. The results support the relevance of the identified factors / criteria.

4.2.6 Combination of Data and Integration into the Sustainability Framework

The question arises on how to integrate the factors and scores into the concept. The relational data needs to be structured to reduce data redundancy and improve data integrity. Different methods exist to structure the data in standard forms. The following discusses these methods and identifies the best-suited method. Z-score normalization is particularly relevant for high numbers of comparisons (Hedderich & Sachs, 2018). However, the z-score standardization is hard to interpret by non-scientific staff and therefore does not meet the required ease-of-use of the STSDF. Hence, z-score normalization is less suitable. The remaining options are the min-max normalization or distance to the reference point. The min-max approach is the most widely used normalization method and is particularly relevant for non-standardized weights (Talukder et al., 2017). However, the identified factors are suitable for standardized evaluation, as no explicit numerical or non-numerical values for single factors could be deduced from the interviews (e.g., amount of drill holes). In consequence, the perceived relevance is a more informative indicator. Thus, the need for outlier adjustments drops out. In that case, reference values are necessary. The reference value is the mean of a single factor. For the present case, the derived mean for the different factors may be used as a reference point. Table 35 displays the development status of the STSDF.

Table 35 Theoretical Test Site Decision Framework

Activity	Alternatives	
Selecting variables	Expert interviews with parties from trusted organization	✓
	Triangulation with public databases	✓
	Statistical methods – factor scores	✓
	Statistical methods – factor score estimates	✗
Data analysis	Component analysis	✓
	Multivariate analysis	✗
Normalization	*z-score normalization*	✗
	Min-max normalization	✗
	Relative value normalization	✓

Checkmarks affirm the relevance; crosses indicate non-applicability for the STSDF

4.2.7 Data Collection for Category Weighing for Technical Framework Components

A way to address outlier effects or assign importance to different categories is to introduce weights into the calculation (OECD, 2008). The introduction of weights can happen at the factor as well as the category level. For the present case, weight assignment occurs at the category level.

The decision has three reasons: (I) Firstly, the choice of reference normalization method requires no additional normalization at the factor level. (II) Secondly, the questionnaire-based category scoring resulted in ambiguous output. (III) Aggregated views on the categories are required to satisfy needs of management decision-makers. Expected category variances relate to (I) the technology (e.g., EM vs. MT), (II) the size or background of a technology developer, or (III) the aim of the survey (testing vs. demonstration).

The difference suggests that technology developers require a case-based approach to category weights. The study identified several strategies for weight assignment. The following discusses the strategies and justifies the final selection.

Statistically, deduced weights can introduce weights into the calculation (Dutta et al., 2018). Deduction of weights aggregates sub-indices to a single number index. One limitation to aggregation is that it conflicts with multidimensional decision-making design criteria. Therefore, statistical deduction of weights is not suitable.

Similarly, indices such as the world economic forum indices (World Economic Forum, 2021) aggregate different analysis levels in combination with an arithmetic mean to aggregate the lower levels, where indicators within the exact dimensions are combined, and afterwards uses a weighted geometric mean to calculate overall index values (Bericat, 2012).

Critics argue that such, weighted averages are hardly accurate models for decision problems (Josselin & Le Maux, 2017), resulting in a lack of indicating the relevance of a decision-making category (Orloci, 1966).

The often-reported source of error stands in conflict with the necessity to ensure consistency across test site comparison. In consequence, averages may only be relevant in conjunction with a distinctive weighing scheme. Common averages to represent a data set meaningfully, are arithmetic and geometric means. Arithmetic means work with independent variables, where little variance is expected, while geometric means are suitable for dependent variables with higher variance. (Jacquier et al., 2003)

Categories are independent and, little variance is expected. This is the case as (I) categories are presented by the sum of normalized factors and (II) exclusion criteria already filtered outlier effects. Hence, arithmetic means can serve to build the average over the sum of factors per analyzed test site.

Reported weighing processes build on the MCDM methods. Comparing the PROMETHEE, TOPSIS, and AHP methods, it appears that both TOPSIS and PROMETHEE and other MCDM methods compute the weights of the criteria. AHP tackles this problem by introducing cross-entropy. Moreover, in both PROMETHEE and TOPSIS, weight computation depends on AHP.

Indeed, the mathematical calculation may also build on other weights. However, AHP weights are then already calculated. Suggesting AHP to fit best. Besides the AHP index method can assign weights to categories and factors. Per the index approach, the factors themselves are weighted using the reference-based factor scoring. The category importance may be identified in a similar fashion.

When comparing the two approaches, the study yet found five distinctive criteria that make the AHP process superior to the index method as well as the MCDM methods. In comparison, AHP:

I. provides a higher degree of context-based analysis
II. incorporates conflicting judgments
III. analyses trade-offs between factors
IV. focuses on differentiating between alternatives more
V. defers subjective judgments early in the decision-making process
VI. allows for fast recompilation of factors as circumstances change.

Considering the widespread application of MCDM, the comparative insights present a substantial research finding. In consequence, the AHP process was chosen for category weighting.

The decision was presented and validated with an expert symposium during a symposium for sustainable mineral exploration on September 18th, 2020. Category weights will be assigned to the arithmetic mean over sum of scored and normalized factors per category and test site.

4.2.8 Data Evaluation and Analysis of Analytical Hierarchy Process Weights

The detailed process of performing the AHP is explained in Appendix 4. Previous literature focused on exemplary calculations rather than mathematically validated approaches. Thus, limited literature on the mathematical composition of AHP exists.

Existing compositions are scattered and broken down into various steps. Another limitation to AHP is that AHP regularly calculates both categories and sub-categories (alternatives). Sub-category calculation with the AHP is a complex task. The calculation requires the generation of new weights. Replicability and ease of use are therefore limited.

To overcome the limitations, the following introduces an adjusted AHP (aAHP) method. For the aAHP, the calculation focuses on weight assignment for categories only. In this way, decision-makers can perform differentiated, yet composite decision-making.

In addition, the study suggests a way to visualize the weights. Visualizing the categorical sums as a composite of weight and normalization may help decision-makers perform composite yet distinguished decisions.

The following introduces the aAHP formula and its derivation. The displayed aAHP formula paired with the demonstrative calculation is a novel more intuitive approach to the AHP process.

The weight assignment starts with the pair-wise comparison of categories on a scale from 1-9. To compute the weights, the $n \times n$ matrix $A \in \mathbb{R}^{n \times n}$ is created.

The elements a_{ij} of the matrix give the relative importance between two categories. Hence items in the diagonal are set at 1.

Items in the lower triangle are inversely related to their counterparts in the upper triangle. Formally, $a_{ij} = \frac{1}{a_{ji}}$, where i indexes' columns. For example, A_1 is three times as important as factor A_3 the ratios mean $a_{13} = \frac{3}{1} = 3; a_{31} = \frac{1}{3};\ a_{33} = 1$.

To be able to compare categories beyond the pair-wise information given by the elements a_{ij} the matrix must be standardized. Hence a category is compared to all possible alternatives $\mathrm{k} = \{1, \dots 5\}$ with n= 5.

For the calculation each a_{ik} is devided by the row total of its respective category. The column total of each normalized a_{kj} is build next. Leading to category weights and the primary formula:

$$\mathrm{pr_i} = \frac{1}{a_{ij}\sum_{k=1}^{n}\frac{1}{a_{ij}}} = \frac{1}{a_{ij}} * \frac{1}{\sum_{k=1}^{n}\frac{1}{a_{ij}}} = \frac{1}{a_{ij}} * \frac{1}{\sum_{k=1}^{n} a_{kj}} = \frac{a_{ji}}{\mathrm{w_j}} \text{; q.e.d} \quad (2)$$

All observations with a consistency ratio higher than 10% will be dropped from the routine. To ensure transparency across the data set, no indices must be suppressed.

4.2.9 Reflection of the Results and Scoring of the Technical Framework Components

While the accuracy and relevance of the factors are ensured through the quality of input data, the timeliness seems most challenging, perhaps because implicitness, interpretability, and coherence are hardly mentioned in the analyzed literature. A challenge, mineral exploration and related technologies poses.The timeliness and accessibility of the framework are challenged as the factor values, weights, and exclusion criteria are subject to change. To ensure timeliness, some authors introduce coverage rates. In the scholarly work of Dutta et al. (2018) or Schwab (2019), this means that an indicator is only included if a certain percentage of data is available for a set time.

Despite the criterion of timeliness, the design criteria of the framework consist of its transferability. Here especially, the need to exchange data or impute missing data emerges. Missing data may be attributed based on statistical data or by assuming values of factors based on the median, mean, or mode of associated factors.

The imputation of missing data depends on the factor. Existing approaches replace missing data with the mean of other variables within the same category. Hierarchically ordered factors can use the last or following ordered weight. For example, a hierarchically ordered row of 2, [...], 3 misses a variable in between. The last order carried forward will input 2, while the following order carried forward will impute 3. The imputation results in an overall dimension value that equals the variable that would result if the missing data indicator is included. (Bouza-Herrera, 2013)

Such imputation appears as the simplest solution. However, other methods such as interpolation are mathematical methods that estimate a value within a known sequence of values. Among the interpolation methods, the simplest is linear interpolation. It computes a mean between the values before the missing data and the value after. (Bouza-Herrera, 2013)

For the present case, the number of categories and missing values is comparatively small. Per the relevance of individual values, non-imputation of missing values and excluding indicators with data gaps are not feasible.

Both approaches may lead to bias and alterations of the underlying framework. For linear interpolation, the small number of factors within specific categories results in errors concerning data availability before and after a variable. (Soley-Bori, 2013)

Challenges concerning multiple imputations and regression imputations include the diversity and independence of the factors and categories. Missing interdependence between the underlying data series results in a narrow fit of added data (Lüdtke et al., 2017).

As the factors are hierarchically arranged, the final decision fell on the last observation carried forward. The advantage of applying the last observation carried forward is that the imputation is forced to inform the hierarchical order and keeps the logical sequence of descending factor importance (van Buuren, 2018). This assumption is considered close to reality and corresponds with the underlying data structure. Variables that would rank highest within a category apply the following variable carried forward. Table 36 illustrates the evaluation included variables. The conceptual procedure for the development of the STSDF puts a mathematical relation to the categories, factors, and processes deemed relevant.

Table 36 Theoretical Test Site Decision Framework

Activity	Alternatives	
Selecting variables	Expert Interviews with parties from trusted organization	✓
	Triangulation with public databases	✓
	Statistical methods – Factor scores	✓
Imputation of missing data	*Mean imputation*	✗
	Last observation carried out forward	✓
	Cold deck	✗
	Non-negative factorization	✗
	Multiple imputations	✗
Data analysis	Component analysis	✓
Normalization	Relative value normalization	✓
Category weighting / aggregation	Arithmetic mean	✓
	Geometric mean	✗
	Harmonic mean	✗
	aAHP	✓
	Scoring (e.g., TOPSIS)	✗
	Outranking of criteria (e.g., PROMETHEE)	✗

Checkmarks affirm the relevance; crosses indicate non-applicability for the STSDF

Considering the test site decision criteria, Table 37 analyzes the fit of the approach regarding the design criteria.

Table 37 Technical Framework Components Design Criteria Fulfillment

Design Criteria	Explanation
Relevant	The combination of expert information and triangulation deems the approach relevant for topics with limited explicit and high amounts of implicit topics. Through the imputation mechanism, the relevance may remain over time.
Easy to understand	The ability to respond to TD experts as well as decision-makers required a factor and category-based weighting. Balancing composite factor analysis with aAHP allows for insights into the utilization of technology-related aspects while integrating more aggregated decision-making. Thus, TD and managerial requirements require balancing.
Multidimensional information	Category-based evaluation enables the fit of the test site decision framework across dimensions. Here the STSDF allows for the comparison of categories and factors.
Comparability	Composite decision-making coupled with advanced AHP allows for comparability at different levels of aggregation.
Replicability	TD in natural sciences aims to develop a test site or choose from an array of available places. The conceptual approach provides researchers, other business actors, or policymakers with a reference and a replicable approach for test site decision-making projects. The procedure includes the different stakeholder requirements through imputation methods, the aAHP process and the novel reference approach.

The purpose of this sub-chapter is to analyze factors that assess the suitability of test sites from a technical, ecological, and social perspective. A closer inspection of the factors shows that technical considerations dominate. So far, it is not conclusive whether the framework sufficiently covers the discourse on social and ecological factors. Reasons for the missing address may lie in the selection of experts, the design of the questionnaire, or other survey design-related biases.

Increasing the spread of expertise might have reduced the accuracy of the technical framework, meaning that simple answers about technical and conversely social and ecological factors reduce the value of the overall model. The study suggests that in-depth analysis of sustainable attributes requires research to specific fields individually. In consequence, ecological and social sustainability assessment was set to happen separately from the technical consideration. The separation does not imply that technical, ecological, and social factors are incompatible. On the contrary, it strengthens the need for technology management in an interdisciplinary context as is the aim of the study. Merging all three perspectives is the subject of the final step of framework generation.

To reduce the risk of generating three independent frameworks which finally do not fit, ecological and social assessments happen with experts and data from related industries. Feedback loops with technical experts are introduced to ensure alignment. Having defined the necessities for framework optimization, the work will move on to discuss the social framework generation.

4.3 Social Framework Component Generation

Figure 26 illustrates the process towards developing the social framework component generation as described in the following sub-chapter. The aim of this sub-chapter is to identify factors that describe and potentially measure social sustainability at test sites. To do so, a qualitative research approach was chosen. Building on focus group research, an initial concept of quantifying social sustainability assessments was discarded.

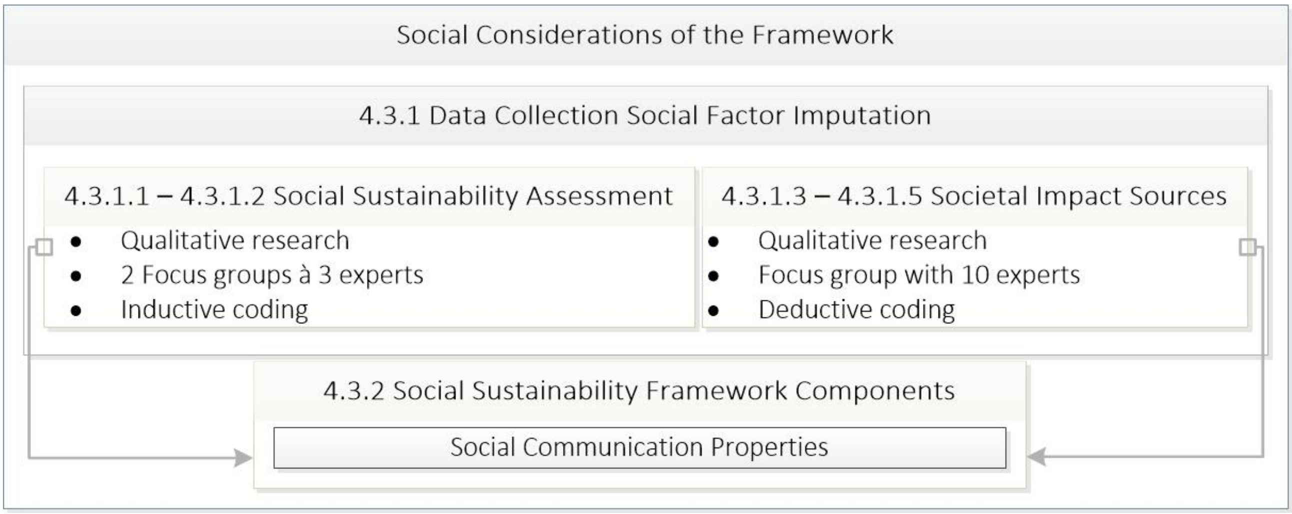


Figure 26 Social Sustainability Framework Input Development Method

4.3.1 Data Collection Social Factor Imputation

The guiding question of the social framework component development is:

How can social sustainability be determined prior to the start of a project?

To answer the research question and in line with Nyumba et al. (2018), the present study identified focus groups to be an appropriate research approach. Reasons for the selection include the fit with research target, resource availability, and level of expertise of potential participants. The data collection builds on two studies:

I. Study with experts from resource, governance, and sustainability sciences to identify sustainability assessment mechanism
II. Study with experts from the INFACT project to identify social sustainability of test sites

The following first introduces the assessment-centered study. Next, the test site-specific characteristics are discussed.

4.3.1.1 Data Collection and Evaluation Social Sustainability Assessment

The identification of test site-centered social sustainability assessment was conducted in July 2019, along with a summer school for resource governance in Dublin, Ireland. Table 38 illustrates the study design. Given the sensitivity of the topics, and to ensure the fluent and unbiased exchange between the participants, audio-recording was neglected. This is in line with the suggestions of authors such as Newcomer et al. (2015). Instead, field notes were made on the computer and a protocol was prepared.

Table 38 Study Design for Social Sustainability Assessment Framework Components

Design Item	Description
Survey method	Unstructured focus groups were chosen as means of study design. Appendix 11 provides a detailed account of the research method and discusses alternative research approaches. The session design was aligned to Tang and Davis (1995).
Sample selection	The participants were experts in resource governance, and social sciences with a focus on natural sciences, and risk mitigation and communication in high-risk projects. Each focus group consisted of three people. Appendix 11 shows the characteristics of each focus group.
Data collection	Two focus group workshops were conducted, lasting between 40 minutes to 60 minutes. Focus group sessions ended when the participants felt they had discussed the topics to their best knowledge. During the session, all participants were encouraged to share their views. In addition to the leading questions, the study introduced probing questions, transitional questions, and summaries to answer the research question (see Nyumba et al., 2018). For purposes of confidentiality, the sessions were anonymized.

4.3.1.2 Data Evaluation and Analysis for Framework Components

Based on the protocols, the data was analyzed. The statements made were categorized through inductive categorization (see Gioia et al., 2013). The participants named five distinct assessment methods. Namely door-to-to, network analysis, public indices, media analysis, and the SLO. Table 39 illustrates the named assessment tools in accordance with their characteristics. Characteristics include the phase when a technology is best applied, the type of research method required, and the stability of the results (dynamic vs. fixed).

Table 39 Assessment Tools for Social Sustainability

Assessment	Project Phase	Type of Research	Stability of Results
Door-to-door	Prior	Field research	Dynamic
Network analysis	Prior	Field research	Dynamic
Public indices	Prior	Desk research	Dynamic
Media analysis	Prior	Desk research	Dynamic
SLO	Prior	Field research	Dynamic

Door-to-door analysis refers to the process of conducting structured interviews with people affected by a project. This assessment method aims to capture the perceived risk, emotions, and trust towards companies and politics.

Network analysis is a tool to determine the interaction within a community and identify contextual premises. Network analysis can be IT-supported (e.g., extracting information about the connectedness via social media), or manual (e.g., interviews). Using network analysis to study the position of stakeholders within a network can support the creation of communication and engagement campaigns and enable more targeted assessments. Learning about the role of different players should happen in consent.

Community attitudes may vary significantly. During the discussions, participants recognized country-level indices to be of low accuracy on the county level. One participant said there is no “one” public. The assumption of a homogeneous community often flaws assessments before a project start.

Media analysis is a method investigating the sentiment of the media coverage towards a specific topic in newspapers and social media. Manual and automated concepts exist to perform such analysis. Participants assumed high effectiveness for automated media analysis tools. Identified limitations are the extraction of sentiment from different forms of writing styles (e.g., irony).

SLO is a metaphor for the acceptance a region has towards a project. Unauthorized analysis may decrease trust. Moreover, the discussion revealed that assessments of social acceptance are tools where the outcome may vary over time. Table 40 displays the limits of existing assessments (per Table 39).

Table 40 Limits of Assessments

Limits of Accuracy	Exemplary (Protocolled) Statements
Varies by individual	There is no one 'public'. Homogeneity assumptions flaw desk-research.
Context dependencies	Desk research is flawed by the context, country-level frameworks fail to deliver community specific answers.
	Assessment of stakeholder salience is determined by the integration into the nexus relation of business-government-community-technology.
Co-dependencies	Education level is considered a driver for higher technology acceptance, but value and knowledge may contradict one another.
Limited quantification	Until the topic of social sustainability can be solved by mathematicians, single parts of acceptance and perception will be subject to field visits.
Varies over time	Social attitudes may change over time.

As the discussion evolved, all participants concurred that the term social sustainability is not a snapshot but an evolving concept. In its most basic form, social sustainability requires the initial communication of the expected project impact and the obligation to comply with the communicated impacts. Table 41 illustrates the information provided as means of social sustainability.

Table 41 Information Provision as Means of Social Sustainability

Exemplary (Protocolled) Statements
• Impact can be made up of any kind of disturbance to the social and physical environment • Disturbance has to be communicated, before a project • Pre-defined disturbance must not be violated, this may sustain the project acceptance • Prior to any step, information about the impact is essential • Project induced impact is crucial to communicate • Economic impact is often little accurate and may create false hope

4.3.1.3 Combination of Data and Framework Social Sustainability Integration

The focus of the analysis was to study how to determine social sustainability before the start of a project. The qualitative research identified three assessment narratives. These are (I) the requirement for field visits, (II) the assumption of heterogeneity in communities, and (III) consideration of co-dependencies between business-government-community-technology. Hence, limited information on remote evaluation principles was identified. A recurrent theme in the interviews was a sense amongst interviewees that project associates must communicate knowledge about a project's impact before any assessment or analysis process. In line with authors such as Labuschagne et al. (2005), the interviewees argued accurately and continued impact communication and knowledge provision link with social sustainability. Bridging the interviewees' demand for impact communication and social assessment targets of 2.3.5, five topics of communication emerge. Figure 27 shows the determinants of social sustainability extracted from the literature.

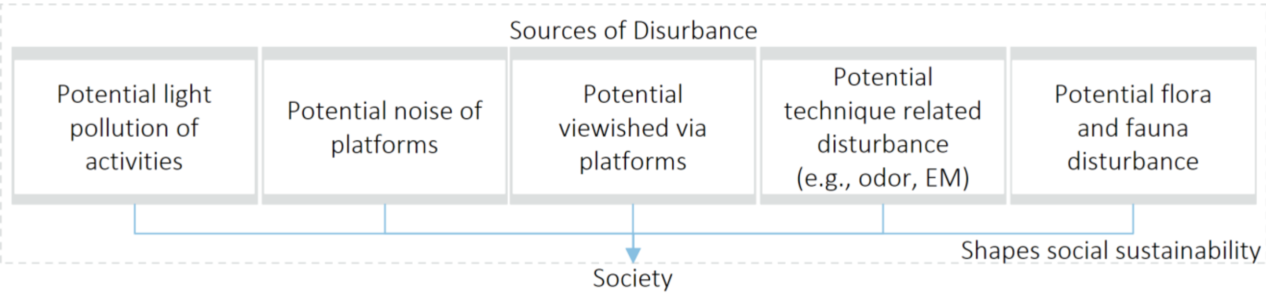


Figure 27 Societal Disturbance Sources

To analyze whether and to what degree these topics are relevant for test sites in mineral exploration, a focus group workshop took place.

4.3.1.4 Data Collection and Evaluation Social Sustainability at Test Sites

Whether or not the disturbance sources are relevant to test sites was evaluated during a focus group workshop. The workshop followed the guidelines for cross-national focus group research (van Bezouw et al., 2019).

Group composition included ten participants from social sciences from Finland, Germany, and Spain. The sample was supplemented with the expertise of the participants for having in-depth knowledge on the social sustainability of the INFACT test sites.

The workshop followed practical considerations in implementing sustainability at test sites. Impacts and communication plans for test sites in mineral exploration was on the agenda of the focus group workshop.

The communication took place through interactive work sessions. The workshop was part of the INFACT project and took place in Heidelberg, Germany, in December 2019. The workshop lasted one day. Relevant topics were protocolled and categorized. [19]

4.3.1.5 Data Evaluation and Analysis for Social Sustainability Framework Components

The data evaluation and analysis followed the principles of qualitative content analysis (Gioia et al., 2013; Mayring, 2020). Inductive coding was applied to assign the discussion topics to the pre-defined disturbance sources. Through triangulation, the statements were verified, heightening the quality of the output. Table 42 illustrates the participants' assessment of the relevance of the disturbance sources.

Table 42 Disturbances Sources that Impact Social Sustainability

Disturbance	Description extracted from the focus group workshop
Light pollution	Technology tests in natural sciences and especially mineral exploration are primarily performed during daylight. One exception is wind farms, which are permanently installed and equipped with warning lights for low-flying aircraft. As the thesis excludes wind farms, light pollution is omitted.
Noise pollution	Generally, noise pollution ticks the factor necessities of linking indicators to test site activities, as the noise of a helicopter or drone is known by the manufacturer. Manufacturer information can provide information about quantifiable noise levels. However, the perception of noise levels is subjective and varies across humans (Ma et al., 2018). At present, little research exists that would objectively report the impact this factor may have on the social environment.
Changes in a magnetic field	Interference with the magnetic field may cause malfunctioning of sensitive magnetic equipment in the vicinity of the test. Sensitive magnetic equipment may be medical devices such as pacemakers or phone-emitted EM fields. Changes that occur may link to the activities at the time of testing. The forte of the intrusion depends on the geology. Given the complexity of the subsurface, individuals can hardly quantify the strength beforehand. However, the higher the degree of fulfilment in factors relating to the geological model, the better the predictions. The relevance to the test site approach is communication-based. This decision roots in previous projects, having identified TEM induced interference as a neglectable issue, as only the test site staff themselves may encounter interference.
Visual pollution	While there is a straightforward way to communicate the visual disturbance (e.g., number of flights, height, flying concepts), concerns regarding landscape aesthetics are subjective. Table 40 further hints to a limited quantifiability. Similar to the results of the focus groups, quantification of subjective perception is of questionable accuracy and varies by context.
Disturbance to fauna and flora	Ecological issues gain attention and form the opinion of policymakers and the public (Santini et al., 2008). Studies reported on habitat disturbance through natural sciences, including research that indicates a negative correlation between disturbance levels and public acceptance (see 2.3.6). Examples of upsets to fauna and their impact on public acceptances include fatalities through wind farms. In the present context, airborne tests may disturb the fauna.

[19] The workshop further inform the INFACT Deliverable 2.7. The data collection and analysis for the deliverable and the thesis were disjunct. The presented output were obtained, and analyzed by the present researcher and were not published before.

4.3.2 Reflection of the Results and Scoring of Social Sustainability Components

The results of the social framework component development showed two key insights. Firstly, social sustainability and social acceptance / perception are two intertwined, yet different approaches. Knowledge about social acceptance measurements is more present than social sustainability assessments. Similarly, Assefa and Frostell (2007) show that social sustainability dimensions are more often than not "approached from an angle of social acceptance" (p. 65). Moreover, the authors say that "for a technical system to be deemed socially sustainable, it should at a minimum enjoy wider social acceptance." (Assefa and Frostell, 2007, p.65).

For the present thesis, social sustainability is thus the means to achieving social acceptance. Secondly, the study found that social sustainability is the process of communicating impacts and ensuring compliance with the effects reported (seeTable 43). Hence, social sustainability shapes and is mediated by perception and acceptance. A forming feature of social sustainability is the accuracy and accessibility of impact. Accessibility provides information about impacts in a way that generates a fundamental understanding of the relationships between the project and the social and physical environment. In consequence, the decision framework must include impact-related measures. For the dissertation, this implies that the impact of the disturbance sources must be communicated. The factor scoring reveals that only noise pollution, visual pollution, and disturbance are relevant to communication. These factors shall be communicated to the communities. For noise pollution and visual pollution, the test site decision-maker shall communicate the expected testing hour, platform type, and expected noise levels.

Table 43 Factor Scoring Social Sustainability Framework Components

	Light pollution	Noise pollution	Visual pollution	Changes in magnetic field	Disturbance to fauna and flora
Relevant	✗	✓	✓	✗	✓
Easy to understand	✓	✓	✓	✗	✓
Multidimensional information	✓	✓	✓	✓	✓
Comparability across test sites	✓	✓	✓	✓	✓
Replicability	✓	✓	✓	✓	✓
To be considered	✗	✓	✓	✗	✓

Checkmarks indicate fulfillment; crosses indicate a lack of fulfillment

To date, no comprehensive assessment that covers the reaction of animals caused by platforms employed in mineral exploration exists. This will be developed in the following ecological factor assessment.

4.4 Ecological Sustainability Framework Component Generation

The ecological concept generation aims (I) to depict the disturbance and impact potential of tests sites, and (II) to determine the suitability of disturbance analysis for STSDF.

Figure 28 depicts the structure of the sub-chapter.

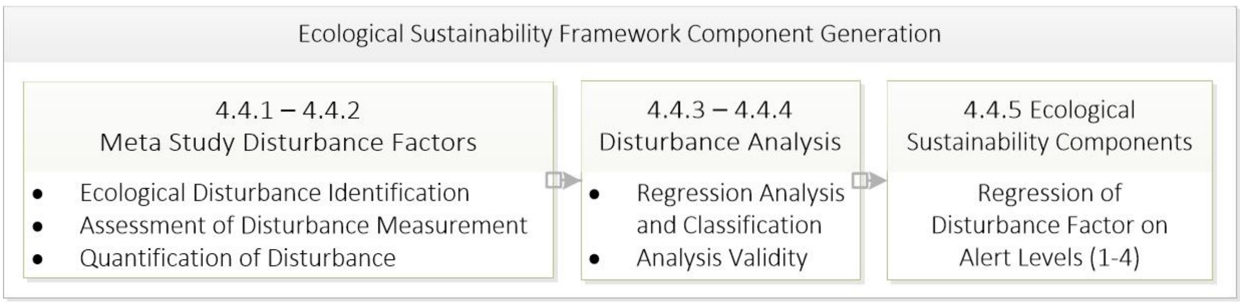


Figure 28 Ecological Sustainability Framework Component Generation

4.4.1 Ecological Impact Determination

The literature reviewed in 2.4.3 shows a need for standardized processes and practices that enable minimally invasive operations at test sites. Technologies, and platforms employed in natural sciences may lead to an impact on the fauna and flora within and beyond a target area. Therefore, it is essential to analyze which ecological measures challenge technical goals and how to balance the extent of disturbance and technological progress.

Having an assessment framework that analyzes the degree of destruction and mitigating mechanism could help balance between objectives of the test operations and ecological considerations. Therefore, the primary purpose of the ecological sustainability framework component was to create systematic literature on wildlife disturbance.

The focus lies on airborne and groundwork disturbance, as is the scope in mineral exploration. The thesis aimed to (I) calculate an estimate of disturbance from existing data, and (II) determine factors implicated in the variability of disturbance by examining the different variables to disturbance intensity, and thus potential mitigation. Given the lack of existing work, the question is phrased exploratory:

How can the ecological impact of test site operations be assessed?

The following outlines present the conceptual approach to integrating ecological sustainability into the STSDF. Thereby the study conducts fauna disturbance approximations for ground and airborne procedures. Mitigation mechanisms, including technological changes required to minimize impact as well as operational considerations, are introduced.

4.4.2 Data Collection for Ecological Sustainability Framework Components

The study performed a systematic review to analyze disturbance profiles of ground and airborne platforms. The approach (I) selects, (II) quantitatively appraises, and (III) synthesizes data across scholarly work to get insights on statistical relevance and significance through systematic analysis. According to authors such as Denyer and Tranfield (2009) and Mikolajewicz and Komarova (2019), evidence extracted from a review allows for reasonably clear conclusions.

The output of such study design is a meta-study. Meta studies are suitable for topics with a vast body of existing literature. Denyer and Tranfield (2009) establish that meta-studies encounter policy and practiced questions. The meta-study is suitable as (I) the underlying study is practical, (II) there is a large body of peer-reviewed literature, and (III) meta-studies have been shown as valuable in the context of ecological impact assessment before (Denyer & Tranfield, 2009; Mikolajewicz & Komarova, 2019).

The study followed Mikolajewicz and Komarova (2019) outlines to ensure the quality of the meta-study. The study implements a five-step research strategy. Appendix 12 shows the research strategy and its properties. The survey review identified 333 studies. After screening titles for relevance, and quality and content check, 24 studies remained. To ensure the (I) quality of the data collected, (II) the comparability, and (III) the replicability of the model, two quality measures guide the research:

I. Single type observations such as species type were excluded
II. Only observations that measured similar alert behavior were included

All available information was extracted from the remaining literature. These included (I) distance at reaction behavior, (II) measured reaction, and (III) technical specifications of the platform (weight (in kg), rotation diameter (in m), length (in m), elevation (in m), and noise (in dB)), and (IV) the species analyzed. Design and shape patterns were excluded, as limited data was available.

It must be noted that for design a correlation with other variables (e.g., helicopter shape correlates with flight pattern and aircraft size) may be expected.

The study set out to limit its observations to the vertical elevation to the species in question. In this way, topography and sound propagation (e.g., Doppler Effect[20]) could have been reduced. However, elevation is no common measure. Hence, the sample size would have been too small for representative analysis. With the inclusion of distance-related measures, the data validity analysis becomes more representative (see 4.4.3.3). Except for bird specific research (Fernández-Juricic et al., 2005; Guay et al., 2013; Samia et al., 2017), response / reaction levels are not standardized. To create consistency across the studies, the most cited papers (Delaney et al., 1999; Fernández-Juricic et al., 2005; Mulero-Pázmány et al., 2017) were taken as a reference to define the response. Responses caused were categorized according to the above-introduced synthesis. Four alert levels (a) resulted:

- a_1 (i.e., study observed no noticeable behavioral change)
- a_2 (i.e., increased attention / alert, vigilance, starring, head rotation at observation point)
- a_3 (i.e., active response such as flight, fleeing, flushing into the water)
- a_4 (i.e., attack and abandonment of nesting place).

Animal type was initially recorded and then categorized by species. The study includes five species. Table 44 lists the considered species and the type of animals that make up the species.

Table 44 Species Classification

Species categories	Animals included and observed
Large mammals	Bears, seals
Mammals	< Large mammals
Large birds	Owls, eagles, geese
Birds	< Large birds
Flightless birds	Penguins

Regarding the research aim, the categorization and joint regression increase the generalizability and encourage to expand the approach beyond the existing model later.

4.4.3 Data Evaluation and Analysis for Ecological Sustainability Framework Components

The goal of the data analysis was to understand the relationship between two or more factors affecting the response of wildlife to platforms employed in natural sciences.

4.4.3.1 Methodological Approach to Ecological Framework Data Analysis

Regression analysis methods and classification approach to analyze the relative quality of statistical models were employed to determine which statistical method best describes the disturbance data. For classification, the study tested Akaike-Information-Criterion (AIC), confusion matrices, k-Nearest Neighbor (kNN), and distribution analysis. For regression, the study performed multilinear regression and Multinomial Logistic Regression. Appendix 13 shows a description of the regression procedures.

4.4.3.2 Ecological Disturbance Data Analysis Results

For the present approach the regression analysis starts with a model, in which the dependent variable reaction $a_i = [1; 4]$ is categorical and is explained by one or more variables x_i, (distance, species etc.). Appendix 14, Figure 46 shows the distribution of the data in each variable. This means that particular species, information about the specifics (elevation, noise etc.) of helicopter, UAS, groundworker, and fixed-wing is assumed to determine the disturbance of animals.

[20] The Doppler Effect refers to the shift in wave frequency in relation to an observer moving relative to the wave source, Foken (2021).

The regression fit builds the basis for the following analysis. Visual inspection of the best unbiased linear estimator criteria shows a fit for regression analysis. Although the distribution of the measurement points is influenced by the way the data is recorded, it can be said that the data allow the regression to be applied.

4.4.3.2.1 Multilinear Regression

The distribution of the comparison values forms the basis of the significance test, a normal distribution according to Gauss and a Poisson distribution were used for comparison. The variables were then categorized and examined with a multiple regression; this step was considered to exclude possible distribution problems. Figure 29 shows the results obtained from the preliminary multilinear analysis the reaction animal's show across all platforms.

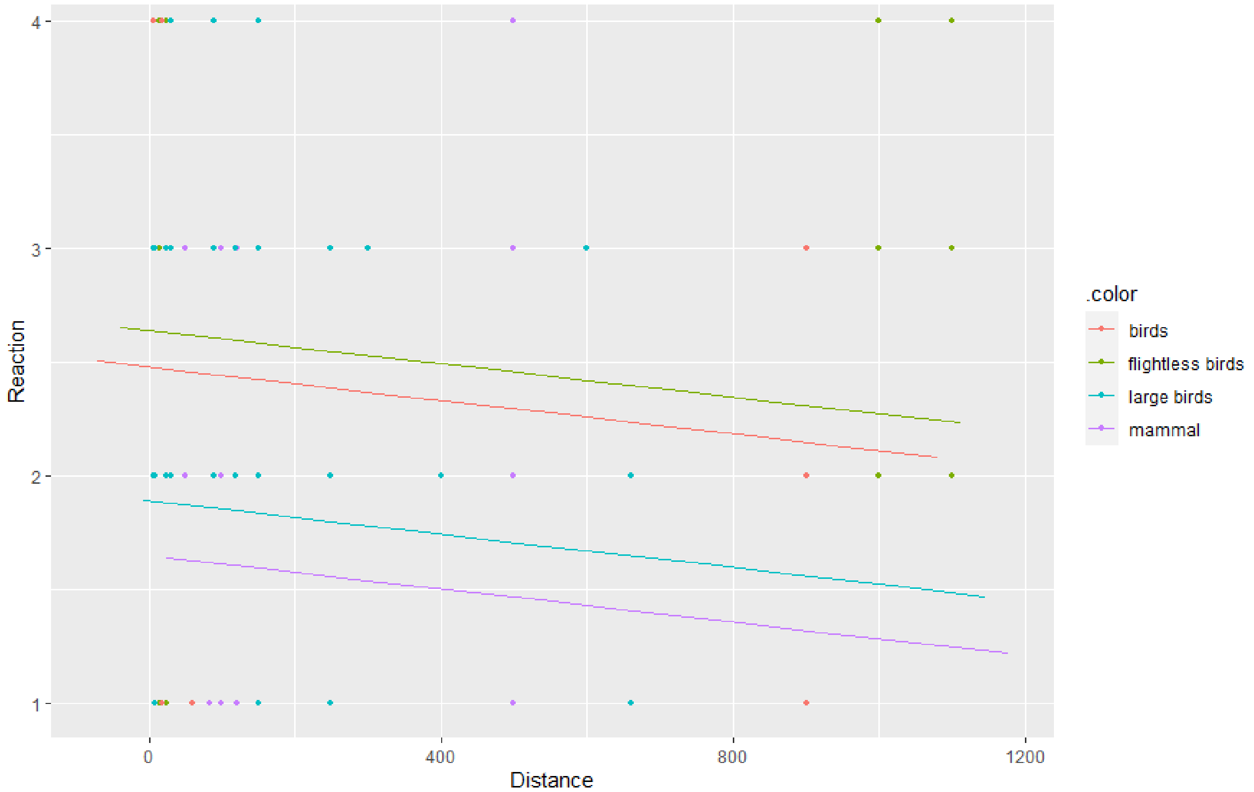


Figure 29 Multilinear Regression across Platforms

Closer inspection shows clustering of observations between 0 and 200m and outliers in a long right tail. This pattern fits with the review of the raw data, as observations of UAS and groundworker are commonly found at smaller distances. The examined model shows a positive correlation between the dependent variable "Reaction" and the independent variable "Distance". The significance test carried out shows a significant correlation between the strength of the reaction and "Distance". The magnitude of reaction decreases with increasing distance, and mammals show a lower degree of a reaction than large and flightless birds. Thus show the strength of the reaction decreases with increasing distance, and mammals show a lower degree of reaction than large and flightless birds R^2 (0.1109) adj. R^2 (0.1101), the R-value indicates acceptable model fit given the small number of explanatories in the sample.

In a subsequent step a more detailed analysis was performed. The multiple linear regression was calculated to predict reaction based on the distance of the helicopter and animal species. Model fit is assessed based on an F-Test with F(4, 1695) = 180.3, p < 2.2e-16), and an R^2 of 0.2986. Appendix 14, Table 78 and Figure 47 display and visualize the respective statistics. Compared to the regression across platforms, the table shows a higher R^2 indicating a better fit of the model.

Next, the dependent variable reaction and the independent variable species, distance, and groundworker was computed. Bird species react similarly to disturbance by groundworkers as they do to helicopters. Similar to the helicopter results, mammals react least strongly to the presence of groundworkers. The measured distance that triggers a reaction is smaller than the measured distance that triggers a reaction for helicopters. However, no data for flightless birds were available. With the explanatory variable of distance to groundworker, the F-Test reports a test statistic of F(3, 2107) = 299.7, p < 22.2e-16, with an R^2 of 0.2991. Appendix 14, Table 79 and Figure 48 display and visualize the respective statistics.

Subsequently, a multiple linear regression was calculated to predict reaction based on the distance between the UAS and animal species. The F-Test reports a test statistic of F(3, 452) = 74.73, p < 2.2e-16), with an R^2 of 0.3315. Appendix 14, Table 80 displays the respective statistics.

The smallest distance to the animals was measured with UAS. Here, mammals react more strongly than flightless birds and larger birds. The multiple linear regression was calculated to predict reaction based on the distance of the Fixed-Wing and animal species. The F-Test reports a test statistic of F(2, 210) = 283, p < 2.2e-16, with an R^2 of 0.5951. Appendix 14, Table 81 displays the respective statistics.

For fixed-wing, the lowest number of observations exist. The analysis showed that only birds, and large birds could be analyzed. The slope is at zero.

4.4.3.2.2 Ordinary Least Square Regression

Given the data analyzed in this study are categorical, ordinal, and interval, ordinary least-squares may be insufficient due to violations of linearity (Best & Wolf, 2010). Multinomial Logistic Regression can reduce limitations and identify the relative importance of the explanatory variables by scaling both the dependent and independent variables. In the model studied, the variable Reaction was divided into four categories to reflect the strength of the response of the animals studied. The influence of the independent variables on the likelihood of an animal's response was then investigated. To check the validity, confusion matrices were employed using random sampling to compare test and training data (Bühl & Zöfel, 2002). Estimates in Figure 30 show the reaction probability across all analyzed species.

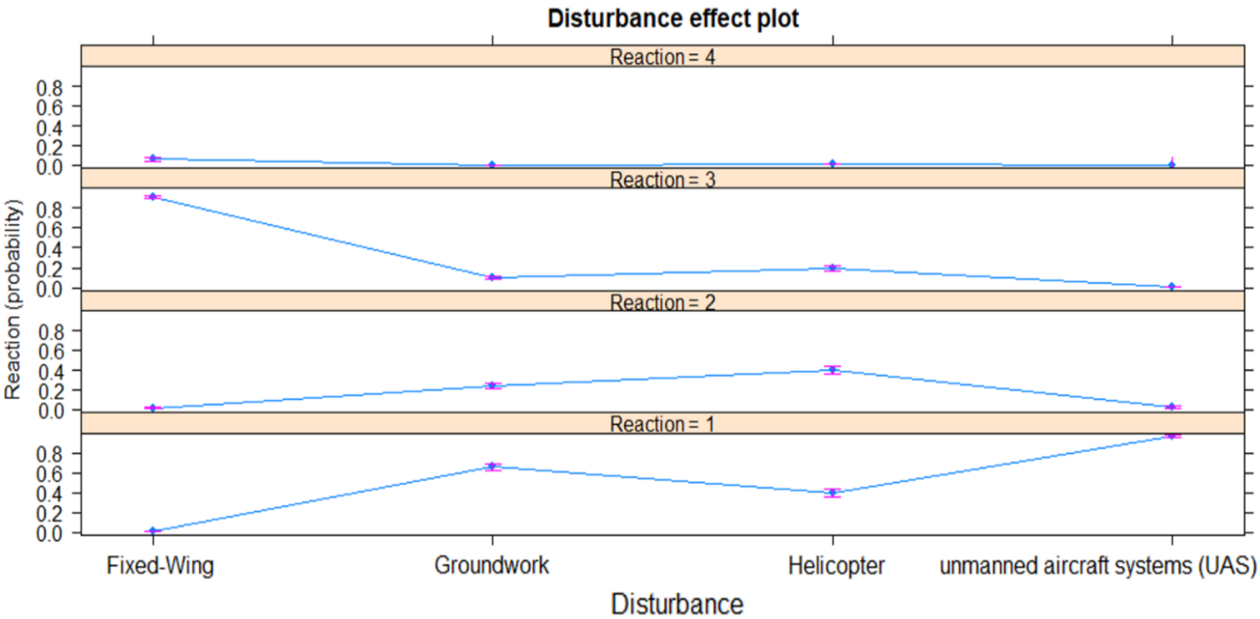


Figure 30 Categorical Regression by Platform and Disturbance

Starting with the distance effect plot for helicopters across species, Figure 31 illustrates the distance effect plot.

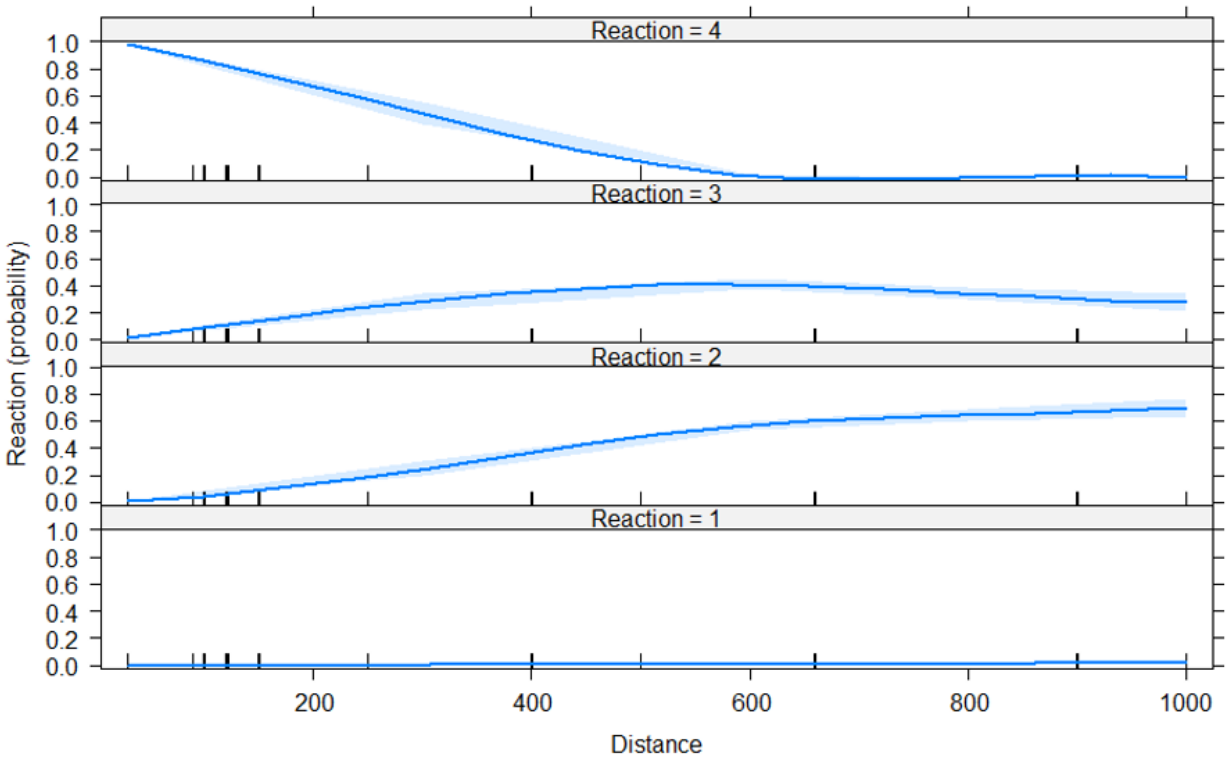


Figure 31 Helicopter Multinomial Logistic Regression Output

Probability for reaction increases with decreasing distances. The black indications at the bottom of each reaction plot indicate the spacing of data collection per distance. The evidence shows small variance across data points, which is shaded in light blue.

Next, the reaction probability for groundworkers across all species was analyzed. Figure 32 illustrates the distance effect plot.

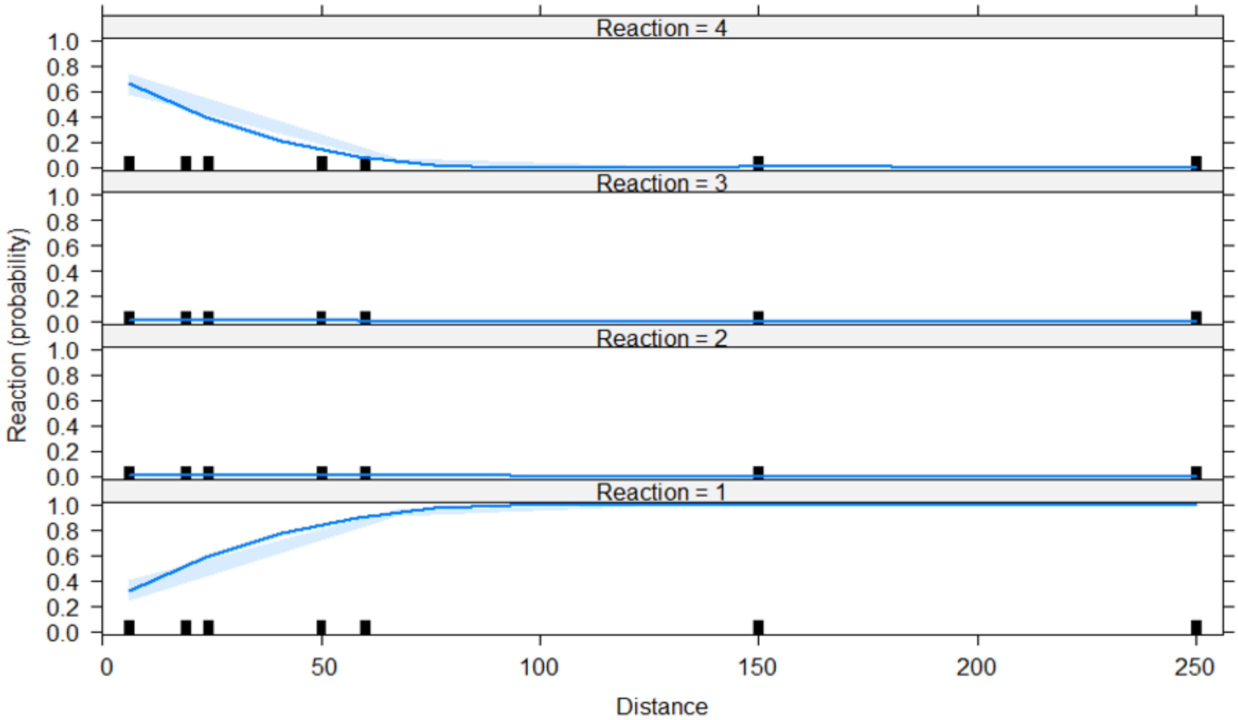


Figure 32 Groundworker Multinomial Logistic Regression Output

Evidence of Figure 32 shows that either reaction categories 4 or 1 occur for the investigated distances. The proposed model suggests a steep decline in reaction probability at 25 m. The observations are not evenly spaced. Especially for distances in the range between 20-50 m, additional data might clarify the reaction behavior for reaction categories 2 and 3.

Figure 33 illustrates estimates of reaction probability for UAS.

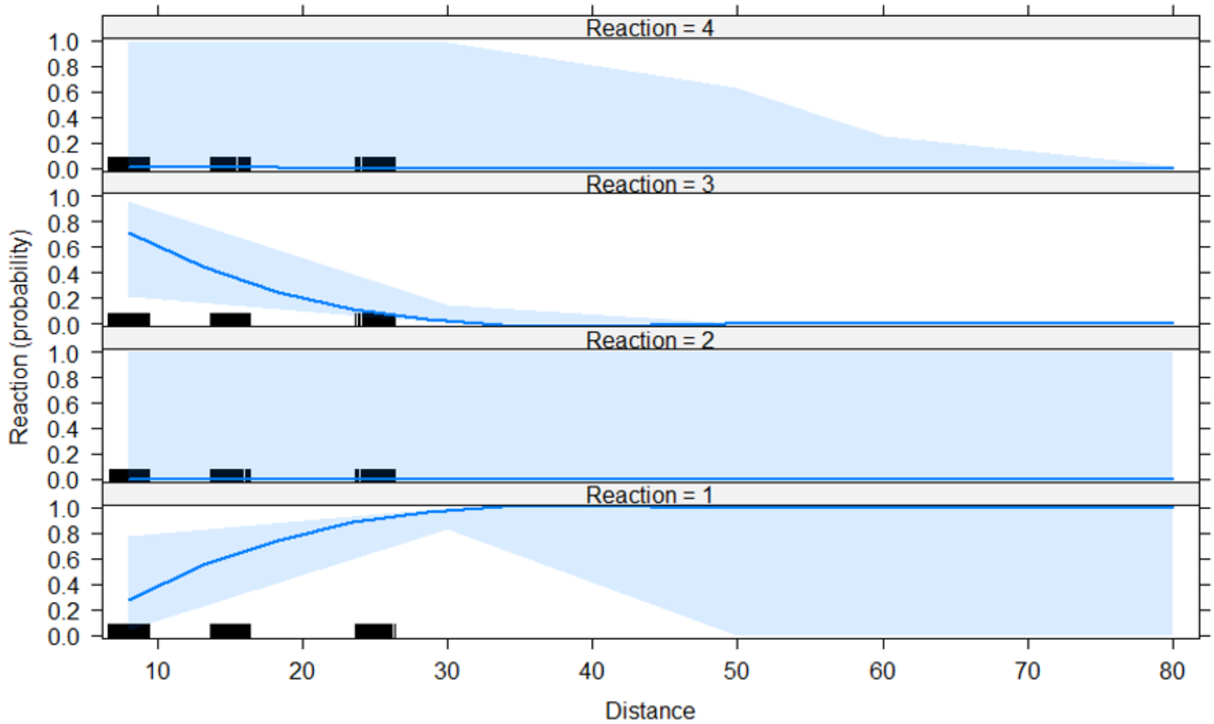


Figure 33 UAS Multinomial Logistic Regression Output

Figure 33 shows a high dispersion around the estimate, suggesting high residual variance. The width of the confidence interval suggest that the model does not accurately plot the reaction across variables.

Previous statistical outputs in the survey were taken to investigate potential sources of this high variability. From the analysis it emerged that species might react differently to UAS. Consequently, species were analyzed separately.

Figure 34 illustrate the results for reaction probability and flightless birds. The plot supports the explanation that variability in reaction probability for UAS originates from the different behavior of species. The data points are not evenly spaced across distances. Reaction category two is missing.[21]

Compared to the effect plot, the line plots hold less illustrative power. In addition, the data sample was too small for line plots across species. In addition, only helicopter and groundwork observations had samples large enough for proper evaluation.

The gap in the distribution suggests that there are either strong or no reactions. Reaction category four is also observed with low likelihood across distances. A more distinguished analysis requires data collection at 20m.

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21 Missing reaction categories, hint on species always reacting, when approached. Another explanation may be that the observations did not include level two observations. It appaers that sub-grouping led to less data points.

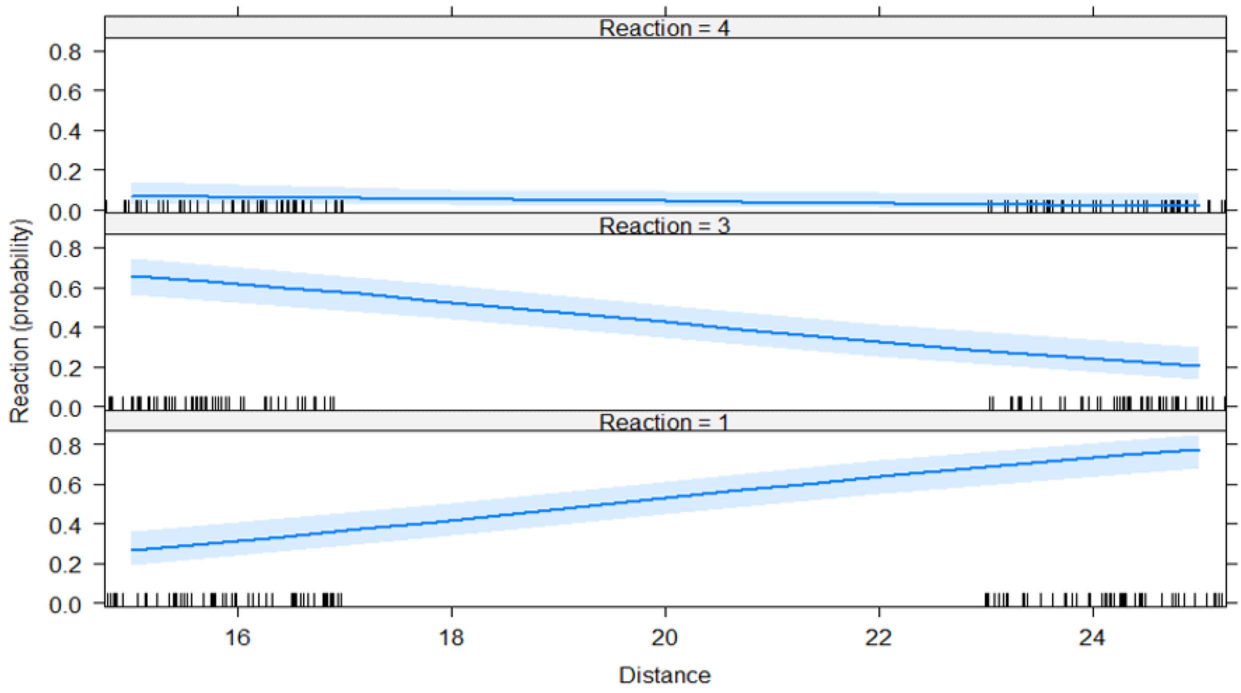

Figure 34 UAS Multinomial Logistic Regression Output for Flightless Birds

Initially, the study examined mammals and large birds individually. For larger species, the data was not sufficient to plot. Mammals and large birds alone were also not supported by enough measurements. The study thus checks the dispersion when different species are combined and found a visual fit for large birds and mammals. Figure 35 illustrates the reaction probability for larger species. Despite the combined analysis, the variability of the sample did not increase. The distance effect plot for mammals and large birds indicates that reaction four observations are insufficiently covered in the underlying data gathered from previous studies.

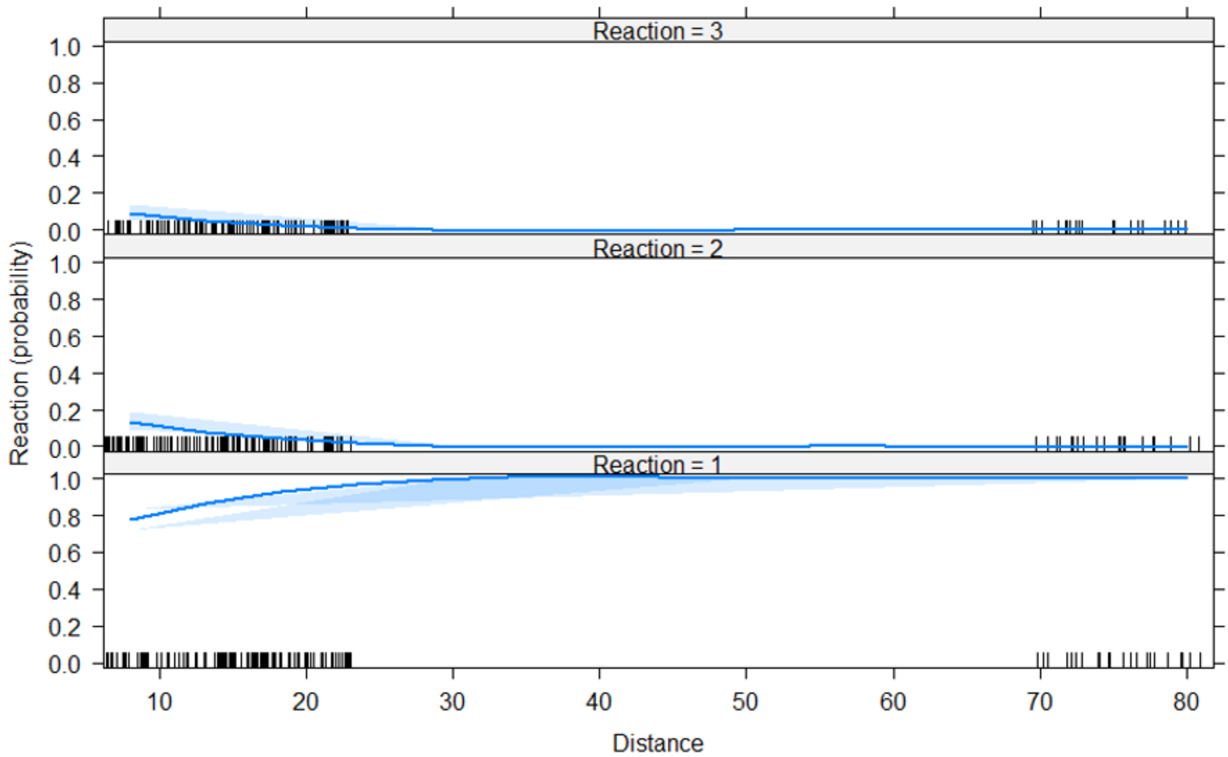

Figure 35 UAS Multinomial Logistic Regression Output for Mammals and Large Birds

For Fixed-Wings proposed model suggests a high probability for reaction three. Because of the limited availability for fixed-wing data, no expressionable figure could be derived.

The probability of Reaction 2 and 3 is small and only occur between 0 and 25m distance. The spacing is again not evenly distributed. Previous analysis showed that reaction probability increases as distance decreases. The analysis produces relatively tight confidence intervals, as low reaction probability across small distances. The UAS analysis shows the least reaction probability compared to helicopters and groundworkers. This supports the results shown of Figure 29.

Besides the effect plots, the study further explored descriptive patterns with common line plots. The line plots plotted the probability on a continuous reaction scale.

4.4.3.3 Validity of the Ecological Data Analysis

Distribution Analysis: A normal distribution according to Gauss and a Poisson distribution were used as a comparison. In an additional step, the dependent variable was then categorized and examined; this step was considered to exclude possible problems with the variability of the sample. The study uses the AIC to compare different model candidates.

When the two estimated models, Model 1 ("Gaussian") and Model 2 ("Poisson"), are compared, Model 1 has a lower AIC (12895) than Model 2 AIC (13549), with the same number of parameters. This fits with alternative indicators of model fit, as the Model 1 fit of reaction based on distance and animal species has a higher F-Test statistic ($F(4, 4547) = 141.7$, $p < 2.2e-16$), with an R^2 of 0.1109.

Therefore, the model based on the Gaussian distribution is better suited to describe the relationship of the present model. When comparing Ordinary least squares (OLS) to Multinomial Logistic Regression, the AIC of the categorical evaluation (Model 3) is AIC (9473). With the same data, the categorical evaluation from Model 3 has the lowest AIC and therefore fits the data best.

The kNN works by determining the distances between a query and all examples in the data, selecting the stated number of cases (K) neighboring to the query, and then polling for the most recurrent tag (in the case of classification) (Begum et al., 2015; S. Zhang et al., 2017).

Table 45 illustrates the output for the categorical analysis. The result of the performed kNN analysis determines the accuracy of the predictor "Distance". The data shows that the space between the data points within the measured “Distances” is sufficiently small.

Table 45 Confusion Matrix Output

	UAS	Helicopter	Fixed-wing	Groundwork
Accuracy	0.9171	0.9635	0.6949	0.9925
95% CI	(0.9531, 0.9721)	(0.9531, 0.9721)	(0.6364, 0.749)	(0.9877, 0.9958)
Kappa	0.8072	0.9456	0.4905	0.9889

In the subgroup UAS the accuracy of 91.70507 reflects a high fit and thus shows that the defined alert categories 1-4 can be separated based on the predictor "Distance". This is also confirmed by the value for Cohen's Kappa of 0.8072, as a value above 0.80 is typically regarded as a very good measurement.

In the Helicopter subgroup, an accuracy value of 96.34675 is obtained. Cohen's kappa of 0.9456 also indicates a good measurement exclusivity in this subgroup, i.e., a given distance value reliably suggests a particular response.

The Fixed-Wing subgroup is the only subgroup where the kNN-Confusion Matrix at an accuracy of 69.48529 and a Cohen’s Kappa of 0.4905 indicate that the fit here is in the lower range.

The groundwork subgroup shows an accuracy of 99.25224 with a Cohens Kappa of 0.9889 and good fit.

4.4.4 Combination of Ecological Sustainability Decision Data and Framework Integration

The ecological sustainability analysis investigated the reaction of different species to platforms used for data collection in mineral exploration. Using technical, campaign plans, and performance criteria to consciously select and adjust data collection behavior enhances the ecological sustainability performance of test sites.

The data shows that the higher the distance, the lower the reaction probability for reactions between alert levels 2-4. Across methods, the multinomial regression appeared best suited for the analysis. The generated plots can visually communicate the expected impact and create sensitivity towards the distance. The distances investigated vary across the platforms.

The distance spectrum of each platform is representative of the distance with which the sensor data is collected. UAS showed the smallest reaction across all species at the given height with no indication for substantial heterogeneity across species.

Two findings for the test site development context emerge: Firstly, UAS can fly lower, decreasing the sensor to target ratio. Secondly, UAS is a more recent platform that shows high potential, with this being an added benefit that had not been studied previously.

However, the study did not check for recurring sources of noise. More elevated flying platforms tend to capture large areas within one flight line. At the same time, UAS fly lower and catch fewer grounds per flight line. In consequence, the UAS will disturb the fauna more frequently than a helicopter. Such differences must be communicated when presenting the disturbance indications.

Aside from the flight lines, the differences between platform noises (e.g., groundwork vs. UAS) appear not to be the single source of distance-induced reaction. Intrusion into the local habitat may as well be a mediating variable.

For sustainable site selection, three aspects are pointed out as contributions from the analysis. Firstly, a model for disturbance analysis in a meta-analysis is set up. Secondly, connections to sustainability impacts were identified and illustrated in Table 46.

Table 46 Sustainability Lever for Ecological Site Usage

Sustainable lever	Description
Survey design	Minimize negative impact: increasing distance to inhabited areas or sensitives (smaller) species
Local conditioning	Integration of local conditioning factors: design plan, schedule campaign plan regarding the constraints identified
Compliance	Compliance with the plan to fulfill emerging local restraints. Unexpected changes must be communicated

The framework must weigh the technical performance, and visual comparisons of distance adjustments or the platform used to ensure the technical relevance of the test site despite adjustments; for example, weighing of adjustments against spatial / spectral resolution, accuracy, precision, repeatability, and the qualitative parameter of fitness for purpose / technological relevance.

The limited availability of additional variables such as noise and speed did not allow for a more detailed analysis of disturbance sources. Limited to distance, this study lacks a more differentiated examination of adaptation potentials such as speed (increases noises), take-off and landing distances to protectable zones, or timing due to seasonal cycles.

Despite the limitations, the results provide a way forward to incorporate wildlife impacts into a structured frame. The results of this ecological sustainability assessment can eventually be communicated to the stakeholder and the affected communities. For communication, the social analysis gains a more substantive grounding.

To this end, three communication and transparency guidelines can be derived (results are derived from 4.3):

I. Comprehensible provision of information increases with advanced and quantitative disturbance analysis
II. Integration of limitations / suggestions from relevant stakeholders can increase trust
III. Appropriate communication about fauna can create spillover understanding and ensure non-disruptive timing for local activities

4.4.5 Reflection of the Results and Scoring of the Ecological Components

Table 47 presents the breakdown of the ecological analysis according to the outlines of 0 and 4.4.4.

Table 47 Ecological Framework Component Reflection

Step	Potential methodologies
Selecting variables	Meta-analysis
Imputation of missing data	Imputation of missing data is enabled through R or Python integration. The imputation is not limited to the given categories. The follow-up data analysis allows multiple factors to be analyzed. The length of the vector is no limitation.
Data analysis	Multinomial Logistic Regression is the best-suited evaluation mechanism. Derivations for the estimators and test statistics involved help applied researchers interpret their findings more easily.

The effects of test site disturbance can thus be approximated and tolerances for testing activities may be derived. It remains critical to analyze different levels of interaction.

Especially where both groundworker (e.g., UAS pilot) and a platform is concerned further data may clarify disturbance of multiple-sources. The components were reviewed to assess the fit with the test site decision framework design criteria. Table 48 introduces the reflection methodology.

Table 48 Ecological Sustainability Framework Components Design Criteria Fulfillment

Design Criteria	Explanation
Relevant	The land is a limited resource. Land-usage is limited, and every decision for or against a change in land use can be accompanied by changes, conflicts, opportunities, or new development potential. Proactive change management can preserve biodiversity and reconcile conflicting goals and the interests of stakeholders. This ecological impact assessment is thus not only relevant for ecological conservation but also as a communication medium between stakeholders. Due to the target species strategy, the approach can protect the respective individual animal and have positive effects on the umbrella species or the biotope itself.
Be easy to understand	Using the categorical analysis approach, recommendations for land use strategies can be communicated. Suitable instruments and solutions can be discussed depending on technological performance.
Multidimensional information	The consideration of all platform types and different animal species enables universal tuning based on different disturbance occurrences.
Ensure comparability between test sites	When comparing any two test sites for a similar platform, at different heights, the aggregated approach allows for approximation. Uncertain comparison judgment may occur due to other topographic features and the associated propagation of sound.
Replicability	Although the previous literature has contributed to establishing ecological disturbance assessments, the unified and structured elaboration of data collection and measurement points collected by previous authors allows for replicability and extension of the approach.

5 Sustainable Test Site Decision Framework

The present work established that testing and demonstrating technologies in natural environments is a complex task. The involvement of different stakeholders and the dispersed decision-making power between technology experts using the sites and managers deciding upon their development and commercial eligibility complicates decision-making. The technical suitability of test sites has a considerable impact on the value of the testing and commercial significance (e.g., demonstrative expression). The developed STSDF combines the conditions for testing at a TRL of 5-9. The STSDF is relevant, easy to understand, multidimensional, comparable, and replicable. The STSDF consists of three pillars:

I. the STSDF process

II. the structural representation of the STSDF

III. the STSDF content model

The following section summarizes these pillars.

5.1 Sustainable Test Site Decision Process

The taxonomy of the STSDF builds on a systematic classification of decision stages (exclusion and evaluation), decision factors, impact assessments, and communication. The structural model computes the relationships between categories and decision factors. The present sub-chapter displays the orchestration of the relationships between these categories and factors. Ecological assessment and social feedback loops ensure ecological and social sustainability. Figure 36 depicts the process model.

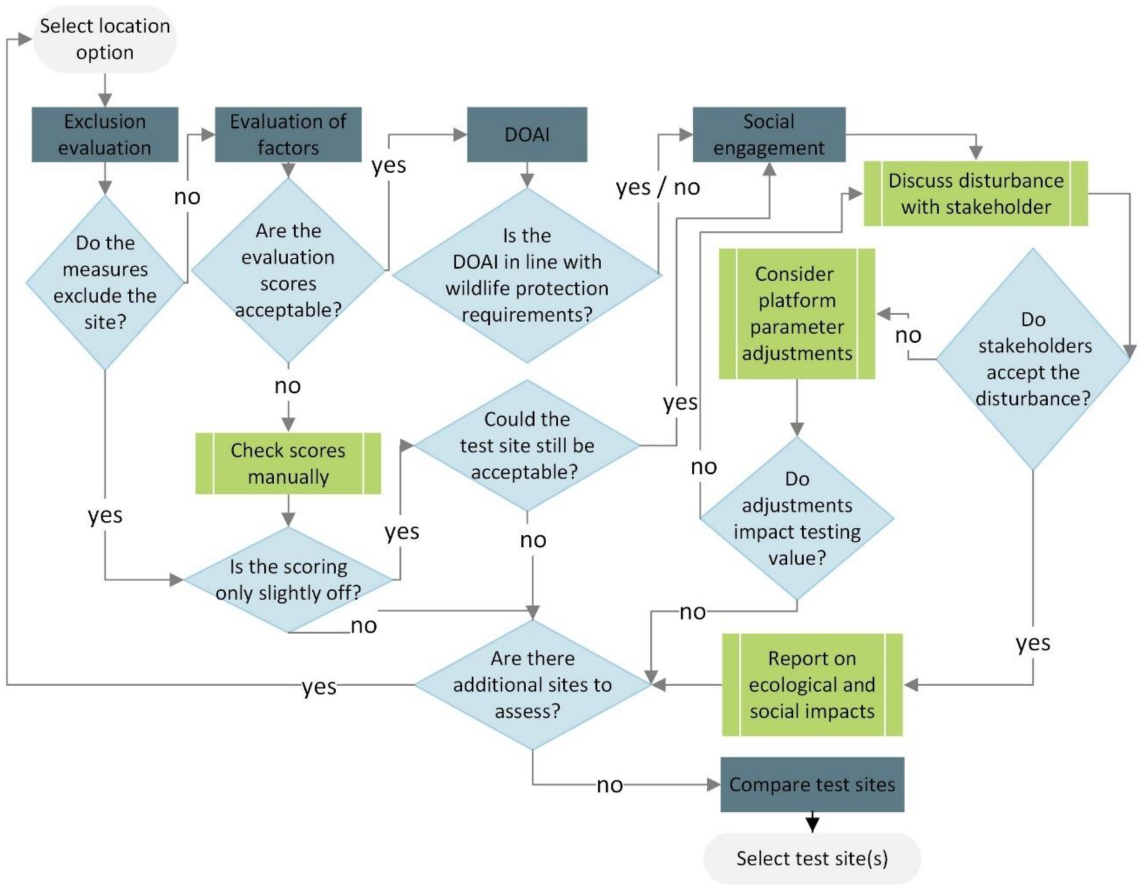

Figure 36 Sustainable Test Site Decision Framework Process

Having introduced the general procedure, the next section will describe the process of deriving input data and computing the data. Any selection starts with setting the strategic decision space. Strategic decision space tends to be influenced by (I) present and future market demand, (II) technical outset, and (III) an initial understanding of test target features. The initial fit provides information for the exclusion stage whereby a set of pre-concluding features are analyzed. In case a fit is given, the process proceeds with the evaluation stage. The design of the evaluation stage includes technical, ecological, logistical, and socio-economic features. Findings of the evaluation stage that cannot be mitigated lead to the termination of the process. Disturbance-oriented-adjustment and information approach (DOAI) and social dialogue mechanism start for positive results or negligible detail. If the social setting and disturbance mitigation suggestions do not preclude value-added, the test site is up for comparison with related test sites. If there are other locations up for consideration, the process starts for associated locations.

5.2 Structural Representation of the Sustainable Test Site Decision Framework

The structural representation is the procedure to develop an STSDF. The approach builds on a sequenced construction of composite indicators and the regressors for a DOAI for test sites. The process structures and computes the identification, sequencing, and comparison of decision categories and factors. The STSDF suggests procedures for the selection of variables, the imputation of missing values, the normalization method, the weighing decision, and the aggregation method. Table 49 displays the process steps and the suggested method.

Table 49 Framework Components for Test Site Selection

Activity	Alternatives
Selecting variables	Expert interviews with parties from trusted organization
	Triangulation with public databases
	Factor scoring – statistical methods
Imputation of missing data	Least observation carried out forward
Factor data analysis	Component analysis
	Relative value normalization
Category weighting / aggregation	Arithmetic mean
	aAHP
Ecological	Multinomial regression

The following sub-chapter discusses each process step respectively.

5.2.1 Selecting Variables for Sustainable Test Site Decision Frameworks

The selection of variables refers to the choice of data and serves the purpose of identifying factors that are relevant, accurate, timely, accessible, interpretable, and coherent. The presented approach identifies factors from expert interviews and backs the quality of the factors through triangulation with technical reports and scientific literature. Table 50 displays the quality criteria.

Table 50 Test Site Decision Framework – Factor Selection Procedure

Quality Criteria	Measures
Relevance	Expert interviews
Accuracy	Triangulation with trusted parties
Timeliness	Integration of present and future technological challenges; allow for factor exchangeability
Accessibility	Open access data insurance
Interpretability	Illustrate expert statements towards factors
Coherence	Ensure absence of multi-collinearity, perform post factor analysis, and build categories on factor similarity

5.2.2 Scoring Variables and Categories within the Framework

The scoring builds on three steps, namely (I) category hierarchies, (II) factor scoring, and (III) normalization of factors.

I. **Category hierarchies:** To achieve relevance and applicability, the decision-maker shall put the identified categories into hierarchical order. Having category hierarchies enables composite decision presentation. The study has developed an aAHP process suited for relevant, easy to use, multidimensional, replicable, and comparable data evaluation

II. **Factor scoring:** Scoring is performed through a 5-Point Likert scale. Allowing for the non-decisive answer introduced disproportional computing efforts and is not suggested for follow-up factor scoring. The survey population is not bound to a specific number. Three aspects are decisive: (I) the level of expertise held by the participants. (II) The diversity of technologies to be tested. (III) The influencing context knowledge. Per context, the data showed that technology experts tend to favor technical aspects. In contrast, industry experts tend to assign higher values to an economic potential such as fit between intended and target environment.

III. **Normalization:** Compute the relative value of each factor, via the reference point of each variable.

5.2.3 Mathematical Computation of the Sustainable Test Site Decision Framework

The mathematical computation of the STSDF, consists of (I) the exclusion stage, (II) the category weighting, (III) the reference value computation as extracted from the factor scoring, and (IV) the evaluation stage.

The evaluation stage composes of a factor specific approach that put the reference value in relation to actually observed expression of a factor at a respective test site, and an aggregated, - category-specific analysis. Table 51 illustrates the variables used in this sub-chapter.

Table 51 Mathematical Decision Model Variables

Variable[22]	Definition
q	Question (s)
b	Binary evaluation level(s)
s	Suitability of a test site
a	Decision matrix, matrix decision points
k	Alternatives
pr	Weight(s) per category
c	Category
$\boldsymbol{r}$	Reference points
$\boldsymbol{y}$	Factor-score
$\boldsymbol{x}$	Factor(s)
$\boldsymbol{z}$	Category valuation

Exclusion criteria build on binary decision.[23] The following outlines use a set of indices to explain the decision structure. A test site is evaluated based on a set of Q questions, q = {1, 2, …, Q}. For each question, the binary evaluation level b takes the value of 1 if the factor e under consideration meets or exceeds a pre-specified requirement level. Levels of b are summed over the complete set of questions. In general form, this can be formalized as follows:

[22] The number of observations or items in a set is indicated by the respective capital letters.

[23] The exclusion criteria do not present a decision tree. There are no internal nodes; the decision structure consists of leaf nodes {0,1} only. The decision structure is, therefore, a flowchart-like structure. Binary decision trees were omitted as dependencies between potential partitions are not apparent.

$$B = \sum_{q=1}^{Q} b_q \qquad\qquad b_q = \begin{cases} 1 \; if \; e \geq \underline{e} \\ 0 \; if \; e < \underline{e} \end{cases} \tag{1}$$

Higher scores of B indicate better value, with the maximum at B = Q.

Applying the general principle to a specific test site t, the decision rule for the suitability S of a test site t as presented on the next page:

$$S_t(B) = \begin{cases} 1 \; if \; \frac{B}{Q} \geq 0.5 \\ 0 \; if \; \frac{B}{Q} < 0.5 \end{cases} \tag{1.1}$$

Category weighting is the next step. It analyses the importance / weights for the different categories. To do so, the nxn matrix A, with $A \in \mathbb{R}^{nxn}$ is composed. The elements a_{ij} of the matrix give the relative importance between two categories. Hence items along the diagonal are set at 1. Items in the lower triangle are inversely related to their counterparts in the upper triangle. Formally, $a_{ij} = \frac{1}{a_{ji}}$, where i indexes columns. For example, A1 is three times as important as factor A3 the ratios mean $a_{13} = \frac{3}{1} = 3; a_{31} = \frac{1}{3} = a_{33}$. To be able to compare categories beyond the pair-wise information given by the elements a_{ij} the matrix must be standardized, bringing about the weight (pr) for each category, c. Formally,

$$\text{pr}_i = \frac{1}{a_{ij} \sum_{k=1}^{n} \frac{1}{a_{ij}}} \tag{2}$$

For comparative evaluation of test sites, decision-makers must integrate the weights and compute relative reference values into the STSDF. This happens during the evaluation stage.

Reference value computation build on the factor scoring and serves as a benchmark, against which the evaluation of individual, test-site specific measurements can be assessed.

For the decision problem, the measurements of the answers to factor scoring y with the different scales [1;5] are combined. Initially, the reference points r of the answers to factor scoring y, are computed. y is obtained from factor scoring measurements considering properties mean importance assigned to the factor. Formally:

$$r = \frac{\sum_{n=1}^{N} y_n}{N} \tag{3}$$

The normalized factor values are first visualized individually and by category. Given the diversity of test targets and considering future progress, calculating r ads to the flexibility of the approach.

Evaluation stage: Following, the reference distance for each factor x, in each category c, and test site t the evaluated factor $x^0{}_{c,t}$, is calculated. Whereby the value of each factor x, within a specific c, relevant to the test site t is put into relation. Here 0 indicates the raw value observed for the respective test site.

$$x_{c,t} = \frac{x^0{}_{c,t} - r}{r} \tag{4}$$

$x_{c,t}$ are hence interpreted as standardized deviations from the factor-specific mean. These values are then plotted for each category c and test site t.

Finally, the deviations captured in the $x_{c,t}$ are summed up and averaged. Then the result is combined with the matrix information to arrive at a composite measure of attractiveness z. The number of retrieved x-scores varies by category.

Reasons are that $x_{c,t}$ present the possible characteristics of which c is composed of. Hence the sum of $x_{c,t}$ needs to be put into relation with the actual amount of considered ${x^0}_{c,t}$.

$$z_{c,t} = pr_{i=c} + \frac{\sum_{n=1}^{N} x_{n,c,t}}{N} \tag{5}$$

Whereby pr_i is the weight of specific category derived from the aAHP. The measurement is plotted so that, $z_{c,t}$ can be visually analyzed by managerial staff. The visualization helps decision-makers process the decision data and reflect the coherence of information. The construction of a coherent picture is critical to the admission of uncertainty. Uncertainty arises as factors may not be present, yet their absence does not influence the overall decision. Hence, decision biases may occur at the detail level.

Although it is not yet confirmed by theory, the experimental results in chapter 5 indicate that the combination of weighted priorities and the normalization of indicator values outperform simple normalization. The computation of said structural constructs via Python is provided via the jupyter respitory.

5.2.4 Mechanism for the Imputation of Missing Data within the Structural Framework

The initial calculation of the STSDF may be subject to further adaptation. The dynamic nature of technology requirements is but one driver of change. The dynamics cause criteria for test sites to shift with time. In addition, imputation can ensure transferability. The need for transferability increases as effective usage of shared spaces becomes vital. It goes hand in hand with the sustainability of land use and the non-exclusivity of land use claims.

Together, the dynamics result in the requirement to iteratively check the STSDF, from selecting indicators over the normalization scheme to choosing categories and factors. As outlined in imputation is suggested to be performed with the last observation being carried forward, i.e., it uses the value of one row before (same column) to impute the missing variable. In cases where the missing value is assigned to the first rows, the process uses the row after.

5.2.5 Ecological Analysis within the Sustainable Test Site Decision Framework

The design of the DOAI proposes to optimize testing behavior regarding safeguarding the habitat. Said optimization introduces new challenges to technology developers. By adapting to disturbance reducing procedures early on, technology developers may increase their responsiveness and awareness to ecological restrictions.

This dissertation introduces the DOAI. The DOAI follows a regression analysis to create a model that describes the relationship between the reaction of different species as the dependent variable (y) in relation to the platform employed, its distance to an animal and noise pollution in dB as independent variables (x). The study showed that for observations within a platform and species, the distribution fits a Poisson distribution. To perform the DOAI, the model is to be fitted to the platform and species present in the region.

$$y_i = \beta_0 + \sum_{j=1}^{p} \beta_j x_{ij} + \varepsilon \tag{6}$$

5.2.6 Social Feedback Loops within the Sustainable Test Site Decision Framework

The study shows that capturing social sustainability is contextual. Figure 37 depicts the identified context test sites are embedded in.

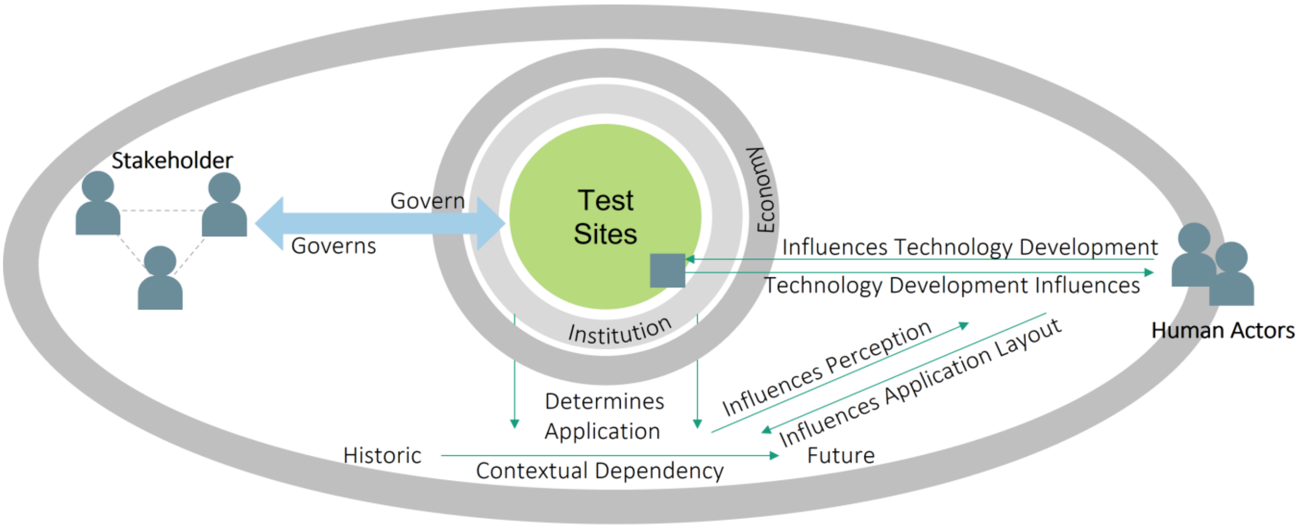

Figure 37 Social Environment of Test Sites

Spatial impact and nature conversation are subject to communication and preparation material. The relationship between operations and natural conversation efforts must be communicated to stakeholders. The image projected through the impact information and ecological value generated through the advancement of technologies must flow into the communication strategy. The communication strategy thus contains feedback loops. Feedback loops can enable transparent planning and acceptance building. For continuous engagement, decision-makers must consider that different sources for information are available. The communication within and outside of the involved groups (e.g., newspaper articles or incidents from afar) has a significant influence on the effectiveness of the engagement. Figure 38 illustrates the relationship between social and ecological feedback and technology.

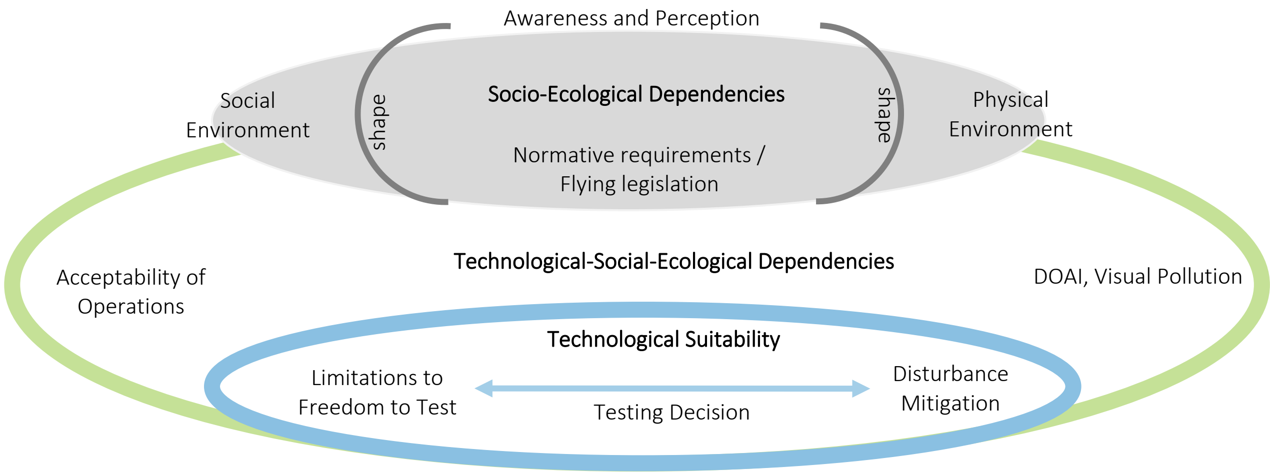

Figure 38 Sustainable Test Site Decision Framework – Sustainable Feedback-Loops

Revisiting the figure, the following details the displayed activity lines. As defined, the socio-ecological feedback loop is narrated by normative requirements, and the perceived safeguarding of natural habitat shapes the social environment. On the lower parts, ecological sustainability considerations may impose regulations (height adjustments) to the testing operations. When communicated, such measures shape the social environment. At the same knot, the limitations for the freedom to operate impact the suitability of a test site. Technology-centered feedback then mediates between the test case requirements and the disturbance mitigation desired / required. At this point, the approximations of the DOAI may determine the expected disturbance and allow for detailed adjustment decisions.

Thus allowing the safeguard of the habitat while ensuring test site relevance. The identification of dependencies provides for a more elaborate social communication guide. With which a governing party can indicate compliance or non-compliance at different decision stages.

5.3 Sustainable Test Site Decision Framework Content Model

Aligned to the process model, sub-chapter 5.3 introduces the categories and factors under consideration. Essentially there are five different decision categories (I) Test target features, (II) Benchmark features, (III) Socio-economic environment, (IV) Logistics, and (V) Ecological environment.

Test target features are tied to structural, topographical, lithological features, mineral occurrence, and sources of noise. Desk research should employ existing spatial and GIS data (e.g., structural, topographical, lithological features, and mineral occurrence) to obtain category knowledge.[24]

Benchmark features refer to availability, quality, and the degree of confidence in geological, geophysical, and geochemical data and depend on the technical capability and capacity of the decision-maker. The evaluation of context data is central to benchmarking. Context is specific to the individual cases but also hinges on the richness of the data. Such context could depend on the type of data as well as the quality of the data and its perceived value.

Socio-economic parameters indicate initial social acceptability and governance. Regularly, such aspects exceed the skill set of technical developers. The social performance focuses on the relevant and accessible features. This analysis includes outlining permission appropriate and accepting relevant local stakeholder details and outlines the relation between test activities and critical political factors.

Logistical considerations link planned technology tests, including infrastructure conditions regarding access and working areas.

During the evaluation stage the **ecological** assessments start with analyzing the presence of protected areas, habitats, and species and their lifecycles (e.g., breeding) during the regular testing periods. In the follow-up DOAI analysis the expected disturbance for the target species is analyzed using the disturbance model. Following these outlines, the disturbance is communicated to the local stakeholders. The social dialogue further includes the determination of seasonal and other constraints related to land and aerial utilization. Scientific priorities shall be consolidated at an early planning stage of test site selection, while selection trajectories can still be changed. The decision-making problem is structured hierarchically at different categories, with each category consisting of a finite number of decision factors.

5.3.1 Sustainable Test Site Decision-Making Composition

The STSDF builds on a sequence of four structural analysis positions: (I) the exclusion stage, (II) the aAHP, (III) the evaluation, and (IV) the DOAI exclusion[25]. The analysis concludes with social feedback loops. The STSDF question bank covers a range of quantitative measures and introduces quantification mechanisms for qualitative (primarily socio-economic measures). By adopting a theoretical rather than data-driven approach, the user can draw on primary and secondary data sources. This is a pragmatic approach led by expert advice on the requirements for an accurate location assessment of technical-centered siting decisions and expands the procedures adopted in other approaches. Responses for the exclusion stage build on nine factors, pre-empting sites that do not meet exclusion requirements.

[24] In some cases, interviewed experts performed an initial google maps search.

[25] The social feedback loop is transactionary and does not follow a quantitative structure. It is therefore not depicted as structural analysis position.

The factors either meet the criteria or fail to meet them. Once the decision-maker perceives the answers as positive, the site may be considered for further evaluation. Table 52 displays the identified exclusion factors.

Table 52 Exclusion Stage

Test Environment	
Is the commodity appropriate	Yes / No
Does the physical property of the target signature / host rock meet your requirements	Yes / No
Is the target area representative for the challenges your technology aims to overcome	Yes / No
Reference data set	
Does the reference data set provide sufficient context	Yes / No
Does the reference data cover the parameters to be validated	Yes / No
Is the data set to be trusted	Yes / No
Ecological factors	
Environmental conditions / regulation prevent from testing	Yes / No
Socio-economic factors	
Is the project socially accepted	Yes / No
Logistical factors	
Is the test area physically in reach	Yes / No

The decision factors present possible characteristics of which a category is composed. The relative importance (weights) of categories is assessed based on paired comparison judgments. The aAHP determines the priority of identified categories through non-linear programming. The overall weight of the categories is calculated by successively multiplying the priorities from the previous level to subsequent levels. The main strengths of this approach are twofold. Firstly, it recognizes that technological decision-making is non-binary while providing a method for prioritizing the categories. Secondly, it solves the problem of fuzzy stakeholder knowledge (intuitive decision-making). The prioritization generates automatic yet conscious decision queries. The composite view allows decision-makers to assess the performance interdependencies of test sites. Here social and ecological responsiveness, test site decision flexibility, customer satisfaction, and sourcing flexibility merge.

Responses for the evaluation stage: Scoring of evaluation factors follows a pre-defied set of question, which may be answered on a scale from 1-5 (does not meet requirements, partially meets requirements, meets the majority of requirements, meets requirements, and exceeds requirements). This scale tracks factor scores and converts them to a normalized expression of their meaning. Initially, the answers for socio-economic scores entail additional description. The decision to introduce detailed options responds to the technical component questionnaire and the customer journey. Survey results indicated limited expertise in social factor components (e.g., what constitutes political stability). Thus pre-defined answers for factors in need of explanation were depicted.[26] Appendix 15 displays the decision framework factors in the evaluation stage.[27]

Responses for ecological assessment: An advisory note accompanying the ecological output data practice supports the disturbance communication. The DOAI builds on the visual markers of the effect plots. Developers shall use the data corresponding to their platform to perform conscious flight campaign planning.

Social feedback is of similar relevance but a STSDF downstream element.

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[26] The depicted levels were informed by INFACT Deliverable D6.3.

[27] The evaluation factors were screened in a pre-test of the validation, resulting in an abandonnment of such factors that are relevant yet hardly available for review (compared to 4.2). And one factor “benchmarking data” was imputated. Thus reducing the evaluation to 41 factors.

5.3.2 Sustainable Test Site Decision Framework Executability via Python

The STSDF utilizes a Python Script with a series of questions and answers to select. Python was chosen for access and transparency reasons. Being widely available, Python provides access to a comprehensive user base and can be employed without internet access. The program also gives transparency that enables the user to scrutinize the underlying STSDF script with version control. Compared to tools such as MSExcel, Python has a higher level of traceability and flexibility.

The script works with predefined questions to reduce execution barriers across hierarchies. The concept starts with binary responses. Next, the category weights are calculated, which generate a sensibility of the decision-maker for the categories in question. Ensuing, the answers to the evaluation stage generate test site profiles, indicating attractiveness and relevance. An algorithm utilizing the mathematical model normalizes the factor scores, calculates, and weighs the category scores per test site. Bar plots visualize the individual scores per category and test site. The weights and the normalized sum of categories are visualized in a 3D histogram, using the matplotlib library of Python. The weights and normalized attractiveness indication are of contrasting color.

Courtesy of the matplotlib package of Python, the 3D visualization can be illustrated in an interactive environment. Optical illusion (e.g., identifying each bar's actual height (length) of each bar) are consequently minimized. Thus decreasing barriers to understandability. Scripts for exclusion, weighting, individual test site evaluation, and joint representation of evaluated test sites are disconnected. While this increases the computational efforts, it increases the transferability and replicability.

Scripts for each STSDF process step and each test site are distinct. Working with separate scripts is courtesy of the diverse nature of potentially involved stakeholders and the resulting requirement to have separate test sites and activity steps operated by different parties and in different workspaces.

To cover continuous decision-making, connectors were introduced, allowing, if so wanted, for a constant workflow with Jupyter by Python. The DOAI was done using Rstudio. As the ecological assessments build on fixed perspectives, there is no current need to integrate them into Python. However, both scripts can be stored in Jupyter Notebook and can be accessed thus following.

5.4 Critical Review of the Sustainable Test Site Decision Framework

The dissertation focuses on researching the viability of test sites for a range of state of the art and innovative sensing methods from a technological, ecological, and social perspective. The STSDF follows a technical development approach for innovative sustainable technologies at a TRL 5-9. Combining quantitative output, conceptual approaches, and content-related approaches allows for adaptability and replicability of different framework entities. Disclosure of decision condition of social and ecological safeguarding can be incorporated into related decision-making processes.

Implicit within this is the choosing or selection of socially and ecologically acceptable technologies. A structural concept to compute the exclusion, weighing, evaluation, and DOAI focuses on a resource-efficient selection. The content-based approach complements the decision framework by focusing on technical, ecological, and social requirements, with input from mineral exploration.

Strategically computed to serve various sustainable test site decision processes, the STSDF can be aligned to socially and ecologically inclusive decision-making standards. The alignment potential is significant should technologies, techniques, and projects seek transparent communication of good practices. The transparency applies to the overall strategy of demonstrating, testing, and selecting specific platforms and testing grounds.

This is a change from current selection procedures, where TD and demonstration are neither considered in the benchmarking and quality nor socio-ecological contexts. Contrary, the approach assesses impacts thoroughly and aggregates them in more advanced stages.

6 Validation

The present dissertation evaluates the practical as well as academic outcomes attained for mineral exploration (sub-chapter 6.1) and checks the transferability of the STSDF (sub-chapter 6.2).

Per the validation for mineral exploration, the thesis applies the STSDF to four test sites. The validation includes (I) the execution of the framework, (II) the analysis of additional requirements, and (III) a usability assessment. The validation employs three STSDF user groups.

For the transfer assessment the fit of the structural concept of STSDF is evaluated. The aim is to evaluate the transferability of the STSDF across disciplines. The transfer validation takes the cases of test site decision-making in mobility, natural sciences, and public grant assessment.

6.1 Validation Mineral Exploration

The INFACT project developed European Reference Sites (ERS) for innovative non-invasive fully acceptable exploration technologies. Starting in 2017, the INFACT project developed four test sites to assess the technical and environmental (physical and social) performance of new technologies. The tasks performed in the test site development process encompass geoscientific site characterization, benchmark data collection, and verification. Finally, conformity of project goals with public expectations and impact on the ecology were considered. (Grant agreement ID: 776487, 2017)

6.1.1 Reference Sites of the INFACT Project

The four reference sites are situated in Rio Tinto, Spain, Cobre Las Cruces, Spain, Sakatti, Finland, and Geyer, Germany. Appendix 16 illustrates the reference site characteristics.

The diversity of the sites challenges technology developers to identify the right site for their actions. Consequently, the project published several brochures and attended conferences to spread knowledge about the benefits of each site (INFACT ERS Brochure, 2020).

The following first introduces the characteristics of each site. In a second and third step, the validation procedure and the validation results are presented.

6.1.2 Validation Methodology

The study tested the fit of the STSDF for industry and academic needs in a four step approach. In line with the guidelines for distancing and consensual validation, the thesis uses surveys and conceptual-analytical arguments and gives decision-makers a case for assessing test site realities (Cassell & Symon, 2006).

Figure 39 illustrates the validation approach. The section to follow describes the figure.

Figure 39 Validation Approach

The researcher chose a small sample to obtain in-depth information. Given the diversity of interest groups and depths of expertise, three types of experts were involved:

(I) For the factor scoring and DOAI, two experts from an industrial SME and an MNE respectively participated in the validation. In addition, three experts from academia evaluated the test sites. The academia sample selection builds on the network perspective defined in 4.1.1 (decisions often build on different expert opinions). Multi-expert inclusion allowed for testing multi-expert decision processes. (II) The social factors of the evaluation processes were backed by social science researchers, and the DOAI was presented to local stakeholders in each county. (III) The social feedback loops (representation of expected disturbance) were discussed with local stakeholders in each test site region.

The technical stakeholders were asked to assess the power of the framework. Criteria for selecting the technical participants are three-fold. (I) Having tested technology at either one of the test sites or having observed or supported testing, (II) being familiar with the benchmark features and having worked on the available benchmarks, and (III) being an expert for the technological composition of the testing object. Social scientists, have to be knowledgeable in the areas in question. The socio-economic evaluation was informed by INFACT deliverable D2.2, D2.3, D2.4, and D6.1.

Social stakeholders were chosen based on their (I) decision-making power, (II) expertise, and (III) their centrality in the local community.

Data was gathered through a two-stage process. Firstly, the STSDF Python script was executed, and the platform(s) considered was (were) checked for its (their) disturbance probability at different heights for different species (only for UAS). Using Python and looking at the tool's actual process helped identify potential obstacles and generate in-depth feedback. During the utilization, participants were encouraged to describe why they chose a specific level for each answer.

Once the procedure of the framework was performed, the follow-up phase of the study started. The follow-up phase evaluated the degree to which the framework meets the pre-defined framework design criteria. Therefore, a series of five pertinent requirement testing factors that depict the five design criteria: (I) Relevance, (II) Ease of use (easy to understand); (III) Effectiveness and efficiency (provide multidimensional information); (IV) Quality and attractiveness of the framework (ensure comparability between test sites); (V) Manageability (replicable).

Participants were asked to respond using a 5-Point Likert scale. The 5-Point Likert scale rooted between the maximum and minimum. The extremes indicate contextual words for each item.

Table 53 displays the factors and their antonyms.

Table 53 Framework Validation Items

Item	Design Criteria
Supporting vs. hindering; unsafe vs. safe, expectation conform vs. not conform with expectation, conservative vs. innovative	Relevance
Dodgy vs. reliable, precise vs. ambiguous, accurate vs. non-conforming, relevant vs. irrelevant, conform vs. flout	Quality
Incomprehensible vs. comprehensible, logic vs. illogic, clear vs. confusing, transferrable vs. not transferrable	Ease of use
Comprehensive vs. singular, consistent vs. incompatible, explicit vs. implicit, incorrect vs. correct	Effectiveness
Fast vs. slow, efficient vs. inefficient, pragmatic vs. unpragmatic, tidy vs. cluttered	Efficiency
Maintainable vs. not maintainable, static vs. modular, replicable vs. unrepeatable, functional vs. ornate	Manageability

The identified items are informed by Bernsen and Dybkjær (2009). The structure of the questions was aligned to Sauro and Lewis (2009). In their empirical work on usability metrics, the authors present "principal components and factor analysis on the prototypical usability metrics" (Sauro & Lewis, 2009, p.1). Pilot interviews were conducted with two academic experts. The validation questionnaire does not provide an overall value for the measured requirements. To optimize single items and identify optimization potential overall values (e.g., the mean value over all scales) are not advisable.

6.1.3 Validation Output

The following section introduces the validation for the cases of (I) SME, (II) MNE, and (III) academia. The sub-chapters to follow, (I) introduce the STSDF output (whereby test sites are pseudonymized), (II) followed by usability. (III) Finally, DOAI in conjunction with social feedback loops are discussed.

6.1.3.1 Validation Output with Small and Medium-Sized Enterprises

The SME aimed to demonstrate a helicopter-based exploration technology at TRL7. During the exclusion stage, the SME excluded two test sites. Raw material productivity and exploration investment risk guided the evaluation of the remaining test sites. Barriers to testing and design of the technologies were of particular importance. Figure 40 displays the evaluation.

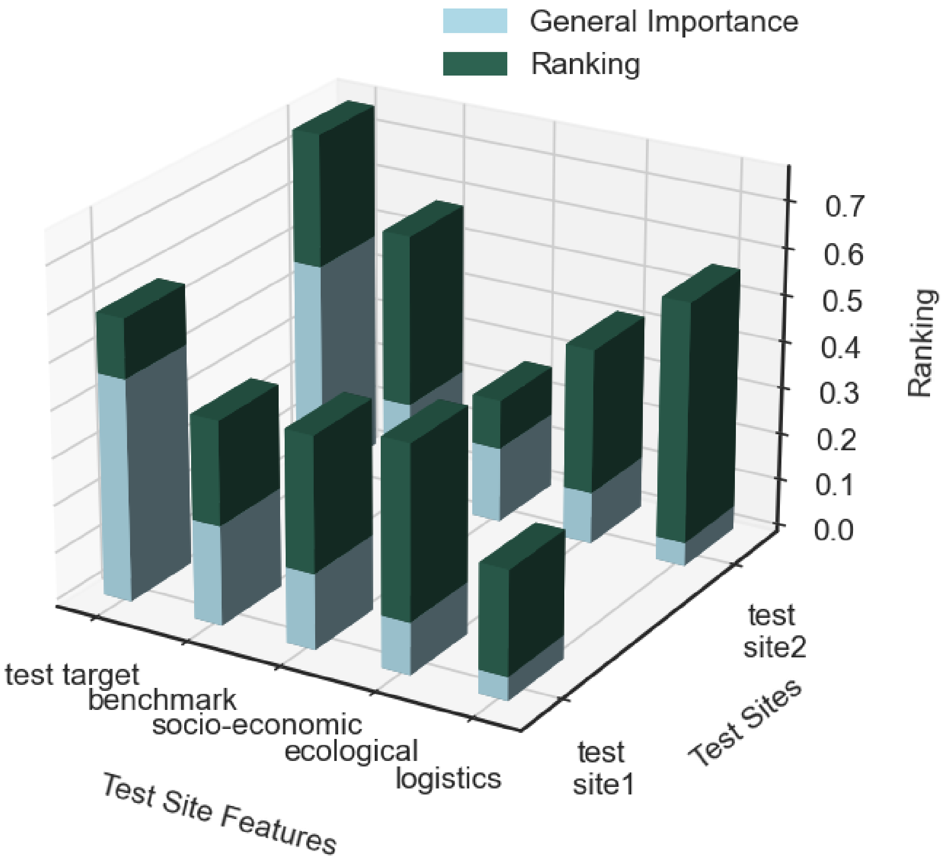

Figure 40 SME Validation – Test Site Evaluation[28]

In the figure, the composite analysis of the test sites reaching the evaluation stage is provided. The categories are listed on the left, while the right side of the figure illustrates the existing test sites.

Per the **DOAI,** helicopter activities at an elevation of ~100 m were analyzed.

Social feedback: The SME suggested that the DOAI and social feedback loops can help sustainable exploration practices. Furthermore, compared to existing methods, the framework provided a common ground between technical experts and industry-led interdisciplinary learning, which may change the conversation about technology testing. Concerning the social discourse, the technology developer supported the idea of a more transparent dialogue.

[28] Colorspace differences between ranking and general importance are deliberate and indicate the difference between weight and actual scores.

6.1.3.2 Validation Output with Multinational Enterprises

The MNE aimed to test a helicopter-based exploration device at TRL 8. During the exclusion stage, the participants eliminated two test sites. Reasons were the ill-suited fit with the strategic decision space. During the evaluation stage, the geophysical models and the understanding of the geology at each site were crucial. The experts were familiar with the data beforehand. Their objective was to compare their measurement to other innovative technologies and test their data analytics. Figure 41 illustrates the composite evaluation of the two remaining test sites.

DOAI: Per the DOAI, a helicopter elevation was checked. The analysis triggered a conversation about the impact of other approaches, in particular UAS.

The DOAI was recognized as an implicit ecological rule for exploration. The expert argued that in the future, technology management should consider the ecological impacts during the TD already. Concerning the social discourse, the technology developer supported the idea of a more transparent dialogue.

Social feedback: Social feedback loops were considered appropriate. Referring to testing staff being approached in the field by locals, the MNE's claimed that more diverse information about the local impact might be favorable. Beyond the social dimension, ecological, and social governance (ESG) was discussed to be trending, with most financiers and investors in the minerals sector requiring due diligence to incorporate ESG risk.

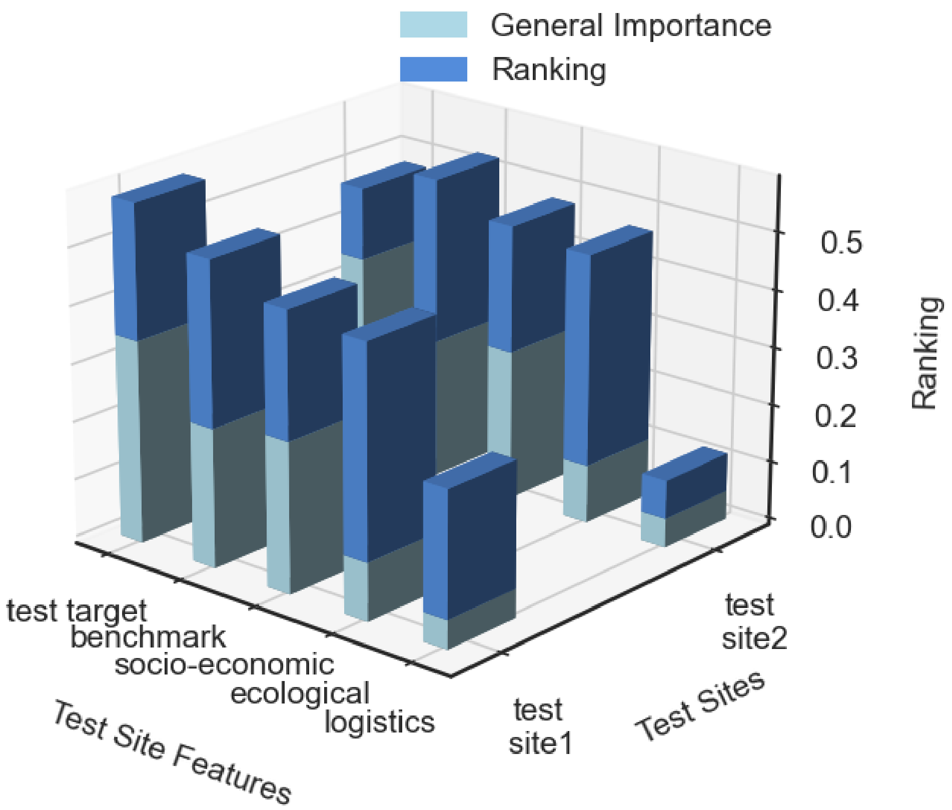

Figure 41 MNE Validation – Test Site Evaluation

Summing up, the framework supports sustainability discourse and coordinates the dissemination of information for the benefit of investors and exploration companies.

6.1.3.3 Validation Output with Academia

Figure 42[29] presents the results obtained from the STSDF execution with academic decision-makers.

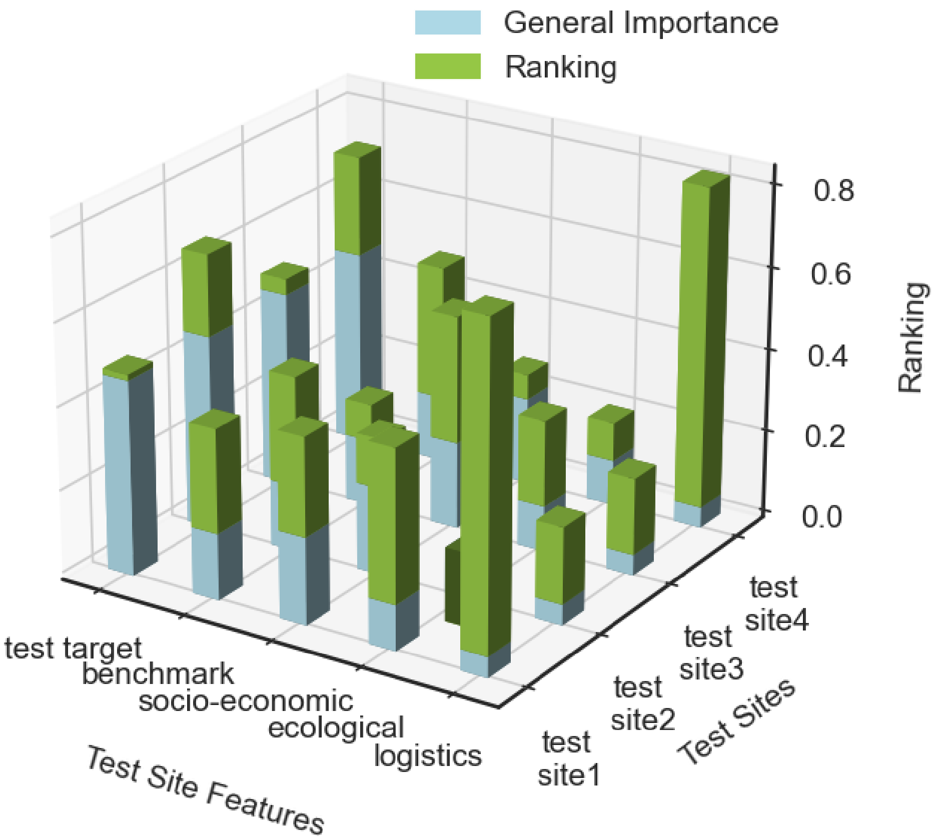

Figure 42 Academia – Test Site Evaluation

In the figure, the composite analysis of all four test sites is provided. The factors identified for the sustainable test site are listed on the left, the right side of the figure illustrates the existing test sites.

The academic experts suggested that decision-making is iterative. Changes occur through additional (previously unknown) circumstances. Such circumstances can either increase or decrease the evaluation efforts. Moreover, category weights may require adjustment. Adjustment requirements emerge from (I) inclusion of additional stakeholders, (II) inclusion or exclusion of specific technology providers, industries or scientific disciplines, or (III) changes in local media reporting. The latter may cause a drastic shift in the importance of the social dimensions. Such changes can occur locally or globally.

6.1.3.4 Social Feedback Loop and DOAI

The study validated the social feedback loops concerning the expected impact with local stakeholders. For each region, the researcher discussed:

- impact on fauna and flora (DOAI)
- visual pollution
- noise pollution, with local stakeholders.

[29] The author recognizes the distortion of visualization for the ecological aspect for test site 2. The distortion is courtesy to the interactive graphic and shall compensate for an otherwise hidden element. In the dynamic environment of matplotlib the distortion is eliminated.

Meetings took place face-to-face. The process allowed to capture the relevance of the STSDF to stakeholders and lend support to validate the robustness across interfaces. All stakeholders claimed that the information about flight disturbance is important not only for ecological safeguarding. The data can help to communicate the expected impact to the local communities.

Stakeholders argued that the analysis helps them identify particular times when flying shall be limited or identify ways to safeguard protected species. Such species were eagle owls in Geyer, Germany, or reindeer in Finland.

6.1.3.5 Usability of the Sustainability Test Site Decision Framework

To evaluate the usability, questionnaire scores from the three investigations were analyzed. The usability was assessed with the participants of the technical scoring. Appendix 17 illustrates the answers depicted for the usability of the framework. Similar patterns emerge across all validation cases and attributes. Table 54 discusses the results of the design criteria fit analysis and indicates optimization potential for all five design criteria.

Table 54 STSDF Usability

Usability Item	Description
Relevance	Across all items, relevance scores were lowest with SME, and MNE. Academics assigned comparable higher relevance to the STSDF. Thus relevance might vary with the number of test sites reaching the evaluation stage.
Manageability	Across all scores the participants indicated that the structural composition is maintainable. As time changes, limits might occur regarding the maintainability of factors and their scores.
Quality	Quality-related factors such as reliability and preciseness were discussed across the cases.
Effectiveness	The capability of selecting and enabling sustainable test sites showed steadily high response rates. To check the activation of participants to what degree the STSDF is consistent, the study reversed the answer. All participants scored incompatibility lowest.
Efficiency	Scores related to efficiency indicated consistently high scores.
Ease of Use	Logics, clarity, transferability showed consistently high ranks. Across all participant groups, comprehensibility was least well received. Suggesting that an advanced approach for delivering the message of the STSDF is required in the future. In addition transferability received lower scores (yet still ~3). A subject that is tested in sub-chapter 6.2.

6.1.4 Validation Review and Summary

Despite the limitations, the framework was seen to be highly relevant and innovative.

Based on the validation key priorities for future development were defined as follows:

- Formalize social and ecological performance practices in TD in real environments
- Develop a value proposition for de-risking ecological factors in TD projects
- Develop guidelines and regulations on reporting technological progress in the field
- Develop policy recommendations for a responsible testing directive to drive the social and ecological element, without jeopardizing technological progress
- Explore the financial dependencies related to testing
- Instigate perception through inter-disciplinary investigation and support / improve engagement

6.2 Validation Transfer

To this point, the framework was informed by, and validated through, mineral exploration. To ensure the contribution to the research discourse, the transferability of the structural construct shall be tested. Structural model validation refers to the procedure of determining the degree to which the model “is an accurate representation of the real world from the perspective of the intended model applications.” (Lam et al., 2007, p. 3). The transfer is thus limited to the structural concept.

According to literature by Autant-Bernard and LeSage (2011), and Fischer et al. (2006), industries with similar targets, challenges, and high technological proximity show strong potential for spillover learnings.

Hence the transfer validation builds on two industries with similar test targets or similar challenges. For test target proximity, transfer to critical zone research is analyzed. Concerning similar challenges, UAS test sites are analyzed. Figure 43[30] illustrates the scope of the transfer selection.

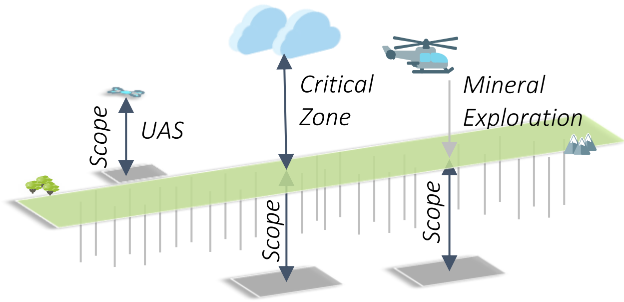

Figure 43 Transfer Selection Mapping

Critical zone research sites include test target features, benchmarks, and measures to evaluate the political, social, and physical environment. Table 55 illustrates the site conditions.

Table 55 Critical Zone Test Site Selection Criteria

Category	Description
Test targets	Test targets must address the physical structure of terrestrial surfaces (e.g., parent material, topography, and orography) be representative for rate-limiting processes of ecosystems (e.g., soil formation, hydrologic partitioning) (Diener & Mudu, 2021; Field et al., 2015).
Benchmarks	The ability to quantify and assess complex process dependencies drives the attractiveness of benchmarks (i.e., a measure of the energy flux available to do physical, chemical, and biological work) (Field et al., 2015). Contextual ecosystem data linkage can enable the valuation of ecosystems in changing environments (Banwart et al., 2012; Field et al., 2015).
Social and physical environment	Critical zone research includes the analysis of multiple functions connecting anthropogenic influences and the impact of human life on planet earth. Mitigation mechanisms to evaluate different adaptive strategies for the impacts of climatic change and human disturbance are among the research topics covered (L. Guo & Lin, 2016).

Contrary to mineral exploration, sustainability is more inherent in critical zone research. Technological applications are already steered towards sustaining the natural environments (L. Guo & Lin, 2016).

Impact assessment of research measurement technologies is a sub-ordinate research construct. However, impact reduction may cater to the overall goal, meaning that the decrease in research impact may contribute to the environmental governance of the scientific discipline.

The second validation case is vertically connected with mineral exploration. Vertical connections are associated with application and value-added outside the geosciences but connected by technology and the related services, for example sensors or platforms.

The validation case responds to the identification of test sites for UASs. Among others, UAS have been established as platforms for sensing, aerial photography as well as delivery. Some respective applications are observation (e.g., fire monitoring, environmental damage), industrial inspection (e.g., bridges, grid, industrial plants, etc.), and large areas. Table 56 illustrates a list of respective site selection criteria.

[30] The drawing is not in scale.

Table 56 UAS Abstract of Test Site Selection Criteria

Category	Description
Test target	Surface slope constraint, men-made interference, height constraint, hazard proximity constraint are among the listed site selection criteria (M. Mueller et al., 2016; Whalley & Takahashi, 2016).
Benchmark	Required benchmarks vary depending on the application scenario (e.g., photo-realistic tracking (M. Mueller et al., 2016) vs. optimized trajectory scheduling (Zhan & Lai, 2019)).
Social and physical environment	Visibility of civil drones increased over the past years. Acceptance of UAS differs by the application scenario. Eißfeldt et al. (2020) found the usage of drones in civil defense, release missions and research is better accepted than flights for advertising, leisure, and parcel delivery. Questions remain about the extent to which UAS disturb the fauna. “Integration into ecological monitoring systems for community wildlife management areas on a spatiotemporal scale” (Mangewa et al., 2019, p.1) are subject to an ongoing research discourse.

6.2.1 Transfer Validation Method

Various authors introduce technology and framework transfer procedures (Carayannis et al., 2020; Del Giudice et al., 2017). Most procedures build on questionnaires, such as the innoSPICE methodology, which analyzes end-user reactions to selected information technologies / solutions (Woronowicz et al., 2012). Following Woronowicz et al. (2012), the validation process starts with describing the decision process, the content, and the structural scripts. Following the introduction, the study participants examined the tool, checked the process approach, analyzed the robustness of the structural model, and checked the transferability of the content model. After the examination, participants evaluated the relevance of the structural concept and the transferability to their field of expertise. The researcher audio-recorded the interviews, transcribed them, and took notes to reconstruct the context correctly and verify the answers provided by the participants. In line with validation guidelines, the process included the discussion of the notes with the participants (Cassell & Symon, 2006). Figure 44 illustrates the procedure.

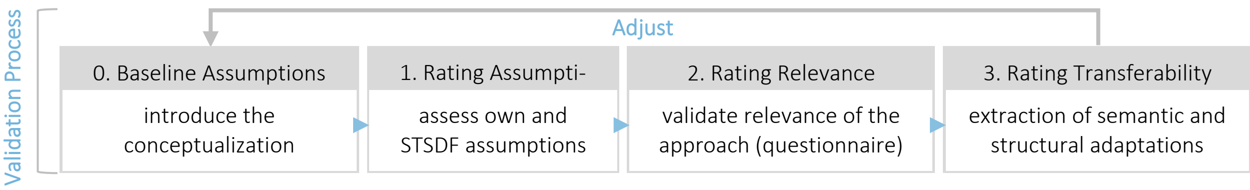

Figure 44 Validation Transfer Procedure

The research questionnaire was aligned to the procedure and informed by the equivalence validation procedures of Belt et al. (2008) and Ulrich et al. (2020). The questionnaire comprises operational, item, conceptual, semantic, and measurement equivalence. Table 57 illustrates the equivalences, their description as well as the question employed to gain insights about the equivalence in question.

Table 57 Transfer Validation Questionnaire Concept

No.	Equivalences	Description	Evaluation
1	Operational equivalence	Concerns the suitability of the framework format, instructions, and administration.	Does the framework format, instructions, and administration respond to your requirements?
2	Item equivalence	Explores whether items and categories are equally relevant and acceptable.	Could items measure the same parameters under study?
3	Conceptual equivalence	Refers to how the mathematical concept responds to the logic required for the respective domain.	Is the weighting and scoring concept of the model transferable?
	Semantic equivalence	Similarity of language and meaning of the wording.	Is the meaning and wording of the framework clear?
	Measurement equivalence	Refers to the properties of the mathematical model and scoring.	Are the properties transferable?

6.2.2 Validation Transfer into Critical Zone Research Sites

Critical zone observatory projects aim to develop research sites for wide-scale and systematic coverage of major terrestrial, freshwater, and transitional water environments. Projects cover the trials of technological, social, and ecological ecosystem considerations. For the development of test sites, projects are often selected from a pool of up to 150 sites (eLTER, 2019; Woronowicz et al., 2012)

Initial remarks by the interviewee were to distinguish between the different fields involved in critical zone research. Naturally, though, the statement depends on the chosen observation methods.

However, all types of observatory actions flow together to build a whole. Consequently, whether it is the study of rocks, soil, water, plants, animal life, or weather, or related phenomena, all perspectives become combined in critical zone observatories (Anderson et al., 2008; Gaillardet et al., 2018).

6.2.2.1 Validation Transfer Output for Critical Zone Research Output

To assess the transfer of the STSDF, the study analyzed the validity and preciseness of the framework and its applicability to critical zone research.

Table 58 illustrates the main insights derived from the validation. Appendix 18 assigns an interview evidence to each statement.

Table 58 Validation Output Critical Zone Research-Transfer Concept

Equivalences	Answer	R	CP	Fit
Operational equivalence	Operations are equivalent	✓	✓	✓
Item equivalence	Technological challenges: Per the interviewee the focus is on “systems rather than single entities.”	p	I	✓
	Test target items are equivalent	✓	✓	✓
	Benchmarks: amount of data, age of data, context, data processing	✓	I	✓
	Socio-economic items are equivalent	✓	I	✓
	Logistics are of lowest important	P	I	✓
	Ecological items are relevant	✓	✓	✓
	Social engagement is critical	✓	I	✓
Conceptual equivalence	The concept is equivalent	✓	✓	✓
Semantic equivalence	Wording is similar	✓	✓	✓
Measurement equivalence	Measurement is suitable	✓	✓	✓

R = Relevant; CP = Currently Practiced; Fit = Fit for Purpose; p = Partially; I = Intended in the Future

6.2.2.2 Summary of Validation Transfer for Critical Zone Research

This investigation shows the relevance of the STSDF for critical zone research. The structural model, including the graph-based visualization, may result in transparent reporting. The development space is ample as more unlabeled data than labelled data exists. Depending on the amount of data to be integrated, the imputation through most minor observations carried forward is a semi-perfect classifier. However, the approach may allow different stakeholders to learn about dialogue, supporting the existing, albeit scarce, theory.

6.2.3 Validation Transfer into Unmanned Aerial Systems

In recent years, several networks for UAS testing have emerged. Among these is the UAS test site infrastructure in North America. Initiated by the Federal Administration Aviation, the infrastructure aims to assist the task to form UAS safety regulations (Aweiss et al., 2018). The test site infrastructure consists of six sites located in New York, New Mexico, North Dakota, Nevada, Texas, Alaska, and Virginia. Accordingly, the test site areas are located in different vegetation, climatic, and topographic zones. Reported test cases include inspecting bridges and pipelines, supply management, wildlife monitoring, and rescue missions (Aweiss et al., 2018).

The test sites analyzed provide engine power measurements, reliability testing, power measurements, long duration, power cycles, failure analysis, fuel consumption, digital data acquisition, and maintenance requirements.

6.2.3.1 Validation Output Unmanned Aerial Systems

The validation output for UAS is highlighted in Table 59. Appendix 18 assigns interview evidence to each statement.

Table 59 Validation Output UAS-Transfer Concept

Equivalences	Answer	R	CP	Fit
Operational equivalence	The process serves the customer requirements, ecological and social conditions are critical, young employees value the structural approach	✓	✓	✓
Item equivalence	Technological challenges items are equivalent	✓	I	✓
	Test target items are equivalent	✓	I	✓
	Benchmark factors are community knowledge, mission planning and operations, vehicle systems, telemetry ground station, post-mission, data reduction, and analysis	✓	I	I
	Ownership and permissions items are equivalent	✓	✓	✓
	Socio-economic items are equivalent	✓	I	✓
	Logistics items are equivalent	✓	✓	✓
	Ecological items are relevant	✓	I	✓
	Social engagement is critical	✓	×	✓
Conceptual equivalence	The concept is equivalent	✓	✓	✓
Semantic equivalence	Wording is similar	✓	✓	✓
Measurement equivalence	Measurement is suitable, imputation is of particular importance	✓	✓	✓

R = Relevant; CP = Currently Practiced; Fit = Fit for Purpose; p = Partially; I = Intended in the Future

6.2.3.2 Summary of Validation Transfer for Unmanned Aerial Systems

There were suggestions that the economic dimension needs detail. A possible explanation could be that interviewees supervise test sites in areas with different economic power (e.g., New Mexico vs. New York). In all cases, the informants reported that testing is iterative. Compared to mineral exploration technology, developers come to the sites more often and require a broader range of services. The frequency raises the importance of the STSDF. In their accounts of the benchmarks, the interviewees argued that the context and quality-based approach is critical.

However, benchmarks in their report are tied to potentially competing technologies and technology developers. In consequence, benchmarks are hard to evaluate from the perspective of a technology developer. For the test site supervisor, this is a unique selling point for their sites, and they recognized the potential. As testing for UAS's is iterative, the interviewees advocated for additional factors concerning the stability of the climate. In addition, the size of the area is critical. Both participants echoed this. Both horizontal and vertical elevation levels are essential criteria of evaluation, and the decision-making process must consider them. This differs from mineral exploration, where the test sites must be at least three times the target size (mineralization). Regarding the noise to target ratio, high elevations are of little concern. The answers across the interviewees were consistent. The framework was proven to be relevant and is argued to be innovative for their field of research.

6.2.4 Grant Decision-Making for Validation Transfer

There is a merit of publicly funded initiatives to support real test site developments. Notwithstanding the current Horizon Europe Program, national and international development activities are plentiful. However, with sustainability and technical innovation at the top of many funding tenders, there is an argument that grant evaluators may need to establish a robust selection process that improves project effectiveness and grant analysis. With this observation, the STSDF was analyzed with two funding tenders involved in test site grant evaluations.

Overall, the STSDF appeared relevant and fit the goal of grant evaluation procedures. However, evidence was found that current practice hardly recognizes ecological and social sustainability. Another finding is the difference in evaluator knowledge, limiting an in-depth analysis of technical fit. As a result, the technical fit is increasingly relevant but undervalued in practice currently. An additional new finding is that the mathematical considerations are robust predictors. However, where limited resources exist, min-max normalization may exchange factor references. Arguably, this introduces a higher subjectivity, and future studies shall assess the predictive value across more contexts. Together, the findings support the need for technology-centered approaches and the introduction of frameworks to support technological innovations.

6.2.5 Summary of Validation Transfer

After three transfer area assessments, the transferability was recognized, and the results were considered stable.

Differences in STSDF usage arose from the frequency and duration of testing and the type of test site evaluator. The transfer validation verified the assumption that category weights vary among decision-makers within the same industry. Mainly grant evaluators verify the assumption that detailed and aggregated visualization is required.

7 Discussion of the Sustainable Test Site Decision Framework

The dissertation set out to model a sustainability-centered approach to test site decisions. Decision outlets are relative reference measures and are replaceable yet with an unchanging scale to ensure the integrity of the approach. The following section discusses the results of the dissertation and essential findings. As there is more than one result, the discussion is structured into four groups. The sequence is as follows: (I) structural model, (II) process model, (III) content approach, and (IV) transferability.

7.1 Structural Decision Model of the Sustainable Test Site Decision Framework

The structural model builds on the mathematical notation that describes the STSDF. The model allows a logical, structured setting of the STSDF. It underpins the applicable regularities of the defined exclusion, evaluation, and analysis stages. It takes the dynamics of the delta T's into account. The structural model aims to ensure the theoretical foundation of the STSDF. The structural model consists of five levels, namely (I) binary factor exclusion, (II) aAHP category weighing, (III) normalized factor scoring, (IV) composite category analysis across test sites, and the (V) DOAI.

A scale of priorities on a granular level and an aggregated priority analysis emerges from the factor, category, and test site comparisons. The procedure allows to follow experts' judgments first and make conflicting priorities that go against STD come second.

The work shows that criteria hierarchies and factor-based rule systems enable sustainable decision-making. The validation shows that the combination of reference distance estimation and weighted priorities provides a practical and usable evaluation and analysis system for technological and managerial decision-makers. Factor-level detailing allows for technical trade-offs, sensitivities, and weighted preferences. Evaluation provides an aggregated category-level assessment of alternative actions, providing an informed basis for managerial decision-making.

While decision-making problems are not new to literature and practice, the technology-centered sequence of planning and evaluating the factors under consideration is novel. The integration of a fuzzy evaluation logic, which considers the uncertainty of the data basis and the technical relevance of individual data points, expands current research.

The incorporation of regression-based disturbance assessment further enlarges insights from practice and literature. Previous authors considered either one source of disturbance or singled out construction grounds based on qualitative judgment. The regression-based approach allows for an integrated assessment of disturbance features in a meta-analysis. Future research must assign importance to the creation of leading and missing indicators that quantify the progress towards STD.

7.2 Discussion of Sustainable Test Site Decision Process

The dissertation showed that the current decision-making process for test sites does not sufficiently include social dialogue and impact assessment. This changes with the current approach. The process model formulates a hierarchy of process steps consisting of the technical objectives, ecological disturbance indicators, and social feedback. The governance process harmonizes TD requirements, transparent regulations, communication protocols, and opportunities to minimize impact. The process takes the steps of:

I. Geographic, target, and benchmark-focused stage-gate analysis
II. DOAI, to promote high-tech and innovative approaches that reduce impact
III. Social feedback and inclusivity from the outset of test site decision-making

Participation and iterated feedback guide the decision-making process.

The process implicitly accepts that restricted areas inhabited, endangered or of natural or cultural significance exist. Through feedback loops within the process, the approach weighs the restrictions against the effectiveness of TD.

The relevance of the process model emerges from the following three aspects: (I) Options for a socio-ecological design of technical development and dissemination of innovative technologies are not yet well developed, let alone elaborated on in detail. The dissertation created a decision-making process that considers technology requirements, social developments, and interdependencies with the ecological environment. (II) The process guide is a model to visualize sustainable feedback loops and plan and advance towards that image. (III) The process model shows how to appoint equal prominence to ecological and social factors with the main decision points in the evaluation stage. The assessment stringency allows responsible test site selection and establishment from the outset of TD.

Furthermore, benefits that accrue for the sustainable future of a project may serve as additional assistance. This applies to the technical development at test sites and the selection of specific testing and demonstration grounds.

The research contribution applies to the performance parameters of coordinated analysis for test target features and benchmark features. The inclusion of social and ecological feedback into test site selection is also new to the research. Since sustainable processes and governance requirements continuously evolve, future research can pick up the discourse and expand on these criteria, as their coverage in the dissertation is still limited in scope. Still, a way forward is paved.

7.3 Discussion of Sustainable Test Site Decision Framework Content Model

Adding to the procedural approach, the supplementary content approach was developed and validated.

The content approach details factors that influence the sustainable performance of uncertain technologies. Table 60 discusses the contents of the STSDF.

Table 60 Sustainable Test Site Decision Framework Dimensions

Dimension	Description
Test Target	Test target features refer to the technological relevance of the area. They include details about the spatial relationships at a test site. In regions without much available data, knowledge-driven approaches can help increase the theoretical understanding and natural foundation of an area. The selection of test targets, and hence, the opportunity of demonstration and performance improvement depend on the test target features, the ecological system, land cover, site accessibility, and governance of socio-ecological factors.
Benchmarking	The proposed assessment introduces an expanded set of parameters such as noise, accuracy, resolution, precision, and repeatability. Regarding performance testing for processing and modelling of datasets to refine identified benchmark targets, the most critical factors are accuracy of data and standardized data collection
Ecological	Ecological factors within the exclusion and evaluation stage include the ecological settings and boundary conditions. Ecological settings include the identifiable and surrounding land use, existence of protected areas, target habitats, and species of conservational importance.
Social	Social Features in the exclusion and evaluation stage include the administrative settings, legal and permitting requirements, governance structure, policies and processes of the exploration company, and social setting (with local progress primacies, infrastructure, and community assets).

In addition to the exclusion and evaluation procedures, a second set of content-based decision features were introduced. Namely the DOAI and the social feedback loops (see Table 61).

Table 61 DOAI and Social Feedback of the Sustainable Test Site Decision Framework

Dimension	Description
DOAI	With the DOAI, the dissertation developed a disturbance assessment and implicitly a disturbance mitigation and communication tool. The DOAI assesses the probability of disturbance to habitat. Disturbance strength refers to alert categories for species reaction. Reaction measurement categories range from 1 (no reaction) to 4 (aggression / abandonment). Assessment criteria include platform type and elevation of the platform. The results are novel as the analysis combines four types of platforms (helicopter, fixed-wing, UAS, groundworker) and four types of target species. Previous research focused on either one platform or species.
Social Feedback Loops	The social feedback loops build on the information of the DOAI as they establish a platform for dialogue and transparency with local stakeholders to explore sensitivities. In addition, they help build capacity to heighten awareness and support the consideration of sustainability, social performance, and technical issues. The extent and degree to which social feedback loops are relevant are context-specific to individual test sites.

Within the content model, technical test target features and benchmarks dictate a test area's ability (and limitations) to serve technological progress (fitness-for-purpose). Social and ecological factors increase sustainability, generate awareness, and govern responsible best practices.

Future research could introduce more scrutiny whereby test site users are held accountable to the disturbance mitigation mechanism and enable full transparency about the impact of the methods used.

7.4 Validation and Transferability of the Sustainable Test Site Decision Framework

The dissertation introduced a new measurement paradigm, process, and concept to TD, accounting for numerous practical implications. For mineral exploration, the outputs of this dissertation enable the management of intangible factors alongside tangibles in a comprehensive, easy to use, multidimensional, and replicable way. As a result, business experts, academics, technology developers, and governments can use technically centered, social, and ecologically enhanced decision-making.

Validation showed that beyond the purely testing perspective. The DOAI triggers discussion on sustainability considerations in technological development. Future exploration companies need to heighten their efforts for non-invasive technologies and expand the reference point for invasiveness beyond the soil horizons but add scope two and three emissions.

Limits of the STSDF result from the co-dependence of strategic decision space and the developer space. In addition, the dependency on context (data models) reduces the ability for definite answers. Forcing an answer might reduce the accuracy of the overall framework. Future research should consider the introduction of context-dependent queries.

Other applications considered in the thesis include UAS and Critical zone research test site decision-making. The validation reports the highest factor similarity with critical zone research and relevance for the UAS test sites' model. A possible explanation lies with the application cases. UAS development primarily focuses on industrial applications. Technology developers in that field thus require robust benchmarks for demonstrative power and stable conditions. In addition, testing is highly iterative, demonstrating that a drone caters for various terrains and applications is critical. Consequently, no single test site might be suitable, but developers require a range of test sites. The study infers that the more a single technology is tested, and the higher the mobility of the test object (e.g., drones versus sensitive SQUID equipment), the more relevant the diversity of framework factors.

Critical zone research appears to have limited direct industrial output. The thesis showed the importance of test target features and the ecological and social dimensions of the STSDF.

One possible explanation for the priority differences between commercial applications and science is that sustainability concerns are not yet fully accounted for or translated into market-related considerations. This argument is also strengthened by the third validation performed.

The validation with grant decision-makers shows that economic ratios dominate when analyzing grant proposals. Considerations about structural, political, and legal restrictions weigh higher than technical or social and ecological considerations. Suggesting that technological understanding, impact or dialogue prevent direct comparison of options.

Limitations in characterizing the technical decision structures may yet hinder innovative advancements. This supports the concept of the dissertation that suggest that inclusive technological advances require robust judgment structures. Hence, setting out to measure technical and ecological suitability objectively and allowing for individual interpretation by stakeholders to account for the significance of the measurement context is relevant.

The transfer validation strengthened the case that comparisons give results against the grain of absolute measurements and finite process models. Furthermore, it shows that the three-pillar approach of mathematical considerations, conceptual / process-based review and contextual considerations allow for transferability, individual assessment, and expansion.

8 Conclusion and Limitations

The study set out to analyze how to define the appropriateness of test sites under technical, social, and ecological considerations and aimed to identify the factors enabling sustainably sound performance at test sites, and generate an effective and decision-making approach and process.

Per the research objective and guiding questions, this thesis produced three main outputs. Firstly, the dissertation builds a flexible decision-making process with composite and hierarchical calculation concepts. Secondly, a model for an informed decision-making process is developed, including technical, social, and ecological dimensions of technology testing in natural environments. The decision-making process consists of a good practice approach for social dialogue. Thirdly, the study details the interplay between test target features, benchmark features, socio-economic, and ecological performance and their impact on test site suitability. Beyond the three main outputs, sub-outputs emerge.

Starting with the ecological dimension, the thesis asked how to assess the ecological impact of test site operations. With multiple regression analyses, the thesis reveals that impact can be measured as means of platform-related disturbance to fauna. The measurements can indicate the disturbance of target species to platform type and result in target species protection. This may suggest that the entire biotope is supported.

Other sub-outputs concern social research. The thesis set out to question how one can determine social sustainability prior to the start of a project. The dissertation provides evidence for the relevance of dialogue for sustainable operations. The study further validates contrasting views on the relevance of technical versus managerial perspectives. The outcomes show that the integration of technical aspects is a reliable predictor for benchmarking success. Finally, it emerges that the mobility of technologies dictates the frequency and required standardization of the STSDF.

Together, these findings suggest a role for technologies in promoting sustainability, which may start as early as technology testing. The lighthouse effect for future operations in the field became visible. Similarly, the findings have implications for theoretical work. They suggest investigating the relation between ecological safeguarding of single species versus entire ecosystems and the umbrella effect of the target species concept. Finally, although this study focuses on sustainable test site selection in general, it showed the findings might well have external validity to other physical test sites. Theoretically speaking, this heightens the need for more inclusive assessment methods and strengthens the flexibility-centered computation approach's value. In sum, the findings have substantial implications for understanding how different technological and social stakeholders can work in unity.

This dissertation is the first comprehensive investigation of technical, social, and ecological forces associated with real test sites. To the author's knowledge, it is the most extensive study documenting efforts to integrate sustainability at the first point a technology meets the physical environment. Before this study, it was difficult for stakeholders to communicate a test site fit and make predictions about its sustainability. The analysis of benchmark features extends knowledge of technical demonstrations. Related industries can leverage conceptual frameworks. The empirical findings contribute to a better understanding of ecological disturbance modelling. The DOAI will prove helpful in expanding knowledge of the technical, social, and ecological nexus and help improve impact predictions of technologies and final products. A limitation to this study is the limited impact evaluation of social dialogue. Future research should track communication about disturbance and social systems, which this study has made provisions for but cannot cover in full breadth. Notwithstanding these limitations, the results indicate that disturbance and social perception are interconnected. While this study cannot speak for the impact of social dialogue in the long term, it partially substantiated the importance of engagement and trust in social settings.

In the dissertation, the scope of the ecological assessment is limited to alert categories. Other limitations result from the type of data collection. Building on existing research, the research is limited to the existing style and scope of considered assessment targets. The resulting challenges include the limited possibility to assess the impact of terrain specifics and noise propagation, introducing uncertainty to the model. Limited availability of species-specific data and technical specification the platforms (e.g. length, rotor diameter) further limit the approach. This is particularly true for fixed-wing. Reviewing the direction of innovation, there is a tendency to intensify UAS and helicopter specific exploration (e.g., per distance to target ratio).

Considering the social perspective the dissertation, finally omitted socio-ecological assessment sources such as air pollution and the framing of social dialogue.

Despite its limitations, the study adds to our understanding of the disturbance categories and valuation procedures across platforms. In the future, more information on disturbance features would help to establish a greater degree of accuracy on impact assessment. A natural progression of this work is to analyze the link between sustainable test sites and TD progress and effects on responsible practice for related industries. In addition, a greater focus on integrating the decision framework into a continuous evaluation mechanism for sustainable technology testing could produce findings that cover the entire technology life cycle and address shifts over time in a more structured manner, as the dynamic aspect was pointed out as necessary during validation. Especially in the current climate of autonomous car testing the sustainable test sites gain visibility.

Beyond the academic research discourse, the findings suggest several courses of action for practitioners. The provision of technical expertise in managerial investment decisions will enhance the innovative capacity of an organization and pave the way for better understanding between technical and management decision-makers. Another important practical implication is that demonstrating and performance testing can shed light on the responsible practice and add to the reputation of companies. Moreover, more sustainability-centered guidelines and good practice guides should be made available to the different stakeholders associated with a test site decision-making process. The challenge now is to accumulate more evidence on the value of the technological, social, and ecological practices that contain economic considerations as translation key accounts.

References

Abdel-Basset, M., Gamal, A., Chakrabortty, R. K., & Ryan, M. (2021). A new hybrid multi-criteria decision-making approach for location selection of sustainable offshore wind energy stations: A case study. *Journal of Cleaner Production*, *280*, 124462. https://doi.org/10.1016/j.jclepro.2020.124462

Abou Chakra, C., Somma, J., Gascoin, S., Fanise, P., & Drapeau, L. (2020). IMPACT OF FLIGHT ALTITUDE ON UNMANNED AERIAL PHOTOGRAMMETRIC SURVEY OF THE SNOW HEIGHT ON MOUNT LEBANON. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLIII-B2-2020*, 119–125. https://doi.org/10.5194/isprs-archives-xliii-b2-2020-119-2020

Acevedo, M. F. (2016). *Simulation of Ecological and Environmental Models*. CRC Press.

Acosta, A. M., & Falcone, P. (2021). Modelling and Control of Test-Scenarios for Validation of Autonomous Driving Functions. *2021 American Control Conference (ACC)*, 2943–2948. https://doi.org/10.23919/ACC50511.2021.9483214

Agrawal, N. (2020). A framework for Crosby's quality principles using ISM and MICMAC approaches. *The TQM Journal*, *32*(2), 305–330. https://doi.org/10.1108/TQM-03-2019-0085

Ahmad, S., Wong, K. Y., Tseng, M. L., & Wong, W. P. (2018). Sustainable product design and development: A review of tools, applications and research prospects. *Resources, Conservation and Recycling*, *132*, 49–61. https://doi.org/10.1016/j.resconrec.2018.01.020

Åhman, M., & Nilsson, L. J. (2008). Path dependency and the future of advanced vehicles and biofuels. *Utilities Policy*, *16*(2), 80–89. https://doi.org/10.1016/j.jup.2007.11.003

Ahmed, N., Islam, M. N., Tuba, A. S., Mahdy, M. R. C., & Sujauddin, M. (2019). Solving visual pollution with deep learning: A new nexus in environmental management. *Journal of Environmental Management*, *248*, 109253. https://doi.org/10.1016/j.jenvman.2019.07.024

Ahmed, P. K., & Rafiq, M. (1998). Integrated benchmarking: a holistic examination of select techniques for benchmarking analysis. *Benchmarking for Quality Management & Technology*, *5*(3), 225–242. https://doi.org/10.1108/14635779810234802

Ajjabou, L., Kirsch, M., Gloaguen, R., & Russil, J. (2019). Certifying best practices in mineral exploration: a step towards an enhanced reputation. *Geophysical Research Abstracts*, *21*.

Al Assadi, A., Waltersmann, L., Miehe, R., Fechter, M., & Sauer, A. (2021). Automated Environmental Impact Assessment (EIA) via Asset Administration Shell. In P. Weißgraeber, F. Heieck, & C. Ackermann (Eds.), *ARENA2036. Advances in automotive production technology – theory and application: Stuttgart Conference on Automotive Production (SCAP2020) ; Philipp Weißgraeber, Frieder Heieck, Clemens Ackermann editors* (pp. 45–52). Springer Vieweg. https://doi.org/10.1007/978-3-662-62962-8_6

Al Garni, H. Z., & Awasthi, A. (2018). Solar PV Power Plants Site Selection. *Volume 1: Solar and Wind Energies*, 57–75. https://doi.org/10.1016/B978-0-12-812959-3.00002-2

Alaei, N., Kurvinen, E., & Mikkola, A. (2019). A Methodology for Product Development in Mobile Machinery: Case Example of an Excavator. *Machines*, *7*(4), 70. https://doi.org/10.3390/machines7040070

Alberto, P. (2000). The Logistics of Industrial Location Decisions: An Application of the Analytic Hierarchy Process Methodology. *International Journal of Logistics Research and Applications*, *3*(3), 273–289. https://doi.org/10.1080/713682767

Albuquerque, P. H. M. (2015). Promethee IV as a Decision Analyst's Tool for Site Selection in Civil Engineering. In P. Guarnieri (Ed.), *Decision Engineering. Decision Models in Engineering and Management* (pp. 257–267). Springer International Publishing. https://doi.org/10.1007/978-3-319-11949-6_14

Almeida, L. de, Diego, Augusto de Jesus Pacheco, Caten, C. S. ten, & Jung, C. F. (2021). A methodology for identifying results and impacts in technological innovation projects. *Technology in Society*, *66*, 101574. https://doi.org/10.1016/j.techsoc.2021.101574

Al-Yahyai, S., Charabi, Y., Gastli, A., & Al-Badi, A. (2012). Wind farm land suitability indexing using multi-criteria analysis. *Renewable Energy*, *44*, 80–87. https://doi.org/10.1016/j.renene.2012.01.004

Amaro, R. V. E., Farfán, C. E. M., Sánchez, W. E., & Achachagua, A. J. Y. (2021). Determining factors of investment in mineral exploration. *International Journal of Mining and Mineral Engineering*, *12*(2), Article 116873, 85. https://doi.org/10.1504/IJMME.2021.116873

American Wind Energy Association. (2019). *Resource Assessment.*

Anastas, P. T., & Zimmerman, J. B. (2003). Design through the 12 principles of green engineering. *Environmental Science & Technology*, *37*(5), 94-101. https://doi.org/10.1021/es032373g

Andersen, A. D., & Wicken, O. (2021). Making sense of how the natural environment shapes innovation, industry dynamics, and sustainability challenges. *Innovation and Development*, *11*(1), 91–117. https://doi.org/10.1080/2157930X.2020.1770975

Anderson, S. P., Bales, R. C., & Duffy, C. J. (2008). Critical Zone Observatories: Building a network to advance interdisciplinary study of Earth surface processes. *Mineralogical Magazine*, *72*(1), 7–10. https://doi.org/10.1180/minmag.2008.072.1.7

Andersson, E., Haase, D., Anderson, P., Cortinovis, C., Goodness, J., Kendal, D., Lausch, A., McPhearson, T., Sikorska, D., & Wellmann, T. (2021). What are the traits of a social-ecological system: Towards a framework in support of urban sustainability. *Npj Urban Sustainability*, *1*(1), 1–8. https://doi.org/10.1038/s42949-020-00008-4

Andrews, T., Elizalde, B., Billon, P. L., Oh, C. H., Thomson, D. R., & Thomson, I. (2001). The Rise in Conflict Associated with Mining Operations: What Lies Beneath. *Nuclear Physics a*, *686*(1-4), 71–108. https://doi.org/10.1016/S0375-9474(00)00572-8

Anell, L., & Nygren, B. (2014). *The Developing Countries and the World Economic Order*. *Bloomsbury Academic Collections*. Bloomsbury Publishing PLC.

Anthonissen, J., Bergh, W., & Braet, J. (2016). Review and environmental impact assessment of green technologies for base courses in bituminous pavements. *Environmental Impact Assessment Review*, *60*, 139–147. https://doi.org/10.1016/j.eiar.2016.04.005

Arbault, D., Rivière, M., Rugani, B., Benetto, E., & Tiruta-Barna, L. (2014). Integrated earth system dynamic modeling for life cycle impact assessment of ecosystem services. *The Science of the Total Environment*, *472*, 262–272. https://doi.org/10.1016/j.scitotenv.2013.10.099

Archambault, S. (2004). Ecological modernization of the agriculture industry in southern Sweden: reducing emissions to the Baltic Sea. *Journal of Cleaner Production*, *12*(5), 491–503. https://doi.org/10.1016/S0959-6526(03)00109-4

Aristodemou, L., Tietze, F., O'Leary, E., & Shaw, M. (2019). *A literature review on technology development process (TDP) models // A Literature Review on Technology Development Process (TDP) Models.* University of Cambridge. https://doi.org/10.17863/CAM.35692

Armenta, S., Garrigues, S., & La Guardia, M. de (2015). The role of green extraction techniques in Green Analytical Chemistry. *TrAC Trends in Analytical Chemistry*, *71*, 2–8. https://doi.org/10.1016/j.trac.2014.12.011

Arnette, A. N., Brewer, B. L., & Choal, T. (2014). Design for sustainability (DFS): the intersection of supply chain and environment. *Journal of Cleaner Production*, *83*, 374–390. https://doi.org/10.1016/j.jclepro.2014.07.021

Arning, K., Offermann-van Heek, J., Sternberg, A., Bardow, A., & Ziefle, M. (2020). Risk-benefit perceptions and public acceptance of Carbon Capture and Utilization. *Environmental Innovation and Societal Transitions*, *35*, 292–308. https://doi.org/10.1016/j.eist.2019.05.003

Assad, F., Konstantinov, S., Rushforth, E. J., Vera, D. A., & Harrison, R. (2021). Virtual engineering in the support of sustainable assembly systems. *Procedia CIRP*, *97*, 367–372. https://doi.org/10.1016/j.procir.2020.05.252

Assefa, G., & Frostell, B. (2007). Social sustainability and social acceptance in technology assessment: A case study of energy technologies. *Technology in Society*, *29*(1), 63–78. https://doi.org/10.1016/j.techsoc.2006.10.007

Atan, R., Goggins, J., & Nash, S. (2018). Galway Bay – The 1/4 scale wave energy test site? A detailed wave energy resource assessment and investigation of scaling factors. *Renewable Energy*, *119*, 217–234. https://doi.org/10.1016/j.renene.2017.11.090

Atthirawong, W [Walaiak]. (2003). *View of An Analytical Approach for International Location Problem*. https://li01.tci-thaijo.org/index.php/cast/article/view/144365/106825

Auken, E., Boesen, T., & Christiansen, A. V [Anders V.]. (2017). A Review of Airborne Electromagnetic Methods With Focus on Geotechnical and Hydrological Applications From 2007 to 2017. In L. Nielsen (Ed.), *Advances in Geophysics: v.Volume 58. Advances in Geophysics* (Vol. 58, pp. 47–93). Elsevier Science. https://doi.org/10.1016/bs.agph.2017.10.002

Australian Society of Exploration Geophysicists. (2016). *Geophysical Test Ranges*. https://www.aseg.org.au/technical/geophysical-test-ranges

Autant-Bernard, C., & LeSage, J. P. (2011). QUANTIFYING KNOWLEDGE SPILLOVERS USING SPATIAL ECONOMETRIC MODELS. *Journal of Regional Science*, *51*(3), 471–496. https://doi.org/10.1111/j.1467-9787.2010.00705.x

Avelino, F., Grin, J., Pel, B., & Jhagroe, S. (2016). The politics of sustainability transitions. *Journal of Environmental Policy & Planning*, *18*(5), 557–567. https://doi.org/10.1080/1523908X.2016.1216782

Aweiss, A. S., Owens, B. D., Rios, J., Homola, J. R., & Mohlenbrink, C. P. (2018). Unmanned Aircraft Systems (UAS) Traffic Management (UTM) National Campaign II. Advance online publication. https://doi.org/10.2514/6.2018-1727

Aydin, N. Y., Kentel, E., & Duzgun, S. (2010). GIS-based environmental assessment of wind energy systems for spatial planning: A case study from Western Turkey. *Renewable and Sustainable Energy Reviews*, *14*(1), 364–373. https://doi.org/10.1016/j.rser.2009.07.023

Azoulay, P., Fuchs, E., Goldstein, A. P., & Kearney, M. (2019). Funding Breakthrough Research: Promises and Challenges of the “ARPA Model”. *Innovation Policy and the Economy*, *19*, 69–96. https://doi.org/10.1086/699933

Bach, T., Pannemans, R., & Schwedes, S. (2018). Effects of an Economic Approach for Test Case Selection and Reduction for a Large Industrial Project. In *2018 IEEE 11th International Conference on Software Testing, Verification and Validation workshops: Icstw 2018 : 9-13 April 2018, Västerås, Sweden : Proceedings* (pp. 374–379). IEEE. https://doi.org/10.1109/ICSTW.2018.00076

Badera, J. (2014). Problems of the social non-acceptance of mining projects with particular emphasis on the European Union – a literature review. *Environmental & Socio-Economic Studies*, *2*(1), 27–34. https://doi.org/10.1515/environ-2015-0029

Badri, M. A. (2007). *Dimensions of Industrial Location Factors: Review and Exploration*. http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.113.9393

Bahill, T. A., & Henderson, S. J. (2005). Requirements development, verification, and validation exhibited in famous failures. *Systems Engineering*, *8*(1), 1–14. https://doi.org/10.1002/sys.20017

Ballance, A. (1987). *International industry and business: Structural change, industrial policy and industry strategies.*

Ballon, P., Pierson, J., & Delaere, S. (2005). Test and Experimentation Platforms for Broadband Innovation: Examining European Practice. *SSRN Electronic Journal.* Advance online publication. https://doi.org/10.2139/ssrn.1331557

Ballon, P., & Schuurman, D. (2015). Living labs: concepts, tools and cases. *Info*, *17*(4). https://doi.org/10.1108/info-04-2015-0024

Ballon, P., van Hoed, M., & Schuurman, D. (2018). The effectiveness of involving users in digital innovation: Measuring the impact of living labs. *Telematics and Informatics*, *35*(5), 1201–1214. https://doi.org/10.1016/j.tele.2018.02.003

Banwart, S., Menon, M., Bernasconi, S. M., Bloem, J., Blum, W. E., Souza, D. M. de, Davidsdotir, B., Duffy, C., Lair, G. J., Kram, P., Lamacova, A., Lundin, L., Nikolaidis, N. P., Novak, M., Panagos, P., Ragnarsdottir, K. V., Reynolds, B., Robinson, D., Rousseva, S., . . . Zhang, B [Bin] (2012). Soil processes and functions across an international network of Critical Zone Observatories: Introduction to experimental methods and initial results. *Comptes Rendus Geoscience*, *344*(11-12), 758–772. https://doi.org/10.1016/j.crte.2012.10.007

Barile, S., Pellicano, M., & Polese, F. (2017). *Social Dynamics in a Systems Perspective*. *New Economic Windows*. Springer International Publishing.

Barragán, A., Arias, P., & Terrados, J. (2017). Renewable Energy Generation Technologies on Urban Scale. *Renewable Energy and Power Quality Journal*, *1*(15), 681–685. https://doi.org/10.24084/repqj15.432

Bateman, P. W., & Fleming, P. A. (2014). Does human pedestrian behaviour influence risk assessment in a successful mammal urban adapter? *Journal of Zoology*, *294*(2), 93–98. https://doi.org/10.1111/jzo.12156

Bates, C. A., & Clausen, C. (2020). Engineering Readiness: How the TRL Figure of Merit Coordinates Technology Development. *Engineering Studies*, *12*(1), 9–38. https://doi.org/10.1080/19378629.2020.1728282

Bauknecht, D., Voss, J.-P., & Kemp, R. (2006). *Reflexive governance for sustainable development*. Edward Elgar.

Baum, C. E. (2019). *Detection and identification of visually obscured targets* (1st). Routledge.

Beauxis-Aussalet, E., & Hardman, L. (2014). Visualization of Confusion Matrix for Non-Expert Users. In *IEEE Conference on Visual Analytics Science and Technology (VAST)-Poster Proceedings.*

Beemsterboer, S., & Kemp, R. (2016). Sustainability Assessment of Technologies. In H. Heinrichs, W. J. M. Martens, G. Michelsen, & A. Wiek (Eds.), *Environment. 978-94-017-7241-9 // Sustainability science: An introduction* (pp. 71–83). Springer. https://doi.org/10.1007/978-94-017-7242-6_6

Begum, S., Chakraborty, D., & Sarkar, R. (2015). Data Classification Using Feature Selection and kNN Machine Learning Approach. In *2015 International Conference on Computational Intelligence and Communication Networks: Cicn 2015 : 12-14 December 2015, Jabalpur : Proceedings* (pp. 811–814). IEEE. https://doi.org/10.1109/CICN.2015.165

Behdad, S., & Thurston, D. (2011). Disassembly Process Planning Tradeoffs for Product Maintenance. In (pp. 427–434). American Society of Mechanical Engineers Digital Collection. https://doi.org/10.1115/DETC2010-28825

Beiki, M., Clark, D. A., Austin, J. R., & Foss, C. A. (2012). Estimating source location using normalized magnetic source strength calculated from magnetic gradient tensor data. *GEOPHYSICS*, *77*(6), J23-J37. https://doi.org/10.1190/geo2011-0437.1

Belt, P., Harkonen, J., Mottonen, M., Kess, P., & Haapasalo, H. (2008). Improving the efficiency of verification and validation. *International Journal of Services and Standards*, *4*(2). https://doi.org/10.1504/IJSS.2008.01663

Bender, N., & Rovira, E. (2021). Beyond product-market fit: Human centered design for social sustainability. In R. Bonacho, M. J. Pires, & E. C. C. d. S. Lamy (Eds.), *Experiencing food: Designing sustainable and social practices : proceedings of the 2nd International Conference on Food Design and Food Studies (EFOOD 2019), 28-30 November, 2019, Lisbon, Portugal* (pp. 59–62). CRC Press/Balkema. https://doi.org/10.1201/9781003046097-9

Bengert, B., Svilans, M., Legault, J., Berardelli, P., & Fenlon, K. (2020). Groundfloor EM – A new adaptation. *SEG International Exposition and Annual Meeting,*, 1414–1418. https://doi.org/10.1190/segam2020-3428168.1

Benighaus, L., Benighaus, C., Kastl, L., Baranski, M., Kotilainen, J., Mononen, T., Kauppi, S [Sari], Kontio, P., Rodriguez, R., Requeji, J., & Del Rio, V. (2018). *Online-Survey of Public Opinion in Finland, Germany, and Spain* (INFACT Deliverable D2.4). INFACT.

Benighaus, L., Benighaus, C., Renn, O., Lyytimäki, J., Gomez, J., & Del Rio, V. (2020). *Europe-wide content analysis report* (INFACT Deliverable D2.2). INFACT.

Berardelli, P., Bengert, B., & Legault, J. M. (2018). *GROUNDFLOOR EM: A NEW ADAPTATION.* geotech Ltd. http://sydney2018.aseg.org.au/Documents/Poster%20Abstracts/P018.pdf. Last Accessed: 01.12.2021

Berg, P., Leinonen, M., Leivo, V., & Pihlajamaa, J. (2002). Assessment of quality and maturity level of R&D. *International Journal of Production Economics*, *78*(1), 29–35. https://doi.org/10.1016/S0925-5273(00)00166-3

Bergeron, F., Gingras, L., Hadaya, P., & Caron, C. (2005). A Framework for Evaluating Strategic Location-Based Applications in Businesses. In R. H. Sprague (Ed.), *0-7695-2268-8 // Proceedings of the 38th Annual Hawaii International Conference on System Sciences: 3 - 6 January 2005, Big Island, Hawaii, [Hilton Waikoloa] ; abstracts and CD-ROM of full papers* (76b-76b). IEEE Computer Society. https://doi.org/10.1109/HICSS.2005.16

Bergh, D. D., Ketchen, D. J., Orlandi, I., Heugens, P. P. M. A. R., & Boyd, B. K. (2019). Information Asymmetry in Management Research: Past Accomplishments and Future Opportunities. *Journal of Management*, *45*(1), 122–158. https://doi.org/10.1177/0149206318798026

Bericat, E. (2012). The European Gender Equality Index: Conceptual and Analytical Issues. *Social Indicators Research*, *108*(1), 1–28. https://doi.org/10.1007/s11205-011-9872-z

Bernsen, N. O., & Dybkjær, L. (2009). *Multimodal usability*. *Human-computer interaction series*. Springer.

Bertoni, A., Hallstedt, S. I., Dasari, S. K., & Andersson, P. (2020). Integration of value and sustainability assessment in design space exploration by machine learning: An aerospace application. *Design Science*, *6.* https://doi.org/10.1017/dsj.2019.29

Best, H., & Wolf, C. (2010). Logistische Regression. In *Handbuch der sozialwissenschaftlichen Datenanalyse* (pp. 827–854). VS Verlag für Sozialwissenschaften. https://doi.org/10.1007/978-3-531-92038-2_31

Bhutta, K. S., Huq, F., Frazier, G., & Mohamed, Z. (2003). An integrated location, production, distribution and investment model for a multinational corporation. *International Journal of Production Economics*, *86*(3), 201–216. https://doi.org/10.1016/S0925-5273(03)00046-X

Bijker, W. E., Hughes, T. P., & Pinch, T. (1987). *The social construction of technological systems, anniversary edition: New directions in the sociology and history of technology*. The MIT Press.

Biloslavo, R., Bagnoli, C., & Edgar, D. (2018). An eco-critical perspective on business models: The value triangle as an approach to closing the sustainability gap. *Journal of Cleaner Production*, *174*, 746–762. https://doi.org/10.1016/j.jclepro.2017.10.281

Bisilkas, M., Ivan, B. T., & Aurora, G. G. (2012). *A Model of the Sustainability Requirements Dynamics for New Product Development*. https://proceedings.systemdynamics.org/2012/proceed/papers/p1345.pdf. Last Accessed: 01.12.2021

Blair, J. P., & Premus, R. (1987). Major Factors in Industrial Location: A Review. *Economic Development Quarterly*, *1*(1), 72–85. https://doi.org/10.1177/089124248700100109

Blavette, A., Bonnard, C.-H., Daminov, I., Bourguet, S., & Soulard, T. (2021). *Upgrading wave energy test sites by including overplanting: a techno-economic analysis*. https://www.researchgate.net/profile/anne-blavette/publication/352045668_upgrading_wave_energy_test_sites_by_including_overplanting_a_techno-economic_analysis/links/60b79136a6fdcc476be4d062/upgrading-wave-energy-test-sites-by-including-overplanting-a-techno-economic-analysis.pdf. Last Accessed: 01.12.2021

BMWE. (2020). *Good signal from the Federal Council: No more continuous flashing on wind turbines. Federal Ministry fo Economic Affairs and Energy*. https://www.bmwi.de/Redaktion/DE/Pressemitteilungen/2020/20200214-gutes-signal-aus-dem-bundesrat-schluss-mit-dauerblinken-an-windraedern.html. Last Accessed: 10.12.2021

Böde, E., Büker, M., Eberle, U., Fränzle, M., Gerwinn, S., & Kramer, B. (2018). Efficient Splitting of Test and Simulation Cases for the Verification of Highly Automated Driving Functions. In M. Hoshi & S. Seki (Eds.), *SpringerLink Bücher: Vol. 11088. Developments in Language Theory: 22nd International Conference, DLT 2018, Tokyo, Japan, September 10-14, 2018, Proceedings* (Vol. 11088, pp. 139–153). Springer International Publishing. https://doi.org/10.1007/978-3-319-99130-6_10

Bond, A., & Morrison-Saunders, A. (2013). *The natural and built environment series*. *Sustainability assessment: Pluralism, practice and progress* (A. J. Bond, Ed.). Routledge.

Bonetti, A., Harispuru, C., Pitzer, M., Pustejovsky, M., Wetterstrand, N., & Kachelries, S. (2021). Digital twin technology for virtual testing of power system relay protection. In *2021 3rd Global Power, Energy and Communication Conference (GPECOM)* (pp. 154–160). IEEE. https://doi.org/10.1109/GPECOM52585.2021.9587869

Bonetto, S., Facello, A., Cristofori, E. I., Camaro, W., & Demarchi, A. (2017). An Approach to Use Earth Observation Data as Support to Water Management Issues in the Ethiopian Rift. In W. Leal Filho, S. Belay, J. Kalangu, W. Menas, P. Munishi, & K. Musiyiwa (Eds.), *Climate Change Management. Climate Change Adaptation in Africa: Fostering Resilience and Capacity to Adapt* (pp. 357–374). Springer International Publishing. https://doi.org/10.1007/978-3-319-49520-0_22

Booysen, R., Lorenz, S., Jackisch, R., Gloaguen, R., & Madriz, Y. (2021). How Can Drones Contribute to Mineral Exploration? In *2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS.* IEEE. https://doi.org/10.1109/igarss47720.2021.9554041

Borah, U. K., & Patro, P. K. (2019). Estimation of the depth of investigation in the magnetotelluric method from the phase. *GEOPHYSICS*, *84*(6), E377-E385. https://doi.org/10.1190/geo2018-0124.1

Borisov, V. N., & Pochukaeva, O. V. (2017). Investment and innovative technological efficiency: Case study of the Arctic project. *Studies on Russian Economic Development*, *28*(2), 169–179. https://doi.org/10.1134/S1075700717020022

Borland, H., & Lindgreen, A. (2013). Sustainability, Epistemology, Ecocentric Business, and Marketing Strategy: Ideology, Reality, and Vision. *Journal of Business Ethics*, *117*(1), 173–187. https://doi.org/10.1007/s10551-012-1519-8

Boström, M., Vifell, Å. C., Klintman, M., Soneryd, L., Hallström, K. T., & Thedvall, R. (2015). Social Sustainability Requires Social Sustainability: Procedural Prerequisites for Reaching Substantive Goals. *Nature and Culture*, *10*(2), 131–156. https://doi.org/10.3167/nc.2015.100201

Bouza-Herrera, C. N. (2013). *Handling missing data in ranked set sampling*. *SpringerBriefs in statistics*. Springer.

Boyd, D. W. (2000). *Systems Analysis and Modeling: A Macro-to-Micro Approach with Multidisciplinary Applications* (1. Aufl.). Elsevier professional. https://doi.org/10.1016/B978-0-12-121851-5.X5000-X

Bradley, S. R., Hayter, C. S., & Link, A. N. (2013). Proof of Concept Centers in the United States: an exploratory look. *The Journal of Technology Transfer*, *38*(4), 349–381. https://doi.org/10.1007/s10961-013-9309-8

Brans, J. P., & Vincke, P. (1985). Note—A Preference Ranking Organisation Method. *Management Science*, *31*(6), 647–656. https://doi.org/10.1287/mnsc.31.6.647

Brans, J. P., Vincke, P., & Mareschal, B. (1986). How to select and how to rank projects: The Promethee method. *European Journal of Operational Research*, *24*(2), 228–238. https://doi.org/10.1016/0377-2217(86)90044-5

Brans, J.-P., & Smet, Y. de. (2016). Promethee Methods. In S. Greco, M. Ehrgott, & J. R. Figueira (Eds.), *International series in operations research & management science: Vol. 233. Multiple criteria decision analysis: State of the art surveys* (Vol. 233, pp. 187–219). London; Springer. https://doi.org/10.1007/978-1-4939-3094-4_6

Brinkmann, R. (2020a). Interconnections: Pollution, Waste Management, and Energy. In R. Brinkmann (Ed.), *Palgrave Studies in Environmental Sustainability Ser. Environmental Sustainability in a Time of Change* (pp. 237–256). Springer International Publishing AG. https://doi.org/10.1007/978-3-030-28203-5_11

Brinkmann, R. (2020b). Megaconnections in Environmental Sustainability Through the Twenty-First Century. In R. Brinkmann (Ed.), *Palgrave Studies in Environmental Sustainability Ser. Environmental Sustainability in a Time of Change* (pp. 279–287). Springer International Publishing AG. https://doi.org/10.1007/978-3-030-28203-5_13

Bristol, T., & Fern, E. F. (1996). Exploring the Atmosphere Created by Focus Group Interviews: Comparing Consumers' Feelings across Qualitative Techniques. *Market Research Society. Journal.*, *38*(2), 1–9. https://doi.org/10.1177/147078539603800208

Bröhl, & Dröschel. (1995). *The V-Model: Standard for Software-Development and Guideline for Practice.*

Brown, N., & Michael, M. (2003). A Sociology of Expectations: Retrospecting Prospects and Prospecting Retrospects. *Technology Analysis & Strategic Management*, *15*(1), 3–18. https://doi.org/10.1080/0953732032000046024

Brown, R. (2018). Physical Test Methods for Elastomers. Advance online publication. https://doi.org/10.1007/978-3-319-66727-0

Brundtland, H. G. (1985). World Commission on environment and development. *Environmental Policy and Law*, *14*(1), 26–30. https://doi.org/10.1016/S0378-777X(85)80040-8

Bühl, A., & Zöfel, P. (2002). *Erweiterte Datenanalyse mit SPSS: Statistik und Data Mining*. VS Verlag für Sozialwissenschaften. https://doi.org/10.1007/978-3-322-89603-2

Bullinger, H.-J. (1994). *Einführung in das Technologiemanagement: Modelle, Methoden, Praxisbeispiele*. *Technologiemanagement - Wettbewerbsfähige Technologieentwicklung und Arbeitsgestaltung*. Vieweg+Teubner Verlag. https://doi.org/10.1007/978-3-322-84858-1

Butts-Wilmsmeyer, C. J., Rapp, S [Samuel], & Guthrie, B. (2020). The technological advancements that enabled the age of big data in the environmental sciences: A history and future directions. *Current Opinion in Environmental Science & Health*, *18*, 63–69. https://doi.org/10.1016/j.coesh.2020.07.006

Cabezas, H., Pawlowski, C. W., Mayer, A. L., & Hoagland, N. T. (2004). Sustainability: Ecological, Social, Economic, Technological, and Systems Perspectives. In S. K. Sikdar, P. Glavič, & R. Jain (Eds.), *Technological Choices for Sustainability* (pp. 37–64). Springer. https://doi.org/10.1007/978-3-662-10270-1_3

Cai, J., Gao, Q., Chun, H., Cai, H., & Nantung, T. (2019). Spatial Autocorrelation in Soil Compaction and Its Impact on Earthwork Acceptance Testing. *Transportation Research Record: Journal of the Transportation Research Board*, *2673*(1), 332–342. https://doi.org/10.1177/0361198118822279

Calzonetti, F. J., & Hemphill, R. C. (1992). *Assessing the impacts of regional characteristics on the location of manufacturing facilities: A review of recent methods and findings* (Argonne National Lab., IL (United States). Environmental Assessment and Information Sciences Div ANL/EAIS/TM-64). https://doi.org/10.2172/5516677

Capello, M. A., Shaughnessy, A., & Caslin, E. (2021). The Geophysical Sustainability Atlas: Mapping geophysics to the UN Sustainable Development Goals. *The Leading Edge*, *40*(1), 10–24. https://doi.org/10.1190/tle40010010.1

Caporale, D., Sangiorgio, V., Amodio, A., & Lucia, C. de (2020). Multi-criteria and focus group analysis for social acceptance of wind energy. *Energy Policy*, *140*, 111387. https://doi.org/10.1016/j.enpol.2020.111387

Carayannis, E. G., Grigoroudis, E., & Alexander, J. M. (2020). In pursuit of smart growth: technology transfer theories, policies and practices. *The Journal of Technology Transfer*, *45*(6), 1607–1610. https://doi.org/10.1007/s10961-020-09779-5

Carini, C., Fidock, M., & van Gool, A. (Eds.). (2019). *Handbook of biomarkers and precision medicine*. CRC Press. https://doi.org/10.1201/9780429202872

Cassell, C., & Symon, G. (2006). *Essential guide to qualitative methods in organizational research* (2. Reprint der Ausg. London [u.a.] 2004). SAGE Publications.

Cecchin, A., Salomone, R., Deutz, P., Raggi, A., & Cutaia, L. (2020). Relating Industrial Symbiosis and Circular Economy to the Sustainable Development Debate. In *Industrial Symbiosis for the Circular Economy* (pp. 1–25). Springer, Cham. https://doi.org/10.1007/978-3-030-36660-5_1

Chang, S.-H. (2021). Technological structure network analysis to explore the hotspots of academic patents in international technology transfer. *Science and Public Policy*, Article scab065. Advance online publication. https://doi.org/10.1093/scipol/scab065

Chaudhary, M., & Chopra, A. (2016). Cmmi Overview. In M. Chaudhary & A. Chopra (Eds.), *Cmmi for Development: Implementation Guide* (pp. 1–7). Apress. https://doi.org/10.1007/978-1-4842-2529-5_1

Chave, A. D., Jones, A. G., Mackie, R., & Rodi, W. (2012). *The magnetotelluric method: Theory and practice*. Cambridge University Press. https://doi.org/10.1017/CBO9781139020138

Chen, L., Olhager, J., & Tang, O. (2014). Manufacturing facility location and sustainability: A literature review and research agenda. *International Journal of Production Economics*, *149*, 154–163. https://doi.org/10.1016/j.ijpe.2013.05.013

Chen, Y [Yu], Chen, S., Zhang, T [Tangyike], Zhang, S [Songyi], & Zheng, N. (2018). Autonomous Vehicle Testing and Validation Platform: Integrated Simulation System with Hardware in the Loop In *2018 IEEE Intelligent Vehicles Symposium (IV): 26-30 June 2018* (pp. 949–956). IEEE. https://doi.org/10.1109/IVS.2018.8500461

Chesbrough, H. W., & Kusunoki, K. (2001). The Modularity Trap: Innovation Technology Phase Shifts and the Resulting Limits of Virtual Organizations. In D. J. Teece & I. Nonaka (Eds.), *Managing industrial knowledge: Creation, transfer and utilization.* SAGE.

Chism, N., Douglas, E., & Hilso, W. J. (2008). *Qualitative research basics: A guide for engineering educators*. https://eer.engin.umich.edu/wp-content/uploads/sites/443/2019/08/chism-douglas-hilson-qualitative-research-basics-a-guide-for-engineering-educators.pdf. Last Accessed: 01.12.2021

Chittick, I. R., & Martins, J. R. (2009). An asymmetric suboptimization approach to aerostructural optimization. *Optimization and Engineering*, *10*(1), 133–152. https://doi.org/10.1007/s11081-008-9046-2

Choi-Fitzpatrick, A. (2019). Chapter 5 - Resisting Drones | Resistance Drones: Resisting Technology and Technology of Resistance. In *The Good Drone.*

Choudhary, D., & Shankar, R. (2012). An STEEP-fuzzy AHP-TOPSIS framework for evaluation and selection of thermal power plant location: A case study from India. *Energy*, *42*(1), 510–521. https://doi.org/10.1016/j.energy.2012.03.010

Chowdhury, R. (2020). Social acceptance being the prime reason of geographic differentiation in laws. Advance online publication. https://doi.org/10.33774/coe-2020-cx8jf

Christensen, C. (1992). EXPLORING THE LIMITS OF THE TECHNOLOGY S-CURVE. PART I: COMPONENT TECHNOLOGIES. *Production and Operations Management*, *1*(4), 334–357. https://doi.org/10.1111/j.1937-5956.1992.tb00001.x

Chrysoulakis, N., Castro, E. A. de, & Moors, E. J. (Eds.). (2015). *Understanding urban metabolism: A tool for urban planning*. Routledge.

Chwala, A., Stolz, R., Zakosarenko, V [V.], Fritzsch, L., Schulz, M., Rompel, A., Polome, L., Meyer, M., & Meyer, H. G. (2012). Full Tensor SQUID Gradiometer for airborne exploration. *ASEG Extended Abstracts*, *2012*(1), 1–4. https://doi.org/10.1071/ASEG2012ab296

Clarke, J., & Braginski, A. I. (2006). *The SQUID Handbook*. Wiley. https://doi.org/10.1002/9783527609956

Clauser, C. (2014). *Einführung in die Geophysik: Globale physikalische Felder und Prozesse in der Erde*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-04496-0

Clauser, C. (2018). *Grundlagen der angewandten Geophysik - Seismik, Gravimetrie* (1. Aufl. 2018). Springer Berlin Heidelberg.

Coccia, M. (2019). The theory of technological parasitism for the measurement of the evolution of technology and technological forecasting. *Technological Forecasting and Social Change*, *141*, 289–304. https://doi.org/10.1016/j.techfore.2018.12.012

Coetzee, B. W. T., & Chown, S. L. (2016). A meta-analysis of human disturbance impacts on Antarctic wildlife. *Biological Reviews of the Cambridge Philosophical Society*, *91*(3), 578–596. https://doi.org/10.1111/brv.12184

Cohen, B., Blanco, H., Dubash, N. K., Dukkipati, S., Khosla, R., Scrieciu, S., Stewart, T., & Torres-Gunfaus, M. (2019). Multi-criteria decision analysis in policy-making for climate mitigation and development. *Climate and Development*, *11*(3), 212–222. https://doi.org/10.1080/17565529.2018.1445612

Collier, Z. A., Lambert, J. H., & Linkov, I. (2018). Resilience, sustainability, and complexity in social, environmental, and technical systems. *Environment Systems and Decisions*, *38*(1), 1–2. https://doi.org/10.1007/s10669-018-9679-4

Common, M., & Perrings, C. (1992). Towards an ecological economics of sustainability. *Ecological Economics*, *6*(1), 7–34. https://doi.org/10.1016/0921-8009(92)90036-R

Coughlin, C. C., Garrett, T. A., & Hernández-Murillo, R. (2007). Spatial Dependence in Models of State Fiscal Policy Convergence. *Public Finance Review*, *35*(3), 361–384. https://doi.org/10.1177/1091142106295766

Cozzani, V., & Salzano, E [E.]. (2016). Quantitative Methods for Natech Risk Assessment. In E. Krausmann, A. M. Cruz, & E. Salzano (Eds.), *Natech Risk Assessment and Management: Reducing the Risk of Natural-Hazard Impact on Hazardous Installations* (pp. 143–156). Elsevier Science. https://doi.org/10.1016/B978-0-12-803807-9.00009-7

Crosby, P. B. (1979). *Quality is free: The art of making quality certain*. McGraw-Hill.

Cukier, D., & Kon, F. (2018). A maturity model for software startup ecosystems. *Journal of Innovation and Entrepreneurship*, *7*(1). https://doi.org/10.1186/s13731-018-0091-6

Czichos, H. (2018). *Measurement, Testing and Sensor Technology: Fundamentals and Application to Materials and Technical Systems*. Springer International Publishing. https://doi.org/10.1007/978-3-319-76385-9

Czyz, Z., & Siadkowska, K. (2020). Measurement of Air Flow Velocity around the Unmanned Rotorcraft. In *2020 IEEE 7th International Workshop on Metrology for AeroSpace (MetroAeroSpace)* (pp. 625–629). IEEE. https://doi.org/10.1109/MetroAeroSpace48742.2020.9160062

D'Alessandro, A., Bucalo, F., Coltelli, M., & Martorana, R. (2015). Drones - New Technologies for Geophysics? In *Conference Proceedings, Near Surface Geoscience 2015 - 21st European Meeting of Environmental and*. European Association of Geoscientists & Engineers. https://doi.org/10.3997/2214-4609.201413681

D'Amato, D., Droste, N [N.], Allen, B., Kettunen, M., Lähtinen, K., Korhonen, J., Leskinen, P [P.], Matthies, B. D., & Toppinen, A. (2017). Green, circular, bio economy: A comparative analysis of sustainability avenues. *Journal of Cleaner Production*, *168*, 716–734. https://doi.org/10.1016/j.jclepro.2017.09.053

Danielsen, J. E., Auken, E., Jørgensen, F., Søndergaard, V., & Sørensen, K. I [Kurt I.] (2003). The application of the transient electromagnetic method in hydrogeophysical surveys. *Journal of Applied Geophysics*, *53*(4), 181–198. https://doi.org/10.1016/j.jappgeo.2003.08.004

Das, S., & Gupta, A. (2021). Multi-criteria decision based geospatial mapping of flood susceptibility and temporal hydro-geomorphic changes in the Subarnarekha basin, India. *Geoscience Frontiers*, *12*(5), 101206. https://doi.org/10.1016/j.gsf.2021.101206

Das Antar, A., Ahmed, M., & Ahad, M. A. R. (2019). Challenges in Sensor-based Human Activity Recognition and a Comparative Analysis of Benchmark Datasets: A Review. In *2019 Joint 8th International Conference on Informatics, Electronics & Vision (ICIEV); 3rd International Conference on Imaging, Vision & Pattern Recognition (icIVPR); International Conference on Activity and Behavior Computing (ABC): Venue: Eastern Washington University, Spokane, Washington, USA : Date: May 30-June 2, 2019* (pp. 134–139). IEEE. https://doi.org/10.1109/ICIEV.2019.8858508

Davis, A. P. (2005). Green engineering principles promote low-impact development. *Environmental Science & Technology*, *39*(16), 338A-344A. https://doi.org/10.1021/es053327e

Davis, F. D., & Venkatesh, V. (1996). A critical assessment of potential measurement biases in the technology acceptance model: three experiments. *International Journal of Human-Computer Studies*, *45*(1), 19–45. https://doi.org/10.1006/ijhc.1996.0040

Davis, K. (2017). An empirical investigation into different stakeholder groups perception of project success. *International Journal of Project Management*, *35*(4), 604–617. https://doi.org/10.1016/j.ijproman.2017.02.004

Dear, M. (1992). Understanding and Overcoming the NIMBY Syndrome. *Journal of the American Planning Association*, *58*(3), 288–300. https://doi.org/10.1080/01944369208975808

Deckert, H., Bauer, W., Abe, S., Horowitz, F. G., & Schneider, U. (2018). Geophysical greenfield exploration in the permo-carboniferous Saar–Nahe basin—The Wiesbaden Geothermal Project, Germany. *Geophysical Prospecting*, *66*(S1), 144–160. https://doi.org/10.1111/1365-2478.12598

Defendi, H., & Santiago, L. P. (2021). Speeding Up Technology Transfer– a case study of an emerging country on the pursuit of a COVID-19 vaccine. *2021 IEEE Technology & Engineering 5/17/2021 - 5/20/2021*, 1–6. https://doi.org/10.1109/TEMSCON-EUR52034.2021.9488650

Degen, R., Ott, H., Overath, F., Klein, F., & Leijon, E. M. (2021). Integration of driving physical properties into the development of a virtual test field for highly automated vehicle systems. In *Presented at the NAFEMS World Congress.* https://www.researchgate.net/profile/rene-degen/publication/355700662_integration_of_driving_physical_properties_into_the_development_of_a_virtual_test_field_for_highly_automated_vehicle_systems/links/617a620beef53e51e1f73dac/integration-of-driving-physical-properties-into-the-development-of-a-virtual-test-field-for-highly-automated-vehicle-systems.pdf. Last Accessed: 01.12.2021

Del Giudice, M., Carayannis, E. G., & Maggioni, V. (2017). Global knowledge intensive enterprises and international technology transfer: emerging perspectives from a quadruple helix environment. *The Journal of Technology Transfer*, *42*(2), 229–235. https://doi.org/10.1007/s10961-016-9496-1

Del Rio, V., Gomez, J., Kotilainen, J., Mononen, T., Lyytimäki, J., Kauppi, S [Sauri], Oinonen, K., Kattainen, M., Benighaus, C., Benighaus, L., & Kastl, L. (2018). *Broad overview reputation of mining and exploration* (INFACT Deliverable D2.3). INFACT.

Delaney, D. K., Grubb, T. G., Beier, P., Pater, L. L., & Reiser, M. H. (1999). Effects of Helicopter Noise on Mexican Spotted Owls. *The Journal of Wildlife Management*, *63*(1), 60. https://doi.org/10.2307/3802487

Dentith, M., & Mudge, S. T. (2014). *Geophysics for the mineral exploration geoscientist*. Cambridge University Press.

Denyer, D., & Tranfield, D. (2009). Producing a systematic review. In D. A. Buchanan & A. Bryman (Eds.), *The Sage handbook of organizational research methods* (pp. 671–689). Sage Publications Ltd.

Devlin, E. (2005). Factors Affecting Public Acceptance of Wind Turbines in Sweden. *Wind Engineering*, *29*(6), 503–511. https://doi.org/10.1260/030952405776234580

DFS Deutsche Flugsicherung (2020). *§ 27d Abs. 1 LuftVG*. https://www.dfs.de/dfs_homepage/en/Drone%20flight/Rules%20and%20regulations/Drones%20near%20airports/. Last Accessed: 01.12.2021

Di Massa, D., Fedi, M., Florio, G., Vitale, A., Viezzoli, A., & Kaminski, V [Vlad] (2018). Joint interpretation of AEM and aeromagnetic data acquired over the Drybones kimberlite, NWT (Canada). *Journal of Applied Geophysics*, *158*, 48–56. https://doi.org/10.1016/j.jappgeo.2018.07.004

DIAS. *QMAGT – FULL-TENSOR MAGNETIC GRADIOMETRY*. http://diasgeo.com/technologies/qftmg-full-tensor-magnetic-gradiometry/

Dibs, H., Al-Hedny, S., & Karkoosh, H. A. (2018). Extracting Detailed Buildings 3D Model with Using High Resolution Satellite Imagery by Remote Sensing and GIS Analysis; Al-Qasim Green University a Case … *International Journal of Civil Engineering and Technology*, *9*(7), 1097–1108. https://www.researchgate.net/profile/hayder-dibs/publication/329388994_extracting_detalied_buildings_3d_model_with_using_high_resolution_satellite_imagery_by_remote_sensing_and_gis_analysis_al-qasim_green_university_a_case_study/links/5c107f4da6fdcc494fed9cca/extracting-detalied-buildings-3d-model-with-using-high-resolution-satellite-imagery-by-remote-sensing-and-gis-analysis-al-qasim-green-university-a-case-study.pdf. Last Accessed: 01.12.2021

Diener, A., & Mudu, P. (2021). How can vegetation protect us from air pollution? A critical review on green spaces' mitigation abilities for air-borne particles from a public health perspective - with implications for urban planning. *Science of the Total Environment*, 148605. https://doi.org/10.1016/j.scitotenv.2021.148605

Dirim, S., & Sozer, H. (2020). Prioritization of Test Cases with Varying Test Costs and Fault Severities for Certification Testing. In *2020 IEEE 13th International Conference on Software Testing, Verification and Validation workshops: Icstw 2020 : Proceedings : 23-27 March 2020, Porto, Portugal* (pp. 386–391). IEEE. https://doi.org/10.1109/ICSTW50294.2020.00069

Doane, D., & MacGillivray, A. (2001). *Economic Sustainability -the business of staying in business*. https://dphu.org/uploads/attachements/books/books_5735_0.pdf. Last Accessed: 01.12.2021

Dong, B., Andrews, B., Lam, K. P., Höynck, M., Zhang, R., Chiou, Y.-S., & Benitez, D. (2010). An information technology enabled sustainability test-bed (ITEST) for occupancy detection through an environmental sensing network. *Energy and Buildings*, *42*(7), 1038–1046. https://doi.org/10.1016/j.enbuild.2010.01.016

Donnadieu, Y., Goddéris, Y., & Bouttes, N. (2009). Exploring the climatic impact of the continental vegetation on the Mezosoic atmospheric CO_2 and climate history. *Climate of the Past*, *5*(1), 85–96. https://doi.org/10.5194/cp-5-85-2009

Dumont, m., & Meeusen, W. (2000). *Knowledge spillovers through R&D cooperation* (OECD-NIS Focus Group on Innovative Firms and Networks). Rome. https://www.oecd.org/sti/inno/2093436.pdf. Last Accessed: 01.12.2021

Dutta, S., Reynoso, R. E., Garanasvili, A., Saxena, K., Lanvin, B., Wunsch-Vincent, S., leon, L. R., & Guadagno, F. (2018). *Energizing the world with innovation: Energizing the World with Innovation*. *The Global innovation index: 11th edition (2018)*. WIPO.

Ehrenfeld, J. R. (2004). Can Industrial Ecology be the "Science of Sustainability"? *Journal of Industrial Ecology*, *8*(1-2), 1–3. https://doi.org/10.1162/1088198041269364

Ehrlich, P. R., & Kennedy, D. (2005). Sustainability. Millennium assessment of human behavior. *Science (New York, N.Y.)*, *309*(5734), 562–563. https://doi.org/10.1126/science.1113028

Eichhorn, M., Tafarte, P., & Thrän, D. (2017). Towards energy landscapes – "Pathfinder for sustainable wind power locations". *Energy*, *134*, 611–621. https://doi.org/10.1016/j.energy.2017.05.053

Eigner, M., Schäfer, P. D., & Apostolov, H. (2013). Leveraging Product Development for a Sustainable Future: Energy and Resource Efficiency in Lifecycle Analysis. In *Smart Product Engineering* (pp. 725–734). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-30817-8_71

Eißfeldt, H., Vogelpohl, V., Stolz, M., Papenfuß, A., Biella, M., Belz, J., & Kügler, D. (2020). The acceptance of civil drones in Germany. *CEAS Aeronautical Journal*, *11*(3), 665–676. https://doi.org/10.1007/s13272-020-00447-w

Eizenberg, E., & Jabareen, Y. (2017). Social Sustainability: A New Conceptual Framework. *Sustainability*, *9*(1), 68. https://doi.org/10.3390/su9010068

Elsahragty, M., & Kim, J.-L. (2015). Assessment and Strategies to Reduce Light Pollution Using Geographic Information Systems. *Procedia Engineering*, *118*, 479–488. https://doi.org/10.1016/j.proeng.2015.08.458

eLTER. (2019). *eLTER Site Catalogue*. https://www.lter-europe.net/elter/outputs/site-catalogue. Last Accessed: 01.12.2021

Emami, A., Sarvi, M., & Asadi Bagloee, S. (2020). A review of the critical elements and development of real-world connected vehicle testbeds around the world. *Transportation Letters*, 1–26. https://doi.org/10.1080/19427867.2020.1759852

Erdin, C., & Ozkaya, G. (2019). Turkey's 2023 Energy Strategies and Investment Opportunities for Renewable Energy Sources: Site Selection Based on ELECTRE. *Sustainability*, *11*(7), 2136. https://doi.org/10.3390/su11072136

Eriksson, M., Niitamo, V.-P., Kulkki, S., & Hribernik, K. A. (2006). Living labs as a multi-contextual R&D methodology. In *2006 IEEE International Technology Management Conference (ICE), Milan* (pp. 1–8). https://doi.org/10.1109/ICE.2006.7477082

Erzgebirge. (2019). *World Heritage Site, the Ore Mountains*. https://www.erzgebirge-tourismus.de/en/extra-seiten/welterbe/?tx_sfalpstein_alpcollections%5B%40widget_0%5D%5Bcur-rentPage%5D=5&cHash=cd654eeddd498539992bf23b6fe92e4e. Last Accessed: 01.12.2021

Essa, K. S., & Munschy, M. (2019). Gravity data interpretation using the particle swarm optimisation method with application to mineral exploration. *Journal of Earth System Science*, *128*(5). https://doi.org/10.1007/s12040-019-1143-4

Exner, K., Zimpfer, R., & Stark, R. (2017). Maturity Model and Action Recommendation: A PSS Capability Self-Assessment Tool for Companies. In *Procedia CIRP* (Vol. 64, pp. 175–180). https://doi.org/10.1016/j.procir.2017.03.050

Fagaly, R. L. (2015). The Commercialization of SQUIDs. *IEEE Transactions on Applied Superconductivity*, *25*(3), 1–7. https://doi.org/10.1109/TASC.2014.2364212

Farahani, R. Z., Asgari, N., Heidari, N., Hosseininia, M., & Goh, M. (2012). Covering problems in facility location: A review. *Computers & Industrial Engineering*, *62*(1), 368–407. https://doi.org/10.1016/j.cie.2011.08.020

Fasanella, E. (2008). *So Soil Impact Testing and Simulation of Aerospace Structures.*

Fasanella, E., Jackson, K. E., Sparks, C. E., & Sareen, A. K. (2005). *Water Impact Test and Simulation of a Composite Energy Absorbing Fuselage Section* (Vol. 50). Vertical Flight Society. https://www.ingentaconnect.com/content/ahs/jahs/2005/00000050/00000002/art00003 https://doi.org/10.4050/1.3092852. Last Accessed: 01.12.2021

Fath, B. D. (2015). Quantifying economic and ecological sustainability. *Ocean & Coastal Management*, *108*, 13–19. https://doi.org/10.1016/j.ocecoaman.2014.06.020

Feindt, P. H., & Weiland, S. (2018). Reflexive governance: exploring the concept and assessing its critical potential for sustainable development. Introduction to the special issue. *Journal of Environmental Policy & Planning*, *20*(6), 661–674. https://doi.org/10.1080/1523908X.2018.1532562

Fenn, J., Linden, L., & Fairchok, S. (2003). *Understanding Gartner's hype cycles*. http://www.askforce.org/web/discourse/linden-hypecycle-2003.pdf. Last Accessed: 01.12.2021

Fernández-Juricic, E., Venier, M. P., Renison, D., & Blumstein, D. T. (2005). Sensitivity of wildlife to spatial patterns of recreationist behavior: A critical assessment of minimum approaching distances and buffer areas for grassland birds. *Biological Conservation*, *125*(2), 225–235. https://doi.org/10.1016/j.biocon.2005.03.020

Field, J. P., Breshears, D. D., Law, D. J., Villegas, J. C., López-Hoffman, L., Brooks, P. D., Chorover, J., Barron-Gafford, G. A., Gallery, R. E., Litvak, M. E., Lybrand, R. A., McIntosh, J. C., Meixner, T., Niu, G.-Y., Papuga, S. A., Pelletier, J. D., Rasmussen, C. R., & Troch, P. A. (2015). Critical Zone Services: Expanding Context, Constraints, and Currency beyond Ecosystem Services. *Vadose Zone Journal*, *14*(1), vzj2014.10.0142. https://doi.org/10.2136/vzj2014.10.0142

Filip, I., Dragan, F., & Szeidert, I. (2021). Considerations about Parameters Estimation into a Minimum Variance Control System. *Applied Sciences*, *11*(13), 6165. https://doi.org/10.3390/app11136165

Firesmith, D. (2013). *Using V Models for Testing.* Software Engineering Institute. https://insights.sei.cmu.edu/blog/using-v-models-for-testing/. Last Accessed: 01.12.2021

First Quantum Minerals (2017). ANNUAL INFORMATION. https://minedocs.com/20/First_Quantum_Minerals_AIF_2017.pdf. Last Accessed: 18.01.2022

Fischer, M. M., Scherngell, T., & Jansenberger, E. (2006). The Geography of Knowledge Spillovers Between High-Technology Firms in Europe: Evidence from a Spatial Interaction Modeling Perspective. *Geographical Analysis*, *38*(3), 288–309. https://doi.org/10.1111/j.1538-4632.2006.00687.x

Fisher, P. F. (1993). Algorithm and implementation uncertainty in viewshed analysis. *International Journal of Geographical Information Systems*, *7*(4), 331–347. https://doi.org/10.1080/02693799308901965

Fitterman, D. V., & Stewart, M. T. (1986). Transient electromagnetic sounding for groundwater. *GEOPHYSICS*, *51*(4), 995–1005. https://doi.org/10.1190/1.1442158

Flick, U. (2017). *The SAGE Handbook of Qualitative Data Collection*. SAGE.

Foged, N., Auken, E., Christiansen, A. V [Anders Vest], & Sørensen, K. I [Kurt Ingvard] (2013). Test-site calibration and validation of airborne and ground-based TEM systems. *GEOPHYSICS*, *78*(2), E95-E106. https://doi.org/10.1190/geo2012-0244.1

Foken, T. (Ed.). (2021). *Springer handbook of atmospheric measurements*. Springer International Publishing AG. https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=6801976

Foley, A., Smyth, B. M., Pukšec, T., Markovska, N., & Duić, N. (2017). A review of developments in technologies and research that have had a direct measurable impact on sustainability considering the Paris agreement on climate change. *Renewable and Sustainable Energy Reviews*, *68*, 835–839. https://doi.org/10.1016/j.rser.2016.11.215

Følstad, A. (2008). Living Labs for Innovation and Development of Information and Communication Technology: A Literature Review. *Electronic Journal of Organizational Virtualness*, *10*, 99–131.

Fontes, J., Tarne, P., Traverso, M., & Bernstein, P. (2018). Product social impact assessment. *The International Journal of Life Cycle Assessment*, *23*(3), 547–555. https://doi.org/10.1007/s11367-016-1125-6

Franquesa, M., Vanderhoof, M. K., Stavrakoudis, D., Gitas, I. Z., Roteta, E., Padilla, M., & Chuvieco, E. (2020). Development of a standard database of reference sites for validating global burned area products. *Earth System Science Data*, *12*(4), 3229–3246. https://doi.org/10.5194/essd-12-3229-2020

Fraser, P., Moultrie, J., & Gregory, M. (2002). The use of maturity models/grids as a tool in assessing product development capability, 244–249. https://doi.org/10.1109/IEMC.2002.1038431

Funaki, M., Higashino, S.-I., Sakanaka, S., Iwata, N., Nakamura, N., Hirasawa, N., Obara, N., & Kuwabara, M. (2014). Small unmanned aerial vehicles for aeromagnetic surveys and their flights in the South Shetland Islands, Antarctica. *Polar Science*, *8*(4), 342–356. https://doi.org/10.1016/j.polar.2014.07.001

Gaillardet, J., Braud, I., Hankard, F., Anquetin, S., Bour, O., Dorfliger, N., Dreuzy, J. R. de, Galle, S., Galy, C., Gogo, S., Gourcy, L., Habets, F., Laggoun, F., Longuevergne, L., Le Borgne, T., Naaim-Bouvet, F., Nord, G., Simonneaux, V., Six, D., . . . Zitouna, R. (2018). OZCAR: The French Network of Critical Zone Observatories. *Vadose Zone Journal*, *17*(1), 180067. https://doi.org/10.2136/vzj2018.04.0067

García-Quintero, A., & Palencia, M. (2021). A critical analysis of environmental sustainability metrics applied to green synthesis of nanomaterials and the assessment of environmental risks associated with the nanotechnology. *The Science of the Total Environment*, *793*, 148524. https://doi.org/10.1016/j.scitotenv.2021.148524

Garrigues, E., Corson, M. S., Angers, D. A., van der Werf, H. M., & Walter, C. (2012). Soil quality in Life Cycle Assessment: Towards development of an indicator. *Ecological Indicators*, *18*, 434–442. https://doi.org/10.1016/j.ecolind.2011.12.014

Gasde, J., Preiss, P., & Lang-Koetz, C. (2020). Integrated Innovation and Sustainability Analysis for New Technologies: An approach for collaborative R&D projects. *TIM Review*, *10*(2), 37–50. https://doi.org/10.22215/timreview/1328

Gasperikova, E., & Cumming, W. (2020). How geophysics can help the geothermal industry. *SEG Technical Program Expanded Abstracts 2020*, 3379–3383. https://doi.org/10.1190/segam2020-3425875.1

Gbededo, M. A., Liyanage, K., & Garza-Reyes, J. A. (2018). Towards a Life Cycle Sustainability Analysis: A systematic review of approaches to sustainable manufacturing. *Journal of Cleaner Production*, *184*, 1002–1015. https://doi.org/10.1016/j.jclepro.2018.02.310

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy*, *31*(8-9), 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8

Geels, F. W. (2004). From sectoral systems of innovation to socio-technical systems. *Research Policy*, *33*(6-7), 897–920. https://doi.org/10.1016/j.respol.2004.01.015

Gehl Sampath, P. (2019). Intellectual Property and Technology Transfer: Why We Need a New Agenda. In C. M. Correa, X. Seuba, & A. A. Yusuf (Eds.), *Intellectual property and development: Understanding the interfaces : Liber amicorum Pedro Roffe* (pp. 37–63). Springer. https://doi.org/10.1007/978-981-13-2856-5_3

Gembarski, P. C., & Lachmayer, R. (2017). Designing Customer Co-Creation: Business Models and CoDesign Activi. *International Journal of Industrial Engineering and Management (IJIEM)*, *8*(3), 121–130. http://ijiemjournal.uns.ac.rs/images/journal/volume8/03_IJIEM_2017_Gembarski.pdf. Last Accessed: 01.12.2021

Genovesi, S., Mittra, R., Monorchio, A., & Manara, G. (2006). Particle Swarm Optimization of Frequency Selective Surfaces for the Design of Artificial Magnetic Conductors. In *Ieee Antennas and Propagation Society international symposium 2006: 9 - 14 July 2006, [Albuquerque, NM ; 2006 IEEE AP-S international symposium and USNC/URSI and AMEREM meetings.* IEEE Operations Center. https://doi.org/10.1109/aps.2006.1711377

Geotech (2016). Airborne Inductively Induced Polarization (AIIP) effects in and their removal from VTEM™ data. https://www.seequent.com/resources/goto/2016-05-10-KEGS-airborne-inductive-IP/ Last Accessed: 01.12.2021

Ghamisi, P., Gloaguen, R., Atkinson, P. M., Benediktsson, J. A., Rasti, B., Yokoya, N., Wang, Q., Hofle, B., Bruzzone, L., Bovolo, F., Chi, M., & Anders, K. (2019). Multisource and Multitemporal Data Fusion in Remote Sensing: A Comprehensive Review of the State of the Art. *IEEE Geoscience and Remote Sensing Magazine*, *7*(1), 6–39. https://doi.org/10.1109/MGRS.2018.2890023

Ghamisi, P., Maggiori, E., Li, S [Shutao], Souza, R., Tarablaka, Y., Moser, G., Giorgi, A. de, Fang, L., Chen, Y [Yushi], Mingmin, C., Serpico, S., & Benediktsson, J. A. (2018). New frontiers in spectral-spatial hyperspectral image classification: The latest advances based on mathematical morphology, Markov random fields, segmentation … In *IEEE Geoscience and remote sensing.*

Gioia, D. A., Corley, K. G., & Hamilton, A. L. (2013). Seeking Qualitative Rigor in Inductive Research. *Organizational Research Methods*, *16*(1), 15–31. https://doi.org/10.1177/1094428112452151

Global Reporting Initiatives. *A Short Introduction to the GRI Standards* (GRI). https://www.globalreporting.org/media/wtaf14tw/a-short-introduction-to-the-gri-standards.pdf. Last Accessed: 01.12.2021

Gochermann, J. (2020). *Technologiemanagement*. Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-28799-3

Gomez, C., Oltra-Carrió, R., Bacha, S., Lagacherie, P., & Briottet, X. (2015). Evaluating the sensitivity of clay content prediction to atmospheric effects and degradation of image spatial resolution using Hyperspectral VNIR/SWIR imagery. *Remote Sensing of Environment*, *164*, 1–15. https://doi.org/10.1016/j.rse.2015.02.019

Gomez, F. (2014). Terrestrial Analog. In *Encyclopedia of Astrobiology* (pp. 1–7). Springer-Verlag. https://doi.org/10.1007/978-3-642-27833-4_1606-2

Gorskii, Y. A., Gavrilov, P. A., & Borovkov, A. I. (2020). Virtual proving ground for aircraft structures. *IOP Conference Series: Materials Science and Engineering*, *986*, 12020. https://doi.org/10.1088/1757-899X/986/1/012020

Gouvea, R., Kapelianis, D., & Kassicieh, S. (2018). Assessing the nexus of sustainability and information & communications technology. *Technological Forecasting and Social Change*, *130*, 39–44. https://doi.org/10.1016/j.techfore.2017.07.023

Graessler, I. (2015). Umsetzungsorientierte Synthese mechatronischer Referenzmodelle Implementation-oriented synthesis of mechatronic reference models. In *Konferenzband der VDI Mechatronik: Fachtagung Mechatronik* (pp. 167–172).

Graessler, I., & Hentze, J. (2020). The new V-Model of VDI 2206 and its validation. *At - Automatisierungstechnik*, *68*(5), 312–324. https://doi.org/10.1515/auto-2020-0015

Gray, D., Cameron, A., & Stone, R., (2015) Cobre Las Cruces Operation Andalucía, Spain. https://www.miningdataonline.com/reports/Cobre%20Las%20Cruces_06302015_Technical%20report.pdf. Last Accessed: 18.01.2022

Greco, S., Ishizaka, A., Tasiou, M., & Torrisi, G. (2019). On the Methodological Framework of Composite Indices: A Review of the Issues of Weighting, Aggregation, and Robustness. *Social Indicators Research*, *141*(1), 61–94. https://doi.org/10.1007/s11205-017-1832-9

Green, J. E. (2017). Greener by Design — the technology challenge. *The Aeronautical Journal.* Advance online publication. https://doi.org/10.1017/S0001924000095993

Groen, A. J., & Walsh, S. T. (2013). Introduction to the Field of Emerging Technology Management. *Creativity and Innovation Management*, *22*(1), 1–5. https://doi.org/10.1111/caim.12019

Groot, B. de, & Franses, P. H. (2005). *Cycles in basic innovations*. Rotterdam. Erasmus University Rotterdam.

Grudens-Schuck, N., & Sirajuddin, Z. (2019). Social impacts of citizen science water monitoring programs. *Journal of Soil and Water Conservation*, *74*(3), 49A-54A. https://doi.org/10.2489/jswc.74.3.49A

Gründler, K., & Krieger, T. (2018). Machine Learning Indices, Political Institutions, and Economic Development. In *CESifo Working Paper Series No. 6930.*

Grunwald, A. (2018). *Technology Assessment in Practice and Theory*. Taylor & Francis.

Guay, P.-J., McLeod, E. M., Cross, R., Formby, A. J., Maldonado, S. P., Stafford-Bell, R. E., St-James-Turner, Z. N., Robinson, R. W., Mulder, R. A., & Weston, M. A. (2013). Observer effects occur when estimating alert but not flight-initiation distances. *Wildlife Research*, *40*(4), 289. https://doi.org/10.1071/WR13013

Gühmann, C., Riese, J., & Rüden, K. von (Eds.). (2016). *Simulation and testing for vehicle technology: 7th Conference, Berlin, May 12-13, 2016 = 7th Conference, Berlin, May 12-13, 2016*. Springer.

Guo, L., & Lin, H. (2016). Critical Zone Research and Observatories: Current Status and Future Perspectives. *Vadose Zone Journal*, *15*(9), vzj2016.06.0050. https://doi.org/10.2136/vzj2016.06.0050

Guo, S [Sen], & Zhao, H. (2015). Optimal site selection of electric vehicle charging station by using fuzzy TOPSIS based on sustainability perspective. *Applied Energy*, *158*, 390–402. https://doi.org/10.1016/j.apenergy.2015.08.082

Gurin, G., Ilyin, Y., Nilov, S., Ivanov, D., Kozlov, E., & Titov, K. (2018). Induced polarization of rocks containing pyrite: Interpretation based on X-ray computed tomography. *Journal of Applied Geophysics*, *154*, 50–63. https://doi.org/10.1016/j.jappgeo.2018.04.019

Häder, M. (Ed.). (2015). *Lehrbuch: Vol. 186*. *Empirische Sozialforschung: Eine Einführung* (3. Auflage). Springer VS. https://doi.org/10.1007/978-3-642-48318-9

Hainge, G. (2013). *Noise matters: Towards an ontology of noise*. *Sound studies*. Bloomsbury Acad.

Haldar, S. K. (2018). *Mineral exploration: Principles and applications* (Second edition). Elsevier.

Hall, J., Matos, S., & Bachor, V. (2019). From green technology development to green innovation: Inducing regulatory adoption of pathogen detection technology for sustainable forestry. *Small Business Economics*, *52*(4), 877–889. https://doi.org/10.1007/s11187-017-9940-0

Halvorsrud, R., Kvale, K., & Følstad, A. (2016). Improving service quality through customer journey analysis. *Journal of Service Theory and Practice*, *26*(6), 840–867. https://doi.org/10.1108/JSTP-05-2015-0111

Han, J., & Wang, Z. (2008). On the key technique of fast monitoring system for land resourses unmanned plane remote sensing. *Bulletin of Surveying and Mapping*, *2*, 4–6.

Hannon, R. S., King, Chris, W., & Palka, J. EUgene, Gilewitch, Daniel, A. (2004). Characterizing Extreme Environments For Army Testing. In *Proceedings for the Army Science Conference (24th),* Orlando. Florida.

Hanssen, O. J. (1995). Preventive strategies for improved environmental performance of product systems. *Journal of Cleaner Production*.

Harris, C. M. (2005). Aircraft operations near concentrations of birds in Antarctica: The development of practical guidelines. *Biological Conservation*, *125*(3), 309–322. https://doi.org/10.1016/j.biocon.2005.04.002

Hauck, T. E., & Weisser, W. W. (2015). *AAD - Animal Aided Design*. Technische Universität München.

Hauschild, M. Z., Kara, S., & Røpke, I. (2020). Absolute sustainability: Challenges to life cycle engineering. *CIRP Annals*, *69*(2), 533–553. https://doi.org/10.1016/j.cirp.2020.05.004

Hedderich, J., & Sachs, L [Lothar]. (2018). *Angewandte Statistik: Methodensammlung mit R* (16. Aufl. 2018). Springer Berlin Heidelberg.

Héder, M. (2017). From NASA to EU: the evolution of the TRL scale in Public Sector Innovation. *The Innovation Journal: The Public Sector Innovation Journal*, *22*(2).

Heeks Richard. (2020). Introduction: Current Issues in the Technology-Development Relationship. In *Technology and Developing Countries* (pp. 1–11). Routledge. https://doi.org/10.1201/9781315037516-1

Heincke, B., Jackisch, R., Saartenoja, A., Salmirinne, H., Rapp, S [Sönke], Zimmermann, R., Pirttijärvi, M., Vest Sörensen, E., Gloaguen, R., Ek, L., Bergström, J., Karinen, A., Salehi, S., Madriz, Y., & Middleton, M. (2019). Developing multi-sensor drones for geological mapping and mineral exploration: setup and first results from the MULSEDRO project. *Geological Survey of Denmark and Greenland Bulletin*, *43.* https://doi.org/10.34194/GEUSB-201943-03-02

Heinson, G., Didana, Y., Soeffky, P., Thiel, S., & Wise, T. (2018). The crustal geophysical signature of a world-class magmatic mineral system. *Scientific Reports*, *8*(1), 10608. https://doi.org/10.1038/s41598-018-29016-2

Hekman, J. S. (1992). What are businesses looking for. *Federal Reserve Bank of Atlanta Economic Review*.

Helgesson, L., Yeni, Y., Höst, M., & Weyns, K. (2012). A review of methods for evaluation of maturity models for process improvement. *Journal of Software: Evolution and Process*, *24*(4), 436–454. https://doi.org/10.1002/smr.560

Henderson, R. P., Martins, J. R. R. A., & Perez, R. E. (2012). Aircraft conceptual design for optimal environmental performance. *The Aeronautical Journal*, *116*(1175), 1–22. https://doi.org/10.1017/S000192400000659X

Hendry, C., Harborne, P., & Brown, J. (2010). So what do innovating companies really get from publicly funded demonstration projects and trials? innovation lessons from solar photovoltaics and wind. *Energy Policy*, *38*(8), 4507–4519. https://doi.org/10.1016/j.enpol.2010.04.005

Heong, K. L., Escalada, M. M., Sengsoulivong, V., & Schiller, J. (2002). Insect management beliefs and practices of rice farmers in Laos. Agriculture, ecosystems & environment, 92(2-3), 137-145. https://doi.org/10.1016/S0167-8809(01)00304-8

Hickel, J. (2020). The sustainable development index: Measuring the ecological efficiency of human development in the anthropocene. *Ecological Economics*, *167*, 106331. https://doi.org/10.1016/j.ecolecon.2019.05.011

Hidayati, A., Purwandari, B., Budiardjo, E. K., & Solichah, I. (2018). Global Software Development and Capability Maturity Model Integration: A Systematic Literature Review. In *2018 Third International Conference on Informatics and Computing (ICIC) // 2018 Third International Conference on Informatics and Computing (ICIC 2018): Palembang, Indonesia, 17-18 October 2018* (pp. 1–6). IEEE. https://doi.org/10.1109/IAC.2018.8780489

Hillers, G., Ben-Zion, Y., Campillo, M., & Zigone, D. (2015). Seasonal variations of seismic velocities in the San Jacinto fault area observed with ambient seismic noise. *Geophysical Journal International*, *202*(2), 920–932. https://doi.org/10.1093/gji/ggv151

Hillman, M. D., Karpanty, S. M., Fraser, J. D., & Derose-Wilson, A. (2015). Effects of aircraft and recreation on colonial waterbird nesting behavior. *The Journal of Wildlife Management*, *79*(7), 1192–1198. https://doi.org/10.1002/jwmg.925

Ho, D. G. (2006). The focus group interview. *Australian Review of Applied Linguistics*, *29*(1), 5.1-5.19. https://doi.org/10.2104/aral0605

Hofstede, G. (2009). *Geert Hofstede cultural dimensions*. http://taylortraining.com/clients/mcc/hofstede_cultural_dimension_explained(external).pdf

Holmlid, S., & Evenson, S. (2008). Bringing Service Design to Service Sciences, Management and Engineering. In B. Hefley & W. Murphy (Eds.), *Service science. Service science, management and engineering: Education for the 21st Century* (pp. 341–345). Springer US. https://doi.org/10.1007/978-0-387-76578-5_50

Hooey, K. (2016). *Sustainability in Finland's extractive industry: Responding to a need for best practice guidelines in early decision making phases* [Master's Degree Programme in Real Estate Economics]. Aalto University.

Howell, S., Rathje, J., van Reenen, J., & Wong, J. (2021). Opening up Military Innovation: Causal Effects of 'Bottom-Up' Reforms to U.S. Defense Research. *National Bureau of Economic Research.* Advance online publication. https://doi.org/10.3386/w28700

Howell, S. D. (1980). Learning curves for new products. *Industrial Marketing Management*, *9*(2), 97–99. https://doi.org/10.1016/0019-8501(80)90014-0

Hu, G., Chen, C., Lu, H. T., Wu, Y [Yue], Liu, C., Tao, L., Men, Y., He, G., & Li, K. G. (2020). A Review of Technical Advances, Barriers, and Solutions in the Power to Hydrogen (P2H) Roadmap. *Engineering*, *6*(12), 1364–1380. https://doi.org/10.1016/j.eng.2020.04.016

Huang, I. B., Keisler, J., & Linkov, I. (2011). Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends. *The Science of the Total Environment*, *409*(19), 3578–3594. https://doi.org/10.1016/j.scitotenv.2011.06.022

Huang, K. Y., Brunner, C. E., Fu, M. K., Kokmanian, K., Morrison, T. J., Perelet, A. O., Calaf, M., Pardyjak, E., & Hultmark, M. (2021). Investigation of the atmospheric surface layer using a novel high-resolution sensor array. *Experiments in Fluids*, *62*(4). https://doi.org/10.1007/s00348-021-03173-z

Hurtubise, F. G., McKAY, D. H., & Macenko, F. (1977). Aircraft noise and other types of pollution. *The Aeronautical Journal*, *81*(103), and is. https://www.cambridge.org/core/journals/aeronautical-journal/article/aircraft-noise-and-other-types-of-pollution/e18b7636b82d940266a6bdd3431b447b. Last Accessed: 01.12.2021

Hwang, C.-L., & Yoon, K. (1981). *Multiple Attribute Decision Making: Methods and Applications A State-of-the-Art Survey*. *Lecture Notes in Economics and Mathematical Systems: Vol. 186*. Springer. https://doi.org/10.1007/978-3-642-48318-9

Hwang, C.-L., & Yoon, K. (2015). Methods for Multiple Attribute Decision Making. In M. Häder (Ed.), *Lehrbuch: Vol. 186. Empirische Sozialforschung: Eine Einführung* (3rd ed., Vol. 186, pp. 58–191). Springer VS. https://doi.org/10.1007/978-3-642-48318-9_3

Hynds, E. J., Brandt, V., Burek, S., Jager, W., Knox, P., Parker, J. P., Schwartz, L., Taylor, J., & Zietlow, M. (2014). A Maturity Model for Sustainability in New Product Development. *Research-Technology Management*, *57*(1), 50–57. https://doi.org/10.5437/08956308X5701143

Ikram, M., Zhang, Q [Qingyu], Sroufe, R., & Ferasso, M. (2021). Contribution of certification bodies and sustainability standards to sustainable development goals: An integrated grey systems approach. *Sustainable Production and Consumption*, *28*, 326–345. https://doi.org/10.1016/j.spc.2021.05.019

Ilbahar, E., Cebi, S., & Kahraman, C. (2019). A state-of-the-art review on multi-attribute renewable energy decision making. *Energy Strategy Reviews*, *25*, 18–33. https://doi.org/10.1016/j.esr.2019.04.014

Imoniana, J. O., Silva, W. L., Reginato, L., Slomski, V., & Slomski, V. G. (2021). Sustainable Technologies for the Transition of Auditing towards a Circular Economy. *Sustainability*, *13*(1), 218. https://doi.org/10.3390/su13010218

Innovative, Non-invasive and Fully Acceptable Exploration Technologies, European Commsion (2017). https://cordis.europa.eu/project/id/776487. Last Accessed: 10.01.2022

INFACT. (2018). *Technical information)*. https://www.infactproject.eu/technical-information/

Inków, M. (2019). Measuring Innovation Maturity Literature Review on Innovation Maturity Models. *BUSINESS INFORMATICS*, *1*(51), 23–34.

Irtyshcheva, I. (2021). The effect of digital technology development on economic growth. *International Journal of Data and Network Science*, 25–36. https://doi.org/10.5267/j.ijdns.2020.11.006

Ismaeel, W. S. (2019). Appraising a decade of LEED in the MENA region. *Journal of Cleaner Production*, *213*, 733–744. https://doi.org/10.1016/j.jclepro.2018.12.223

ISO. *ENVIRONMENTAL MANAGEMENT* (ISO 14000 FAMILY). https://www.iso.org/iso-14001-environmental-management.html

ISO (2010). *Guidance on social responsibility* (ISO 26000).

ISO (2012). *Soil quality — Determination of the effects of pollutants on soil flora* (ISO 11269). https://www.iso.org/obp/ui/#iso:std:iso:11269:-1:ed-2:v1:en

ISO (2014a). *Environmental management — Water footprint — Principles, requirements and guidelines* (ISO 14046:2014).

ISO (2014b). *Geotechnical investigation and testing — Laboratory testing of soil* (ISO/TC 182/WG 13). https://www.iso.org/standard/55243.html. Last Accessed: 01.12.2021

ISO (2019). *Space systems — Definition of the Technology Readiness Levels (TRLs) and their criteria of assessment* (ISO 16290:2013). https://www.iso.org/standard/56064.html

Iwanaga, T., Wang, H.-H., Hamilton, S. H., Grimm, V., Koralewski, T. E., Salado, A., Elsawah, S., Razavi, S., Yang, J., Glynn, P., Badham, J., Voinov, A., Chen, M., Grant, W. E., Peterson, T. R., Frank, K., Shenk, G., Barton, C. M., Jakeman, A. J., & Little, J. C. (2021). Socio-technical scales in socio-environmental modeling: Managing a system-of-systems modeling approach. *Environmental Modelling & Software : With Environment Data News*, *135*, 104885. https://doi.org/10.1016/j.envsoft.2020.104885

Jackisch, Madriz, Zimmermann, Pirttijärvi, Saartenoja, Heincke, Salmirinne, Kujasalo, Andreani, & Gloaguen (2019). DroneBorne Hyperspectral and Magnetic Data Integration: Otanmäki FeTiV Deposit in Finland. *Remote Sensing*, *11*(18), 2084. https://doi.org/10.3390/rs11182084

Jacquier, E., Kane, A., & Marcus, A. J. (2003). Geometric or Arithmetic Mean: A Reconsideration. *Financial Analysts Journal*, *59*(6), 46–53. https://doi.org/10.2469/faj.v59.n6.2574

Jensen, L. A., Arnett, J. J., & McKenzie, J. (2011). Globalization and Cultural Identity. In S. J. Schwartz (Ed.), *Springer Psychology. Handbook of identity theory and research* (pp. 285–301). Springer. https://doi.org/10.1007/978-1-4419-7988-9_13

Jobin, C., Hooge, S., & Le Masson, P. (2020). What does the proof-of-concept (POC) really prove? A historical perspective and a cross-domain analytical study. In *XXIXème conférence de l'Association Internationale de Management Stratégique (AIMS)*. https://hal.archives-ouvertes.fr/hal-02570321/. Last Accessed: 01.12.2021

Johansson, C., & Bucanac, C. (1998). *The V-Model*. http://www.bucanac.com/documents/The_V-Model.pdf. Last Accessed: 01.12.2021

Joiner, K. F., Atkinson, S. R., Christensen, P., & Sitnikova, E. (2018). Cybersecurity for Allied Future Submarines. *World Journal of Engineering and Technology*, *06*(04), 696–712. https://doi.org/10.4236/wjet.2018.64045

Jones, A. (2018). *Magnetotellurics: The scalable EM exploration too*. https://www.pdac.ca/docs/default-source/conventions/convention-2018/technical-sessions/alan-jones.pdf?sfvrsn=87288398_2. Last Accessed: 01.12.2021

Jones, B., & Mendieta, E. (2021). *The ethics of policing: New perspectives on law enforcement*. New York University Press.

Jones, R., Stokes, S., Lockaby, B., & Stanturf, J. (2000). Vegetation responses to helicopter and ground based logging in blackwater floodplain forests. *Forest Ecology and Management*, *139*(1-3), 215–225. https://doi.org/10.1016/S0378-1127(00)00269-3

Joshi, A., Kale, S., Chandel, S., & Pal, D. (2015). Likert Scale: Explored and Explained. *British Journal of Applied Science & Technology*, *7*(4), 396–403. https://doi.org/10.9734/BJAST/2015/14975

Josselin, J.-M., & Le Maux, B. (2017). Multi-criteria Decision Analysis. In *Statistical Tools for Program Evaluation* (pp. 385–416). Springer, Cham. https://doi.org/10.1007/978-3-319-52827-4_11

Jotikapukkana, S., Berg, Å., & Pattanavibool, A. (2010). Wildlife and human use of buffer-zone areas in a wildlife sanctuary. *Wildlife Research*, *37*(6), 466. https://doi.org/10.1071/WR09132

Jovanović, M., Rakićević, J., Jeremic, V., & Jaksic, M. L. (2018). How to measure Triple Helix performance? A fresh approach. In *II International Triple Helix Summit.* https://www.researchgate.net/profile/milica-jovanovic/publication/328512660_agile_approach_to_creating_composite_indices_in_technology_management/links/5bd1d03ea6fdcc690ae38632/agile-approach-to-creating-composite-indices-in-technology-management.pdf. Last Accessed: 01.12.2021

Jürgens, B [Björn], Ruiz-Coupeau, S., Herrero-Solana, V [Victor], & Kirsch, M. (2020). *Infact technology watch report.* https://doi.org/10.5281/ZENODO.4302430

Kaiser, C., Vogt, S., & Tilebein, M. (2017). Virtual development and production framework for textile orthotics. *International Journal of Computer Integrated Manufacturing*, *30*(7), 680–689. https://doi.org/10.1080/0951192X.2015.1066859

Kaminski, V [Vladislav], & Viezzoli, A. (2017). Modeling induced polarization effects in helicopter time-domain electromagnetic data: Field case studies. *GEOPHYSICS*, *82*(2), B49-B61. https://doi.org/10.1190/geo2016-0103.1

Kang, S., Fournier, D., & Oldenburg, D. W. (2017). Inversion of airborne geophysics over the DO-27/DO-18 kimberlites — Part 3: Induced polarization. *Interpretation*, *5*(3), T327-T340. https://doi.org/10.1190/INT-2016-0141.1

Kasperson, R. E [Roger E.], Renn, O., Slovic, P., Brown, H. S., Emel, J., Goble, R., Kasperson, J. X., & Ratick, S. (1988). The Social Amplification of Risk: A Conceptual Framework. *Risk Analysis*, *8*(2), 177–187. https://doi.org/10.1111/j.1539-6924.1988.tb01168.x

Kates, R. W., Clark, W. C., Corell, R., Hall, J. M., Jaeger, C. C., Lowe, I., McCarthy, J. J., Schellnhuber, H. J., Bolin, B., Dickson, N. M., Faucheux, S., Gallopin, G. C., Grübler, A., Huntley, B., Jäger, J., Jodha, N. S., Kasperson, R. E [R. E.], Mabogunje, A., Matson, P., . . . Svedlin, U. (2001). Environment and development. Sustainability science. *Science (New York, N.Y.)*, *292*(5517), 641–642. https://doi.org/10.1126/science.1059386

Kaya, İ., Çolak, M., & Terzi, F. (2019). A comprehensive review of fuzzy multi criteria decision making methodologies for energy policy making. *Energy Strategy Reviews*, *24*, 207–228. https://doi.org/10.1016/j.esr.2019.03.003

Kemp, R. (2010). Eco-innovation: Definition, Measurement and Open Research Issues. *Economia Politica*, *3.* https://doi.org/10.1428/33131

Kergroach, S., Meissner, D., & Vonortas, N. S. (2018). Technology transfer and commercialisation by universities and PRIs: benchmarking OECD country policy approaches. *Economics of Innovation and New Technology*, *27*(5-6), 510–530. https://doi.org/10.1080/10438599.2017.1376167

Kersting, A. B., Efurd, D. W., Finnegan, D. L., Rokop, D. J., Smith, D. K., & Thompson, J. L. (1999). Migration of plutonium in ground water at the Nevada Test Site. *Nature*, *397*(6714), 56–59. https://doi.org/10.1038/16231

Kesselring, M., Gloaguen, R., & Ajjabou, L. (2020). The Development of Reference Sites for Mineral Exploration under Tec-Soc-Env Conditions. In *Symposium Sustainable Mineral Exploration* (pp. 1–3). https://doi.org/10.3997/2214-4609.202089026

Kesselring, M., Ruiz-Coupeau, S., Kirsch, M., Wagner, F., & Gloaguen, R. (2021). Integrated Test Sites for Innovative Ecosystems. *TIM Review*, *11*(7/8), 20–32. https://doi.org/10.22215/timreview/1454

Kesselring, M., Wagner, F., Kirsch, M., Ajjabou, L., & Gloaguen, R. (2020). Development of Sustainable Test Sites for Mineral Exploration and Knowledge Spillover for Industry. *Sustainability*, *12*(5), 2016. https://doi.org/10.3390/su12052016

Keyser, W. de, & Peeters, P. (1996). A note on the use of PROMETHEE multicriteria methods. *European Journal of Operational Research*, *89*(3), 457–461. https://doi.org/10.1016/0377-2217(94)00307-6

Khalili, N. R., & Duecker, S. (2013). Application of multi-criteria decision analysis in design of sustainable environmental management system framework. *Journal of Cleaner Production*, *47*, 188–198. https://doi.org/10.1016/j.jclepro.2012.10.044

King, W. C., Harmon, R. S., Bullard, T., Evans, T., Juvik, J., Johnson, R., & Larsen, M. (1998). *A Technical Analysis to Identify Ideal Geographic Locations for Tropical Testing of Army Materiel and Systems.* Army Research Office.

Kirincich, A. R., Borkland, J., Hines, E., & Lohrenz, S. E. (2018). The development of ocean test beds for ocean technology adaptation and integration into the emerging U.S. offshore wind energy industry. Advance online publication. https://doi.org/10.1575/1912/10412

Kirsch, M. (2019). *Datasets containing prognostics part 2: INFACT Deliverable 5.4.* European Union.

Kirsch, M., Ajjabou, L., & Kesselring, M. (2020). *European Reference Sites*. https://www.infactproject.eu/wp-content/uploads/2020/03/INFACT_ERS_brochure_A4_20191016.pdf. Last Accessed: 01.12.2021

Kirsch, M., Blanco, Joane: Viezzoli, Andrea, Ugalde, H., & Morris, B. (2020). *Datasets containing prognostics* (INFACT Deliverable D5.4).

Klappert, S., Schuh, G [Günther], Möller, H., & Nollau, S. (2011). Technologieentwicklung. In S. Klappert (Ed.), *SpringerLink Bücher. Technologiemanagement: Handbuch Produktion und Management 2* (pp. 223–239). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-12530-0_8

Klein, H. K., & Kleinman, D. L. (2002). The Social Construction of Technology: Structural Considerations. *Science, Technology, & Human Values*, *27*(1), 28–52. https://doi.org/10.1177/016224390202700102

Klotz, L., Weber, E., Johnson, E., Shealy, T., Hernandez, M., & Gordon, B. (2018). Beyond rationality in engineering design for sustainability. *Nature Sustainability*, *1*(5), 225–233. https://doi.org/10.1038/s41893-018-0054-8

Komac, M., Roffey, S [Sam], Koepf, H., Correia, V., Braña Bergshjorth, A., Benighaus, L., Fernandez, I [Isabel], Fernandez, I [Isla], Gloaguen, R., Kirsch, M., Ruiz-Coupeau, S., & Russill, J. (2018). The next step towards the mineral exploration in Europe - project INFACT - Innovative, non-invasive and fully acceptable exploration technologies. *EGU General Assembly Conference Abstracts*, 15491.

Komac, M., Ruiz-Coupeau, S., & Kesselring, M. (2020). *Assessment of legislation relevant to test site commissioning and operation* (INFACT Deliverable D6.1). INFACT.

Konrad, K., Rip, A., & Schulze Greiving, V. (2017). Constructive Technology Assessment – STS for and with Technology Actors. *EASST Review*, *36*(3).

Kontio, P. (2019). *ENVIRONMENTAL IMPACT AND SOCIAL ACCEPTABILITY*. (INFACT Deliverable D2.7). INFACT

Kornwachs, K. (2018). Let it Grow – About the Biologisation of Technology and Work. *BIOLOGICAL TRANSFORMATION OF MANUFACTURING*. Berlin. Fraunhofer Gesellschaft.

Korol, E., & Shushunova, N. (2019). Multi-Criteria Evaluation of the Organizational and Technological Options for Green Roof Systems Installation. *IOP Conference Series: Materials Science and Engineering*, *471*, 82011. https://doi.org/10.1088/1757-899x/471/8/082011

Kratzer, T., & Macnae, J. C. (2012). Induced polarization in airborne EM. *GEOPHYSICS*, *77*(5), E317-E327. https://doi.org/10.1190/geo2011-0492.1

Kumar, N. (2015). *Review of innovation diffusion models*. New Dehli. CSIR-National Institute of Science, Technology and Development Studies. https://www.researchgate.net/profile/naresh-kumar-6/publication/279099570_review_of_innovation_diffusion_models/links/558a59e908ae2affe7154477/review-of-innovation-diffusion-models.pdf. Last Accessed: 01.12.2021

Kuras, O., Swift, R., Uhlemann, S., Wilkinson, P., Inauen, C., & Meldrum, P. (2018, September 9). Geoelectrical Imaging of Concealed Objects with Capacitive Sensor Arrays. In *24th European Meeting of Environmental and Engineering Geophysics* (pp. 1–5). European Association of Geoscientists & Engineers. https://doi.org/10.3997/2214-4609.201802649

Kurnianingtyas, D., Santosa, B., & Siswanto, N. (2020). Structural and Behavioral Validity using a System Dynamic Simulation Approach: The Indonesian National Health Insurance System Problem, 36–45. https://doi.org/10.5220/0009404300360045

Kütz, M. (2022). The Benchmarking Process. In *The Art of Benchmarking* (pp. 155–157). Springer, Cham. https://doi.org/10.1007/978-3-030-90586-6_6

Kuznichenko, S., Buchynska, I., Kovalenko, L., & Gunchenko, Y. (2019). Suitable Site Selection Using Two-Stage GIS-Based Fuzzy Multi-criteria Decision Analysis. In *Advances in Intelligent Systems and Computing: Vol. 1080. Advances in Intelligent Systems and Computing IV: Selected Papers from the International Conference on Computer Science and Information Technologies, CSIT 2019, September 17-20, 2019, Lviv, Ukraine* (1st ed., Vol. 1080, pp. 214–230). https://doi.org/10.1007/978-3-030-33695-0_16

Kwan, K., Prikhodko, A., Legault, J., Plastow, G., Xie, J., & Fisk, K. (2015). *Airborne Inductive Induced Polarization Chargeability Mapping of VTEM™ Data*. http://geotech.ca/papers/airborne-inductive-induced-polarization-chargeability-mapping-of-vtem-data/. Last Accessed: 01.12.2021

Labuschagne, C., Brent, A. C., & Claasen, S. J. (2005). Environmental and social impact considerations for sustainable project life cycle management in the process industry. *Corporate Social Responsibility and Environmental Management*, *12*(1), 38–54. https://doi.org/10.1002/csr.76

Lam, C., Gray, G., Martinez-Canales, M., & Owens, B. (2007). *The Importance of Dedicated Experiments to Support Validation and Calibration Activities*. https://www.researchgate.net/profile/genetha-gray/publication/265159124_the_importance_of_dedicated_experiments_to_support_validation_and_calibration_activities/links/5574ce6c08ae7536374ff1e4/the-importance-of-dedicated-experiments-to-support-validation-and-calibration-activities.pdf. Last Accessed: 01.12.2021

Lambeck, R. J. (1997). Focal Species: A Multi-Species Umbrella for Nature Conservation. Especies Focales: Una Sombrilla Multiespecifica para Conservar la Naturaleza. *Conservation Biology*, *11*(4), 849–856. https://doi.org/10.1046/j.1523-1739.1997.96319.x

Lamelas, M. T., Marinoni, O., Hoppe, A., & La Riva, J. de (2008). Doline probability map using logistic regression and GIS technology in the central Ebro Basin (Spain). *Environmental Geology*, *54*(5), 963–977. https://doi.org/10.1007/s00254-007-0895-3

Langer, K., Decker, T., Roosen, J., & Menrad, K. (2016). A qualitative analysis to understand the acceptance of wind energy in Bavaria. *Renewable and Sustainable Energy Reviews*, *64*, 248–259. https://doi.org/10.1016/j.rser.2016.05.084

Latan, H., Chiappetta Jabbour, C. J., Lopes de Sousa Jabbour, A. B., Wamba, S. F., & Shahbaz, M. (2018). Effects of environmental strategy, environmental uncertainty and top management's commitment on corporate environmental performance: The role of environmental management accounting. *Journal of Cleaner Production*, *180*, 297–306. https://doi.org/10.1016/j.jclepro.2018.01.106

Lee, C. G., & Park, S. C. (2014). Survey on the virtual commissioning of manufacturing systems. *Journal of Computational Design and Engineering*, *1*(3), 213–222. https://doi.org/10.7315/JCDE.2014.021

Lee, D. S., Pitari, G., Grewe, V., Gierens, K., Penner, J. E., Petzold, A., Prather, M. J., Schumann, U., Bais, A., Berntsen, T., Iachetti, D., Lim, L. L., & Sausen, R. (2010). Transport impacts on atmosphere and climate: Aviation. *Atmospheric Environment (Oxford, England : 1994)*, *44*(37), 4678–4734. https://doi.org/10.1016/j.atmosenv.2009.06.005

Leibniz-IPHT. (2010). *Mit dem Hubschrauber auf Schatzsuche.* Leibniz-IPHT. https://www.leibniz-ipht.de/de/mit-dem-hubschrauber-auf-schatzsuche/

Lemu, H. G. (2014). Virtual engineering in design and manufacturing. *Advances in Manufacturing*, *2*(4), 289–294. https://doi.org/10.1007/s40436-014-0085-y

Lesser, P., Gugerell, K., Poelzer, G., Hitch, M., & Tost, M. (2021). European mining and the social license to operate. *The Extractive Industries and Society*, *8*(2), 100787. https://doi.org/10.1016/j.exis.2020.07.021

Levidow, L., Blind, M., Lindgaard-Jørgensen, P., Nilsson, Å., & Alongi Skenhall, S. (2016). Industry eco-innovation strategies for process upgrading: Systemic limits of internalising externalities. *Technology Analysis & Strategic Management*, *28*(2), 190–204. https://doi.org/10.1080/09537325.2015.1093106

Li, M., Wiedmann, T., Fang, K., & Hadjikakou, M. (2021). The role of planetary boundaries in assessing absolute environmental sustainability across scales. *Environment International*, *152*, 106475. https://doi.org/10.1016/j.envint.2021.106475

Liberato, M., Varajão, J., & Martins, P. (2017). Cmmi Implementation and Results: The Case of a Software Company. In *Project Management: Concepts, Methodologies, Tools, and Applications* (pp. 958–974). IGI Global. https://doi.org/10.4018/978-1-5225-0196-1.ch047

Lin, C. P., Lin, C. H., Wu, P. L., Liu, H. C., & Hung, Y. C. (2015). Applications and challenges of near surface geophysics in geotechnical engineering. *Acta Geophysica Sinica*, *58*(8), 2664–2680. https://doi.org/10.6038/cjg20150806

Linares, C., Lawson, C. P., & Smith, H. (2013). Multidisciplinary optimisation framework for minimum rotorcraft fuel and air pollutants at mission level. *The Aeronautical Journal*, *117*(1193), 749–767. https://doi.org/10.1017/S0001924000008411

Lindblad-Gidlund, K. (2009). The Reflexive Designer : A method for sustainable technology development. In (pp. 166–167). University of Twente. https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A285118&dswid=3752. Last Accessed: 01.12.2021

Lindgreen, A., & Swaen, V. (2010). Corporate Social Responsibility. *International Journal of Management Reviews*, *12*(1), 1–7. https://doi.org/10.1111/j.1468-2370.2009.00277.x

Linkov, I., Satterstrom, F. K., Steevens, J., Ferguson, E., & Pleus, R. C. (2007). Multi-criteria decision analysis and environmental risk assessment for nanomaterials. *Journal of Nanoparticle Research*, *9*(4), 543–554. https://doi.org/10.1007/s11051-007-9211-0

Littig, B., & Griessler, E. (2005). Social sustainability: a catchword between political pragmatism and social theory. *International Journal of Sustainable Development*, *8*(1/2), Article 7375, 65. https://doi.org/10.1504/IJSD.2005.007375

Liu, F [Fei], Nie, P., He, X [Xiantao], & Liu, X [Xiaodan]. (2021). Soil Information Sensing Technology. In Y. He, P. Nie, Q. Zhang, & F. Liu (Eds.), *Springer eBook Collection. Agricultural Internet of Things: Technologies and Applications* (1st ed., pp. 99–120). Springer International Publishing; Imprint Springer. https://doi.org/10.1007/978-3-030-65702-4_4

Liu, X [Xiuli], Guo, P., & Guo, S [Shufeng] (2019). Assessing the eco-efficiency of a circular economy system in China's coal mining areas: Emergy and data envelopment analysis. *Journal of Cleaner Production*, *206*, 1101–1109. https://doi.org/10.1016/j.jclepro.2018.09.218

Liu, Z [Ziye], & Cheng, L. (2020). Review of GIS Technology and Its Applications in Different Areas. *IOP Conference Series: Materials Science and Engineering*, *735*, 12066. https://doi.org/10.1088/1757-899X/735/1/012066

Lo, K. Y., & Kwan, C. L. (2017). The Effect of Environmental, Social, Governance and Sustainability Initiatives on Stock Value - Examining Market Response to Initiatives Undertaken by Listed Companies. *Corporate Social Responsibility and Environmental Management*, *24*(6), 606–619. https://doi.org/10.1002/csr.1431

Loiseau, E., Saikku, L., Antikainen, R., Droste, N [Nils], Hansjürgens, B., Pitkänen, K., Leskinen, P [Pekka], Kuikman, P., & Thomsen, M. (2016). Green economy and related concepts: An overview. *Journal of Cleaner Production*, *139*, 361–371. https://doi.org/10.1016/j.jclepro.2016.08.024

Lonjarret, C., Robardet, C., Plantevit, M., Auburtin, R., & Atzmueller, M. (2020). Why Should I Trust This Item? Explaining the Recommendations of any Model. In *2020 IEEE 7th International Conference on Data Science and Advanced Analytics (DSAA)* (pp. 526–535). https://doi.org/10.1109/DSAA49011.2020.00067

Lorek, S., & Spangenberg, J. H. (2014). Sustainable consumption within a sustainable economy – beyond green growth and green economies. *Journal of Cleaner Production*, *63*, 33–44. https://doi.org/10.1016/j.jclepro.2013.08.045

Loukogeorgaki, E., Vagiona, D., & Vasileiou, M. (2018). Site Selection of Hybrid Offshore Wind and Wave Energy Systems in Greece Incorporating Environmental Impact Assessment. *Energies*, *11*(8), 2095. https://doi.org/10.3390/en11082095

Lüdtke, O., Robitzsch, A., & Grund, S. (2017). Multiple imputation of missing data in multilevel designs: A comparison of different strategies. *Psychological Methods*, *22*(1), 141–165. https://doi.org/10.1037/met0000096

Luengo Frades, J., Negro, V., García Barba, J., Martín-Antón, M., López-Gutiérrez, J., Esteban, M., & Moreno Blasco, L. (2019). Preliminary Design for Wave Run-Up in Offshore Wind Farms: Comparison between Theoretical Models and Physical Model Tests. *Energies*, *12*(3), 492. https://doi.org/10.3390/en12030492

Ma, J., Li, C [Chunjiang], Kwan, M.-P., & Chai, Y. (2018). A Multilevel Analysis of Perceived Noise Pollution, Geographic Contexts and Mental Health in Beijing. *International Journal of Environmental Research and Public Health*, *15*(7). https://doi.org/10.3390/ijerph15071479

MacCallum, C., & Russil, J. (2020). *License to operate components of the business plan* (INFACT Deliverable D6.3). INFACT.

MacCallum, C., Russill, J., Kirsch, M., Ajjabou, L., Salam, I., & Bennet, L. (2020). Theory of change for the mineral Exploration - INFACT project. *EGU General Assembly Conference Abstracts*, 18416.

MacCarthy, B. L., & Atthirawong, W [W.] (2003). Factors affecting location decisions in international operations – a Delphi study. *International Journal of Operations & Production Management*, *23*(7), 794–818. https://doi.org/10.1108/01443570310481568

Maccioni, L., Borgianni, Y., & Pigosso, D. C. (2021). Creativity in successful eco-design supported by ten original guidelines. *International Journal of Design Creativity and Innovation*, 1–24. https://doi.org/10.1080/21650349.2021.1965033

Macharet, D. G., Perez-Imaz, H. I. A., Rezeck, P. A. F., Potje, G. A., Benyosef, L. C. C., Wiermann, A., Freitas, G. M., Garcia, L. G. U., & Campos, M. F. M. (2016). Autonomous Aeromagnetic Surveys Using a Fluxgate Magnetometer. *Sensors (Basel, Switzerland)*, *16*(12), 2169. https://doi.org/10.3390/s16122169

Macnae, J. (2016). Quantifying Airborne Induced Polarization effects in helicopter time domain electromagnetics. *Journal of Applied Geophysics*, *135*, 495–502. https://doi.org/10.1016/j.jappgeo.2015.10.016

Maier, A., Kim, H., Oehmen, J., Salustri, F., Škec, S., & Kokkolaras, M. (Eds.). (2018). *DS: 87, 1. Resource-sensitive design, Design.Research applications and case studies*. Curran Associates Inc.

Malehmir, A., Dynesius, L., Paulusson, K., Paulusson, A., Johansson, H., Bastani, M., Wedmark, M., & Marsden, P. (2017). The potential of rotary-wing UAV-based magnetic surveys for mineral exploration: A case study from central Sweden. *The Leading Edge*, *36*(7), 552–557. https://doi.org/10.1190/tle36070552.1

Malhorta, N. K. (2006). In R. Grover (Ed.), *The handbook of marketing research: Uses, misuses, and future advances.* Sage Publ.

Malkowsky, E. (2019). *Advanced Functional Analysis*. Chapman and Hall/CRC.

Mandić, V., & Ćosić, P. (2011). INTEGRATED PRODUCT AND PROCESS DEVELOPMENT IN COLLABORATIVE VIRTUAL ENGINEERING ENVIRONMENT. *Tehnicki Vjesnik / Technical Gazette*, *18*(18), 369–378.

Mangewa, L. J., Ndakidemi, P. A., & Munishi, L. K. (2019). Integrating UAV Technology in an Ecological Monitoring System for Community Wildlife Management Areas in Tanzania. *Sustainability*, *11*(21), 6116. https://doi.org/10.3390/su11216116

Mani, M., Johansson, B., Lyons, K. W., Sriram, R. D., & Ameta, G. (2013). Simulation and analysis for sustainable product development. *The International Journal of Life Cycle Assessment*, *18*(5), 1129–1136. https://doi.org/10.1007/s11367-012-0538-0

Mankins, J. (1995). *Technology readiness levels*. https://aiaa.kavi.com/apps/group_public/download.php/2212/trls_mankinspaper_1995.pdf. Last Accessed: 01.12.2021

Mankins, J. (2009). Technology readiness assessments: A retrospective. *Acta Astronautica*, *65*(9-10), 1216–1223. https://doi.org/10.1016/j.actaastro.2009.03.058

Markard, J., Hekkert, M., & Jacobsson, S. (2015). The technological innovation systems framework: Response to six criticisms. *Environmental Innovation and Societal Transitions*, *16*, 76–86. https://doi.org/10.1016/j.eist.2015.07.006

Masimba, F., Appiah, M., & Zuva, T. (2019). A Review of Cultural Influence on Technology Acceptance. In *2019 International Multidisciplinary Information Technology and Engineering Conference (IMITEC): Proceedings : 21-22 November 2019, Emerald Resort & Casino, Vanderbijlpark, Gauteng, South Africa* (pp. 1–7). IEEE. https://doi.org/10.1109/IMITEC45504.2019.9015877

Masior, J., Schneider, B., Tasci, T., & Riedel, O. (2020). Modellvernetzung im Advanced Systems Engineering. *Zeitschrift Für Wirtschaftlichen Fabrikbetrieb*, *115*(7-8), 545–549. https://doi.org/10.3139/104.112305

Maskus, K. (2004). Encouraging International Technology Transfer. *Intellectual Property Rights and Sustainable Development*, *7*.

Mayring, P. (2020). Qualitative Inhaltsanalyse. In *Designs und Verfahren* (pp. 495–511). Springer. https://doi.org/10.1007/978-3-658-26887-9_52

Mazé, R., Gregory, J., & Redström, J. (2011). Social Sustainability: A design research approach to sustainable development. In *4th World Conference on Design Research (IASDR)*. https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A1042947&dswid=2646. Last Accessed: 01.12.2021

McGurty, E. M. (1997). From NIMBY to Civil Rights: The Origins of the Environmental Justice Movement. *Environmental History*, *2*(3), 301. https://doi.org/10.2307/3985352

McKenna, H. P. (2020). Awareness and Smart City Implementations: Sensing, Sensors, and the IoT in the Public Sector. In J. R. Gil-Garcia, T. A. Pardo, & M. Gasco-Hernandez (Eds.), *Springer eBook Collection: Vol. 30. Beyond Smart and Connected Governments: Sensors and the Internet of Things in the Public Sector* (1st ed., Vol. 30, pp. 111–137). Springer International Publishing; Imprint Springer. https://doi.org/10.1007/978-3-030-37464-8_6

McLean, N. D., Holland, M. A., Maciver, R. D., & Bannon, E. B. (2020). Site selection for scaled open water testing of a wave energy converter. *International Marine Energy Journal*, *3*(2), 101–110. https://doi.org/10.36688/imej.3.101-110

McMillan, M. S., Schwarzbach, C., Haber, E., & Oldenburg, D. W. (2015). 3d parametric hybrid inversion of time-domain airborne electromagnetic data. *GEOPHYSICS*, *80*(6), K25-K36. https://doi.org/10.1190/geo2015-0141.1

Melin, C. B., Hagentoft, C.-E., Holl, K., Nik, V. M., & Kilian, R. (2018). Simulations of Moisture Gradients in Wood Subjected to Changes in Relative Humidity and Temperature Due to Climate Change. *Geosciences*, *8*(10), 378. https://doi.org/10.3390/geosciences8100378

Mendes, G. V., Lopes, L. A. S., da Silva Júnior, O. S., Perucci, F. O., & Heringer, F. M. (2020). Analysis of Greenhouse Gases and Atmospheric Pollutants Emissions by Helicopters in the Oil and Gas Industry. In M. Amorim, R. G. Barbastefano, J. Reis, L. F. Scavarda, & A. M. T. Thomé (Eds.), *Springer Proceedings in Mathematics & Statistics: volume 337. Industrial Engineering and Operations Management: XXVI IJCIEOM, Rio de Janeiro, Brazil, July 8-11, 2020 : challenge and trends for sustainability in the 21st century* (Vol. 337, pp. 325–337). Springer International Publishing. https://doi.org/10.1007/978-3-030-56920-4_26

Mihelcic, J. R., & Zimmerman, J. B. (2021). *Environmental Engineering: Fundamentals, Sustainability, Design*. John Wiley & Sons.

Mikolajewicz, N., & Komarova, S. V. (2019). Meta-Analytic Methodology for Basic Research: A Practical Guide. *Frontiers in Physiology*, *10*, 203. https://doi.org/10.3389/fphys.2019.00203

Milsom, J., & Eriksen, A. (2013). Field Geophysics, Fourth Edition. *Environmental & Engineering Geoscience*, *19*(2), 205–206. https://doi.org/10.2113/gseegeosci.19.2.205

Minasny, B., Fiantis, D., Mulyanto, B., Sulaeman, Y., & Widyatmanti, W. (2020). Global soil science research collaboration in the 21st century: Time to end helicopter research. *Geoderma*, *373*, 114299. https://doi.org/10.1016/j.geoderma.2020.114299

Minsley, B. J., Smith, B. D., Hammack, R., Sams, J. I., & Veloski, G. (2012). Calibration and filtering strategies for frequency domain electromagnetic data. *Journal of Applied Geophysics*, *80*, 56–66. https://doi.org/10.1016/j.jappgeo.2012.01.008

Mitchell, P. (2020). *Top 10 business risks and opportunities – 2020*. https://www.ey.com/en_gl/mining-metals/10-business-risks-facing-mining-and-metals#License%20to%20operate

Mohammed, H. I., Majid, Z., Yusof, N. B., & Yamusa, Y. B. (2019). A Review of GIS-Based and Multi-criteria Evaluation Method for Sustainable Landfill Site Selection Model. In B. Pradhan (Ed.), *SpringerLink Bücher: Vol. 9. Gcec 2017: Proceedings of the 1st Global Civil Engineering Conference* (Vol. 9, pp. 741–751). Springer. https://doi.org/10.1007/978-981-10-8016-6_55

Mol, A. P. J. (Ed.). (2000). *Environmental politics Special issue: Vol. 9.2000,1*. *Ecological modernisation around the world: Perspectives and critical debates*. Cass.

Moradi, S., Yousefi, H., Noorollahi, Y., & Rosso, D. (2020). Multi-criteria decision support system for wind farm site selection and sensitivity analysis: Case study of Alborz Province, Iran. *Energy Strategy Reviews*, *29*, 100478. https://doi.org/10.1016/j.esr.2020.100478

Mosleh, Z., Salehi, M. H., Amini Fasakhodi, A., Jafari, A., Mehnatkesh, A., & Esfandiarpoor Borujeni, I. (2017). Sustainable allocation of agricultural lands and water resources using suitability analysis and mathematical multi-objective programming. *Geoderma*, *303*, 52–59. https://doi.org/10.1016/j.geoderma.2017.05.015

Mrosik, J. (2018, June 28). *Ingenuity inspired by biology.* Siemens. Fraunhofer. Biologische Transformation, Berin.

Mudd, G. M. (2010). The Environmental sustainability of mining in Australia: key mega-trends and looming constraints. *Resources Policy*, *35*(2), 98–115. https://doi.org/10.1016/j.resourpol.2009.12.001

Mueller, C. E., Keil, S. I., & Bauer, C. (2017). Effects of spatial proximity to proposed high-voltage transmission lines: Evidence from a natural experiment in Lower Saxony. *Energy Policy*, *111*, 137–147. https://doi.org/10.1016/j.enpol.2017.09.023

Mueller, M., Smith, N., Ghanem, B., Leibe, B., Matas, J., Sebe, N., & Welling, M. (Eds.). (2016). *Lecture Notes in Computer Science: Vol. 9905*. *A Benchmark and Simulator for UAV Tracking // Computer Vision - ECCV 2016: 14th European Conference, Amsterdam, The Netherlands, October 11-14, 2016, Proceedings, Part I*. Springer International Publishing. https://doi.org/10.1007/978-3-319-46448-0_27

Mulero-Pázmány, M., Jenni-Eiermann, S., Strebel, N., Sattler, T., Negro, J. J., & Tablado, Z. (2017). Unmanned aircraft systems as a new source of disturbance for wildlife: A systematic review. *PloS One*, *12*(6), e0178448. https://doi.org/10.1371/journal.pone.0178448

Mwitwa, J., Paumgarten, F., & German, L. (2011). Evaluating the Impacts of Expanded Trade and Investment in Mining on Forests: Customary Rights and Societal Stakes in the Copper Belt of Zambia. *IASC*. iasc2011.fes.org.in

Myers, D. R. (2012). Solar Radiation Resource Assessment for Renewable Energy Conversion. In *Comprehensive Renewable Energy* (pp. 213–237). https://doi.org/10.1016/B978-0-08-087872-0.00112-8

Naderpajouh, N., Mahdavi, A., Hastak, M., & Aldrich, D. P. (2014). Modeling Social Opposition to Infrastructure Development. *Journal of Construction Engineering and Management*, *140*(8), 4014029. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000876

Nass, M., Alégroth, E., & Feldt, R. (2021). Why many challenges with GUI test automation (will) remain. *Information and Software Technology*, *138*, 106625. https://doi.org/10.1016/j.infsof.2021.106625

Natarajan, S., & Sinha, D. (2021). *World Quality Report 2020-2021 Twelfth Edition.* Capgemini. www.worldqualityreport.com

National Geographic. *Anthropocene*. https://www.nationalgeographic.org/encyclopedia/anthropocene/#:~:text=The%20Anthropocene%20Epoch%20is%20an,the%20planet%27s%20climate%20and%20ecosystems. Last Accessed: 01.12.2021

Nazari, M. A., Aslani, A., & Ghasempour, R. (2018). Analysis of Solar Farm Site Selection Based on TOPSIS Approach. *International Journal of Social Ecology and Sustainable Development*, *9*(1), 12–25. https://doi.org/10.4018/IJSESD.2018010102

Nazmul Haque Mondol. (2010). Seismic Exploration. In *Petroleum Geoscience* (pp. 375–402). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-02332-3_17

Nesta. (2016). *European Digital City Index*. https://digitalcityindex.eu/

Neurohr, C., Westhofen, L., Butz, M., Bollmann, M. H., Eberle, U., & Galbas, R. (2021). Criticality Analysis for the Verification and Validation of Automated Vehicles. *IEEE Access*, *9*, 18016–18041. https://doi.org/10.1109/ACCESS.2021.3053159

Neurohr, C., Westhofen, L., Henning, T., Graaff, T. de, Mohlmann, E., & Bode, E. (2020). Fundamental Considerations around Scenario-Based Testing for Automated Driving. In *2020 IEEE Intelligent Vehicles Symposium (IV)* (pp. 121–127). IEEE. https://doi.org/10.1109/IV47402.2020.9304823

Nevalainen, J., Ranta, J.-P., Kozlovskaya, E., Kirsch, M., Ajjabou, L., & Gloaguen, R. (2021). Non-invasive Exploration technologies in the INFACT project: Examples from the reference sites. In *ELEVENTH SYMPOSIUM ON STRUCTURE, COMPOSITION AND EVOLUTION OF THE LITHOSPHERE*.

Newcomer, K. E., Hatry, H., & Wholey, J. (2015). *Handbook of practical program evaluation* (Fourth edition). *Essential texts for nonprofit and public leadership and management*. Jossey-Bass a Wiley Imprint.

Ng, A. H., Adolfsson, J., Sundberg, M., & Vin, L. J. de (2008). Virtual manufacturing for press line monitoring and diagnostics. *International Journal of Machine Tools and Manufacture*, *48*(5), 565–575. https://doi.org/10.1016/j.ijmachtools.2007.08.008

Niedzielski, T. (2018). Applications of Unmanned Aerial Vehicles in Geosciences: Introduction. *Pure and Applied Geophysics*, *175*(9), 3141–3144. https://doi.org/10.1007/s00024-018-1992-9

Nobelius, D. (2002). *Managing R&D Processes - Focusing on Technology Development, Product Development, and their Interplay.* Chalmers Tekniska Hogskola.

Noble, A. F. de, & Galbraith, C. S. (1992). Competitive strategy and high technology regional/site location decisions: A cross-country study of Mexican and U.S. electronic component firms. *The Journal of High Technology Management Research*, *3*(1), 19–37. https://doi.org/10.1016/1047-8310(92)90003-K

Noble, H., & Heale, R. (2019). Triangulation in research, with examples. *Evidence-Based Nursing*, *22*(3), 67–68. https://doi.org/10.1136/ebnurs-2019-103145

Norris, P. (2008). *Spies in the sky: Surveillance satellites in war and peace*. *Springer-Praxis books in space exploration*. Springer. https://doi.org/10.1007/978-0-387-71673-2

Nuttavuthisit, K. (2019). Focus Group Interview. In K. Nuttavuthisit (Ed.), *Qualitative Consumer and Marketing Research: The Asian Perspectives and Practices* (pp. 141–164). Springer Singapore. https://doi.org/10.1007/978-981-13-6142-5_6

Nybacka, M. (2009). Opportunities in Automotive Winter Testing, 879–886. https://doi.org/10.1115/DETC2009-87264

Nybacka, M. (2010). Asme Power Transmission and Gearing Conference - 3rd International Conference on Micro- and Nanosystems - 11th International Conference on Advanced Vehicle and Tire Technologies, *presented at 2009 ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, August 30 - September 2, 2009, San Diego, California, USA / sponsored by the Design Engineering Division, ASME; the Computers and Information in Engineering Division, ASME ; Vol. 6*.

Nybacka, M., Ericson, A., & Larsson, T. C. (2010). Prospective service innovation in automotive testing: beyond distributed technology. *International Journal of Technology Intelligence and Planning*, *6*(1), Article 33921, 14. https://doi.org/10.1504/IJTIP.2010.033921

Nybacka, M., He, X [X.], Gómez, G., Bakker, E., & Drugge, L. (2014). Links between subjective assessments and objective metrics for steering. *International Journal of Automotive Technology*, *15*(6), 893–907. https://doi.org/10.1007/s12239-014-0094-7

Nyumba, T., Wilson, K., Derrick, C. J., & Mukherjee, N. (2018). The use of focus group discussion methodology: Insights from two decades of application in conservation. *Methods in Ecology and Evolution*, *9*(1), 20–32. https://doi.org/10.1111/2041-210X.12860

Obade, V. d. P., & Gaya, C. (2021). Digital technology dilemma: On unlocking the soil quality index conundrum. *Bioresources and Bioprocessing*, *8*(1), 6. https://doi.org/10.1186/s40643-020-00359-x

Ocampo, L. A., Himang, C. M., Kumar, A., & Brezocnik, M. (2019). A novel multiple criteria decision-making approach based on fuzzy DEMATEL, fuzzy ANP and fuzzy AHP for mapping collection and distribution centers in … // A novel multiple criteria decision-making approach based on fuzzy DEMATEL, fuzzy ANP and fuzzy AHP for mapping collection and distribution centers in reverse logistics. *Advances in Production Engineering & Management*, *14*(3), 297–322. https://doi.org/10.14743/apem2019.3.329

Odu, G. O. (2019). Weighting methods for multi-criteria decision making technique. *Journal of Applied Sciences and Environmental Management*, *23*(8), 1449. https://doi.org/10.4314/jasem.v23i8.7

Handbook on constructing composite indicators: Methodology and user guide. (2008). OECD.

Olechowski, A. L., Eppinger, S. D., Joglekar, N., & Tomaschek, K. (2020). Technology readiness levels: Shortcomings and improvement opportunities. *Systems Engineering*, *23*(4), 395–408. https://doi.org/10.1002/sys.21533

Oliveira, d. F. G., & Rabechini, R. (2019). Stakeholder management influence on trust in a project: A quantitative study. *International Journal of Project Management*, *37*(1), 131–144. https://doi.org/10.1016/j.ijproman.2018.11.001

Orloci, L. (1966). Geometric Models in Ecology: I. The Theory and Application of Some Ordination Methods. *The Journal of Ecology*, *54*(1), 193. https://doi.org/10.2307/2257667

Oudinot, A. Y., Riestenberg, D., Esposito, R., & Trautz, R. (2018). *Demonstration of Non-Endangerment at the Secarb Anthropogenic Test Site.* https://doi.org/10.2139/ssrn.3365764

Panagiotidou, M., Xydis, G., & Koroneos, C. (2016). Environmental Siting Framework for Wind Farms: A Case Study in the Dodecanese Islands. *Resources*, *5*(3), 24. https://doi.org/10.3390/resources5030024

Papathanasiou, J., & Ploskas, N. (2018). *Multiple Criteria Decision Aid: Methods, Examples and Python Implementations*. *Springer Optimization and Its Applications: Vol. 136*. Springer International Publishing. https://doi.org/10.1007/978-3-319-91648-4

Parris, K., & McCauley, R. (2019). *Noise pollution and the environment.* Australian Academy of Science. https://www.science.org.au/curious/earth-environment/noise-pollution-and-environment

Parshin, A. V., Morozov, V. A., Blinov, A. V., Kosterev, A. N., & Budyak, A. E. (2018). Low-altitude geophysical magnetic prospecting based on multirotor UAV as a promising replacement for traditional ground survey. *Geo-Spatial Information Science*, *21*(1), 67–74. https://doi.org/10.1080/10095020.2017.1420508

Partridge, E. (2005). Social sustainability: a useful theoretical framework. In *Australasian political science association annual conference,* (pp. 28–30).

Passarelli, M., Landi, G. C., Cariola, A., & Sciarelli, M. (2021). Open innovation in the new context of proof of concepts: evidence from Italy. *European Journal of Innovation Management*, *24*(3), 735–755. https://doi.org/10.1108/EJIM-02-2020-0052

Paulk, M. C. (2009). A History of the Capability Maturity Model for Software. *SQP*, *12*(1), 5–19.

PDAC. (2020). *INNOVATION IN MINERAL EXPLORATION 2020*. Toronto. https://www.pdac.ca/docs/default-source/priorities/access-to-land/geosciences/pdac-2020-innovation-in-mineral-exploration-v10.pdf. Last Accessed: 01.12.2021

Peach, M. (2000). Seismic Acquisition in Sensitive Desert Environment. In *International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production*.

Pedersen, L. B., & Rasmussen, T. M. (1990). The gradient tensor of potential field anomalies: Some implications on data collection and data processing of maps. *GEOPHYSICS*, *55*(12), 1558–1566. https://doi.org/10.1190/1.1442807

Peldzius, S., & Ragaisis, S. (2011). Comparison of Maturity Levels in CMMI-DEV and ISO/IEC 15504. In A. Zemliak & N. Mastorakis (Eds.), *Proceedings of the WSEAS international conferences. Proceedings of the WSEAS international conferences: Puerto Morelos, Mexico, January 29 - 31, 2011 ; 8th WSEAS International Conference on Fluid Mechanics (FM '11), 8th WSEAS International Conference on Heart and Mass Transfer (HMT '11), 8th WSEAS International Conference on Mathematical Biology and Ecology (MABE '11), 5th WSEAS International Conference on Business Administration (ICBA '11), American Conference on Applied Mathematics (AMERICAN-MATH '11), 5th WSEAS International Conference on Computer Engineering and Applications (CEA '11), 5th WSEAS International Conference on Circuits, Systems, Signal and Telecommunications (CISST '11).* WSEAS Press.

Pelletier, N., Bamber, N., & Brandão, M. (2019). Interpreting life cycle assessment results for integrated sustainability decision support: can an ecological economic perspective help us to connect the dots? *The International Journal of Life Cycle Assessment*, *24*(9), 1580–1586. https://doi.org/10.1007/s11367-019-01612-y

Penadés-Plà, V., García-Segura, T., Martí, J., & Yepes, V. (2016). A Review of Multi-Criteria Decision-Making Methods Applied to the Sustainable Bridge Design. *Sustainability*, *8*(12), 1295. https://doi.org/10.3390/su8121295

Pepper, C. B., Nascarella, M. A., & Kendall, R. J. (2003). A review of the effects of aircraft noise on wildlife and humans, current control mechanisms, and the need for further study. *Environmental Management*, *32*(4), 418–432. https://doi.org/10.1007/s00267-003-3024-4

Peter, M., Gatziu, S., Horn, D., Rüegg, F., Barba, R., & Graf, M. (2019). THE TECHNOLOGY MATRIX – A TOOL-BASED METHOD FOR TECHNOLOGY SCOUTING. https://www.fhnw.ch/de/die-fhnw/hochschulen/hsw/iwi/cloud-computing-digitalisation-transformation/abili-methodik/media/technology-matrix.pdf. Last Accessed: 01.12.2021

Petrasch, R., Fieber, F., Winkler, D., & Biffl, S. (2008). V-Modell XT und Standards. In R. Höhn, S. Höppner, & A. Rausch (Eds.), *Springer Lehrbuch. Das V-Modell XT: Anwendungen, Werkzeuge, Standards* (pp. 463–570). Springer. https://doi.org/10.1007/978-3-540-30250-6_6

Pettit, C., Stimson, B., Barton, J., Goldie, X., Greenwood, P., Lovelace, R., & Eagleson, S. (2020). Open access, open source and cloud computing: A glimpse into the future of GIS. In S. Geertman & J. Stillwell (Eds.), *Research handbooks in planning series. Handbook of planning support science* (pp. 56–71). Edward Elgar Publishing. https://doi.org/10.4337/9781788971089.00011

Pförtner, A., Buchert, T., Lindow, K., Stark, R., & Hayka, H. (2016). Information Management Platform for the Application of Sustainable Product Development Methods. *Procedia CIRP*, *48*, 437–442. https://doi.org/10.1016/j.procir.2016.04.091

Pichler, M., Schaffartzik, A., Haberl, H., & Görg, C. (2017). Drivers of society-nature relations in the Anthropocene and their implications for sustainability transformations. *Current Opinion in Environmental Sustainability*, *26-27*, 32–36. https://doi.org/10.1016/j.cosust.2017.01.017

Pilecki, Z. (2017). Basic principles for the identification of landslides using geophysical methods. *E3S Web of Conferences*, *24*, 1001. https://doi.org/10.1051/e3sconf/20172401001

Pinet, N., Gloaguen, E., & Giroux, B. (2019). Introduction to the special issue on geophysics applied to mineral exploration. *Canadian Journal of Earth Sciences*, *56*(5), v–viii. https://doi.org/10.1139/cjes-2018-0314

Pohekar, S. D., & Ramachandran, M. (2004). Application of multi-criteria decision making to sustainable energy planning—A review. *Renewable and Sustainable Energy Reviews*, *8*(4), 365–381. https://doi.org/10.1016/j.rser.2003.12.007

Porritt, J. (2007). *Capitalism as if the World Matters: As If the World Matters*. Earthscan.

Prikhodko, A., Morrison, E., Bagrianski, A., Kuzmin, P., Tishin, P., & Legault, J. (2010). Evolution of VTEM ? Technical solutions for effective exploration. *ASEG Extended Abstracts*, *2010*(1), 1–4. https://doi.org/10.1071/aseg2010ab093

Proctor, M., & MacCallum, C. (2019). The Canary in the Cage: Community Voices and Social License to Operate in Central Eastern Europe. In *6th International Congress on Environment and Social Responsibility in MIning.*

Pschybilla, T., Baumann, D., Wenger, W., Wagner, D., Manz, S., & Bauernhansl, T. (2019). A Maturity Model for the Classification of RealWorld Applications of Data Analytics in the Manufacturing Environment. In B. Fortz & M. Labbé (Eds.), *Operations Research Proceedings, GOR (Gesellschaft für Operations Research e.V.). Operations Research Proceedings 2018: Selected Papers of the Annual International Conference of the German Operations Research Society (GOR), Brussels, Belgium, September 12-14, 2018* (1st ed., pp. 67–73). https://doi.org/10.1007/978-3-030-18500-8_10

Puaschunder, J. (2020). Intergenerational Equity. In Puaschunder (Ed.), *Governance & Climate Justice* (pp. 9–14). Springer International Publishing. https://doi.org/10.1007/978-3-319-63281-0_2

Quadra, G. R., Teixeira, J. R. P. V. A., Barros, N., Roland, F., & Amado, A. M. (2019). Water pollution: one of the main Limnology challenges in the Anthropocene. *Acta Limnologica Brasiliensia*, *31*, Article e203. https://doi.org/10.1590/S2179-975X5118

Queitsch, M., Schiffler, M., Stolz, R., Rolf, C., Meyer, M., & Kukowski, N. (2019). Investigation of 3D magnetisation of a dolerite intrusion using airborne full tensor magnetic gradiometry (FTMG) data. *Geophysical Journal International.* Advance online publication. https://doi.org/10.1093/gji/ggz104

Ramana, V., Narayana Rao, K., & Suresh Kumar, J. (2013). Evaluation of performance metrics of leagile supply chain through fuzzy MCDM. *Decision Science Letters*, 211–222. https://doi.org/10.5267/j.dsl.2013.03.003

Rana, L., & Chudoba, B. (2020). Demonstration of a prototype design synthesis capability for space access vehicle design. *The Aeronautical Journal*, *124*(1281), 1761–1788. https://doi.org/10.1017/aer.2020.55

Ray, S., Simion, B., & Demke Brown, A. (2011). Jackpine: A benchmark to evaluate spatial database performance. In *2011 IEEE 27th International Conference on Data Engineering (ICDE 2011): Hannover, Germany, 11 - 16 April 2011* (pp. 1139–1150). IEEE. https://doi.org/10.1109/ICDE.2011.5767929

Reford, S. W., & Fyon, A. (2000). Airborne magnetic and electromagnetic surveys, Reid-Mahaffy airborne geophysical test site survey, miscellaneous release—Data (MRD) 55, geological setting … http://www.geologyontario.mndm.gov.on.ca/mndmfiles/pub/data/imaging/mrd055/mrd055.pdf. Last Accessed: 01.12.2021

Renn, O. (2008). *Risk governance: Coping with uncertainty in a complex world*. *Earthscan Risk in society series*. Earthscan.

Ridder, S. de, Grobbe, N., Egbert, G., Fichtner, A., Keranen, K., Li, Y., Müller, T., & Romanowicz, B. (2018). Shared advances in exploration and fundamental geophysics — Introduction. *GEOPHYSICS*, *83*(3), WCi-WCii. https://doi.org/10.1190/geo2018-0316-spseintro.1

Rikalovic, A., Cosic, I., & Lazarevic, D. (2014). GIS Based Multi-criteria Analysis for Industrial Site Selection. *Procedia Engineering*, *69*, 1054–1063. https://doi.org/10.1016/j.proeng.2014.03.090

Ringen, G., & Welo, T. (2021). Material substitution innovation-a framework assessing enablers and barriers. In *ISPIM Conference Proceedings.*

Rip, A. (2018). Constructive Technology Assessment. *Futures of Science and Technology in Society*, 97–114. https://doi.org/10.1007/978-3-658-21754-9_6

Rip, A., Misa, T. J., & Schot, J. (1995). *Managing technology in society*. Pinter Publishers.

Roddis, P., Carver, S., Dallimer, M., Norman, P., & Ziv, G. (2018). The role of community acceptance in planning outcomes for onshore wind and solar farms: An energy justice analysis. *Applied Energy*, *226*, 353–364. https://doi.org/10.1016/j.apenergy.2018.05.087

Rodgers, E., Hay, J., & Lussos, R. (2021). NASA Strategy for Technology Development. *Foresight, Strategy and Futures Studies for Defense and Security*. https://ntrs.nasa.gov/citations/20210013666. Last Accessed: 01.12.2021

Roszkowska, E. (2011). *Multi-criteria decision making models by applying the TOPSIS method to crisp and interval data.* Multiple Criteria Decision Making/University of Economics in Katowice. http://mcdm.ue.katowice.pl/files/mcdm11.pdf#page=200. Last Accessed: 01.12.2021

Ruaro, R., Gubiani, É. A., Hughes, R. M., & Mormul, R. P. (2020). Global trends and challenges in multimetric indices of biological condition. *Ecological Indicators*, *110*, 105862. https://doi.org/10.1016/j.ecolind.2019.105862

Rugman, A. M., & Verbeke, A. (1998). Corporate strategies and environmental regulations: an organizing framework. *Strategic Management Journal*, *19*(4), 363–375. https://doi.org/10.1002/(SICI)1097-0266(199804)19:4<363::AID-SMJ974>3.0.CO;2-H

Ruiz-Ben, E. (2020). Methodologies for a Participatory Design of IoT to Deliver Sustainable Public Services in "Smart Cities". In J. R. Gil-Garcia, T. A. Pardo, & M. Gasco-Hernandez (Eds.), *Springer eBook Collection: Vol. 30. Beyond Smart and Connected Governments: Sensors and the Internet of Things in the Public Sector* (1st ed., Vol. 30, pp. 49–68). Springer International Publishing; Imprint Springer. https://doi.org/10.1007/978-3-030-37464-8_3

Ruiz-Coupeau, S., Jürgens, B [Björn], Kesselring, M., & Herrero-Solana, V [Victor] (2020). Sustainability in Mineral Exploration—Exploring Less Invasive Technologies via Patent Analysis. *Sustainability*, *12*(22), 9761. https://doi.org/10.3390/su12229761

Ruiz-Coupeau, S., Kesselring, M., Jürgens, B [B.], & Herrero-Solana, V [V.] (2020, September 17). Technology watch of airborne mineral exploration methods. In *Mineral Exploration Symposium* (pp. 1–3). European Association of Geoscientists & Engineers. https://doi.org/10.3997/2214-4609.202089034

Rürup, A. C. (2017). *Strengthening capacities for the use of GIS in disaster risk reduction*. https://lup.lub.lu.se/student-papers/record/8927256. Last Accessed: 01.12.2021

Russo, D., Serafini, M., Rizzi, C., & Duci, s. (2015). Comparison AND CLASSIFICATION OF ECO IMPROVEMENT METHODS. *2220-4334*, 77–86. https://www.designsociety.org/publication/37613/comparison+and+classification+of+eco+improvement+methods. Last Accessed: 01.12.2021

Saaty, T. L. (1989). Group Decision Making and the AHP. In *The Analytic Hierarchy Process* (pp. 59–67). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-50244-6_4

Saaty, T. L. (2004). Decision making — The Analytic Hierarchy and Network Processes (AHP/ANP). *Journal of Systems Science and Systems Engineering*, *13*(1), 1–35. https://doi.org/10.1007/s11518-006-0151-5

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *International Journal of Services Sciences*, *4*(1), 83–98.

Sabtiana, R., Yudhoatmojo, S. B., & Hidayanto, A. N. (2018). Data Quality Management Maturity Model: A Case Study in BPS-Statistics of Kaur Regency, Bengkulu Province, 2017. In *2018 6th International Conference on Cyber and IT Service Management (CITSM) // 2018 6th International Conference on Cyber and IT Service Management: Convention Hall, Inna Parapat Hotel, August 7-9, 2018* (pp. 1–4). IEEE. https://doi.org/10.1109/CITSM.2018.8674323

Sadeh, A., Radu, C. F., Feniser, C., & Borşa, A. (2021). Governmental Intervention and Its Impact on Growth, Economic Development, and Technology in OECD Countries. *Sustainability*, *13*(1), 166. https://doi.org/10.3390/su13010166

Safarzyńska, K., & van den Bergh, J. C. (2010). Demand-supply coevolution with multiple increasing returns: Policy analysis for unlocking and system transitions. *Technological Forecasting and Social Change*, *77*(2), 297–317. https://doi.org/10.1016/j.techfore.2009.07.001

Sakamoto, Y., Ishiguro, M., & Kitagawa, G. (1988). Akaike Information Criterion. *Journal of the American Statistical Association*, *83*(403), 902–926. https://doi.org/10.1080/01621459.1988.10478680

Salafsky, N. (2010). Sustainability through computing. *Nature*, *465*(7297), 425. https://doi.org/10.1038/465425a

Salih, M. M., Zaidan, B. B., Zaidan, A. A., & Ahmed, M. A. (2019). Survey on fuzzy TOPSIS state-of-the-art between 2007 and 2017. *Computers & Operations Research*, *104*, 207–227. https://doi.org/10.1016/j.cor.2018.12.019

Salman, M. (2017). UAVs and geophysics: The way of the future. *Int'l Journal of Advances in Agricultural & Environmental Engg. (IJAAEE)*, *4*(1), 178–179. https://iicbe.org/upload/5937408%20d%20new%20formatted.pdf. Last Accessed: 01.12.2021

Salzmann, N., Frei, C., Vidale, P.-L., & Hoelzle, M. (2007). The application of Regional Climate Model output for the simulation of high-mountain permafrost scenarios. *Global and Planetary Change*, *56*(1-2), 188–202. https://doi.org/10.1016/j.gloplacha.2006.07.006

Samia, D. S. M., Blumstein, D. T., Díaz, M., Grim, T., Ibáñez-Álamo, J. D., Jokimäki, J., Tätte, K., Markó, G., Tryjanowski, P., & Møller, A. P. (2017). Rural-Urban Differences in Escape Behavior of European Birds across a Latitudinal Gradient. *Frontiers in Ecology and Evolution*, *5*, Article 66. https://doi.org/10.3389/fevo.2017.00066

Sanchez-Gordon, S., & Viera-Bautista, D. (2019). Mapping between CMMI-DEV v1.3 and ISO/IEC 90003:2014. In M. Hallo, M. Molina, & L. Valdivieso (Eds.), *2019 International Conference on Information Systems and Software Technologies: ICI2ST 2019 : Escuela Politécnica Nacional, Quito, Ecuador, 13-15 November 2019 : proceedings* (pp. 134–140). IEEE. https://doi.org/10.1109/ICI2ST.2019.00026

Sanft, R., & Walter, A. (Eds.). (2020). *Exploring mathematical modeling in biology through case studies and experimental activities // Exploring Mathematical Modeling in Biology Through Case Studies and Experimental Activities*. Elsevier. https://doi.org/10.1016/C2017-0-04789-4

Santini, S., Ostermaier, B., & Vitaletti, A. (2008). First experiences using wireless sensor networks for noise pollution monitoring, 61. https://doi.org/10.1145/1435473.1435490

Sapia, V., Viezzoli, A., Menghini, A [Antonio], Marchetti, M., & Chiappini, M. (2015). The Italian reference site for TEM methods. *Annals of Geophysics*, *58*(5), Article 2. https://doi.org/10.4401/ag-6805

Saputri, T. R. D., & Lee, S.-W. (2020). Addressing sustainability in the requirements engineering process: From elicitation to functional decomposition. *Journal of Software: Evolution and Process*, *32*(8). https://doi.org/10.1002/smr.2254

Sauro, J., & Lewis, J. R. (2009). Correlations among prototypical usability metrics. In Association for Computing Machinery (Chair), *Proceedings of the SIGCHI Conference on Human Factors in Computing*.

Schiffler, M., Stolz, R., Chwala, A., Queitsch, M., Meyer, M., Meyer, H.-G., & Kukowski, N. (2012). Calibration and evaluation of SQUID-FTMG data using Hilbert transforms. *EGU General Assembly Conference Abstracts*, 4022.

Schimpf, S., Heubach, D., & Rummel, S. (2016). Technologieentwicklung als Innovationstreiber in bestehenden und disruptiven Märkten – von der Beobachtung zur Umsetzung. In T. Abele (Ed.), *FOM-Edition. Die frühe Phase des Innovationsprozesses: Neue, praxiserprobte Methoden und Ansätze* (pp. 31–49). Springer Gabler. https://doi.org/10.1007/978-3-658-09722-6_3

Schlör, H., Fischer, W., & Hake, J.-F. (2015). The system boundaries of sustainability. *Journal of Cleaner Production*, *88*, 52–60. https://doi.org/10.1016/j.jclepro.2014.04.023

Schöggl, J.-P., Baumgartner, R. J., & Hofer, D. (2017). Improving sustainability performance in early phases of product design: A checklist for sustainable product development tested in the automotive industry. *Journal of Cleaner Production*, *140*, 1602–1617. https://doi.org/10.1016/j.jclepro.2016.09.195

Scholtes, M., Westhofen, L., Turner, L. R., Lotto, K., Schuldes, M., Weber, H., Wagener, N., Neurohr, C., Bollmann, M. H., Kortke, F., Hiller, J., Hoss, M., Bock, J., & Eckstein, L. (2021). 6-Layer Model for a Structured Description and Categorization of Urban Traffic and Environment. *IEEE Access*, *9*, 59131–59147. https://doi.org/10.1109/ACCESS.2021.3072739

Schoukens, M., & Noël, J. P. (2017). Three Benchmarks Addressing Open Challenges in Nonlinear System Identification * *We thank Torbjorn Wigren and Per Mattsson (Uppsala University, Sweden) for their help in realizing the cascaded tanks benchmark. This work was funded by the Fund for Scientific Research (FWO), the Methusalem grant of the Flemish Government (METH-1), the IAP VII/19 DYSCO program, and the ERC advanced grant SNLSID under contract 320378. The author J.P. Noel is a Postdoctoral Researcher of the Fonds de la Recherche Scientifique - FNRS which is gratefully acknowledged. *IFAC-PapersOnLine*, *50*(1), 446–451. https://doi.org/10.1016/j.ifacol.2017.08.071

Schuh, G [G.], Prote, J. P., Dany, S., Molitor, M., & Pagano, L. (2017). Adaptation of a product maturity model to highly iterative product development. In *2017 IEEE International Conference on Industrial Engineering & Engineering Management: Ieee IEEM2017 : 10-13 Dec, Singapore* (pp. 485–489). IEEE. https://doi.org/10.1109/IEEM.2017.8289938

Schumacker, R. E., & Tomek, S. (2013). *Understanding statistics using R*. Springer.

Schuurman, D., Marez, L. de, & Ballon, P. (2015). Living Labs: a systematic literature review. https://biblio.ugent.be/publication/7026155/file/702617. Last Accessed: 01.12.20211

Schwab, K. (2019). *The Global Competitiveness Report 2018*. http://reports.weforum.org/global-competitiveness-report-2018/chapter-3-benchmarking-competitiveness-in-the-fourth-industrial-revolution-introducing-the-global-competitiveness-index-4-0/

Scurati, G. W., Bertoni, M., Graziosi, S., & Ferrise, F. (2021). Exploring the Use of Virtual Reality to Support Environmentally Sustainable Behavior: A Framework to Design Experiences. *Sustainability*, *13*(2), 943. https://doi.org/10.3390/su13020943

Seider, G. (2013). Virtual Testing is Essential at Component Level. *Auto Tech Review*, *2*(1), 64–67. https://doi.org/10.1365/s40112-013-0214-1

Şengül, H., & Theis, T. L. (2011). An environmental impact assessment of quantum dot photovoltaics (QDPV) from raw material acquisition through use. *Journal of Cleaner Production*, *19*(1), 21–31. https://doi.org/10.1016/j.jclepro.2010.08.010

Senior, C., Bustard, C., Durham, M., Baldrey, K., & Michaud, D. (2004). Characterization of fly ash from full-scale demonstration of sorbent injection for mercury control on coal-fired power plants. *Fuel Processing Technology*, *85*(6-7), 601–612. https://doi.org/10.1016/j.fuproc.2003.11.019

Sethi, A. P. S., Ahuja, I. P. S., & Singla, A. (2018). Shifts Between Technology Push and Market Pull Strategies for Sustainable Development in Manufacturing Industries. In J. Connell, R. Agarwal, Sushil, & S. Dhir (Eds.), *Flexible Systems Management. Global value chains, flexibility and sustainability* (pp. 319–331). Springer. https://doi.org/10.1007/978-981-10-8929-9_21

Seyedmohammadi, J., Sarmadian, F., Jafarzadeh, A. A., Ghorbani, M. A., & Shahbazi, F. (2018). Application of SAW, TOPSIS and fuzzy TOPSIS models in cultivation priority planning for maize, rapeseed and soybean crops. *Geoderma*, *310*, 178–190. https://doi.org/10.1016/j.geoderma.2017.09.012

Shakirov, V. A., Artemyev, Y., & Nefedov, A. S. (2019). Decision Support for the Windfarms Siting Based on Multi-Attribute Analysis and Aerodynamic Modeling. In *2019 International Multi-Conference on Industrial Engineering and Modern Technologies (FarEastCon)* (pp. 1–6). https://doi.org/10.1109/FarEastCon.2019.8934159

Shao, M., Han, Z [Zhixin], Sun, J., Xiao, C., Zhang, S [Shulei], & Zhao, Y. (2020). A review of multi-criteria decision making applications for renewable energy site selection. *Renewable Energy*, *157*, 377–403. https://doi.org/10.1016/j.renene.2020.04.137

Sharlov, M. V., Buddo, J., Misyurkeeva, N., Shelokhov, I. A., & Agafonov, Y. (2017). Transient electromagnetic surveys for highresolution near-surface exploration: basics and case studies. *First Break*, *35*(9). https://doi.org/10.3997/1365-2397.35.9.90112

Shelbourn, M., Bouchlaghem, D., Anumba, C., Carrillo, P., Khalfan, M., & Glass, J. (2006). Managing knowledge in the context of sustainable construction. *Journal of Information Technology in Construction*, *11*, 57–71. http://www.itcon.org/2006/4. Last Accessed: 01.12.2021

Shukla, A., & Kot, R. (2016). An Overview of Hyperspectral Remote Sensing and its applications in various Disciplines. *IRA-International Journal of Applied Sciences (ISSN 2455-4499)*, *5*(2), 85. https://doi.org/10.21013/jas.v5.n2.p4

Simley, E., Fleming, P., & King, J. (2020). Field Validation of Wake Steering Control with Wind Direction Variability. *Journal of Physics: Conference Series*, *1452*, 12012. https://doi.org/10.1088/1742-6596/1452/1/012012

Simons, D. G., Snellen, M., van Midden, B., Arntzen, M., & Bergmans, D. H. T. (2015). Assessment of Noise Level Variations of Aircraft Flyovers Using Acoustic Arrays. *Journal of Aircraft*, *52*(5), 1625–1633. https://doi.org/10.2514/1.C033020

Simthsonian Institution. (2021). https://naturalhistory.si.edu/education/teaching-resources/paleontology/extinction-over-time#:~:text=Extinction%20Rates&text=Regardless%2C%20scientists%20agree%20that%20today%27s,one%20million%20species%20per%20year. Last Accessed: 01.12.2021

Singh, A., Jyoti, Kumar, Bhim, Kumar, S., & Lenka, Kumar, Sanjaya (2021). Assessment of global sustainable development, environmental sustainability, economic development and social development index in selected economies. *International Journal of Sustainable Development and Planning*, *6*(1), 123–136.

Sinnwell, C., Siedler, C., & Aurich, J. C. (2019). Maturity model for product development information. *Procedia CIRP*, *79*, 557–562. https://doi.org/10.1016/j.procir.2019.02.111

Sivertsen, O. I., & Haugen, B. (2018). *Automation in the Virtual Testing of Mechanical Systems: Theories and Implementation Techniques*. Chapman and Hall/CRC.

Smith, C. J., Kramer, R. J., Myhre, G., Forster, P. M., Soden, B. J., Andrews, T., Boucher, O., Faluvegi, G., Fläschner, D., Hodnebrog, Ø., Kasoar, M., Kharin, V., Kirkevåg, A., Lamarque, J.-F., Mülmenstädt, J., Olivié, D., Richardson, T., Samset, B. H., Shindell, D., . . . Watson-Parris, D. (2018). Understanding Rapid Adjustments to Diverse Forcing Agents. *Geophysical Research Letters*, *45*(21), 12023–12031. https://doi.org/10.1029/2018GL079826

Solangi, Y., Tan, Q., Khan, M., Mirjat, N., & Ahmed, I. (2018). The Selection of Wind Power Project Location in the Southeastern Corridor of Pakistan: A Factor Analysis, AHP, and Fuzzy-TOPSIS Application. *Energies*, *11*(8), 1940. https://doi.org/10.3390/en11081940

Soley-Bori, M. (2013). *Dealing with missing data: Key assumptions and methods for applied analysis* (Technical Report No.4). Boston University. http://www.bu.edu/sph/files/2014/05/marina-tech-report.pdf. Last Accessed: 01.12.2021

Sonesson, C., Davidson, G., & Sachs, L [Lisa]. (2016). *Mapping Mining to the Sustainable Development Goals: An Atlas.* https://www.commdev.org/pdf/publications/P_Mapping_Mining_SDGs_An_Atlas.pdf. Last Accessed: 01.12.2021

Sorensen, K. I., & Auken, E. (2004). SkyTEM–a New High-resolution Helicopter Transient Electromagnetic System. *Exploration Geophysics*, *35*(3), 194–202. https://doi.org/10.1071/EG04194

Sotoudeh, M. (2005). Links between sustainability and technology development. *IEEE Technology and Society Magazine*, *24*(1), 9–14. https://doi.org/10.1109/mtas.2005.1407742

Spichak, V. V. (2015). Modeling of Magnetotelluric Fields in 3-D Media, 339–377. https://doi.org/10.1016/B978-0-444-63554-9.00012-X

Spyridonidou, S., Sismani, G., Loukogeorgaki, E., Vagiona, D. G., Ulanovsky, H., & Madar, D. (2021). Sustainable Spatial Energy Planning of Large-Scale Wind and PV Farms in Israel: A Collaborative and Participatory Planning Approach. *Energies*, *14*(3), 551. https://doi.org/10.3390/en14030551

St Flour, P. O., & Bokhoree, C. (2021). Sustainability Assessment Methodologies: Implications and Challenges for SIDS. *Ecologies*, *2*(3), 285–304. https://doi.org/10.3390/ecologies2030016

Staples, M., Niazi, M., Jeffery, R., Abrahams, A., Byatt, P., & Murphy, R. (2007). An exploratory study of why organizations do not adopt CMMI. *Journal of Systems and Software*, *80*(6), 883–895. https://doi.org/10.1016/j.jss.2006.09.008

Starr, S. O., Linne, D. L., O'Malley, T. F., Anderson, M. S., Eisenman, D. J., Sanders, G. B., Araghi, K. R., & Suzuki, N. H. (2017). *Overview of NASA Technology Development for In-Situ Resource Utilization (ISRU)*. https://core.ac.uk/download/pdf/154738518.pdf. Last Accessed: 01.12.2021

Stavesand, J.-E., Reglitz, S., & Himmler, A. (2017). Optimizing the Benefit of Virtual Testing with a Process-Oriented Approach. *SAE International Journal of Aerospace*, *10*(1), 46–55. https://doi.org/10.4271/2017-01-2114

Steen, M., Manschot, M., & Koning, N. de (2011). Benefits of Co-design in Service Design Projects. *International Journal of Design*, *5*(2), 53–60.

Stolz, R., Schmelz, M., Zakosarenko, V [Vyacheslav], Foley, C. P., Tanabe, K., Xie, X., & Fagaly, R. (2021). Superconducting sensors and methods in geophysical applications. *Superconductor Science and Technology*, *34*(3), 33001. https://doi.org/10.1088/1361-6668/abd7ce

Stolz, R., Zakosarenko, V [V.], Schulz, M., Chwala, A., Fritzsch, L., Meyer, H.-G., & Köstlin, E. O. (2006). Magnetic full-tensor SQUID gradiometer system for geophysical applications. *The Leading Edge*, *25*(2), 178–180. https://doi.org/10.1190/1.2172308

Stonebraker, P. W., & Leong, G. K. (1994). *Operations strategy: Focusing competitive excellence*. *Quantitative methods and applied statistics series*. Prentice Hall.

Stotzem, H. C. (2017). *Artenschutzkonzept*. Landeshauptstadt Stuttgart Amt für Umweltschutz.

Sumathi, V. R., Natesan, U., & Sarkar, C. (2008). Gis-based approach for optimized siting of municipal solid waste landfill. *Waste Management (New York, N.Y.)*, *28*(11), 2146–2160. https://doi.org/10.1016/j.wasman.2007.09.032

Sun, Q., Miao, C., Duan, Q., Ashouri, H., Sorooshian, S., & Hsu, K.-L. (2018). A Review of Global Precipitation Data Sets: Data Sources, Estimation, and Intercomparisons. *Reviews of Geophysics*, *56*(1), 79–107. https://doi.org/10.1002/2017RG000574

Suopajärvi, L., & Kantola, A. (2020). The social impact management plan as a tool for local planning. *Land Use Policy*, *93*, 104046. https://doi.org/10.1016/j.landusepol.2019.104046

Suopajärvi, L., Poelzer, G. A., Ejdemo, T., Klyuchnikova, E., Korchak, E., & Nygaard, V. (2016). Social sustainability in northern mining communities: A study of the European North and Northwest Russia. *Resources Policy*, *47*, 61–68. https://doi.org/10.1016/j.resourpol.2015.11.004

Supracon (2014). *Full Tensor Magnetics: Energy Exploration And Engineering Benefits.* supracon AG. http://www.supracon.com/files/online/SQUIDSysteme/JessyStar_broschur_en_Okt2014_m.pdf. Last Accessed: 01.12.2021

Supriyasilp, T., Pongput, K., & Boonyasirikul, T. (2009). Hydropower development priority using MCDM method. *Energy Policy*, *37*(5), 1866–1875. https://doi.org/10.1016/j.enpol.2009.01.023

Swofford, J., & Slattery, M. (2010). Public attitudes of wind energy in Texas: Local communities in close proximity to wind farms and their effect on decision-making. *Energy Policy*, *38*(5), 2508–2519. https://doi.org/10.1016/j.enpol.2009.12.046

Tahera, K. (2014). *The role of testing in engineering product development processes*. https://search.proquest.com/openview/6c8169b5f9f5b8b5108b3de340f596e0/1?pq-origsite=gscholar&cbl=51922&diss=y. Last Accessed: 01.12.2021

Tahera, K., Wynn, D. C., Earl, C., & Eckert, C. M. (2019). Testing in the incremental design and development of complex products. *Research in Engineering Design*, *30*(2), 291–316. https://doi.org/10.1007/s00163-018-0295-6

Tahri, M., Hakdaoui, M., & Maanan, M. (2015). The evaluation of solar farm locations applying Geographic Information System and Multi-Criteria Decision-Making methods: Case study in southern Morocco. *Renewable and Sustainable Energy Reviews*, *51*, 1354–1362. https://doi.org/10.1016/j.rser.2015.07.054

Talukder, B., W. Hipel, K., & W. vanLoon, G. (2017). Developing Composite Indicators for Agricultural Sustainability Assessment: Effect of Normalization and Aggregation Techniques. *Resources*, *6*(4), 66. https://doi.org/10.3390/resources6040066

Tang, K. C., & Davis, A. (1995). Critical factors in the determination of focus group size. *Family Practice*, *12*(4), 474–475. https://doi.org/10.1093/fampra/12.4.474

Tasdemir, C., Gazo, R., & Quesada, H. J. (2020). Sustainability benchmarking tool (SBT): theoretical and conceptual model proposition of a composite framework. *Environment, Development and Sustainability*, *22*(7), 6755–6797. https://doi.org/10.1007/s10668-019-00512-3

Thiele, S. T., Lorenz, S., Kirsch, M., Cecilia Contreras Acosta, I., Tusa, L., Herrmann, E., Möckel, R., & Gloaguen, R. (2021). Multi-scale, multi-sensor data integration for automated 3-D geological mapping. *Ore Geology Reviews*, *136*, 104252. https://doi.org/10.1016/j.oregeorev.2021.104252

Tiruta-Barna, L., Benetto, E., & Perrodin, Y. (2007). Environmental impact and risk assessment of mineral wastes reuse strategies: Review and critical analysis of approaches and applications. *Resources, Conservation and Recycling*, *50*(4), 351–379. https://doi.org/10.1016/j.resconrec.2007.01.009

Truffer, B., Schippl, J., & Fleischer, T. (2017). Decentering technology in technology assessment: prospects for socio-technical transitions in electric mobility in Germany. *Technological Forecasting and Social Change*, *122*, 34–48. https://doi.org/10.1016/j.techfore.2017.04.020

Truffer, B., Voss, J.-P., & Konrad, K. (2008). Mapping expectations for system transformations. *Technological Forecasting and Social Change*, *75*(9), 1360–1372. https://doi.org/10.1016/j.techfore.2008.04.001

Tsai, Y.-Y., Xu, H., Ding, Z., Zhang, C., Johns, E., & Huang, B. (2021). DROID: Minimizing the Reality Gap Using Single-Shot Human Demonstration. *IEEE Robotics and Automation Letters*, *6*(2), 3168–3175. https://doi.org/10.1109/LRA.2021.3062311

Tukker, A. (2015). Product services for a resource-efficient and circular economy – a review. *Journal of Cleaner Production*, *97*, 76–91. https://doi.org/10.1016/j.jclepro.2013.11.049

Ulrich, K. T., Eppinger, S. D., & Yang, M. C. (2020). *Product design and development* (Seventh edition, international student edition). McGraw-Hill.

Unger, D., & Eppinger, S. (2011). Improving product development process design: a method for managing information flows, risks, and iterations. *Journal of Engineering Design*, *22*(10), 689–699. https://doi.org/10.1080/09544828.2010.524886

United Nations (1997). *Report of the World Commission on Environment and Development: Our Common Future: Transmitted to the General Assembly as an Annex to document A/42/427 - Development and International Co-operation: Environment.* United Nations. http://www.un-documents.net/ocf-01.htm. Last Accessed: 01.12.2021

United Nations. (2015). *Transforming our world: the 2030 Agenda for Sustainable Development*. https://sdgs.un.org/publications/transforming-our-world-2030-agenda-sustainable-development-17981. Last Accessed: 01.12.2021

Unsworth, M. (2018). *Magnetotelluric imaging for mineral exploration.* University of Alberta. https://www.pdac.ca/docs/default-source/conventions/convention-2018/technical-sessions/martyn-unsworth.pdf?sfvrsn=a89e8098_2

Urban, D., & Mayerl, J. (2011). *Regressionsanalyse: Theorie, Technik und Anwendung: Lehrbuch ; Neu: jetzt auch mit logistischer Regression* (4., überarb. und erw. Aufl.). *Studienskripten zur Soziologie*. VS Verl. für Sozialwiss. https://doi.org/10.1007/978-3-531-93114-2

Vacchi, M., Siligardi, C., Demaria, F., Cedillo-González, E. I., González-Sánchez, R., & Settembre-Blundo, D. (2021). Technological Sustainability or Sustainable Technology? A Multidimensional Vision of Sustainability in Manufacturing. *Sustainability*, *13*(17), 9942. https://doi.org/10.3390/su13179942

Vagiona, D. G., & Kamilakis, M. (2018). Sustainable Site Selection for Offshore Wind Farms in the South Aegean—Greece. *Sustainability*, *10*(3), 749. https://doi.org/10.3390/su10030749

Valenta, J. (2015). Introduction to Geophysics. Lecture Notes. http://www.geology.cz/projekt681900/english/learningresources/Geophysics_lecture_notes.pdf. Last Accessed: 01.12.2021

Vallance, S., Perkins, H. C., & Dixon, J. E. (2011). What is social sustainability? A clarification of concepts. *Geoforum*, *42*(3), 342–348. https://doi.org/10.1016/j.geoforum.2011.01.002

van Bezouw, M. J., Garyfallou, A., Oană, I.-E., & Rojon, S. (2019). A methodology for cross-national comparative focus group research: Illustrations from discussions about political protest. *Quality & Quantity*, *53*(6), 2719–2739. https://doi.org/10.1007/s11135-019-00887-5

van Buuren, S. (2018). *Flexible imputation of missing data* (Second edition). CRC Press.

van Schoubroeck, S., Thomassen, G., van Passel, S., Malina, R., Springael, J., Lizin, S., Venditti, R. A., Yao, Y., & van Dael, M. (2021). An integrated techno-sustainability assessment (TSA) framework for emerging technologies. *Green Chemistry*, *23*(4), 1700–1715. https://doi.org/10.1039/D1GC00036E

Vannette, D. L., & Krosnick, J. A. (Eds.). (2017). *The Palgrave Handbook of Survey Research*. Palgrave Macmillan US.

Vas, E., Lescroël, A., Duriez, O., Boguszewski, G., & Grémillet, D. (2015). Approaching birds with drones: First experiments and ethical guidelines. *Biology Letters*, *11*(2), 20140754. https://doi.org/10.1098/rsbl.2014.0754

VDI (2007). *Zuverlässigkeitsmanagement* (VDI 4003). Engl. VDI-Gesellschaft Produkt- und Prozessgestaltung. https://www.vdi.de/richtlinien/details/vdi-4003-reliability-management

VDI (2013). *Acceptance specification for automated guided vehicle systems (AGVS)* (Guideline VDI 2710). VDI-Gesellschaft Produktion und Logistik. https://term.vdi-online.de/index.php/definition/updateDefinition/485/14703/show. Last Accessed: 01.12.2021

VDI (2015). *Biomimetics - Architecture, civil engineering, industrial design - Basic principle* (Guideline VDI 6226). VDI-Gesellschaft Technologies of Life Sciences. https://www.vdi.de/richtlinien/details/vdi-6226-blatt-1-bionik-architektur-ingenieurbau-industriedesign-grundlagen. Last Accessed: 01.12.2021

VDI (2017). *Terminology of energy management and waste treatment; Fundamentals* (VDI 3459). VDI/DIN-Kommission Reinhaltung der Luft (KRdL) - Normenausschuss.

VDI (2018a). *Quality assurance; Requirements on bodies for the determination of air pollutants at stationary sources and in ambient air; General requirements* (Guideline VDI 4220). VDI/DIN-Kommission Reinhaltung der Luft (KRdL) - Normenausschuss.

VDI (2018b). *Simulation von Logistik-, Materialfluss- und Produktionssystemen - Begriffe* (Guideline VDI 3633). Engl. VDI-Gesellschaft Produktion und Logistik. https://term.vdi-online.de/index.php/definition/updateDefinition/1148/32403/show. Last Accessed: 10.12.2021

VDI (2019). *Design of technical products and systems; Model of product design* (Guideline VDI 2221). VDI-Gesellschaft Produkt- und Prozessgestaltung. https://term.vdi-online.de/index.php/definition/updateDefinition/1296/37414/show. Last Accessed: 10.12.2021

VDI (2020a). *Development of cyber-physical mechatronic systems (CPMS)* (Guideline VDI 2206). https://www.vdi.de/fileadmin/pages/vdi_de/redakteure/richtlinien/dateien/V-Modell_nach_VDIVDE_2206.pdf. VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik. Last Accessed: 10.12.2021

VDI (2020b). *Development of cyber-physical mechatronic systems (CPMS)* (Draft VDI/VDE 2206). VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik. https://term.vdi-online.de/index.php/definition/updateDefinition/1355/38631/show. Last Accessed: 10.12.2021

VDI (2021). *Erfinderisches Problemlösen mit TRIZ - Grundlagen und Begriffe* (Guideline VDI 4521). Engl. VDI-Gesellschaft Produkt- und Prozessgestaltung. https://www.vdi.de/richtlinien/details/vdi-4521-blatt-1-inventive-problem-solving-with-triz-fundamentals-terms-and-definitions. Last Accessed: 10.12.2021

VDI (2021-06-0). *Medical device software; Medical SPICE; Qualification of developers and assessors* (Draft VDI-MT 5702). VDI-Gesellschaft Technologies of Life Sciences. https://term.vdi-online.de/index.php/definition/updateDefinition/1391/39521/show. Last Accessed: 10.12.2021

VDI/ VDE (2019). *Capability test for bolting technology machines; Process capability test (PFU)* (Guideline VDI/ VDE 2645). https://term.vdi-online.de/index.php/definition/updateDefinition/1180/33808/show. Capability test for bolting technology machines; Process capability test (PFU). Last Accessed: 10.12.2021

Venkatesh, V., & Zhang, X. (2010). Unified Theory of Acceptance and Use of Technology: U.S. Vs. China. *Journal of Global Information Technology Management*, *13*(1), 5–27. https://doi.org/10.1080/1097198X.2010.10856507

Viezzoli, A., & Kaminski, V [Vlad] (2016). Airborne IP: examples from the Mount Milligan deposit, Canada, and the Amakinskaya kimberlite pipe, Russia. *Exploration Geophysics*, *47*(4), 269–278. https://doi.org/10.1071/EG16015

Viezzoli, A., Kaminski, V [Vladislav], & Fiandaca, G. (2017). Modeling induced polarization effects in helicopter time domain electromagnetic data: Synthetic case studies. *GEOPHYSICS*, *82*(2), E31-E50. https://doi.org/10.1190/geo2016-0096.1

Viezzoli, A., & Manca, G. (2020). On airborne IP effects in standard AEM systems: tightening model space with data space. *Exploration Geophysics*, *51*(1), 155–169. https://doi.org/10.1080/08123985.2019.1681895

Viezzoli, A., Menghini, A [A.], Selfe, G., & Kaminsky, V. (2018). Sunnyside Deposit: A Calibration Site for Airborne EM Systems. *24th European Meeting of Environmental and Engineering Geophysics*, *2018*(1), 1–6. https://doi.org/10.3997/2214-4609.201802455

Viezzoli, A., Roffey, S [S.], Wijns, C., Fernandez, I [I.], & Blanco Gonzalez, J. M. (2018). Presenting Non-Invasive and Fully Acceptable Exploration Technologies - The INFACT Project. In *2nd Conference on Geophysics for Mineral Exploration and Mining* (pp. 1–5). European Association of Geoscientists & Engineers. https://doi.org/10.3997/2214-4609.201802752

Villacreses, G., Gaona, G., Martínez-Gómez, J., & Jijón, D. J. (2017). Wind farms suitability location using geographical information system (GIS), based on multi-criteria decision making (MCDM) methods: The case of continental Ecuador. *Renewable Energy*, *109*, 275–286. https://doi.org/10.1016/j.renene.2017.03.041

Wallmark, O., Nybacka, M., Malmquist, D., Burman, M., Wennhage, P., & Georen, P. (2014). Design and Implementation of an Experimental Research and Concept Demonstration Vehicle. In *2014 IEEE Vehicle Power and Propulsion Conference (VPPC): 27 - 30 Oct. 2014, Coimbra* (pp. 1–6). IEEE. https://doi.org/10.1109/vppc.2014.7007042

Walsh, C., & Holmes, N. G. (2019). Assessing the assessment: Mutual information between response choices and factor scores. https://pdfs.semanticscholar.org/0e89/5b1f048e6ea4a5fc563a903b3a43b5588c85.pdf. Last Accessed: 01.12.2021

Wang, C.-N., Huang, Y.-F., Chai, Y.-C., & van Nguyen (2018). A Multi-Criteria Decision Making (MCDM) for Renewable Energy Plants Location Selection in Vietnam under a Fuzzy Environment. *Applied Sciences*, *8*(11), 2069. https://doi.org/10.3390/app8112069

Wang, J., Wei, X., & Guo, Q. (2018). A three-dimensional evaluation model for regional carrying capacity of ecological environment to social economic development: Model development and a case study in China. *Ecological Indicators*, *89*, 348–355. https://doi.org/10.1016/j.ecolind.2018.02.005

Watkins, S., Burry, J., Mohamed, A., Marino, M., Prudden, S., Fisher, A., Kloet, N., Jakobi, T., & Clothier, R. (2020). Ten questions concerning the use of drones in urban environments. *Building and Environment*, *167*, 106458. https://doi.org/10.1016/j.buildenv.2019.106458

Watz, M., & Hallstedt, S. I. (2020). Profile model for management of sustainability integration in engineering design requirements. *Journal of Cleaner Production*, *247*, 119155. https://doi.org/10.1016/j.jclepro.2019.119155

Waye, A., Young, D., Richards, J. P., & Doucet, J. A. (2009). Sustainable Development and Mining—An Exploratory Examination of the Roles of Government and Industry, 151–182. https://doi.org/10.1007/978-3-642-01103-0_7

Weaver, P. (2017). *Sustainable Technology Development* (First edition). Taylor and Francis. https://www.taylorfrancis.com/books/mono/10.4324/9781351283243/sustainable-technology-development-paul-weaver-leo-jansen-geert-van-grootveld-egbert-van-spiegel-philip-vergragt https://doi.org/10.4324/9781351283243

Weber, C., Königsberger, J., Kassner, L., & Mitschang, B. (2017). M2DDM – A Maturity Model for Data-Driven Manufacturing. *Procedia CIRP*, *63*, 173–178. https://doi.org/10.1016/j.procir.2017.03.309

Wei, L. (2021). Evolution Trend of Social Governance. In *General Theory of Social Governance in China* (pp. 415–444). Springer, Singapore. https://doi.org/10.1007/978-981-16-5715-3_12

West, A., Kramer, S., Bar, Z., & Roberts, J. D. (2018). *2018 Workshop Summary: MHK Environmental Compliance Cost Reduction Strategies Workshop*. Office of Scientific and Technical Information (OSTI). https://doi.org/10.2172/1471283

Wey, W.-M. (2015). Smart growth and transit-oriented development planning in site selection for a new metro transit station in Taipei, Taiwan. *Habitat International*, *47*, 158–168. https://doi.org/10.1016/j.habitatint.2015.01.020

Whalley, M., & Takahashi, M. (2016). Field-Testing of a Helicopter UAV Obstacle Field Navigation and Landing System. https://nams.usra.edu/sites/nams/assets/AFDD/AHS2009_Field-Testing.pdf. Last Accessed: 01.12.2021

White, T [Timothy], Wymore, A., Dere, A., Hoffman, A., Washburne, J., & Conklin, M. (2017). Integrated Interdisciplinary Science of the Critical Zone as a Foundational Curriculum for Addressing Issues of Environmental Sustainability. *Journal of Geoscience Education*, *65*(2), 136–145. https://doi.org/10.5408/16-171.1

Williamson, & Christina. (2013). Questionnaires, individual interviews and focus groups. In PublisherTilde University Press (Ed.), *Information Studies* (Vol. 16, pp. 349–372).

Winner, H., Hakuli, S., Lotz, F., & Singer, C. (Eds.). (2015). *ATZ / MTZ-Fachbuch*. *Handbuch Fahrerassistenzsysteme: Grundlagen, Komponenten und Systeme für aktive Sicherheit und Komfort* (3., überarbeitete und ergänzte Auflage). Springer Vieweg. https://doi.org/10.1007/978-3-658-05734-3

Witherly, K., & Irvine, R. (2006). The VTEM airborne electromagnetic system-benchmarking continuous improvement via repeat surveys over time. In *SEG Technical Program Expanded Abstracts 2006.* Society of Exploration Geophysicists. https://doi.org/10.1190/1.2369753

Witherly, K., Irvine, R., & Godbout, M. (2004). Reid Mahaffy Test Site, Ontario Canada: an example of benchmarking in airborne geophysics. In *SEG Technical Program Expanded Abstracts 2004.* Society of Exploration Geophysicists. https://doi.org/10.1190/1.1843294

Wood, A. D., & Hedenquist, J. (2019). Mineral Exploration: Discovering and Defining Ore Deposits. *SEG Discovery*(116), 1–22. https://doi.org/10.5382/Geo-and-Mining-02

World Economic Forum. (2021). *The Global Social Mobility Report 2020 Equality, Opportunity and a New Economic Imperative*. http://www3.weforum.org/docs/Global_Social_Mobility_Report.pdf

Woronowicz, T., Boronowsky, M., & Mitasiunas, A. (2012). innoSPICE(TM): A Standard Based Model for Innovation, Knowledge and Technology Transfer. In *ISPIM Conference Proceedings* (pp. 1–14).

Wu, T., Huang, W., Chen, X., Ma, X., Han, Z [ZiQi], & Tong, P. (2017). Calibration of discrete element model parameters for cohesive soil considering the cohesion between particles, Article 38, 93–98.

Wu, Y [You], & Su, D. (2020). Social Life Cycle Assessment. In D. Su (Ed.), *Sustainable Product Development: Tools, Methods and Examples* (1st ed., pp. 127–152). Springer International Publishing; Imprint: Springer. https://doi.org/10.1007/978-3-030-39149-2_7

Wu, Y [Yunna], Tao, Y., Zhang, B [Buyuan], Wang, S., Xu, C., & Zhou, J. (2020). A decision framework of offshore wind power station site selection using a PROMETHEE method under intuitionistic fuzzy environment: A case in China. *Ocean & Coastal Management*, *184*, 105016. https://doi.org/10.1016/j.ocecoaman.2019.105016

Wu, Y [Yunna], Wang, Y., Chen, K., Xu, C., & Li, L. (2017). Social sustainability assessment of small hydropower with hesitant PROMETHEE method. *Sustainable Cities and Society*, *35*, 522–537. https://doi.org/10.1016/j.scs.2017.08.034

Wu, Y [Yunna], Yang, M., Zhang, H., Chen, K., & Wang, Y. (2016). Optimal Site Selection of Electric Vehicle Charging Stations Based on a Cloud Model and the PROMETHEE Method. *Energies*, *9*(3), 157. https://doi.org/10.3390/en9030157

Wu, Y [Yunna], Zhang, B [Buyuan], Wu, C., Zhang, T [Ting], & Liu, F [Fangtong] (2019). Optimal site selection for parabolic trough concentrating solar power plant using extended PROMETHEE method: A case in China. *Renewable Energy*, *143*, 1910–1927. https://doi.org/10.1016/j.renene.2019.05.131

WWF. *WWF Water Risk Filter: From Risk Assessment to Response* (WWF Water Risk Filter). https://waterrisk-filter.panda.org/. Last Accessed: 01.12.2021

Ximenes, S. W., Hooper, D. M., Palat, A., Cantwell, L., Appleford, M., Webb, J., Wells, R., Patrick, E. L., & Necsoiu, M. (2020). Lunar Caves Analog Test Sites for Space-STEM Engagement. *3rd International Planetary Caves Conference*, *2197*, 1035.

Xu, J., Ho, D., & Capretz, L. F. (2015). *Building an OSS Quality Estimation Model with CATREG.*

Yang, F., Liu, J., Li, S [Shijiw], & Ma, F. (2011). Virtual-Real Interaction Testing for Functions of Intelligent Ships, 194–200.

Yap, J. Y. L., Ho, C. C., & Ting, C.-Y. (2019). A systematic review of the applications of multi-criteria decision-making methods in site selection problems. *Built Environment Project and Asset Management*, *9*(4), 548–563. https://doi.org/10.1108/BEPAM-05-2018-0078

Yavich, N., Malovichko, M., & Shlykov, A. (2020). Parallel Simulation of Audio- and Radio-Magnetotelluric Data. *Minerals*, *10*(1), 42. https://doi.org/10.3390/min10010042

Yesares, L., Sáez, R., De Almodóvar, G. R., Nieto, J. M., Gómez, C., & Ovejero, G. (2017). Mineralogical evolution of the Las Cruces gossan cap (Iberian Pyrite Belt): from subaerial to underground conditions. Ore Geology Reviews, 80, 377-405. https://doi.org/10.1016/j.oregeorev.2016.05.018

Yun, J. J., & Liu, Z [Zheng] (2019). Micro- and Macro-Dynamics of Open Innovation with a Quadruple-Helix Model. *Sustainability*, *11*(12), 3301. https://doi.org/10.3390/su11123301

Zhan, C., & Lai, H. (2019). Energy Minimization in Internet-of-Things System Based on Rotary-Wing UAV. *IEEE WIRELESS COMMUNICATIONS LETTERS,*, *8*(3), 1341–1345.

Zhang, D., Wilke, J., Hendry, G., & Dechev, D. (2016). Validating the Simulation of Large-Scale Parallel Applications Using Statistical Characteristics. *ACM Transactions on Modeling and Performance Evaluation of Computing Systems*, *1*(1), 1–22. https://doi.org/10.1145/2809778

Zhang, P., Jing, S., Nie, Z., Zhao, B., & Tan, R. (2021). Design and Development of Sustainable Product Service Systems Based on Design-Centric Complexity. *Sustainability*, *13*(2), 532. https://doi.org/10.3390/su13020532

Zhang, S [Shichao], Li, X., Zong, M., Zhu, X., & Cheng, D. (2017). Learning k for kNN Classification. *ACM Transactions on Intelligent Systems and Technology*, *8*(3), 1–19. https://doi.org/10.1145/2990508

Zhao, D., Guo, Y., & Jia, Y. J. (2017). TrafficNet: An open naturalistic driving scenario library. In *2017 IEEE 20th International Conference on Intelligent Transportation Systems (ITSC)* (pp. 1–8). https://doi.org/10.1109/ITSC.2017.8317860

Zhou, W., Newsam, S., Li, C [Congmin], & Shao, Z. (2018). PatternNet: A benchmark dataset for performance evaluation of remote sensing image retrieval. *ISPRS Journal of Photogrammetry and Remote Sensing*, *145*, 197–209. https://doi.org/10.1016/j.isprsjprs.2018.01.004

Ziemba, P., Wątróbski, J., Zioło, M., & Karczmarczyk, A. (2017). Using the PROSA Method in Offshore Wind Farm Location Problems. *Energies*, *10*(11), 1755. https://doi.org/10.3390/en10111755

Zillmer, A., Rao, D., & Johnson, S. (2020). Evolution of space reactor qualification methods and a path forward for new space reactors under consideration. In *2020 IEEE Aerospace Conference.* IEEE. https://doi.org/10.1109/aero47225.2020.9172482

Zorin, N., Aleksanova, E., Shimizu, H., & Yakovlev, D. (2020). Validity of the dispersion relations in magnetotellurics: Part I—Theory. *Earth, Planets and Space*, *72*(1), 1–18. https://doi.org/10.1186/s40623-020-1133-4

Zorzetti, M., Moralles, C., Salerno, L., Pereira, E., Marczak, S., & Bastos, R. (2021). Adopting Agile Software Development Combined with User-Centered Design and Lean Startup: A Systematic Literature Review on Maturity Models. In J. Filipe, M. Śmiałek, A. Brodsky, & S. Hammoudi (Eds.), *Enterprise Information Systems* (pp. 517–541). Springer International Publishing.

Appendix

Appendix 1 Technology Maturity Models

Technology S-curve: The technology S-curve is a tool for decision support and assessing technologies. The S-curve illustration is a function of the capability of a technology and the accumulated R&D expenses. The resulting graphics indicate the maturity of a technology. Five indicators govern the capability categorization of technological invention and indicate the maturity level of technology. These five are research programs, scientific publications, venture capital, search requests, and patents. Empirical evidence supports the accuracy of the S-curve (Christensen, 1992; S. D. Howell, 1980). Previous literature further highlights the wide applicability or adaptability to diverse research purposes (e.g., innovation, management, investment) (Kumar, 2015). Critics point to opposing research that shows only static performance evolvement rather than the assumed dynamics. S. D. Howell (1980) and Chesbrough and Kusunoki (2001) extend the critical evaluation. They argue that real-world developments do not match the ideal S-curve and that performance criteria give information about technological abilities but not about integrating technologies into surrounding systems. Hence, performance criteria are difficult to operationalize. Perhaps the most robust deficit is the insufficient recognition of the maturity evaluation of the technology itself (Christensen, 1992). Despite critics, the S-curve remains a common tool to assess the performance of technology and find explanation and decision-support for maturity considerations and market adoption behavior. The S-curve is a well-recognized tool, especially comparing the gap between state of the art and research.

Mankins (1995) developed the **TRL**. The TRL provides a precise understanding of maturity from a more technical perspective. Based on a systematic analysis, this approach assesses technological readiness using its development state. Each technology readiness scale drills down into nine critical phases of a technology's life cycle. Table 62 illustrates the TRL scale phases and the related test program per stage.

Table 62 Technology Readiness Levels

TRL	Description	Test Program
1	Kick-off scientific research	First simulations
2	Formulation of practical concepts and applications	Simulation
3	Experimental proof of concept/ Analytical and experimental proof of concept of critical functions and/or characteristics	Laboratory studies for the physical validation and analytical prediction (laboratory; simulation)
4	Technology validated in lab/ Component and/or breadboard validation in a laboratory environment	Integration of technological components (laboratory; simulation)
5	Technology validated in relevant environment/ Component and/or breadboard validation in a relevant environment	Integrated component tests in relevant controlled environments (may be supported by simulation)
6	System/sub-system model or prototype demonstration in a relevant environment	Prototype testing in relevant environment (may be supported by simulation)
7	System prototype demonstration in an operational environment	Prototype close to operational system. Demonstration in operational setting (e.g., in space). Only performed for mission critical; high risk and uncertainty projects.
8	System complete and qualified	Technology has been proven to work in its final form and under expected conditions
9	Technology system in its final form and in full commercial deployment	Ongoing demonstration to customers

Source Mankins (2009) and Bates and Clausen (2020)

The scope of the approach includes all technology development activities from observation and description of a functional principle (TRL 1) to the point where a capable system with proof of successful operation emerges (TRL 9) (Mankins, 1995, 2009). Thus, the TRL model is an instrument for decision-making about a technological system and its performance. Indicators for the maturity of technology build on system integration and proven technological capabilities. By linking maturity to the test program, the TRL provides a stage-gate perspective to technology assessment. Since its development in 1995, several authors suggested adaptations (Defendi & Santiago, 2021). The most considerable momentum came from the advent of simulated tests (Bates & Clausen, 2020). Through the translation of end-setting conditions and diverse market knowledge (e.g., user and customer demands) into virtual environments, prototype simulation has changed much of the initial physical test centred approach. While the test program has changed over time, the TRL remains a typical structure to identify and communicate technological maturity. Following the European Commissions decision to adopt the TRL as an innovation policy tool, the popularity of the TRL increased significantly. Results included the establishment of an ISO standard in 2013 (ISO, 2019). Authors such Héder (2017) criticized the transition from technology evaluation into the public sector. Discipline independent usage may lead to a distortion of TRL accuracy, so the authors stated (Héder, 2017). Opposing arguments, advocate that standardization across disciplines increases transparency in grant decision (Olechowski et al., 2020). Technology and Knowledge Transfer Literature support the argument (Defendi & Santiago, 2021). By combining S-curve insights and the technology readiness level, future development potential emerge. For example the position on the S-curve or the intensity of the indicators can aid the definition of technological maturity.

V-Model: Originating from software development, the V-Model structures the development and maintenance of entities, requirements, designs (Bröhl & Dröschel, 1995). Similar to TRL, it organizes the development process into phases and structures. The V-model and calls for iterative verification and validation of development quality. Evolution from one to the next phase builds on iterative performance measurements. Visually, the V-model juxtaposes individual development phases with test phases, which can be displayed as a V-shape. The left leg of the V starts with the functional specification. The further the process gets to the top of the V, the more detailed are the technical specifications. In sum, the left side forms the implementation basis. (VDI, 2020a) Implementation of requirements into mechatronic systems happens where the right and the left leg meet. Then, the implemented system is verified against the set requirements, which means that a case for each defined requirement is made. Once the implemented system has passed the V-Model, a functional sample, prototype, pre-production sample and subsequent intermediate steps emerge. Product maturity is not an indicator of the system model (Firesmith, 2013; Johansson & Bucanac, 1998). Thus, the V-Modell is iterative. Until the final solutions exist, a developer passes many iteration cycles.

CMMI: Challenged by delays and lack of transparency, software companies employ the CMMI to gauge that processes follow a transparent procedure and yield consistent, high-quality products on time (Chaudhary & Chopra, 2016). Peldzius and Ragaisis (2011) break-down the CMMI into five distinct stages. Gatekeeper of each stage are maturity levels and later capability levels. Areas of investigation include requirements elicitation, software design, and configuration management. Upon compliance with the maturity and capability of the investigation areas, organizations receive CMMI ratings from Level 1-5. CMMI is often associated with the ISO audit standards such as ISO / IEC 15504-5 process assessment and ISO / IEC 90003:2014. Differences lie in the nature between standards such as ISO and models such as CMMI. The advantages of CMMI over ISO standards are the broad applicability. Sanchez-Gordon and Viera-Bautista (2019) state that there multiple standards, which make it difficult to determine which of them best fits the objectives of each organization. Costs and resources associated with the approach challenge the adoption rates of CMMI (Staples et al., 2007).

Appendix 2 Magnetotellurics Background Information

Within the area of MT, three distinct techniques exist. First, to analyze conductivity, MT uses the natural current of the atmosphere and magnetosphere (ionospheric and magnetospheric currents). Ionospheric and magnetosphere currents arise when Earth's magnetic field and plasma emitted from the sun interacts. The generated currents induce eddy currents in the Earth. The density of the current is an indicator of the conductivity structure of the subsurface. (Spichak, 2015)

Audiomagnetotellurics (AMT) is the second method. AMT measures radiation and reflectance of atmospheric thunderstorm events (Zorin et al., 2020). Finally, Radio Magnetotellurics (RMT) uses electromagnetic waves emitted by radio transmitters. The target and its depth determine the applicability of each method. The signals recorded by MT range between the period of 1s- 10^5 s; AMT ranges between the period of 10^{-4} s – 1s, and RMT ranges between the period of 10^{-6} s - 10^{-4} s. Consequently, RMT is suitable to analyze shallow targets, whereby classical MT can record subsurface conductivity/resistivity at depths up to 10km (Heinson et al., 2018). RMT and MT measurements are often used in combination to extrapolate better/ reduce the ambiguity of the modelled/ inverted measures at depth (Yavich et al., 2020).

Appendix 3 Literature Review on Location Factor Overview

Table 63 Traditional Location Decision Factors

Factor	Criteria	Author
Logistics	Logistical Infrastructure (airports, railroads and roads), parking area, Pipeline facilities, quality of services, Traffic connections (sea, air, rail, road), Transportation costs, Trucking facilities; Lead Time; Accessibility of land ; Availability of and/or building(s) for business; Closeness to other (related) industries; Community industrial development projects; Cost of construction, land, lending, remove – relocate – close down; Proximity to headquarter	(Alberto, 2000; Archambault, 2004; Atthirawong, 2003; Badri, 2007; Calzonetti & Hemphill, 1992; Coughlin et al., 2007; Farahani et al., 2012; MacCarthy & Atthirawong, 2003)
Economic	Market size, Market growth, Per capita income and associated growth rates; Supply side structure (incl. raw materials and services); Market structure fluctuation of currency and interest; Location and number of existing competitors; Proximity and access to markets and customers; Taxes; Labor climate; Labor market structure	(Alberto, 2000; Archambault, 2004; Badri, 2007; Bergeron et al., 2005; Blair & Premus, 1987; MacCarthy & Atthirawong, 2003; A. de Noble & Galbraith, 1992)
Environment	Air pollution; Climate; Natural disaster (flood, earthquake, perils of the sea, or tsunami); Opportunity for year-round construction; Percent rain fall; Humidity;	(Alberto, 2000; Farahani et al., 2012; Hekman, 1992; MacCarthy & Atthirawong, 2003)
Social / Political Situation	Foreign capital; Government structure; History of country; Political and socio-economic stability; Political attitude towards business; Treaties and pacts; Attitude of community leaders; Availability of/ Distance to colleges/universities, Medical services; Community attitude; Cost and availability of housing; Cost of living; Entertainment; Hotels; Income per capita; Demographics; Quality of life; Religious facilities; Social and cultural climate	(Alberto, 2000; Atthirawong, 2003; Ballance, 1987; Blair & Premus, 1987; Farahani et al., 2012; Hekman, 1992; MacCarthy & Atthirawong, 2003; A. de Noble & Galbraith, 1992; Stonebraker & Leong, 1994)
Legal	Attitude of government investment; Clarity laws; Compensation, Ownership, relation, Insurance Laws; Industrial standard and international agreement; Insurance law; Number of international fund firms versus local firms; Regulations concerning internationalization and price controls; Safety inspection; Trade barrier	(Anell & Nygren, 2014; Badri, 2007; Bergeron et al., 2005; Bhutta et al., 2003; MacCarthy & Atthirawong, 2003)

Appendix 4 Multi-criteria Decision Making Methods

AHP: For the development of the AHP method, Saaty (1989) suggests six steps. The following details Saaty's (1989) taxonomy.

Step 1: Determination of the goal, alternatives and the structure of the hierarchy. The first tasks within this step are the manifestation of the analysis (e.g., identifying suitable test sites) and the identification of criteria associated with this decision (e.g., technological, social, ecological) (Saaty, 2008). Task two defines the hierarchy of the weighting scheme. Table 64 illustrates the process.

Table 64 Analytical Hierarchical Process Scale

Weight	Definition
1	Equal importance; Two criteria are of similar importance
3	Slightly importance from one over another
5	Medium importance difference
7	Strong importance difference
9	Very strong importance difference
2,4,6,8	Intermediate values, when compromise is required

Source Own Representation Aligned to Saaty, (1990)

Step 2: The pairwise comparisons of all criteria influencing the decision. In a second step, criteria influences are measured. The criteria used in the present study are introduced in Table 64. Saaty (2008) suggests to perform pairwise comparison with a decision matrix (A). The matrix constitutes of n criteria (A={$A = 1,2..n$}), affecting the selection alternative (C.-N. Wang et al., 2018). An example of the judgement matrix is displayed below. In line with Table 64, aij is the relative importance of criterion ai over criterion aj.

$$A = \begin{pmatrix} a_{12} & \cdots & a_{1(n-1)} & a_{n1} \\ \vdots & \ddots & \vdots & \\ a_{n1} & \cdots & a_{n(n-1)} & a_{n1} \end{pmatrix}$$

Step 3: Pairwise comparison of the alternatives considering the criteria. If the importance of criterion ai over criterion aj is k, then the relative importance of aj over ai is 1/k. For A this means, $a_{ij} = 1/a_{ji}, \forall$ i ≠ j and $a_{ii} = 1 \; for \; i,j = 1,2,\ldots,n$. Such matrix is termed a reciprocal matrix. Having checked the reciprocal relationships, the priority vector (v) is calculated.

Step 4: Calculation of priority vectors. The priority vector calculates the importance of each criteria and the influence of the individual criteria on the overall goal. The priority vector can be based on the eigenvalue method. The eigenvalue method, solves for the principal eigenvector w of matrix A.

$$A \; x \; w = (\lambda \max x \; w)$$

λmax is the maximal eigenvalue. Saaty (2004) calculates λmax by adding the columns within the judgement matrix and multiplying the results vector with the vector x.

Step 5: Calculation of the consistency ratio (CR). To check the quality and robustness of the outcomes, consistency must be checked. The consistency index (CI) is calculated as follows:

$$CI = (\lambda \max - n)/\,(n-1)$$

CR is calculated as follows:

$$CR = \frac{I}{RI}$$

RI is the random index value, and varies by the matrix size. Table 65 shows the RI values for a specific n.

Table 65 Random Index Value

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.52	1.54	1.56	1.58	1.59

Source Saaty and Tran (2007)

$$CR = \frac{CI}{RCI} \rightarrow\ If\ CR < 10\%, achieved\ data\ is\ consistent; If\ CR\ \geq 10\%, achieved\ data\ is\ inconsistent$$

Step 6: Analysis of the AHP scores. If the model is consistent, the alternative selection is possible. The application of AHP is manifold. Authors report on its value for sustainable energy planning (Pohekar & Ramachandran, 2004) or environmental siting wind farms (Panagiotidou et al., 2016).

TOPSIS: Initially developed by Hwang and Yoon (1981), TOPSIS is a practical method for dealing with decision-making tasks. In a review on MCDM methods, define TOPSIS as “a multiple criteria method to identify solutions from a finite set of alternatives based upon simultaneous minimization of distance from an ideal point and maximization of distance from a nadir point.” The definition implies that TOPSIS is capable of integrating weights and enables the comparison of distance metrics. Weighted metrics help decision-makers as well as engineers to rank and compare alternatives. With TOPSIS, alternative ranking builds on the least square method. Papathanasiou and Ploskas (2018) clarify this statement by saying that TOPSIS can identify the shortest distance between the ideal solution and some option under consideration.

In a scholarly journal on MCDM, Roszkowska (2011) describes the seven steps to follow during the TOPSIS procedure. Table 66 illustrates these steps.

Table 66 TOPSIS Process Steps

Step	Description
1	Determination of the weight of criteria and construction of the decision matrix
2	Calculation of the normalized decision matrix
3	Calculation of the weighted normalized decision matrix
4	Determination of the positive ideal solutions and negative ideal solutions
5	Calculation of the separation of each alternative from the positive ideal solution and the negative ideal solution
6	Calculation of the relative closeness to the positive ideal solution
7	Determination of the rank of the alternatives according to the relative closeness

Source Saaty (2008)

Starting from the original TOPSIS methodology, various modifications have emerged. The authors introduce a normalization procedure and elaborated metrics to calculate deviations for the ideal solution. Scholarly work also introduced fuzzy logics or intervals. Supply chain management and logistics, design, engineering, manufacturing systems, and business and marketing management most recognize TOPSIS (Papathanasiou & Ploskas, 2018).

PROMETHEE: Initially developed in 1982, the PROMETHEE method is an outranking method for a finite set of alternatives (J. P. Brans & Vincke, 1985). Similar to TOPSIS, PROMETHEE evaluates multiple criteria of a limited set of predetermined alternatives. Each criterion is independent, and weighted preference functions are calculated separately. Preference functions depict the spread between the evaluation of alternative through a preference degree (J. P. Brans et al., 1986). The preference degree indicates to what extent the individual prefers the criteria or alternative to the other prospects.

Based on the preference degree, PROMETHEE calculates a ranking of actions. Steps towards the order include: (1) pairwise comparison of actions on each criterion, (2) computation of unicriterion flows and (3) aggregation of unicriterion flows into holistic flows.

Since PROMETHEEs' development, Geometrical Analysis for Interactive Aid, a two-dimensional graphical decision aid, FlowSort, a sorting method of the PROMETHEE flow scores and PROMETHEE I-VI added to the original method (J.-P. Brans & Smet, 2016). Table 67 illustrates the PROMETHEE family. Typical PROMETHEE applications select one alternative from a given set of other options, prioritization, resource allocation and conflict resolution (J.-P. Brans & Smet, 2016). The applications are most recognized in location siting, environment management, services and public applications, industrial applications, and energy management as most recognized application fields (Papathanasiou & Ploskas, 2018).

Table 67 PROMETHEE Family

PROMETHEE I	Partial ranking of alternatives ranking them as preferred, indifferent or incomparable
PROMETHEE II	Complete ranking of alternatives ranking them as most efficient to the least efficient
PROMETHEE III	Final ranking method mostly used for risk assessment. Ranks alternatives based on interval preferences (probabilistic framework of flows)
PROMETHEE IV	Ranks infinite set of situations
PROMETHEE V	Procedure for multiple selection of alternatives under constraints Introduces restrictions to selected alternative, through integer programming methods. (builds on PROMETHEE II)
PROMETHEE VI	Advanced sensitivity analysis tools, providing richer information at the outlay of added complexity.

Source Albuquerque (2015), J.-P. Brans and Smet (2016)

Despite the wide applicability, Keyser and Peeters (1996) indicate, that PROMTHEE methods must only be applied when:

- expression of preferences on ratio scales is possible
- all criteria can be taken into account
- the difference between evaluations is meaningful
- there is no opportunity for discordance.

Appendix 5 Mineral Exploration Criteria Fulfillment

Table 68 Mineral Exploration – Case Relevance

Criteria	Description
Degree of coverage of physical parameters	The sum of tasks aims to achieve the common goal of discovery within a given time and fund. Different disciplines work together to enhance the confidence about the knowledge of a surface and subsurface structure through these tasks. Among these disciplines are geology, geochemistry, petrophysics, hydrology and geophysics. While geologists and geochemists work by analyzing rock samples either visually in the case of a geologist or regarding the material character (geochemist), other disciplines work with techniques able to infer the subsurface. Acquiring data can be performed on different platforms. These platforms range from space borne or airborne platforms such as satellites, helicopter (Haldar, 2018) and UAS's (D'Alessandro et al., 2015) to ground surveys, performed stationary or by foot (Haldar, 2018). Higher altitudes allow for a greater volume of subsurface structure to be covered by one measurement, reducing resolution. In general, surveying starts with higher altitude equipment and subsequently narrows the distance to the target area as confidence about the geologic structure grows. Despite the positive correlation associated with sensor proximity, the highest proximity is neither always feasible nor necessarily yields optimal results. For example, most electrical methods require electrical induction which challenges their aerial application. Regarding the active wavelength-based method, closer proximity may cause more short wave response, leading to signal distortion. Noise refers to natural inhibitors such as terrain, topography or other sources of distortion. Noise results in the contamination of the data with unwanted information. In a complex and unpredictable environment, one cannot eliminate unwanted details beforehand. The data processing stage clears the data from noise. Yet, this procedure cannot eliminate all noise unless one can overcome the geophysical paradox. (Dentith & Mudge, 2014)
Connectedness and transferability of technologies and player in the field	As the work of Kesselring et al., (2021) shows, there are similarities between industries when characterizing surfaces and subsurface properties. The application range of technologies in mineral exploration and related sectors is bounded by the target's physical properties (such as spectral reflectance). Much sensing equipment has its origin in defense or aerospace (Holmes, 2015). Beyond the origin, fields as diverse as archaeology, agriculture and arts use sensing equipment in mineral exploration. For a complete record of the application range of mineral exploration equipment, please refer to Kesselring et al., (2021). In addition to the sensing devices themselves, platforms employed in mineral exploration have multiple usage scenarios. Driven by the miniaturization of technologies and initially used for military operations, aerial photography and monitoring now operate UASs (or drones). UAS's receive substantial attention in R&D. In mineral exploration, researchers have identified multi-system applications allowing for the more efficient exploration, whereby the system is potentially beneficial in the surveillance of mining operations or other geotechnical problems (Heincke et al., 2019). Such innovations are not limited to mineral exploration. Still, Elsahragty and Kim (2015) argue that the evaluation of new and adapted concepts for using UAS-based multi-sensor observation and monitoring methods can be expected across natural sciences.
The cumulative number of existing test site facilities	In mineral exploration, test sites enable proving a concept and support robustness-, accuracy tests, calibration, and validation (Kesselring, Wagner, et al., 2020). Test sites range from informal places where tests were previously performed and are now exploitation fields (active mines) or administered test sites which cater for performance testing, configuration and improvement to sites serving as a legislative instance (Reford & Fyon, 2000). Per the legislative instance technology developer aiming to bring a new system into the market, must prove that their technology is safe and does not jeopardize Legislations. At Reid Mahaffy (CA), technical staff can develop this proof. Australian test sites primarily enable calibration and testing operations (Australian Society of Exploration Geophysicists, 2016). They offer online booking and provide open access to the available data sets. In contrast, test sites such as the caber deposit are not official test sites. The Caber deposit, located in Quebec, Canada, was used for case studies by several companies but had no official website or is administered by a professional third party. (McMillan et al., 2015; Prikhodko et al., 2010)

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Table 68 continued

The degree of risk imposed through social and environmental challenges	Discovery, extraction, processing of raw materials is fundamental to sustain the energy transition and ensure social welfare. However, mineral exploration is often characterized as destructive and unacceptable (Proctor & MacCallum, 2019). A paradigm shift requires bridging the gap between the requirement for raw materials and the negative image. In recent years, many works were published asking what would make mineral exploration more acceptable and how should activities be designed to increase sustainability. The concept of sustainability in TD is no theoretical concept. In their patent analysis paper Ruiz-Coupeau, Jürgens, et al. (2020) find the legitimate plea to apply less stress to the environment drives innovation activities in mineral exploration. Platforms (e.g., helicopter vs. drones) or the exploration technique (e.g., extraction or sensing) are stressors of mineral exploration. Researchers focused on developing less invasive sensing techniques (Ruiz et al., 2020). There is no one-size-fits-all innovation or sustainability concept that will resolve mineral exploration challenges and contribute positively to sustainability.
Innovative capacity	Given the dependency of humans on mineral resources and their non-renewable nature, the industry's capacity for innovation is a topic of many public funds and stakeholder discussions. Ruiz-Coupeau, Kesselring, et al. (2020) show that the funding intensity coincides with heightened patent filing activities. The authors argue that sustainable technologies are currently on the verge of a growth phase in mineral exploration.

Appendix 6 Technical Framework Component Creation – Sample Description

Table 69 Technical Concept Creation – Sample Description

Expert	Occupational Description	Field of Expertise
E1-4	Academia	Geophysics General
E5-6	Academia	Remote Sensing
E7-8	Academia	Electromagnetic
E9	Academia	Magnetics
E10-11	Academia	Seismic
E12	Academia	Remote Sensing
E13	Academia	Gravity
E14	Academia	Seismic
E15-20	Consulting	Geophysics General
E21	Consulting	Electromagnetic
E22	Consulting	Remote Sensing
E23	Consulting	Gravity, Magnetics
E24	Industry	Gravity, Magnetics
E25	Industry	Geophyiscs General
E27	Industry	Seismic
E28-29	Industry	Electromagnetic
E30-31	Industry	Economic
E32	Industry	Magnetic
E33	Industry	Remote Sensing

Appendix 7 Technical Framework Component Creation – Background

The following outlines provide an explanation to each identified factor (Table 70-72). The explanations are derived from the conducted interviews (see interview evidence Table 73).

Table 70 Technical Framework Factors

Factor	Explanation
Type of commodity	Sensing devices target specific physical properties. These properties differ by commodity. Therefore, the suitability of the commodity dictates the demonstrative power of the tests.
Grade of mineralization	The grade of mineralization can be a proxy for the longevity of the test area, the economic attractiveness of the area beyond testing and the indication for the physical challenges.
Depth of targets	Depth is a physical challenge. Therefore, future technologies likely have to penetrate deeper depth. This has two reasons: (I) most surface deposits are exploited, (II) to decrease the invasiveness of the industry, technologies have to compare with drilling practices that can reach depths of > 20km.
Ore-body geometry	Refers to the geometry of geological features and associates with the current and future challenges.
Size of the area	The directional measurements and the survey design (e.g., flight line planning) require a specific availability of land.
Type of host rock	Host rock is the host for other rocks or mineral deposits and can modify the signal response.
Physical property of the target signature	Target susceptibility is among the primary concerns of the market and or audience. The physical property needs to resonate with the physical properties a system aims to analyze. In this way, technology developers may gain feedback that will help them improve the design or successfully enter the market.
Petrophysical property of the host rock	Petrophysics indicate variations in physical properties. Therefore, knowledge about different rock types and properties can sharpen the geological understanding.
Geological complexity	Albeit decreasing accuracy of the benchmarks (requires sufficiently higher profiling data), the complexity of test sites can add to the economic relevance (complexity of targets will increase in the future) or technology developers may want to avoid complexity to increase the predictability their results.
Structural complexity	
Area is representative for current and future challenges	Representativeness and coverage of challenges dictate the demonstrative value and the economic relevance of the test site.
Climate	Climate can impact vibration, corrosion, emissions, or atmospheric conditions of testing. The stability of climate can allow for iterative testing. Conversely, changing environments can show the versatility of the approach. Instability can challenge the robustness of benchmarks.
Topography	Topography may impact the platform use, survey planning and relevance of the test site.
Cultural and atmospheric noise	Noise levels can impact measurements (e.g., power lines distort the receivers). Depending on the challenge a technology aims to solve, the presence of noise is beneficial or detrimental. Independent of the obstacles, well-mapped noise levels are required.

Table 71 Technical Decision Space – Benchmark Features

Factor	Explanation
Coverage of physical parameter	The number of physical parameters can reduce the ambiguity of interpretation. However, not all technology developers require this factor. For example, some geophysics argued that the comparison of raw data is feasible for some methods (e.g., TEM).
Drillhole data	Proxy for the objectivity of the model space.
Ground-based database	Proxy for benchmark relevance and suitability for a specific (ground-based) technology.
Coverage of airborne surveys	Proxy for benchmark relevance and suitability for a specific (airborne) technology)
Geological model	The geological model provides the context for the benchmark.
Depth the database covers (depth of recorded data)	Proxy for benchmark relevance and suitability for a specific (depth seeking) technology.
Structural data	Proxy for the accuracy of the benchmark. Structural data refer to the geometric representations of elements, boundaries, faults, horizons and intrusions.
Geochemical data	Proxy for the accuracy of the benchmark. Geochemical data detects inter-element relationships and infers geological procedures.
Availability of petrophysical model	Proxy for the accuracy and relevance of the benchmark. Physical properties have complex variations. Petrophysical information expresses these variations. It maps overlapping subpopulations for contrasts and susceptibility.
Ore-reserve model	Proxy for the accuracy of the benchmark.
Geophysical model	Proxy for the accuracy and relevance of the benchmark.
Lithological model	Proxy for the accuracy and relevance of the benchmark. Depending on the hosting sediments, technologies are more or less suitable. For example, the clay content of hosting sediments impacts variations between natural gamma values, the coal and the hosting deposits.
Statistically representative amount of data	A statistically representative amount of data includes relative and absolute measures. Thus, data quantity can yield the most accurate and representative subset of benchmarks.
Age of existing data	Age of existing is a relative measure. The measure includes the degree of data usage (models generated, modified and verified), the average of times the benchmark was used and validity of data collection (statistical/ automated data collection versus manual data collection).
Type of drillhole	Downhole instruments may require different borehole types to demonstrate their capabilities. Hence, it is a proxy for benchmark accuracy and relevance.
Types of techniques and technologies employed to generate the benchmark	Since the benchmarks in a benchmark indicate, the technological progress made. Therefore, at least the benchmark subset against technology is referenced and represents the state of practice in a specific application domain.
Resolution/pixel size of database	Benchmarks must include comparative validations under the required conditions to demonstrate or test the enhancement of spatial resolution.
Accuracy and preciseness of database	Seizing the actual reality of data is a challenging assignment. Seizing has absolute accuracy and relative accuracy. Relative accuracy is the assumed accuracy across the range of systems and subsystems that generated the benchmark. Absolute accuracy describes how well single entities of the benchmark cover the characteristics of the area and the entire benchmark.
Preciseness of database	Distribution of data across the benchmark suite.
Data formats are industry standard	The benchmark should be comparable to facilitate the computation of tests across technology developers.
Data collection was performed by suitably qualified professionals	Competent staff should have performed data collection and reporting. In mineral exploration, several codes of conduct and certificates for such experts exist.

Table 72 Technical Assessment Factors – Socio-Economic; Ecological; Logistical Factors

Factor	Explanation
Stability of government	This factor refers to the likelihood of instability for landowner and governance change. The stability of governments is a measure of broad concept (e.g., country values are aggregated). Therefore, interpretation of this factor requires caution.
Government support for TD	Funding may help SMEs and entrepreneurs to perform costly tests. In addition, government support for entrepreneurs can support the occupation rate of the test site and, thereby, the absorptive capacity of regions (Kesselring et al., 2021).
Clear landownership	Landownership of the test area and neighboring areas can impact the longevity of test sites and avoid conflicts.
Level of bureaucracy	The level of bureaucratic clarity helps to start and maintain operations at a test site. However, circumventing unclear bureaucratic procedures is but one resource-intensive act.
Availability or easiness to obtain flying permits	
Ability to publish data	Landownership often limits the ability to publish data. Said ability is a necessity for the development of proof of concepts. Nuances of this factor may include the ability to post location-independent data only.
Duration of license	Especially for iterative demonstration, proof of concepts requires prolonged duration for land and air use is favorable. However, the uncertainty of land use duration may decrease the attractiveness of an area.
Strong intellectual property rights	Intellectual property rights for radically innovative processes must be ensured.
Acceptance of local community	Acceptance, if known, can help the screening of social sustainability and facilitate due diligence for responsible and socially acceptable projects.
Image of mineral exploration and related activities	The image of an industry or sector is a significant risk to test site projects. It is increasingly accepted as being intrinsically linked to the social performance of a project and or company.
Proximity to airborne landing and take-off facilities	Proximity to take-off facilities can impact the cost of a campaign and the ease of reinvestigation / troubleshooting.
Proximity to platform maintenance	Especially for sensitive equipment, maintenance and ground process may add to the value of a test site. In addition, handling sensitive material, e.g., hydrogen, may become more relevant as time progress.
Accessibility by road	Determines the scope of additional equipment and the accessibility (e.g., transportation for personnel and equipment). Of particular relevance for heavy machinery or equipment that requires safe passage (e.g., helium-cooled FTMG) or is very sensitive.
Proximity to hotels	
Proximity to airport	
Availability of business services (e.g., consulting)	Entrepreneurs and SMEs may require additional experts for flight planning, interpretation, calibration etc.
Environmental condition (fauna, flora)	Sharing spaces in the public domain requires knowledge about protected species and measures to prevent invasive testing. Preventive measures can restrict the freedom to operate.
Safety standards may be followed	Safety standards can prevent invasive behavior. Safety standards aid the reputation of the test site as being environmentally acceptable. Respectively, the case study may align with companies' environmental, social governance.

Table 73 Technical Framework Component Creation – Interview Evidence

	Factor	Interview Evidence
Test Target Features	Type of commodity	"Depending on the industry and the techniques, some commodities are more relevant than others."
	Grade of mineralization	"Grade of mineralization is very important, especially for industries and stakeholders. It may stand for the longevity of the test area as well as the interest in the community to test."
	Depth of targets	"Deep is anything beyond 500m"; "“deep” depends on the system being tested, the target type it is designed for, etc. It can be anything from 1m to 1000m."; "[..] test sites must provide the ground for benchmarking depths."
	Ore-body geometry	"It’s the geometry of geological features. So it’s the shape of targeted feature. If you have the same feature whether it’s flat, or vertical, or tilted or something may give completely different responses in geophysics."
	Size of the area	"The area should be three times the anomaly size: to establish background."
	Type of host rock	"Rock properties are going to tie your geology to your geophysics."
	Physical property of the target signature	"You bring in rocks of the type you are wanting to measure and measure their actual physical properties."
	Petrophysical property of the host rock	"The technical problem is also is seeing the target through the host rock noise, this includes the physics of the target and host rock."
	Geological & structural complexity	"Complex geology and structures are increasingly required because the earth is not a simple system."; "Complexity comes down to interpretation."
	Area presents current and future challenges	"Challenging is the important thing. The environment has to be appropriate for the particular problem that people are seeking to solve at the time."
	Topography	"[..] if it is gravity accurate heights / topography are needed."; “There is certain geological methods that are difficult in mountainous areas."
	Cultural noise; Atmospheric noise	"Noise depends on the stage and the objective of your campaign, initially you want to determine how to get rid of the noise. Later you might favor an easier environment.”; "Noise is valuable to show how well you cope with an anomaly."; "Infrastructure may influence the geophysical response."
	Proximity to economic ore body	"[..] proximity to an economic ore-body may increase the attractiveness of the site from a commercial perspective."
	Climate	"[..] you want stable climatic conditions, so that comparability is given."
Socio-Economic Factors	Government stability	"Longevity of a test site requires stable socio-political environments."
	Government support for technology development	"Especially small SME's might require support for their test procedures. With support monetary or technical support may work."
	Clear landownership	"[..] the airspace is often public but - lands, the access is critical because the permits are bound to landowner, for one line you need so many permits that is in-deed a big limitation."
	Level of bureaucracy	"The higher the levels of bureaucracy, the less attractive a test site. Just imagine waiting for a permit while another’s innovation is already marketed"; "Legislative barriers are a tough thing to fix, especially in the EU, because of the number of subsets of legislative controls."
	Availability or easiness to obtain flying permits	
	Ability to publish data	"Reprocessing or modelling the data for new purposes must be possible."
	Duration of license	"You want to make sure that retesting is possible, the longer the license holds, the better the institutional sustainability of the test site."
	Strong intellectual property rights	"For innovation, intellectual property is always an issue. Especially if you want to re-test something, you have to ensure intellectual property"
	Acceptance of local community	"Acceptance and approval are equally important as cooperation and trust to minimize risk"; Public acceptance, combined with legislation, are essential."
	Image of mineral exploration / related activities	"[…] the main barrier of exploration is a mixture of public acceptance, combined with legislation, you have to make sure that your operations are socially credible."

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Table 73 continued

	Factor	Interview Evidence
Benchmark Features	Coverage of physical parameter	"Ideally, you then have different sites, with different physical parameters and settings."
	Drillhole data	"[..] having geology and properties and boreholes and then you can launch your geophysics."
	Ground-based database	"[..] for ground-based methods, you want something comparable."
	Structural data	"[..] wherever detailed structural analysis is aimed for, oriented cores are an effective proxy."
	Geochemical data	"Geochemical map contains information critical for mineral exploration."
	Petrophysical model	"As we go deeper reliance on geophysical data increases. Petrophysical datasets associated with altered rocks show complex variations. Reflecting of combined effects increases the understanding of the geology."
	Ore-reserve models	"An accurate orebody model is the basis of any resource estimations."
	Geophysical model	"We cannot produce a robust quantified assessment of the performance just based on the geological model. [..] geological model is just a representation of reality, and it is not perfect."
	Lithologic model	"[..] for surface methods the physical characteristic of the outcrop is vital."
	Geological model	"[..] geological models that provides information about the lithological, facial, and stratigraphic structure of the geological subsurface."
	Depth the database covers (depth of recorded data)	"[..] the idea is as you test, you want to go deeper in your development and then you can go back to your test site again."
	Coverage of airborne surveys	"[..] that is your goal you want to go over existing airborne-data."
	Statistically representative data	"The more data there is the more developer may find a site attractive."
	Age of existing data	"Age depends - if things have changed / improved since the data were acquired."; "Age [..] is not so interesting, unless it is before GPS."
	Type of drillhole	"You want access to boreholes and to know their type to check for validity."
	Types of techniques and technologies employed to generate the reference database (as a proxy for resolution)	" [..] developers want to show what they can do better, than someone else. Also, the more recent the techniques the better the assumed quality and the more attractive the benchmarks"; "You want something with multiple technologies."
	Resolution / pixel size of database	"Decimating the test range data allows for comparison."
	Accuracy and preciseness of database	"Accuracy is crucial, it refers to a measure of quality that indicates whether the obtained data is close to its true value."
	Preciseness of database	"Preciseness is a repeatability measures within a sensitivity scale."
	Data formats are industry standard	"For third parties to access and assess data sources and processing steps must be traceable and aligned to industry standards."
	Data collection was performed by suitably qualified professionals	"Renowned procedures such as QAQC procedures enable problem solving."
	Data processed by a renowned expert	"Record methods and assumptions used when producing models from the data."

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Table 73 continued

	Factor	Interview Evidence
Logistical Factors	Proximity to airborne landing and take-off facilities	"[…] flying distance from the airfields where the aircraft are based."
	Accessibility by road	"Reasonable driving distance/time in the case of ground measurements."
	Proximity to platform maintenance	"Proximity to aircraft infrastructure i.e., local airport with workshops and maintenance facilities."
	Proximity to hotels	"The site needs to be reasonably close to civilization – hotels, airports, are convenient when enclosed."
	Proximity to airport	
	Availability of business services (e.g., consulting)	"We come from physics we are no experts in exploration, to test means to talk and be available to consult experts that may provide such things like helicopter or help us work out survey design."
Ecological	Environmental condition (fauna, flora)	"Potential impacts must be as small as possible, land clearance and must be in balance. Customer become sensitive to such issues."
	Safety standards may be followed	"[…] if you need to deploy for a long time then safety becomes an issue."

Appendix 8 Technical Framework Component Creation – Questionnaire Design

According to Joshi et al. (2015), the symmetric Likert scale, whereby the averages lie between the maximum and minimum response, is most suitable to synthesize participants' stance.

Traditionally Likert rankings may include 5-, 7-, and 10-Point scales. The most common approach is the 5-Point scale. Compared to the higher point scales, 5-Point scales answers are more gradually than radically different. Often scholars argue that larger-scale ranges enable people to pick the exact scale rather than "the nearby" option, which provides higher validity and lower ambiguity when experts are asked about a topic (Joshi et al., 2015). In the present case, the factors identified were initially proven relevant by the comparably high expert sample during the qualitative factor analysis. Judgment about the overall relevance, meaning a large scale in the negative spectra, is deemed unnecessary. Options close to the original expert's interviews reduce ambiguity in the responses. Therefore, the present study builds on a 5-Point Likert scale with not important, slightly important, important (average), very important, indispensable. In addition, respondents were able to state, "I don't know". The "I don't know" option improves the overall response quality while reducing forced answers in a topic where the respondent shows lower expertise. As the scale is no longer closed, the inclusion of a non-disclosing reply is a controversially discussed topic. However, leaving out the non-disclosing response leads to forced answers which are ethically and statistically sensitive. To rightfully handle "I don't know" the answer, scholars suggest missing data through single imputation, multiple imputation or maximum likelihood. Due to the upscaling of single factors, biased result are expected, in case the data is not missing at random. Indicators for the type of missing data (e.g., random) arise if respondents are more likely not to answer a query founded on what their response to that query would have been. However, such constructs are mainly used for sensitive topics in social sciences. The current issue does not classify as such given the respondents professional expertise.

Consequently, "I don't know" may be treated as a missing variable without the need to impute data and cause unintended bias. Statistical programs such as R denote the missing value category with the NA package and run the analysis in the presence of missings. Summing up the theoretical survey consideration, the survey combines the advantages of context and construct validity while enabling high usability concerning the time and memory span required to answer the means presented.

Appendix 9 Technical Framework Component Creation – Study Demographics

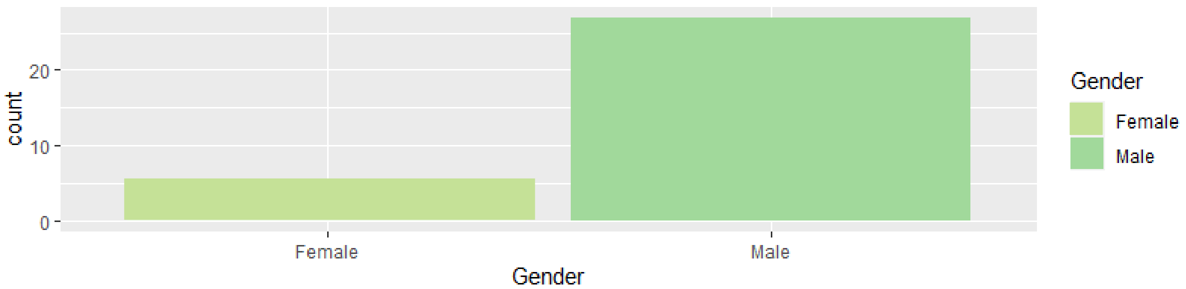

Figure 45 Gender Distribution

Appendix 10 Technical Framework Component Creation – Quantitative Survey Output

Table 74 Technical Framework Component Creation – Quantitative Survey Output

	N	Mean	Std. Dev.	Min	Pctl. 25	Pctl. 75	Max
Ecological condition	48	3.167	0.883	1	3	4	5
Climate	49	2.49	0.982	1	2	3	5
Topography	49	3.143	0.791	1	3	4	5
Vegetation	49	2.449	1.138	1	2	3	5
Cultural noise	48	3.875	1.044	1	3	5	5
Atmospheric noise	45	3.067	1.105	1	2	4	5
Statistically representative amount of data	46	4.022	0.774	2	4	5	5
Coverage of physical parameter	43	3.744	0.79	1	3.5	4	5
Statistically representative amount of data	45	4.022	0.988	1	3	5	5
Coverage of physical parameter	43	3.744	0.79	1	3,5	4	5
Availability of drillhole data	45	4.022	0.988	1	3	5	5
Availability of ground-based database	45	3.800	0.894	1	3	4	5
Coverage of airborne surveys	45	3.644	0.773	2	3	4	5
Availability of a geological model	45	3.756	1.131	1	3	5	5
Depth the database covers (depth of recorded data)	43	3.512	0.736	1	3	4	5
Availability of structural data	44	0.943	0.943	1	3	4	5
Availability of a geochemical data	45	2.933	0.986	1	2	4	5
Availability of a petrophysical model	44	3.364	1.059	1	3	4	5
Availability of ore-reserve models	44	2.5	0.928	1	2	3	5
Availability of oriented core	45	2.156	1.167	1	1	3	5
Availability of lithologic model	44	3.136	1.091	1	3	4	5
Age of existing data	45	2.822	0.806	1	3	3	4
Type of drillhole	43	2.628	1.024	1	2	3	5
Types of techniques and technologies employed to generate the reference database	44	3.614	0.841	2	3	4	5
Resolution/pixel size of database	44	3.682	0.708	2	3	4	5
Accuracy of database	44	4.182	0.786	3	4	5	5
Robustness of database	44	3.955	0.806	2	3	5	5
Well-defined contacts	44	3.455	0.848	2	3	4	5
Well-defined overlayer	45	3.267	0.809	1	3	4	5
Well-defined surface features	43	3.163	0.814	1	3	4	5
Data formats are industry standard	43	3.605	1.072	1	3	4	5
Software the data is processed with	43	2.977	1.080	1	2	4	4
Was the data processed by suitably qualified / experienced professionals	43	4.186	0.932	2	4	5	5
Was the data processed by a renowned expert	42	2.500	1.153	1	2	3	5

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Table 74 continued

Test Target Features							
Type of commodity	40	3.775	0.862	1	3	4	5
Grade of mineralization	41	3.122	0.954	1	3	4	5
Depth of targets	41	3.756	0.699	2	3	4	5
Ore-body geometry	41	3.293	0.873	1	3	4	5
Characteristics of geometry	40	3.300	0.911	1	3	4	5
Type of host rock	41	3.561	1.001	1	3	4	5
Physical property of the target signature	40	4.200	0.723	2	4	5	5
Petrophysical property of the host rock	40	4	0.716	2	4	4	5
Geological complexity	40	3.675	0.616	2	3	4	5
Structural complexity	40	3.600	0.672	2	3	4	5
Size of the area	41	4.341	0.693	3	4	5	5
Geological noise	45	3.067	1.095	1	2	4	5
Proximity to economic ore body	49	3.633	1.395	1	3	5	5
Safety	49	4.327	0.944	2	4	5	5
Area is representative for current and future challenges in mineral exploration	49	4.306	0.871	2	4	5	5
Socio-economic factors							
Stability of government	40	3.625	0.705	2	3	4	5
Government support for technology development	40	2.425	1.318	1	1	3.25	5
Bureaucracy	40	3.150	0.834	1	3	4	5
Duration of license	40	3.650	0.864	1	3	4	5
Clear landownership	39	4.231	0.959	1	4	5	5
Availability or easiness to obtain flying permits	41	4.317	0.85	2	4	5	5
Ability to publish data	40	3.850	1.406	1	3	5	5
Strong intellectual property rights	37	3.432	1.168	1	3	4	5
Acceptance of local community	40	4.350	0.736	3	4	5	5
Image of mineral exploration and related activities	39	3.410	0.938	1	3	4	5
Logistics							
Proximity to airborne landing and take-off facilities	41	3.317	0.850	2	3	4	4
Proximity to platform maintenance	40	2.725	0.877	1	2	3.25	4
Accessibility by road	41	3.415	0.921	2	3	4	5
Proximity to hotels	41	2.415	0.805	1	2	3	4
Proximity to airport	41	2.488	0.84	1	2	3	4
Availability of business services (e.g., consulting)	41	1.878	1.029	1	1	2	5

Appendix 11 Social Sustainability Framework Component Creation – Focus Group

One-on-one interviews or questionnaires are standard in the existing research (Williamson & Christina, 2013). Conversely, group interaction is valuable to capture different viewpoints and perspectives of complex and context dependent topics (Bristol & Fern, 1996; Ho, 2006). An approach previously used in social perception and acceptance of sustainable technologies are focus groups (Arning et al., 2020; Caporale et al., 2020). Focus groups employ a series of meetings with a group of individuals. During the meetings, around 3-21 experts meet to discuss the topic of consideration (Nyumba et al., 2018). Tang and Davis (1995) suggest that group sizes rise with the number of questions and the duration of the meeting and decrease with the degree of expertise of the participants. The selection of participants is a crucial determinant for the value of the discussion. For scientific rejection or confirmation of research, authors such as Nyumba et al. (2018) suggest choosing participants with high expertise in the subject at hand. Thus, discussions will happen on higher levels of objectivity rather than being driven by subjectivity. Dialogue can be structured or unstructured. Unstructured discussion often starts with a single opening question and are free to progress from the initial set-up (Nyumba et al., 2018). Thus the participants can explore a topic in-depth, ask a question, exchange anecdotes and comment on one another's experiences and views (Nuttavuthisit, 2019). The literature review revealed that social sustainability is a topic shaped by knowledge, experience, own thoughts and the thoughts of others (Hooey, 2016).

Table 75 illustrates the characterisctics of the focus group.

Table 75 Focus Group Experts Characteristics

No.	Level of expertise	Field of expertise
1	Senior experts	Communication and Dialogue
	Senior experts	Social Engagement
	Senior experts	Risk Management
2	Senior expert	Social Engagement
	Junior expert	Communication and Dialogue
	Junior expert	Resource Governance

Appendix 12 Ecological Framework Component Creation – Research Strategy

Table 76 Ecological Framework Component Creation – Research Strategy

No.	Step	Properties
1	Specification of research objective	Calculate a worldwide-pooled estimate of disturbance Determine factors that describe the disturbance of platforms to fauna Include only platforms used in exploration [31]
2	Identify search strategy and set quality standards	Quality criteria: only peer-reviewed paper Search engine: WoS was used as a database. Compared to, google scholar, WoS performs citation based searches rather than full text searches, which increases the quality of the outcome and increases search effectiveness. Four search categories were employed [1] 3.1 "helicopter" AND "wildlife" AND "disturbance"; "helicopter" AND "fauna" AND "disturbance" ; "helicopter" AND "mammals" OR "birds" OR "Invertebrates" OR "amphibian" OR "reptiles" AND "disturbance" 3.2 "UAV" AND "wildlife" AND "disturbance"; "UAV" AND "fauna" AND "disturbance" OR "reaction"; "UAV" AND "mammals" OR "birds" OR "Invertebrates" OR "amphibian" OR "reptiles" AND "disturbance" 3.3 "fixed-wing" AND "wildlife" AND "disturbance" ; "fixed-wing" AND "fauna" AND "disturbance"; "fixed-wing" AND "mammals" OR "birds" OR "invertebrates" OR "amphibian" OR "reptiles" AND "disturbance" 3.4 "pedestrian" OR "walker" OR "hiker" AND "wildlife" AND "disturbance" ; "pedestrian" OR "walker" OR "hiker" AND "fauna" AND "disturbance"; "pedestrian" OR "walker" OR "hiker" AND "mammals" OR "birds" OR "invertebrates" OR "amphibian" OR "reptiles" AND "disturbance"[32] 4) Search strategy: Step 1. Check titles for their research object. Titles that merely employed the disturbance source for species observation were excluded. Step 2. Quality check (paper peer-reviewed) Step 3. Abstracts were reviewed in accordance with the following criteria: 1) Originality of research 2) assessment of species reaction to one of the disturbance sources Step 4. Paper analysis
3	Extract and consolidate study-level data	Data extraction from relevant studies Collection of study-level characteristics and experimental covariates Clustering data into Excel. Extracted data were: a) species b) degree of reaction c) disturbance source, -weight (in kg), -length (in m), -rotor diameter (in m), -wing span (in m), distance to species at measured reaction (in m), volume level in (dB)
4	Data appraisal and preparation	Selection of Rstudio as data analysis tool Regression Analysis
5	Synthesize study-level data	Synthetization of disturbance data into disturbance analysis

[31] The study only includes UAS rotary systems. Other platforms (e.g., hybrid aerial vehicles) are currently not subject to earth observation. The parameter increases the validity of the follow-up evaluation. An explanation for the validity increase is that rotary UAS work within comparable noise spectra. Other propulsion systems operate on different noise levels / and colors.

[32] Groundworker reactions included the categorization of distances.

Appendix 13 Ecological Framework Component Creation – Statistical Models

Table 77 Ecological Framework Component Creation – Classification of Statistical Models

Classification – Relative quality of statistical models	
AIC	The AIC is used to compare different model candidates. This is done using the value of the log-likelihood. The higher the value the model better the model explains the dependent variable. In addition to the log-likelihood the number of estimated parameters is also included as a penalty term. In this ways the model avoids classifying a more complex model as consistently better. The AIC is no absolute measure of quality. A poor fit to the data is remains possible for the model with the best AIC fulfillment. Compared to alternative models the fit is merely better (Sakamoto et al., 1988).
Confusion Matrix	The confusion matrix is a measure to solve classification problems. Confusion matrices signify amounts from predicted and definite values. Among others, the confusion matrix measures the accuracy of classification. The accuracy estimate builds on the number of falsely and rightly classified polarities. The notation for these dependencies is as follows: true negatives (TN) and true positive (TP) are the numbers accurately classified negative and positive examples, respectively. Similarly, false positives (FP) and false negatives (FN) indicate falsely classified polarities. The formula below measures the accuracy of a model (through a NxN confusion matrix): $$ACC = \frac{TN + TP}{TN + FP + FN + TP}$$ Other measures for classification accuracy are the classification error $(1 - ACC)$, recall, precision and the Matthew Correlation Coefficient. ACC is most commonly used, to reporting classification performance. According to Beauxis-Aussalet and Hardman (2014) the popularity roots in the ease of use and comparability. For the present analysis, ACC therefore fits.
kNN	In a robustness check, non-parametric identification is pursued through the kNN. It is used to analyze the plurality of k objects nearest to another object. The object is assigned to the objects most common among its kNN. For k = 1, the object is assigned to the class of a single nearest neighbor. (Beauxis-Aussalet & Hardman, 2014)
Distribution Analysis	The model can show different distributions of the error term. To analyze the distribution, two different distributions were examined, the normal distribution close to Gauss and the Poisson distribution. The distribution of the comparison values forms the basis of the significance test in the analysis carried out. (Urban & Mayerl, 2011)
Regression Analysis	
Multilinear Regression	Linear regression analysis created a model that describes the relationship between a dependent variable (Y) and one or more independent variables (X). The results of an OLS can be depicted concretely and without complicated interpretation. The calculated parameters of the linear regression can be used to make statements about significance (p), model fit (R^2) and average change per unit (β). (Best & Wolf, 2010).
CATREG	Categorical regression (CATREG) enumerates categorical data by allocating mathematical values to the categories (Heong et al., 2002). This results in a linear regression equation for the transformed variables. In the ordinal regression model, we assume a dependent variable with several categories, whereby an order of the categories can be reasonably formed. Compared to the linear regression model, the modelling of the category probabilities changes. The study analyzes the relationship between the height of a variable and the category of the target variable. The more significant (or smaller) the relationship value, the greater (or smaller) the probability of it falling into a higher category. CATREG is particularly useful when dealing with datasets with a combination of nominal, ordinal and interval variables (D. Zhang et al., 2016). The data analyzed in this study are categorical, ordinal, and interval, which presents several limitations when using the OLS. Limitations result as OLS relies on linearity, normality, homoscedasticity and independence of error terms. (Xu et al., 2015). The main argument that justifies the use of CATREG analysis in this context is that it identifies the relative importance of the explanatory variables. It does this via an ideal scaling process to scale the dependent and independent variables. (Urban & Mayerl, 2011)

Appendix 14 Distribution Analysis

Figure 46 shows the regression fit analysis as basis for the best unbiased linear estimator analysis.

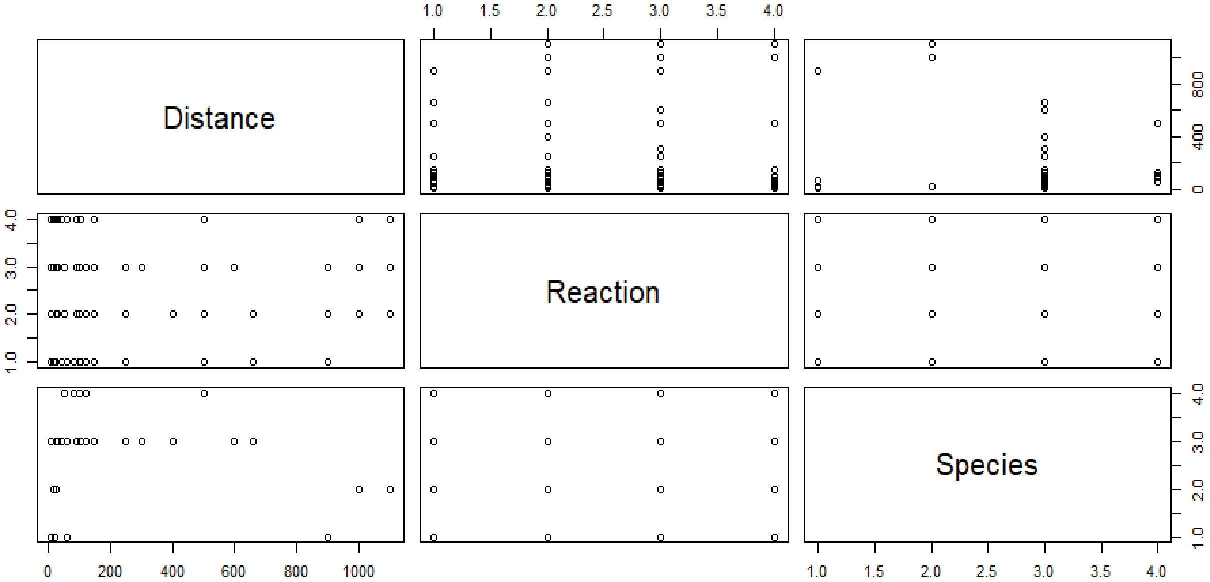

Figure 46 Regression Fit Analysis for Outcome Reaction

Figure 47 illustrates the reaction of different species to helicopters.

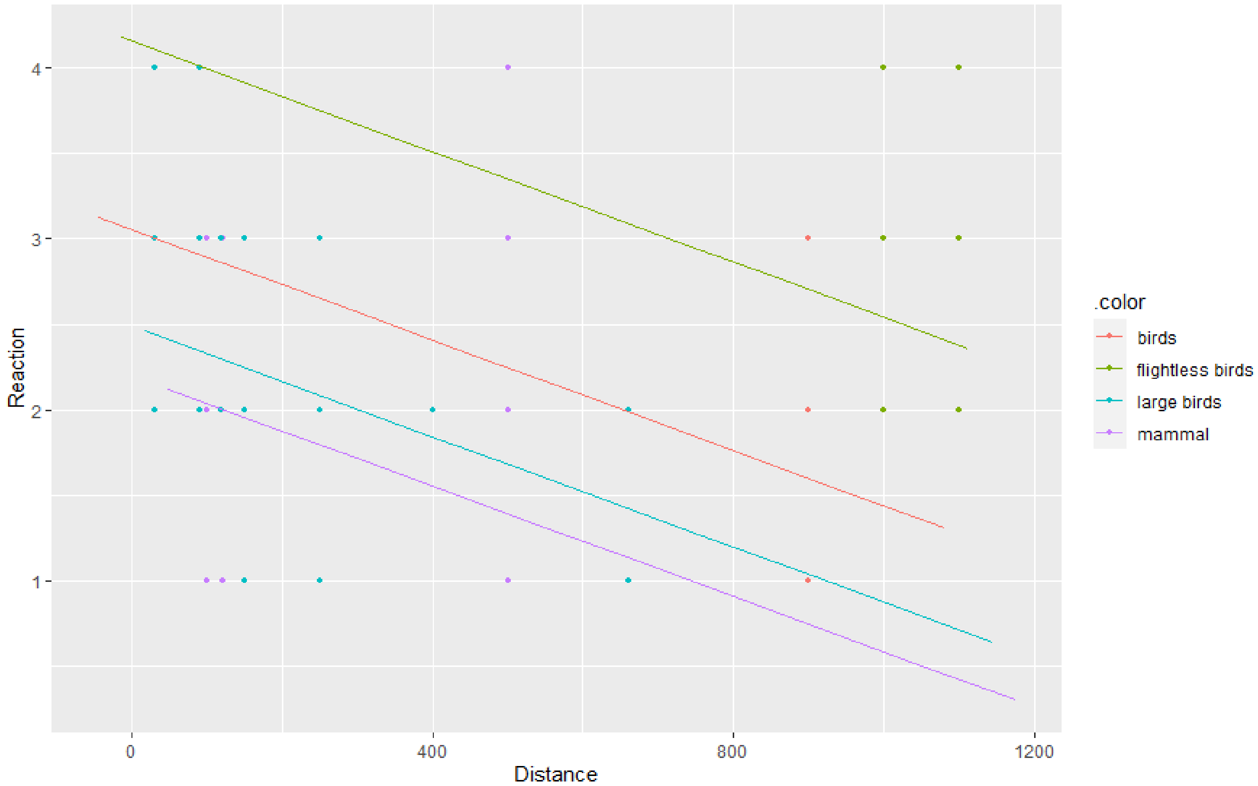

Figure 47 Multilinear Regression for Helicopter

Table 78 displays the respective statistics.

Table 78 Multilinear Statistical Analysis for Helicopter Regression Model

Residuals			
Min	Median		Max
-1.2464	-0.3785		2.6068
Coefficient			
	Estimate	Std. Error	t value
Distance	-0.0016129	0.0001348	-11.964
Flightless birds	1.0991921	0.0806272	13.633
Large Birds	-0.5652747	0.1246715	-4.534
Mammal	-0.8538784	0.1002225	-8.520
Residual standard error: 0.7306 on 1694 degrees of freedom			
Multiple R-squared: 0.2986, Adjusted R-squared: 0.2969			
F-statistic: 180.3 on 4 and 1694 DF, p-value: < 2.2e-16			

Figure 48 shows the results of the multilinear regression for the dependent variable reaction and the independent variable species, distance, and groundworker.

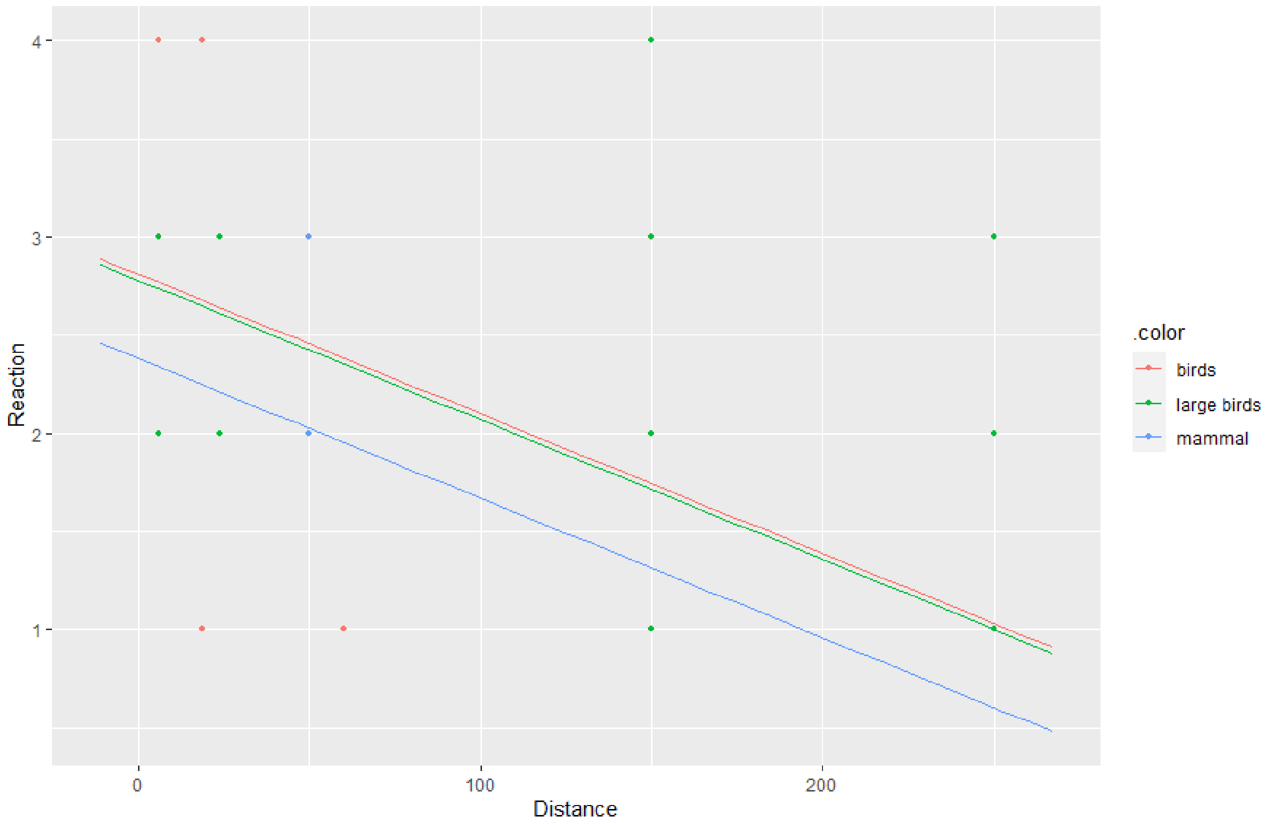

Figure 48 Multilinear Regression for Groundwork

Table 79 displays the respective statistics.

Table 79 Multilinear Statistical Analysis for Groundworker Regression Model

Residuals			
Min	Median		Max
-1.67646	-0.00079		2.28701
Coefficient			
	Estimate	Std. Error	t value
Distance	2.8117787	0.0367524	76.506
Flightless birds	-0.0071220	0.0003088	-23.067
Large Birds	-0.0304874	0.0584984	-0.521
Mammal	-0.4300364	0.1661900	-2.588
Residual standard error: 1.013 on 2107 degrees of freedom			
Multiple R-squared: 0.2991, Adjusted R-squared: 0.2981			
F-statistic: 299.7 on 3 and 2107 DF, p-value: < 2.2e-16			

Table 80 displays the statistics for the UAS Regression Model.

Table 80 Multilinear Statistical Analysis for UAS Regression Model

Residuals			
Min	Median		Max
-1.5300	-0.3113		2.5269
Coefficient			
	Estimate	Std. Error	t-value
Distance	-0.1057	0.0107	-9.874
Large Birds	-1.9585	0.1465	-13.367
Mammal	5.7096	0.6916	8.256
Residual standard error: 0.743 on 452 degrees of freedom			
Multiple R-squared: 0.3315, Adjusted R-squared: 0.3271			
F-statistic: 74.73 on 3 and 452 DF, p-value: < 2.2e-16			

Table 81 displays the statistics for the Fixed-Wing Regression Model

Table 81 Multilinear Statistical Analysis for Fixed-Wing Regression Model

Residuals			
Min	Median		Max
- 0.7372	0.000		1.2628
Coefficient			
	Estimate	Std. Error	t-value
Distance	1.737e+00	2.599e-01	1.24e-10
Birds	5.386e-17	2.846e-04	0.000
Large Birds	1.263e+00	1.444e-01	0.000
Residual standard error 0.5201 on 283 degrees of freedom			
Multiple R-squared: 0.5979, Adjusted R-squared: 0.5951			
F-statistic: 210.4 on 2 and 283 DF, p-value: < 2.2e-16			

Table 82 displays the statistics for the Gauss Distribution.

Table 82 Model 1 – Gauss Distribution

Gauss Distribution			
Min	Median		Max
1.6365	-0.2389		2.5317
Coefficient			
	Estimate	Std. Error	t value
Distance	-3.665e-04	5.165e-05	-7.096
Flightless birds	1.621e-01	5.551e-02	2.920
Large Birds	-5.871e-01	3.872e-02	15.164
Mammal	-8.284e-01	4.691e-02	-17.658
Residual standard error: 0.9967 on 4547 degrees of freedom			
Multiple R-squared: 0.1109, Adjusted R-squared: 0.1101			
F-statistic: 141.7 on 4 and 4547 DF, p-value: < 2.2e-16; AIC: 12895			

Table 83 displays the statistics for the Poisson Distribution.

Table 83 Model 2 – Poisson Distribution

Poisson Distribution			
Min	Median		Max
-1.1688	-0.1575		1.7052
Coefficient			
	Estimate	Std. Error	z-score value
Distance	-1.628e-04	3.449e-05	-4.722
Flightless birds	7.228e-02	3.623e-02	1.995
Large Birds	-2.772e-01	2.641e-02	-10.497
Mammal	-4.346e-01	3.499e-02	-12.422
(Dispersion parameter for poisson family taken to be 1)			
Null deviance: 2462.4 on 4551 degrees of freedom			
Residual deviance: 2181.0 on 4547 degrees of freedom			
AIC: 13549; Number of Fisher Scoring iterations: 4			

Appendix 15 Evaluation Stage Criteria

Table 84 Evaluation Stage – Test Environment

Approriateness of the Test Target Features
Size of the test area
Proximity to an economic ore body
Representativeness for current and future use cases / Appropriateness of the test target
Physical property of the target signature
Type of host rock
Commodity
Geometry
Grade of mineralization
Depth of the target(s)
Geological complexity
Topography
Climate
Absence / presence of non-geologic environmental noise (man made e.g., power lines)

Table 85 Evaluation Stage – Reference Data Set

Approriateness of Benchmarks
Available benchmarks
Availability of drillhole data
Availability of a geological model
Coverage of physical parameters
Coverage of previous surveys (e.g., state-of the art system, to demonstrate the innovativeness of your technology)
Depth the database covers
Accuracy of the (reference-)database
Robustness of (reference-)database
Resolution/pixel size of the (reference-)database
Data on contacts
Data on the overburden
Definition of surface features
Age of existing data
Professionals that collected the data
Data formats (e.g., data formats are industry standard)
Expert(s) that processed the data

Table 86 Evaluation Stage – Logistical Factors

Logistical Factors
How appropriate is the proximity to airborne landing and take-off facilities for your test mission?
How appropriate are logistical connections (e.g., accessibility)?
How appropriate is the proximity to hotels?

Table 87 Evaluation Stage – Ecological Factors

Approriateness of Ecological Conditions
Ecological conditions
Seasonal activities

Table 88 Evaluation Stage – Socio-Economic Factors

Socio-Economic Factors	Answer Categories
How does the local media report on the project?	Adverse; Slightly adverse; Neutral; Slightly in favor; favorable
Which of the following best describes the project ownership?	Sole Ownership; Tenancy Common; Joint Tenancy; Scattered Ownership Structure; Unclear ownership structure
What level of formal approval is required to run the project?	Not Applicable; One-level approval; Two-level approval (e.g., Local and regional approval); Multiple government approval; Multiple-level government and public approval; No decisive approval atructure
What is the status of permit and licensing agreements?	Permits are issued for short-term occupation; Permits are issued for mid-term; Permits are issued for long-term
What is the recognized level of acceptance by communities?	High levels of trust towards the project; Project is co-owned by the community; Approval; Acceptance; Withheld / withdraw
To what degree does the intellectual property regulations meet your requirements?	Exceeds requirements; Meets requirements; Meets the majority of requirements; Meets requirements only partially; Does not meet requirements
Does the ability or limitation to publish the measured data respond to your requirements?	Exceeds requirements; Meets requirements; Meets the majority of requirements; Meets requirements only partially; Does not meet requirements

Appendix 16 Validation Mineral Exploration – Reference Site Description

Finish Reference Site: The Sakatti Reference Site is located in Finish Lapland. Table 89 illustrates the characteristics of the site. The contents are extracted from the INFACT ERS Brochure (2020).

Table 89 Finnland Background Data

Topic	Scope
Industry context	Scandinavia is one of the most attractive area for exploration in the EU. Sakatti discovery was announced by Anglo American in 2009 and is still under their Exploration License. (INFACT ERS Brochure, 2020)
Geological intro	Sakatti is a nickel-copper-platinum group elements deposit located within the Paleoproterozoic Central Lapland Greenstone belt, around 150 km north of the Arctic Circle. The mineralization is magmatic, predominantly ultramafic hosted and consists of massive, disseminated and vein sulphides. The Sakatti deposit includes three distinct bodies of mineralized olivine cumulate called “main body”, “northeast body” and “southwest body”. The northwest-plunging “main body is the largest and deepest of the three, extending to a depth” (p.2) of ca. 1100 m below surface, with a maximum thickness of > 400 m. (INFACT ERS Brochure, 2020)
Reference database	Well-positioned drill holes and geological model; Downhole susceptibility and conductivity; Regional datasets (airborne mag, radiometrics, EM), VTEM and airborne mag (Geotech, 2009), SQUID mag (FTMG, Supracon, 2018), Airborne TEM data using VTEM ET™ system (incl. magnetic and radiometric data) + AIP (INFACT ERS Brochure, 2020)
Technological challenges / opportunities	Deep (>500 m) massive sulphide main orebody; Thin, conductive glacial till cover; Location north of Arctic circle: subarctic climate with short, mild summers and long, freezing, extremely snowy winters. Avg. temperature/precipitation -1.1°C/515 mm; Deposit over a Natura 2000 protected area (Viiankiaapa mire). (INFACT ERS Brochure, 2020)
Social / environmental context	In Finland, the reference municipality of Sodankylä is a sparsely populated municipality with a population density of 0.75 inhabitants per square kilometer. The “economic activities in the area focus around mining” (INFACT ERS Brochure, 2020, p.1), with an active mining industry as well as reindeer herding, forestry and tourism. The reference area of Sakatti, has no active mine and has almost intact environmental features. Most of the territory is covered by conifer forests, marshes and water bodies of high environmental value. Indeed, the reference site is close to Viiankiaava mire, an area protected by the Natura 2000 network and Finnish national mine protection program. Nearby the Sakatti reference site lives the Sami indigenous people’s minority. (INFACT ERS Brochure, 2020)

Geyer Germany: The Geyer Reference Site is located in Saxony, Germany. Table 90 illustrates the characteristics of the site. The contents originate from INFACT ERS Brochure (2020), and informed by literature.

Table 90 Geyer Background Data

Topic	Scope
Industry context	Mining industry has been part of the region for 500 years and the local population is generally supportive of mining-related activities. “Today, forestry and agriculture are the main land uses.” (INFACT ERS Brochure, 2020, p.1). UNESCO World Heritage Site since 2019 (Erzgebirge, 2019).
Geological intro	“The Erzgebirge geographically belongs to the German federal state of Saxony and a small northern stripe of the Czech Republic.” (D2.3, p.27). “Tin-tungsten deposits at the Geyer site in Germany have a late-Variscan magmatic origin and are hosted by a variety of vein structures (stringers, veins, and vein zones) and metasomatic structures (vein-type greisens in the granite exo- and endocontact, stockwork-like greisen bodies, and skarns).” (INFACT ERS Brochure, 2020, p.1). Although laterally extensive (several hundred meters), the thicknesses of the mineralizations are generally small and vary depending on type. In the area of Ehrenfriedersdorf (part of the Geyer site) thicknesses are 6–10 m for stringer zones, 2–10 m for vein zones, <10 cm for vein-type greisens, and 0.2–2 m for skarns. The sulphide and tin mineralisation is genetically and spatially related to the granite pluton, so the maximum depth of the mineralized veins depends on the depth of the granite, which goes from surface to about 1000 m below sea level. (INFACT ERS Brochure, 2020)

Table continues on the next page

Table 90 continued

Reference database	High amount of drill holes and geological model; Petrophysical data (average values from exploration reports); Reference Systems Airborne EM; radiometry, mag (BGR, 2013–14, reprocessed 2018), SQUID mag (FTMG, Supracon, 2014), Hyperspectral VNIR–SWIR (C. Gomez et al., 2015), Ground mag and gravity (1950–1980), SQUID mag (FTMG, Supracon, 2018), Airborne TEM data using VTEM ET™ system (incl. magnetic and radiometric data) + AIP, UAS magnetic. (INFACT ERS Brochure, 2020)
Technological challenges / opportunities	Cultural noise: densely populated, power lines and radio towers; Large forested areas (about 1/2 of area); “Veins and skarn bodies of narrow width and steep geometry” (INFACT ERS Brochure, 2020, p.1); Metamorphic and igneous host rocks with steeply dipping contacts, steep foliation; Local occurrence of highly conductive graphitic layers; Humid continental climate. Avg. temperature/rainfall 6.2°C/728 mm; 300 m of relief; Possible airborne induced polarization effects (INFACT ERS Brochure, 2020)
Social / environmental context	Geyer is located close to a wildlife park.
Logistics	For the test flights, the regional airport Chemnitz-Jahnsdorf has been used as the main base for take-off and landing of the helicopter, for handling and testing of all research equipment and organization of staff. (INFACT ERS Brochure, 2020)

Rio Tinto and Cobre Las Cruces: Two of the four reference sites are located in Andalusia, Spain. The two Spanish Reference Sites are similar concerning the industry and social and environmental context. Table 91 illustrates the characteristics that Rio Tinto and Cobre las Cruces have in common. The contents are extracted from the INFACT brochure (INFACT ERS Brochure, 2020) and informed by literature and field visits.

Table 91 Spanish Reference Sites Background Data

Topic	Scope
Industry context	Spanish reference region includes two reference sites: Cobre Las Cruces and Rio Tinto. Both sites belong to the Iberian Pyrite Belt, “a 300 kilometre long and 80 kilometer wide geologic belt that extends eastward from southern Portugal into southern Spain.” (First Quantum Minerals, 2017, p.28). “The belt is host to more than 100 mineral deposits, some of which were exploited for metals as long ago as the Bronze Age. The Cobre Las Cruces is an open pit copper mine in Seville province while Rio Tinto is an ancient opencast polymetallic mine in Huelva province.” (INFACT ERS Brochure, 2020, p.2)
Social / environmental context	“The Iberian Pyrite Belt is an active mining region with a medium density population.” (INFACT ERS Brochure, 2020, p.2). The centuries-old mining activity has shaped their landscape and local communities. However, it coexists with habitats of environmental value (INFACT ERS Brochure, 2020).

Cobre las Cruces: Despite the spatial proximity the Rio Tinto and Cobre Las Cruces differ in terms of the industry context, geology as well as the technical challenges and the logistics. Minas de Rio Tinto is an ancient opencast polymetallic mine. Located in Huelva province, the site is operated by Atalaya Mining. Table 92 illustrates the characteristics of Rio Tinto. The contents are extracted from the INFACT ERS Brochure (2020) and informed by literature and field visits.

Table 92 Rio Tinto Background Data

Topic	Scope
Industry context	Since 2014 this historic mine has been operated by Atalaya Mining PLC which produces copper concentrates from mineralization with a grade of ca. 0.42% Cu. (INFACT ERS Brochure, 2020)
Geological intro	The Riotinto mining district is located inside the Iberian Pyrite Belt. It is one of the largest concentration of sulfide in the world. Mined probably since pre-Phoenician time, the Rio Tinto mine produced around 700 Mt at an average grade of 0.40% Cu. Volcanogenic massive sulfide (VMS) deposits is characterized by a large stock. Geophysical data suggest a possible extension of the ore body to the east and west. (INFACT ERS Brochure, 2020)

Table continues on the next page

Table 92 continued

Technological challenges	High levels of cultural noise; Several large graphitic shale lenses; Active mining environment; Tailings; Hot summer Mediterranean climate. Avg. temperature / rainfall 16.5°C / 581 mm. (INFACT ERS Brochure 2020)
Reference data	representative drill holes; Downhole density, resistivity for drillholes and in-situ; Airborne mag and radiometry (Sanders, 1996–97), Ground AMT (Geognosia, 2015–17), gravity (various), AEM (VTEM–Max, GFEM), Airborne magnetic (ZTEM), Ground gravity, UAS magnetic, hyperspectral. (INFACT ERS Brochure, 2020)
Logistics	The site is located in Huelva province, 65 km northwest of Seville (1h car ride from Seville airport). The availability of hotels in Huelva is limited.

Similar to Rio Tinto, Cobre las Cruces is an active open-pit mining sites in the Iberian Pyrite Belt. Cobre Las Cruces operates an on-site plant and is operated by First Quantum Minerals. Table 93 illustrates the characteristics of Cobre las Cruces, the contents are extracted from the INFACT brochure and informed by literature and field visits.

Table 93 Cobre las Cruces Background Data

Topic	Scope
Industry context	"Las Cruces is owned by First Quantum Minerals", average copper grade at this opencast mine is 5%, operations began in 2009 (INFACT ERS Brochure, 2020, p.2).
Geological intro	The Las Cruces VHMS deposit is located at the eastern margin of the Iberian Pyrite Belt. The "deposit is composed of a polymetallic massive sulfide orebody, a Cu-rich stockwork and an overlying supergene profile that includes a Cu-rich" (Yesares et al., 2016, p. 377) secondary ore and a gossan cap. "Cobre Las Cruces is a blind deposit with no outcrop because of the 50 to 200 metres of sedimentary marls overlying the deposit" (Gray et al., p.10). "A regional saline aquifer from 0-10 m thick sits at the interface between marls and basement volcanic." (INFACT ERS Brochure, 2020, p. 2)
Technological **challenges**	Conductive marl cover from 50 to 200 m with 0-10 m thick saline aquifer at cover / basement interface; Semi-massive economic sulphide targets as small as 100 x 200 x 200 m; Active mining environment; Debris from mining-induced landslide (Jan 2019) covering part of pit; Hot summer Mediterranean climate. Avg. temperature / rainfall 18.1°C / 563 mm. (INFACT ERS Brochure, 2020)
Reference data	Water wells (constraining depth of cover-basement interface), 500 drill holes (103,000 m drilled): Airborne EM (SKYTEM, 2017), Ground AMT (Geognosia, 2016), gravity (Rio Tinto, 1990–2007), TEM (Rio Tinto, 1992–2002), 37 Ground-EM soundings, AIP from airborne EM (SkyTEM), Passive seismic, Airborne EM (VTEM–Max, GFEM), Ground gravity, UAS mag, hyperspectral. (INFACT ERS Brochure, 2020)
Logistics	Cobre las Cruces is located in Gerena, 20 kilometers northwest of Seville. The close proximity to Seville offers a variety of hospitality services. (INFACT ERS Brochure, 2020)

Appendix 17 Sustainable Test Site Decision Framework – Usability

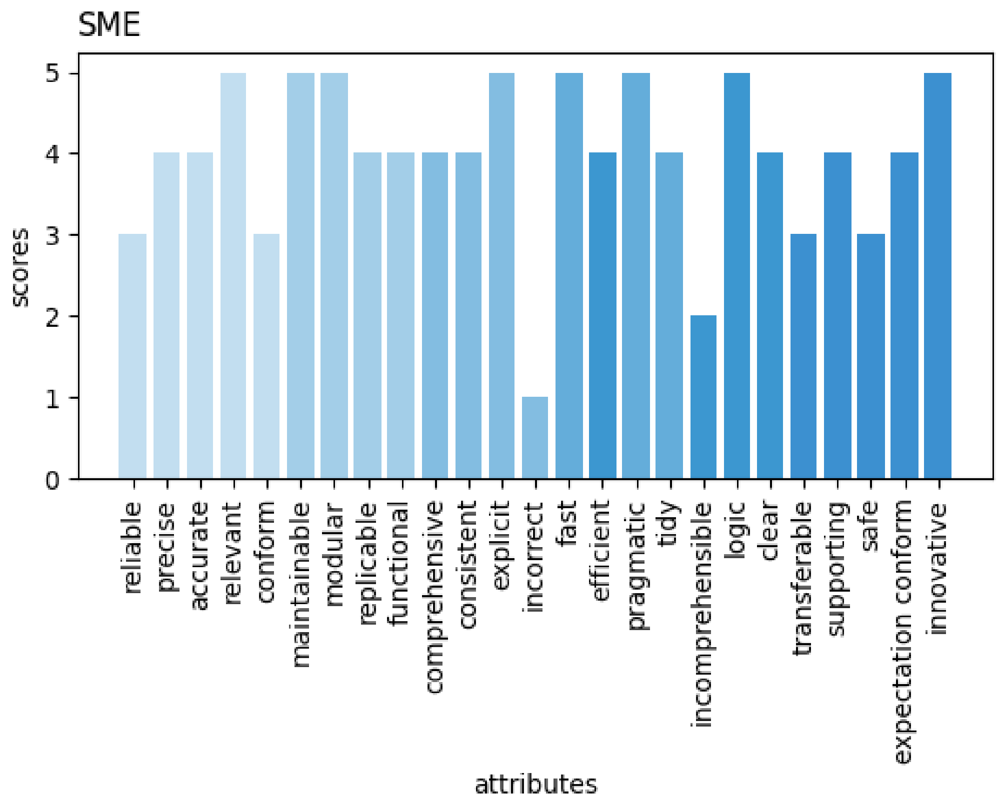

Figure 49 SME Validation – Usability

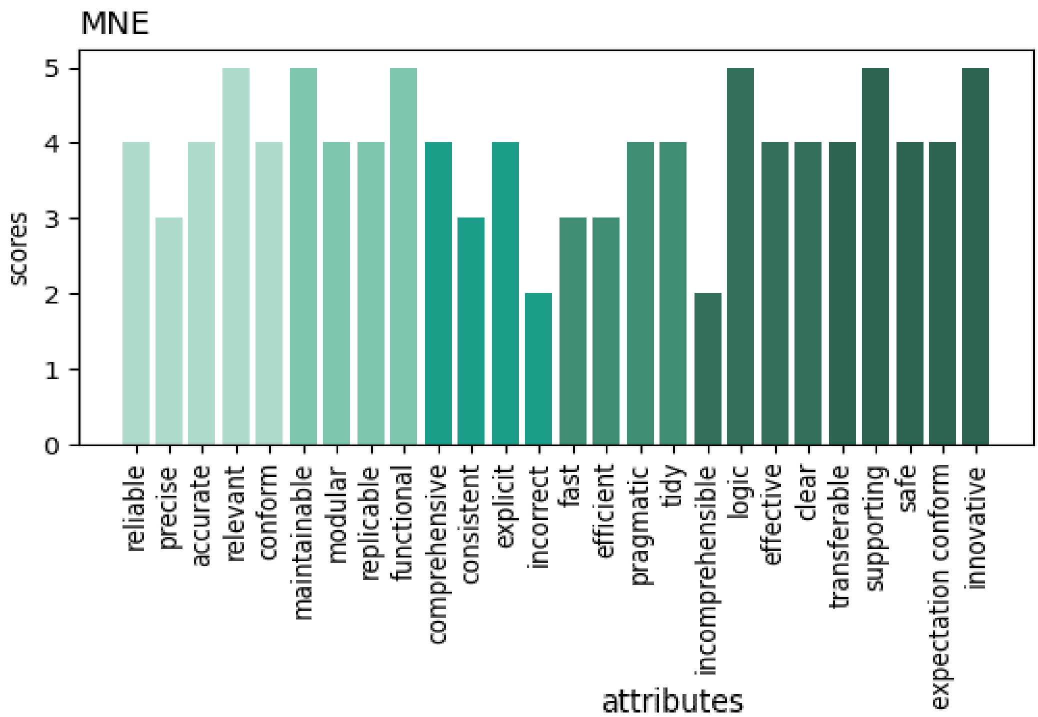

Figure 50 MNE Validation – Usability

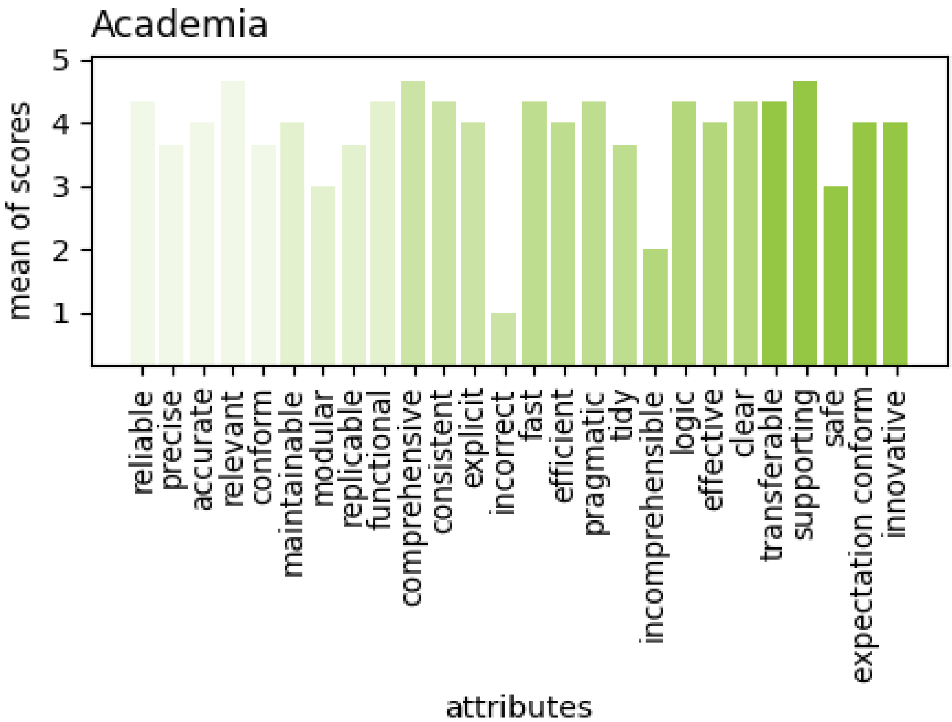

Figure 51 Academia Validation – Usability

Appendix 18 Transfer Validation

Table 94 Transfer Validation Critical Zone Research

Equivalences	Answer	R	CP	Fit
Operational Equivalence	"[Our operations work] exactly as described here, I have already done the selection procedures. Implicitly, of course. Little by little, they (sites) were screened out. I now need to provide data about the process, and that's where I need this framework."	✓	✓	✓
Item Equivalence	Technological challenges: The interviewee argued that the focus is on "[..] systems rather than single entities, [..] new system context (challenges) yes."	p	i	✓
	Test target: "[..] Mineral exploration deals with context, we need the same context and variations. (we target dependencies between) resources, places, people, landscape power relations but also institutions."	✓	✓	✓
	Benchmark features "all available [and valid] data is better than none. Assuming separation between age to provide context and research is lunacy. [..] For what and by whom was the object created; how was it created and when [..] are some questions I ask. I also look at data and data gaps, e.g., dates. Where have the data been corrected, for example, and so on."	✓	i	✓
	Socio-economic: "Observatories or test sites are set for long-term observations, [..] Political stability is important. [..] Permits are not always explicit, social permits are also relevant [..]. [Important] knowledge between land ownership and claims for the land. However, the factors named (factors of the socio-economic category) all fit, I always check stability."	✓	i	✓
	Logistics: "Similar to your priorities, logistics are least important, yet necessary to consider. [..] You enter remote zones. Nature is so diverse however, if there is approximately the same behavior of phenomena I analyze, logistics matter."	p	i	✓
	Ecological: "It's about genius. It's about what you can show. What will be the impact. Today I know, little, with this I know way more"	✓	✓	✓
	Social Engagement: "It's about what you can show. [..] What will be the first step? What the second step who and why must one have contacted? A few also know what kind of data they are communicating exactly – but the data are partly only from assumption."	✓	i	✓
Conceptual Equivalence	"That is relevant for today, but also for the future, looking at that part of the area. What are the atmospheric conditions there, but also the geological conditions and then the data quality? What data do I already have? How good are they and how well can I use them? Moreover, it's not only about some European currencies, but also in areas where there is extremely important information. According to your model, I can actually equate the data – perfect."	✓	✓	✓
Semantic Equivalence	„It's about what you want to try to do. Some definite explanations of the wording is necessary for unity. That is to say, there are actually concepts to be equipped with uniform measurement procedures that all have to be the same in order to reach the point that we can really compare data both across space, across the board."	✓	✓	✓
Measurement Equivalence	"Relatively lucrative is the question of how to bring others into it, but also how to make sure it stays for the long term".	✓	✓	✓

Table 95 Transfer Validation UAS

Equivalences	Answer	R	CP	Fit
Operational Equivalence	"The process is interesting, [..] customers can use it for their selection. [..] Ecological and social conditions [are crucial] it's our legacy and duty. [..] young folks would want the mathematical aspects, I am fine with knowing skilled and trusted professional did the work"; "I think it's great. We could use this to optimize our services. Show customers, what [to test]"	✓	✓	✓
Item Equivalence	**Technological challenges: "Technological challenges are key.** [..] [test target suitability varies]."	✓	i	✓
	Test target is associated with "airworthiness process, including topography, vegetation and associated location assets."	✓	i	✓
	Benchmark features "[..] We promote the technologies approved [..]. Intellectual property often deny direct comparison [..]. Community knowledge, mission planning and operations, vehicle systems, telemetry ground station, post-mission, data reduction and analysis [are our benchmarks]"	✓	i	i
	Ownership and permissions: "Much of it (test range) is owned by the federal government. The permissions and legal procedures are straight forward."; **"**[..] Elevation wise, we're at about [thirteen hundred meters]."	✓	✓	✓
	Socio-economic: "If somebody wants to come and do tests, we have open areas with low population density [..]."	✓	i	✓
	Logistics: "To enable flight testing for any drone or industry user we have different facilities and assets, all items (factors) listed here are relevant."	✓	✓	✓
	Ecological: "[..] The disturbance assessment is crucial, even [..] an initial estimate [..] may generate awareness."	✓	i	✓
	Social Engagement: „Dialogue and engagement is what we perform on a daily basis, the stream of information has to be constant [..]. Sure ecological disturbance must be on the table."	✓	✗	✓
Conceptual Equivalence	"The concept is equivalent. Yet, the focus on permissions and stability of what you call test target requirements."	✓	✓	✓
Semantic Equivalence	"Wording is similar."	✓	✓	✓
Measurement Equivalence	"The measurement works [..]. Imputation is of particular importance [..] an expert should perform the measurement initially [..] we adapt as technology changes."	✓	✓	✓

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Sustainable technology advancements ushered in various industries and sustainable development methods have spurred. Recent technological innovations in environmental sensing, computing, and automation offer the potential to revolutionize existing industries. However, in highly innovative and therefore often high-risk fields, a principal barrier to sustainable technology adoption is the provision of a body of evidence to provide to regulatory, scientific, or investment communities. Physical test sites can serve to verify and validate technologies in their end-setting. Barriers to the development of physical test sites stem from the requirement to balance technological, social, and ecological stakeholders.

The practical need for an interdisciplinary approach and the absence of theoretical work to support sustainable test site development in real environments often exceeds the capabilities of single companies or entire industries. Thus the present thesis reflects on the theorical and practical work on sustainable technology development in real environments and develops a framework for the development of test sites under technological, social, and ecological considerations.

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ISBN 978-3-8396-1875-2
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