JOURNAL OF BUSINESS CHEMISTRY

The academic journal for management issues in the chemical industry

Volume 22

Issue 1

Universität Münster

provadis Hochschule

ISSN 1613-9623

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The Journal of Business Chemistry (JoBC) focuses on current developments and insights at the intersection of management and chemistry, biotechnology or pharmacy.

The JoBC provides an international forum for researchers and practitioners in companies, research institutes, public authorities, consultancies or NGOs to present and discuss current challenges as well as potential solutions in an interdisciplinary manner. Thus, the JoBC aims to foster the dialog between science and business, to support management practice in the chemical and pharmaceutical industry and to indicate where further research from academia is needed. The JoBC offers high quality publications with academic standards, a fast publishing process and global reach. With this multidisciplinary and boundary-spanning approach, the JoBC intends to become the leading journal for decision makers in the chemical and pharmaceutical industry.

Publisher

The Journal of Business Chemistry (Online ISSN 1613-9623) is jointly published by Prof. Dr. Jens Leker (affiliated with the Institute of Business Adminstration, University of Münster) and Prof. Dr. Hannes Utikal (affiliated with the Center for Industry and Sustainability, Provadis School of International Management and Technology). It is published every four months as an open access journal.

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BUSINESS CHEMISTRY

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Letter from the Editor

Innovation Management Challenges for the Chemical Industry

Starting 2025, the chemical industry is undergoing significant transformations, marked by major players implementing cost reductions and shutting down plants in response to evolving market dynamics and economic pressures.

As companies navigate these challenges, it becomes increasingly clear that innovation is essential for long-term success. In this first issue of the Journal for 2025, we are mentioning these developments, and we are pleased to present a collection of five insightful articles that offer valuable perspectives on innovative management. This issue of the Journal of Business Chemistry can be categorized into two overarching themes: Innovation Approaches and Sustainability.

The paper "Frugal Innovation in Oncology: Tracing the Arc of Microchip Technology in Early Cancer Detection and Treatment" by Abhijeet Chaturvedi, Janvee Garg, and Anil Kumar Singh highlights the role of microchip technology in enhancing early cancer detection and treatment, particularly in low-resource settings through the use of ‚Lab on a Chip' technologies. The paper evaluates the technical specifications and cost-efficiency of these systems, emphasizing their potential for timely intervention.

Continuing with the innovation management approaches, the paper "Strategic Corporate Venturing to Design Targeted Innovation Initiatives" by Vinzenz Zauner and Philip Emmerich discusses how corporate venturing can enhance innovation capabilities in high-tech multinationals by integrating internal and external stakeholders through a structured initiative. The authors present best practices and propose a corporate venturing initiative aimed at boosting innovation and providing a competitive advantage.

Additionally, the authors Niklas Huber, Daniel Eggart, and Arko Graf-Bürk offer insights into the use of artificial intelligence (AI) in the article "Leveraging Generative AI for Rapid Competition Landscape Analysis: A Feasibility Study for the Chemical Industry." This paper explores the application of generative AI to automate competitive analysis in the chemical industry, improving accuracy and efficiency in strategic decision-making. Their methodology links market data to historical growth rates, revealing strategic opportunities and market risks for selected companies.

In the Sustainability section, we highly recommend the paper by Prof. Thomas Lager, Cali Nuur, and Andreas Feldmann, titled "The Illustrative Case of the HYBRIT Fossil-Free Steel Production Initiative in the Perspective of Industrial Symbiosis." This article examines the HYBRIT initiative as a case study to bridge the concepts of industrial symbiosis and industrial convergence in the context of sustainable steel production. The authors advocate for the development of a specific transformation model to address unique industrial conditions for product and process innovation.

Finally, the last paper of this issue, "Environmental Impacts of Pyro- and Hydrometallurgical Recycling for Lithium-Ion Batteries - A Review" by Luca Stegemann and Moritz Gutsch, provides a comparative analysis of the environmental impacts of different recycling methods for lithium-ion batteries. The authors highlight the benefits of hydrometallurgical recycling in reducing emissions and energy demand while offering recommendations for future research in this critical area.

Please enjoy reading the first issue of this year; we are grateful for the support of all authors and reviewers for this enlightening edition. If you have any comments or suggestions, please do not hesitate to contact us at contact@businesschemistry.org. For more updates and insights on management issues in the chemical industry, follow us on LinkedIn: www.linkedin.com/company/jobc/ and subscribe to our newsletter.

We wish you all a successful and inspiring year ahead!

Andrea Kanzler, (Executive Editor)

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BUSINESS CHEMISTRY

Vol.22, Iss.1, February 2025
URN: urn:nbn:de:hbz:6-43998536451
DOI: 10.17879/43998526070

Research Paper

Abhijeet Chaturvedi*, Janvee Garg, Prof. Anil Kumar Singh*****

Frugal Innovation in Oncology: Tracing the Arc of Microchip Technology in Early Cancer Detection and Treatment

This paper explores the transformative role of microchip technology in oncology, focusing on its potential through the lens of frugal innovation. Specifically, it examines how 'Lab on a Chip' (LOC) technologies - miniaturized systems that consolidate multiple laboratory functions onto a single chip can significantly enhance early cancer detection and treatment, particularly in low-resource settings. By streamlining diagnostic processes, LOC devices offer faster, more affordable, and efficient cancer detection, which is critical for timely intervention. The study addresses two central research questions: how effectively can LOC microchips detect cancer cells in early stages, and how can they be integrated into cost-effective treatment strategies?

Through an exploratory literature review, the paper evaluates the technical specifications, diagnostic accuracy, and cost-efficiency of LOC technologies. It also investigates the role of nano-enabled biosensors in enhancing the sensitivity of cancer detection within these systems. Such advancements not only increase the chances of early diagnosis but also improve ongoing cancer monitoring, which is crucial for optimizing treatment outcomes. Beyond individual patient care, the broader implications of LOC technology are considered, particularly its capacity to reduce financial and infrastructural barriers associated with traditional diagnostics.

Keywords: *Frugal innovation, Cancer care, Early detection, Microchip technology*

Introduction

In recent years, the number of cancer survivors has grown exponentially and is expected to continue (Weir et al., 2021). By 2035, 24 million new cancer cases are expected worldwide, up from 18.1 million in 2018, highlighting a pervasive and pressing global health issue (Mollica et al., 2020). The variability in tumor growth rates among individuals highlights the urgency for early detection, which is critical in improving outcomes and survival rates (Crosby et al., 2022). Timely identification of cancer can significantly boost the effectiveness of treatments, reducing mortality rates and improving quality of life (Nass et al., 2019). In this context, microchip technology, particularly the 'lab on a chip' (LOC) innovation, emerges as a significant advancement, offering hope in improving diagnostic capabilities (Nagrath et al., 2007). This technological leap is not limited to diagnosing formidable diseases like cancer; it extends to enhancing

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URN: urn:nbn:de:hbz:6-43998536451
DOI: 10.17879/43998526070

diagnostic processes globally, which is particularly vital in developing nations where limitations in resources compound the challenges of cancer care (Francies et al., 2020). The need for such innovations is emphasized by the increasing incidence of cancer and the economic strain it places on healthcare systems, making cost-effective solutions imperative (Patel et al., 2020). LOC technologies have the potential to streamline diagnostics, reduce costs, and make cancer care more accessible, particularly in low-resource settings (Mishra, 2023). These devices integrate multiple lab functions onto a single chip, offering a faster, cheaper, and more efficient means of cancer detection, which is crucial for early intervention (Bargahi et al., 2022).

This paper aims to take a critical look at microchip technology, focusing on how it can be used to detect cancer cells early and how it could be used to make treatment more affordable. The primary points of discussion are two research questions: how well microchips work for finding cancer cells early on and how modern technology for finding cancer cells connects with low-cost treatments made possible by microchips. The research questions are addressed through an exploratory analysis of literature, drawing from diverse sources available on Google Scholar across microchip technology, oncology, and frugal innovation. The methodology involves examining studies that assess the effectiveness of microchip technologies in early cancer detection, focusing on their diagnostic accuracy, sensitivity, and potential for improving early intervention. Additionally, the paper explores the role of these technologies in reducing treatment costs by enhancing diagnostic efficiency and accessibility. The analysis includes an evaluation of the technical specifications of microchips, such as their integration of multiple lab functions onto a single chip, and their impact on diagnostic outcomes. The exploration includes an analysis of technical specifications, diagnostic outcomes, and cost-efficiency contributing to frugal innovation (Grover, Garg and Singh, 2024), to provide a comprehensive overview of how these technologies can impact cancer care. This exploration not only reflects on current capabilities but also identifies potential areas for future development and application in global health systems (Winton et al., 2016).

Early Detection of Cancer: The Crucial First Step

Early cancer detection is crucial for improving prognosis and significantly enhancing survival rates for individuals affected by cancer (Shaver, Croom-Perez and Copik, 2021). Traditionally, diagnostics have relied on methods such as mammography, colonoscopy, and Pap smears, which, despite their effectiveness, are resource-intensive, demanding substantial financial investment, sophisticated equipment, and specialized personnel (Schootman et al., 2015). This creates barriers to access, especially in low- and middle-income countries where the need for affordable and accessible cancer diagnosis is most pressing (Brand et al., 2019).

Frugal innovation becomes essential in this context, focusing on delivering substantial value while drastically reducing the resources required. Microchip technology, particularly LOC systems, embodies this approach by providing a robust yet cost-effective solution to the challenges of early cancer detection (Özyurt et al., 2023). These microchips integrate with nanotechnology, enhancing diagnostic capabilities; nano-enabled biosensors, for instance, can detect multiple biomarkers, improving the sensitivity and accuracy of cancer detection (Patel et al., 2020; Dubey et al., 2022). This not only increases the likelihood of early detection but also supports the monitoring of cancer progression and the effectiveness of treatments, which are vital for optimizing patient outcomes (Caballero et al., 2017).

The implications of this innovation extend beyond individual patient care. By alleviating the significant financial burden associated with traditional cancer diagnostics, microchip technology has the potential to catalyze a systemic transformation. While microchip-based diagnostic platforms are designed to enhance accessibility and affordability, economic barriers persist, particularly in low-resource settings where upfront costs can limit adoption (Tripathi et al., 2014). For healthcare providers operating with constrained budgets, the initial investment required to procure and implement these technologies poses a significant challenge. Mitigating these costs necessitates innovative financial and operational strategies. For instance, public-private partnerships can play a critical role in subsidizing the acquisition of microchip devices, especially in underserved areas. Furthermore, international funding agencies and organizations like the World Health Organization (WHO) could provide grants or low-interest loans to healthcare facilities in resource-limited settings. Coupled with capacity-building initiatives, such as training programs and mobile diagnostic units, these efforts would enable healthcare providers to integrate microchip technologies more effectively. Portable and low-cost

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URN: urn:nbn:de:hbz:6-43998536451
DOI: 10.17879/43998526070

microchip-based diagnostic platforms can bridge the gap between urban and rural cancer care, promoting a more equitable approach to health across different regions (Haney et al., 2017).

Microchip technology, particularly through the LOC paradigm, encapsulates a future where cancer detection is not only economically viable but also highly efficient (Mishra, 2023; Özyurt et al., 2023). LOC technology minimizes the need for extensive infrastructure by consolidating multiple laboratory processes onto a single microchip. These devices efficiently identify circulating tumor cells (CTCs) or biomarkers related to cancer directly from blood samples, facilitating early detection crucial for improving treatment outcomes and patient survival rates (Ju et al., 2022). Additionally, the integration of microchip technology with nanotechnology has encouraged the development of highly effective nano-enabled biosensors for cancer biomarkers, enhancing the overall potential of LOC technology to provide a comprehensive, yet frugal, solution for cancer diagnostics (Ramesh et al., 2022). Furthermore, these advancements align with global health priorities, addressing disparities in cancer care and supporting the aims of international health initiatives such as the World Health Organization's cancer control strategies (Ngoma, 2006).

Chemical Material Considerations for Lab-on-a-Chip (LOC) Devices

The selection of materials for Lab-on-a-Chip (LOC) devices is paramount, as it directly influences the device's chemical properties, fabrication techniques, and overall performance (Kipling, Haswell and Brown, 2015). Polydimethylsiloxane (PDMS), a silicon-based elastomer, is particularly favored in biomedical LOC applications due to its unique chemical characteristics (Nahak et al., 2022). Its low surface energy contributes to its hydrophobic nature, which is advantageous in microfluidic applications where the prevention of non-specific adsorption is crucial and it also exhibits excellent gas permeability due to its molecular structure, which includes a flexible Si-O backbone that allows for efficient gas diffusion, an essential factor for cell culture applications (Sengupta et al., 2019). Epoxy resins, such as SU-8, offer distinct advantages, including exceptional chemical resistance and thermal stability, attributable to their highly cross-linked polymer network (Abgrall et al., 2007). However, the high cost of these resins can be a limiting factor, especially when considering large-scale production (Ali@ Hasim, Ahaitouf and Abdullah, 2021). Silicon is a cornerstone material in microfabrication, revered for its semiconducting properties and chemical inertness (Kumar and Kumbhat, 2016). It shares many properties with glass, such as good thermal stability and solvent resistance, which are vital for maintaining the integrity of the LOC under various chemical conditions but the anisotropic etching process used to create microstructures in silicon results in vertical sidewalls, which are geometrically distinct from the rounded profiles observed in glass structures, influencing fluid dynamics within the chip (Sengupta et al., 2019). Glass is another critical material, especially in applications requiring optical transparency and chemical inertness (Neužil et al., 2014). Furthermore, glass exhibits electroosmotic mobility, which is advantageous for applications involving electrokinetic flow control but the high hardness of glass poses challenges in microfabrication, often necessitating the use of advanced, and costly, micromachining techniques (Hamed et al., 2023). In the emerging field of paper-based microfluidics, materials like cellulose and hydrophobically modified cellulose are gaining traction (Anushka, Bandopadhyay and Das, 2023). While paper-based LOCs are promising due to their low cost and simplicity, challenges remain in improving channel resolution, integrating additional chemical functionalities, and enhancing detection sensitivity (Li, Ballerini and Shen, 2012; Iqbal et al., 2022).

Chemical Applications of Lab-on-a-Chip: Immuno-Biochip in Cancer Treatment

The potential for diagnosing various types of cancer using molecular-based detection methods is significant; however, these methods are often time-consuming, costly, and labor-intensive (Iqbal et al., 2022). To overcome these limitations, biological chips are increasingly being employed for cancer diagnosis, providing rapid, accurate, and cost-effective results (Iqbal et al., 2022). The sensitivity and specificity of these biochips are comparable to traditional molecular and serological assays (Bargahi et al., 2022). A key example is the immuno-biochip, a LOC device designed to detect the epidermal growth factor receptor 2 (EGFR2) protein in breast cancer through antigen-antibody conjugation (Iqbal et al., 2022). The sensitivity of the immuno-biochip can be significantly improved by incorporating nanoparticles (Bargahi et al., 2022). Among various nanomaterials, graphene nanosheets are preferred for their superior

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URN: urn:nbn:de:hbz:6-43998536451
DOI: 10.17879/43998526070

electrical and optical conductivity (Radhakrishnan, Mathew and Rout, 2022). The small pores in the graphene foam facilitate effective sample handling during detection in the microfluidic device (Han et al., 2019). Additionally, the immuno-biochip includes an analyzer for visual antigen detection, utilizing electrochemical impedance spectroscopy (EIS) and differential pulse voltammetry (DPV) (Benjamin and Júnior, 2023).

Bridging Treatment Gaps: Microchip Technology and Frugal Innovation in Cancer Care

As healthcare costs continue to escalate and disparities in access to care grow, the concept of frugal innovation becomes increasingly important, particularly within the domain of cancer treatment (Bhatti et al., 2017). The integration of microchip technology with frugal innovation practices offers a transformative pathway from diagnosis to therapy, promising to reshape healthcare landscapes, especially in developing nations. This section explores how microchip technology can bridge the gap between diagnosis and advanced treatment modalities, enhancing access to cancer care in resource-limited settings. Microchips, particularly when integrated with CRISPR-Cas9 technology, offer precise targeted drug delivery and revolutionary gene therapy capabilities, which can significantly improve the efficacy of treatments while reducing costs and side effects (Zhang et al., 2021). This precision in drug delivery exemplifies the core principles of frugal innovation; minimizing resource use while maximizing therapeutic benefits (Ramdorai and Herstatt, 2015; Grover, Garg and Singh, 2024). Additionally, microchip technology facilitates early and accurate cancer detection, crucial for effective treatment planning and improved patient outcomes (Muluneh and Issadore, 2014).

The economic advantages of microchip-facilitated treatments, compared to conventional methods, are substantial. These devices require less infrastructure and generate lower levels of medical waste, contributing to more personalized and cost-effective therapies (Santini et al., 2000). By enabling the customization of treatment plans based on the genetic and molecular profiles of individual tumors, microchips can help clinicians achieve better treatment outcomes while potentially reducing the incidence of adverse side effects (Rahmanian et al., 2023). On a broader scale, the expansion of access to cancer care in developing countries is critical. In developed nations, stringent regulations, while ensuring patient safety and efficacy, may inadvertently slow down the adoption process due to the extensive approval procedures (Sorenson and Drummond, 2014). In developing countries, the regulatory landscape presents additional challenges. The lack of consistent regulatory frameworks across regions may create barriers for global companies seeking to scale microchip technologies (Al Meslamani, 2023). The healthcare gaps in these regions, characterized by limited resources, a shortage of specialized personnel, and high costs, can be significantly mitigated through the adoption of microchip technology and related frugal innovations.

Microchip Technologies & Organoids

Microchip technologies have advanced significantly in the biomedical field, branching out from their conventional electronic applications to encompass sophisticated biological modeling tools such as organoids and organ chips (Huh, Hamilton and Ingber, 2011). Stemming from advancements in stem cell technology and microfabrication, both organoids and organ chips offer unique platforms for studying complex biological processes, though they differ in their designs and functionalities.

Organoids, intricate three-dimensional structures derived from stem cells, closely mimic the cellular organization and function of real tissues, allowing researchers to delve into tissue development, disease progression, and drug response (Lancaster and Knoblich, 2014). However, organoids lack precise control over the microenvironment, limiting their utility in studying critical interactions among different tissue types within an organ. On the other hand, organ chips integrate microfluidic principles to create detailed analogs of human organs on miniature silicon chips (Ingber, 2016). While organoids provide realistic models of tissue architecture, they are less amenable to studying critical interactions necessary for replicating organ functions (Lancaster and Knoblich, 2014). Organ chips, with their intricate microfluidic channels, offer precise control over environmental conditions, enabling more accurate modeling of organ-level functions and disease processes (Ingber, 2016).

Despite their potential, challenges remain in the widespread adoption of organ chips. The validation process for organ chips is complex and lacks standardization, posing barriers

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URN: urn:nbn:de:hbz:6-43998536451
DOI: 10.17879/43998526070

to smaller entities with limited funding (Moraes et al., 2012). However, recent milestones, such as Sanofi Pasteur's FDA Investigational New Drug (IND) application based on organ chip data, highlight the technology's potential in drug development (Kissner et al., 2021). A multidisciplinary approach involving specialists in stem cell biology, microfabrication, microelectronics, and more is essential for the development of organ chips (Bhatia and Ingber, 2014). While organ chips offer cost savings over traditional animal testing in the long term, their initial costs and complexities hinder widespread adoption, particularly among smaller research groups or startups (Marx, 2016).

Analyzing the data sufficiency and cost components of organoids and organ chips further illuminates their potential impact. Organ chips, despite their higher initial costs, promise more cost-effective solutions compared to conventional animal testing in the long run (Esch, King and Shuler, 2011) leading to frugal innovation. For example, a liver chip sold by C.N. Bio innovations in 2015 was priced at US$22,000 but is argued to be more cost-effective due to reduced reliance on animal testing and associated care costs (Marx, 2016). This projection aligns with estimates suggesting that organ chips could reduce overall drug research and development costs by 10-26 percent (Esch, King and Shuler, 2011). However, accessibility remains a challenge for smaller research groups or startups due to high initial costs associated with organ chip technology (Esch, King and Shuler, 2011). To address this issue, blank microfluidic chips offer a frugal alternative, allowing researchers to customize their experiments by inserting their own cell lines, thereby reducing overhead costs (Meer and Berg, 2012). Despite significant progress, the development of organ chips is still moving slowly, partly due to regulatory challenges and the need for further validation (Ingber, 2022). However, continued investment and regulatory innovation are crucial for overcoming these challenges and fully realizing the potential of organ chips in advancing biomedical research and improving patient care.

Chemistry Aspects of Nanomaterials in Microchip Technology and Their Use in Targeted Drug Delivery for Cancer Treatment

Microchip electrophoresis (ME) operates on the principle of electrophoresis, where a microchip with microchannels is subjected to an electric field and the chemical properties of the materials used in the fabrication and modification of these chips are crucial for optimal ME performance (Bargahi et al., 2022). Gold Nanoparticles (AuNPs) are widely utilized in ME due to their excellent colloidal stability, ease of synthesis, and versatility in chemical modification as they can enhance separation efficiency by interacting with functional groups such as hydroxyl (OH), amino (NH2), or sulfhydryl (SH) groups (Muluneh and Issadore, 2014). Silica Nanoparticles (SiO2 NPs) are valued for their high surface area, chemical stability, and ease of modification and they are often used to coat the inner surfaces of microchannels, improving biomolecule separation (Muluneh and Issadore, 2014). Nanomaterials have revolutionized targeted drug delivery systems, particularly in cancer therapy and their unique physical and chemical properties facilitate the precise delivery of therapeutic agents to cancer cells while minimizing damage to healthy tissues (Elumalai, Srinivasan and Shanmugam, 2024).

This section discusses nanomaterials in the context of cancer diagnosis and treatment because of their potential to revolutionize medical practices. Nanomaterials offer unique properties such as small size, large surface area-to-volume ratio, and tunable surface chemistry, making them highly versatile for biomedical applications (Lan et al., 2023). In the field of oncology, nanomaterials have shown promise in improving cancer detection, drug delivery, and therapy monitoring. Firstly, nanomaterials can enhance cancer diagnosis by enabling highly sensitive and specific imaging techniques. Nanoparticles functionalized with targeting ligands can selectively accumulate in tumor tissues, allowing for precise detection using imaging modalities such as magnetic resonance imaging (MRI), computed tomography (CT), or fluorescence imaging (Lan et al., 2023). Additionally, nanomaterial-based contrast agents can enhance the contrast between healthy and diseased tissues, improving the accuracy of diagnostic imaging (Jiang et al., 2023). Secondly, nanomaterials play a crucial role in drug delivery for cancer therapy. Their small size and customizable surface properties enable efficient delivery of therapeutic agents to target sites, minimizing systemic toxicity and enhancing treatment efficacy (Sengupta and Sasisekharan, 2007). By incorporating targeting moieties and therapeutic payloads into nanocarriers, clinicians can tailor treatment regimens to individual patients based on their molecular profiles and disease characteristics (Din et al., 2017). This personalized approach improves treatment outcomes and

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URN: urn:nbn:de:hbz:6-43998536451
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reduces adverse effects by ensuring that therapies are specifically tailored to the patient's unique biology.

Given these potential benefits, discussing nanomaterials in the context of cancer diagnosis and treatment is essential for understanding the current landscape of oncology research and development. Nanotechnology offers innovative solutions to longstanding challenges in cancer care, such as early detection, targeted therapy, and personalized medicine. By exploring the applications and challenges of nanomaterials in oncology, researchers and clinicians can work towards harnessing their full potential to improve patient outcomes and advance cancer treatment strategies. Nanomaterials represent a promising frontier in cancer diagnosis and treatment, offering a multitude of benefits and adaptability. However, alongside their potential advantages come several considerations, including production cost, scalability, safety, and the complexity of nano formulations. As the design and material complexity of nanomedicines increase, so do costs, production requirements, and testing parameters (Lan et al., 2023). Despite the clinical advantages demonstrated by some nanomedicines over conventional formulations, the affordability of production and scalability may hinder their translation into clinical practice.

Moreover, the environmental impact of manufacturing by-products and energy costs, coupled with the complexities of navigating FDA approval, pose additional challenges. Depending on their mode of action, nano formulations may fall under different regulatory classifications by the FDA, further complicating the regulatory landscape (Zhang et al., 2021). However, with rapidly advancing technologies in nanomedicine, there is a pressing need for more consistent and robust guidelines to evaluate clinical trials for nanomaterials (Đorđević et al., 2022).

The cost vs. benefit analysis of nanomedicine poses many questions, even without the issue of unclear regulatory guidelines. Depending on formulation and complexity, nanomedicine can have substantially higher manufacturing costs than conventional medications (Sengupta and Sasisekharan, 2007). Quality of life considerations, often overlooked in clinical trials, are crucial for assessing the value of research and development centered on nanotechnology (Bernhard et al., 1998). Patient quality of life is a critical parameter to evaluate over an extended period because nanomedicine formulations are frequently modified to improve specificity, efficacy, and resistance to medications (Lancaster and Knoblich, 2014; Thapa and Kim, 2023). With cutting-edge technology enhancing therapies and diagnostics, and machine learning applications saving time and money, the future of nanomedicine is undoubtedly bright (Haleem et al., 2022). Preclinical and clinical studies have demonstrated the advantages of nanotechnology in imaging, diagnostics, and cancer treatment (Kemp and Kwon, 2021). However, to fully realize the benefits of early detection in cancer patients, diagnostic screenings must be highly accurate to avoid overtreatment and incorrect diagnoses (Loud and Murphy, 2017). The use of nanotechnology in cancer diagnostics, chemotherapy, and radiation therapy is expected to grow significantly in the near future, providing patients and physicians with highly controllable cancer treatment options (Jin et al., 2020).

Microchip Technologies and Stakeholders Perspectives

In the area of microchip technology applied to oncology, various stakeholders offer unique perspectives that enrich the understanding of its implications and potential. From healthcare providers to patients, policymakers to industry stakeholders, and academic researchers, each group plays a crucial role in shaping the development, adoption, and implementation of microchip technology in cancer care.

From the perspective of healthcare providers, the integration of microchip technology presents both opportunities and challenges. On one hand, it offers the promise of more efficient and accurate cancer detection, which can lead to improved patient outcomes and streamlined workflows. For example, microchip-based diagnostic platforms can reduce the time and resources required for traditional diagnostic procedures, allowing healthcare providers to allocate their time more effectively and potentially reach more patients. However, healthcare providers may also face challenges in adopting and integrating these technologies into their practice, including concerns about training, infrastructure requirements, and workflow disruptions (Borges do Nascimento et al., 2023). Training healthcare professionals to use these advanced technologies requires tailored programs that include both technical and clinical applications (Meyer-Szary et al., 2022). Modular, simulation-based training, and train-the-trainer approaches are essential to scaling knowledge across diverse settings, especially in resource-limited areas (Robinson et al., 2024). Infrastructure

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URN: urn:nbn:de:hbz:6-43998536451
DOI: 10.17879/43998526070

barriers, particularly in rural settings, demand innovative solutions such as mobile diagnostic units and partnerships with technology providers to deliver affordable, scalable microchip devices (Wang et al., 2016). Cross-disciplinary collaboration, data integration with Electronic Health Records (EHR), and automated tools for administrative tasks can streamline this process (Yeung, 2021). Addressing these challenges will facilitate the widespread adoption of microchip technology, making it a transformative tool in improving cancer care, particularly in underserved regions.
Viewing from the lens of patients, patients stand to benefit significantly from the advancements in microchip technology in oncology. Early cancer detection facilitated by microchip-based diagnostic tools can lead to timely intervention and improved treatment outcomes, potentially saving lives. Additionally, the integration of microchip technology into treatment modalities, such as targeted drug delivery, offers the promise of more personalized and effective therapies with fewer side effects. From the patient perspective, access to these innovations is paramount, highlighting the importance of affordability, accessibility, and patient-centered care (Arora, 2009). Patients may also value the convenience and efficiency of microchip-based diagnostics, particularly if it reduces the need for invasive procedures or lengthy wait times for test results.

For policymakers, the adoption and integration of microchip technology in oncology care represent opportunities to improve healthcare delivery, enhance public health outcomes, and drive economic growth. Policymakers play a crucial role in shaping the regulatory environment, allocating resources, and encouraging collaboration among stakeholders to facilitate the development and implementation of these technologies. Additionally, policymakers must address ethical, legal, and social implications, such as data privacy, equity in access, and reimbursement policies, to ensure that microchip technology benefits society as a whole (Gerke, Minssen and Cohen, 2020). By supporting research and development, investing in infrastructure, and creating incentives for innovation, policymakers can help accelerate the adoption of microchip technology and ensure that it reaches underserved populations.

Academic researchers play a vital role in advancing the understanding of microchip technology in oncology through basic and translational research. Their perspectives encompass a wide range of disciplines, including engineering, biology, medicine, and ethics. Academic researchers contribute to the development of new technologies, evaluate their efficacy and safety, and disseminate knowledge through publications and collaborations. Their perspectives shape the direction of research, influence policy decisions, and drive innovation in the field (Singh et al., 2022). By conducting rigorous studies, exploring novel applications, and engaging in interdisciplinary collaborations, academic researchers contribute to the advancement of microchip technology and its translation into clinical practice.

Microchip Technology and Frugal Innovation

As highlighted in table 1, it is evident that microchip technology in oncology aligns closely with principles that emphasize cost-effectiveness, simplicity, and accessibility, particularly in resource-constrained environments. Microchip technologies, particularly LOC, encapsulate multiple laboratory functions into a single device, significantly reducing the complexity and resource requirements traditionally associated with cancer diagnostics. This integration streamlines the diagnostic process, making it faster and more accessible, particularly in environments where resources are scarce (Nagrath et al., 2007). The cost-effectiveness of these technologies is a key attribute, as they are designed to lower both production and operational costs, thus making cancer care more affordable and accessible, especially in low-resource settings (Patel et al., 2020). Furthermore, the ability of microchip technologies to enable early and accurate detection of cancer enhances the potential for timely and precise treatments, thereby improving survival rates (Shaver, Croom-Perez and Copik, 2021). The portability and accessibility of these devices expand their utility to rural and underserved areas, removing significant barriers to access and democratizing health care (Haney et al., 2017). Advanced integration with technologies such as CRISPR-Cas9 facilitates targeted therapies and personalized treatment plans, highlighting the use of cutting-edge technology to maximize therapeutic benefits while minimizing resource use—a core principle of frugal innovation (Zhang et al., 2021). Additionally, the reduction in infrastructure and personnel needs further lowers barriers to entry for advanced diagnostics and treatments, which is particularly beneficial in regions with limited healthcare infrastructure (Mishra, 2023). Supporting global health initiatives, microchip technology helps in tackling the global cancer burden by aligning with international health goals that aim to make healthcare affordable and accessible globally (Ngoma, 2006). Lastly, the scalability of these technologies

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URN: urn:nbn:de:hbz:6-43998536451
DOI: 10.17879/43998526070

ensures that they can be produced on a large scale without excessive costs, facilitating their adoption across different healthcare systems and environments (Ramdorai and Herstatt, 2015; Grover, Garg and Singh, 2024).

Discussion & Conclusion

The landscape of microchip technology in oncology represents a journey of exploration and revelation, unveiling both the vast potential and intricate challenges inherent in harnessing this innovative approach to cancer detection and treatment. This study, guided by specific research inquiries, draws upon insights from extant literature and synthesizes perspectives from diverse stakeholders in the domain. At its core, the investigation was anchored by two pivotal research questions: the efficacy of microchips in early cancer detection and their role in facilitating affordable treatment modalities. Through an exhaustive review of the literature spanning microchip technology, oncology, and frugal innovation, the authors endeavored to illuminate these questions.

Addressing the first research question regarding the effectiveness of microchips in early cancer detection, LOC technology emerged as a revolutionary paradigm consolidating multiple laboratory functions onto a single microchip. Resonating throughout the literature is the potential of LOC technology to enhance diagnostic capabilities, offering a faster, more cost-effective, and efficient means of cancer detection. Notably, studies highlight the transformative impact of LOC technology in identifying circulating tumor cells (CTCs) and cancer biomarkers directly from blood samples, thus enabling early interventions crucial for improving treatment outcomes and patient survival rates (Mishra, 2023; Özyurt et al., 2023).

Turning to the second research question concerning the intersection of microchip technology with frugal innovation in facilitating affordable cancer treatment, the researchers encountered a literature marked by promise and complexity. The integration of microchips with CRISPR-Cas9 technology emerged as a beacon of hope, offering precise targeted drug delivery and revolutionary gene therapy capabilities that could significantly improve treatment efficacy while mitigating costs and side effects. Studies provide compelling evidence of the economic advantages and clinical benefits afforded by microchip-facilitated treatments, emphasizing the potential for personalized medicine approaches tailored to individual patient profiles (Moraes et al., 2012; Bhatia and Ingber, 2014). However, scalability and regulatory obstacles may pose challenges to widespread implementation.

In addition to the promise of microchip technology, the study acknowledges the complementary roles played by organoids and nanomaterials in reshaping oncology research and practice. Organoids, intricate three-dimensional structures derived from stem cells, offer realistic models of tissue architecture enabling the study of tissue development, disease progression, and drug response. Studies illuminate the potential of organ chips in providing controlled settings for monitoring cellular responses to various stimuli, thereby facilitating precise analysis critical for preclinical testing and personalized medicine strategies (Lancaster and Knoblich, 2014; Ingber, 2016). However, challenges such as validation processes and cost barriers serve as poignant reminders of the hurdles that must be overcome to fully realize their potential.

The scope for future research is vast and multi-dimensional. Refining the accuracy and reliability of microchip diagnostics, exploring novel applications in cancer treatment, and understanding long-term cost-effectiveness are essential research trajectories. Additionally, addressing scalability and production challenges such as business models, logistical hurdles, and supply chain constraints is critical to ensure these technologies meet global demand without compromising quality. Developing a conducive regulatory and policy environment to facilitate the integration and scaling of microchip technology in healthcare systems globally is another crucial area of inquiry.

Future studies should also delve deeper into the sustainability of microchip technologies, particularly in low-resource settings. Research should explore how these technologies will be maintained, serviced, and disposed of to avoid creating additional burdens in underserved regions. The environmental impact of mass production, particularly electronic waste, and strategies to mitigate such concerns through eco-friendly manufacturing and recycling practices, require thorough investigation.

Engaging in multidisciplinary collaborations among policymakers, healthcare providers, technologists, and patient advocacy groups could significantly accelerate the advancement and adoption of microchip technology. By harnessing frugal innovation, the global healthcare community has the opportunity to democratize access to early cancer detection and effective treatment, especially in low-resource settings. Furthermore, the role of international organizations like the WHO in catalyzing global adoption

Vol.22, Iss.1, February 2025
URN: urn:nbn:de:hbz:6-43998536451
DOI: 10.17879/43998526070

underscores the importance of supporting policies, funding, and innovation-friendly environments to promote equitable and accessible cancer care worldwide.

Table 1: Microchip Technology in Oncology and Frugal Innovation

Aspect of Microchip Technology	Relevance to Frugal Innovation	Impact on Oncology	Reference
Integration of Multiple Lab Functions	Reduces complexity and resource requirements.	Streamlines diagnostics, making cancer detection more accessible and faster.	(Nagrath et al., 2007)
Cost-effectiveness	Lowers production and operational costs.	Makes cancer care more affordable, especially in low-resource settings.	(Patel et al., 2020)
Early and Accurate Detection	Enhances product value by improving outcomes.	Improves survival rates by enabling timely and precise treatments.	(Shaver, Croom-Perez and Copik, 2021)
Portability and Accessibility	Simplifies deployment in diverse environments.	Expands access to diagnostics in rural and underserved areas.	(Haney et al., 2017)
Integration with Advanced Technologies	Leverages cutting-edge technologies for better results.	Enables targeted therapies and personalized treatment plans.	(Zhang et al., 2021)
Reduction in Infrastructure and Personnel Needs	Minimizes the need for extensive medical infrastructure.	Lowers barriers to entry for implementing advanced diagnostics and treatments.	(Mishra, 2023)
Support of Global Health Initiatives	Aligns with international goals for affordable healthcare.	Contributes to reducing the global cancer burden.	(Ngoma, 2006)
Scalability	Adaptable to large scale production without excessive costs.	Facilitates widespread adoption across various healthcare systems.	(Ramdorai and Herstatt, 2015; Grover, Garg and Singh, 2024)

Acknowledgement

The infrastructural support provided by the Center for Research and Innovation in Frugal Technology (CRIFT), FORE School of Management, New Delhi, in completing this paper is gratefully acknowledged. We also extend our sincere gratitude to the reviewers for their constructive feedback and to Ms. Andrea Kanzler, Executive Editor of the Journal of Business Chemistry, for the unwavering support.

Vol.22, Iss.1, February 2025
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JOURNAL OF
BUSINESS CHEMISTRY

Vol.22, Iss.1, February 2025
URN: urn:nbn:de:hbz:6-43998539881
DOI: 10.17879/43998528063

Research Paper

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Strategic corporate venturing to design targeted innovation initiatives

High-tech multinationals face a strong need for efficient innovation. Methods beyond conventional research, referred to as corporate venturing (CV), have proven capable of increasing innovativeness. This work presents the results of a conducted action research project following the action innovation management research-framework (AIMR-framework). Over a six-month period, the author accompanied a CV management team of a high-tech multinational corporation.

The course of the project and the results are presented in this paper. First, specific characteristics of central CV management units are compiled. Next, best practices from across CV literature are systematically extracted to match these characteristics. As a result, an aligned CV initiative for integration of novel technologies is proposed.

The paper contributes to the methodological base of corporate technology management and innovation management literature. By design, the proposed CV initiative connects internal and external stakeholders and combines attributes, such as a broad scope of innovation, employee-sourced ideas, and direct financial support. The methodology applied in this work paves the way for strategic CV by which corporate innovation units can increase their innovation capabilities. The findings will subsequently help managers to increase their company´s innovation capabilities and thus provide a competitive advantage.

Keywords: corporate innovation management, technology management, corporate venturing, corporate innovation initiative portfolio, action innovation management research framework

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Vol.22, Iss.1, February 2025
URN: urn:nbn:de:hbz:6-43998539881
DOI: 10.17879/43998528063

1 Introduction

1.1 Recent developments in corporate venturing

Innovation is an essential element of today's corporate strategies. Corporations pursue innovation in multiple ways (Cefis and Marsili, 2005; Gardiner et al., 2006; de Jong et al., 2015; Bradley et al., 2018; Zander, 2022). As one element, corporate venturing (CV) refers to a loose set of corporate innovation initiatives (CIIs) designed to accelerate, create, capture and deliver different types of innovation (Burgelman, 1983; Gutmann, 2019). As a typical characteristic, CIIs include some form of innovation funnel and project portfolio management (Enkel and Sagmeister, 2020; Kock and Gemünden, 2021).

Over recent years CV received increased attention, resulting in a growing number of presented CIIs (Zahra et al., 2016) (see Figure 1). Some types, such as accelerator and incubator emerged dominant but remain rather vague (Roessler and Velamuri, 2015). Overall comparability between CIIs is described as low as well as high in ambiguity which limits overall effectiveness of CV research (Phan et al., 2009; Heinzelmann et al., 2020). Recently, scholars have begun to form clusters in which CIIs are taken and put in context to each other (Gutmann, 2019; Heinzelmann and Baltes, 2019; Heinzelmann et al., 2020).

Like a puzzle, the ideal corporate innovation initiative portfolio (CIIP) follows the MECE-principle (mutually exclusive and collectively exhaustive). Each CII acts as an essential part of the CIIP, while no two CIIs compete against each other (Rasiel, 1999; Gutmann, 2019). This systematic approach to CIIs and the CIIP is referred to as strategic CV management.

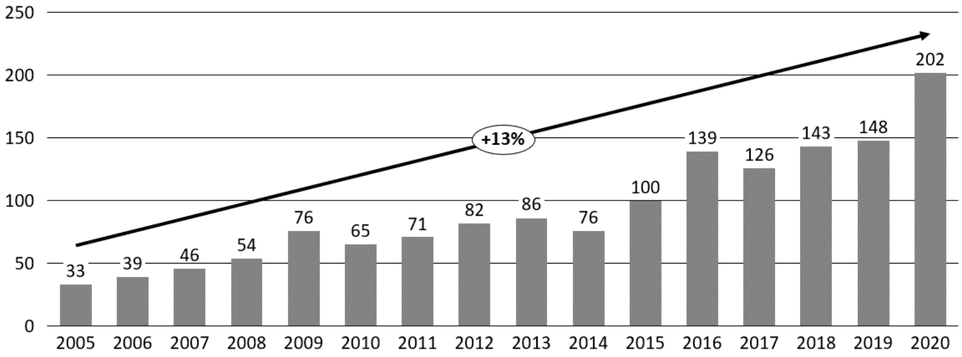

Figure 1: Number of publications on the topic "corporate venturing" over time, Compound annual growth rate between 2005-2020 of 13 %, Indexes=SCI-EXPANDED, SSCI, A&HCI, ESCI. Source: webofscience, 14.04.2021

1.2 Strategic corporate venturing management in high-tech multinational corporations

In multiple high-tech industries, such as the chemical and pharmaceutical industry innovation is a key element of business value (Shah, 2004; Festel, 2013; Festel and Rammer, 2015; Bradley et al., 2018; Glaß et al., 2020). Within multinational corporations (MNC) central functions manage CV activities. This setting comes with several characteristics which allow the application of strategic CV management (see Table 1).

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Table 1: Selected characteristics of corporate innovation management functions.

Characteristics	Description
Complexity	Each area of the value chain applies many different technologies of different maturity levels. Also, many globally situated employees with different areas of expertise are involved. Novel technologies continuously emerge from inside an outside the organization (Chesbrough and Garman, 2009; Lee et al., 2019).
Ambidexterity	The capability to exploit incremental innovation and at the same time explore radical innovation for lasting success is described as ambidextrous and seen as a key challenge for MNC innovation management (Andriopoulos and Lewis, 2008).
Ivory tower syndrome	The ivory tower syndrome refers to the gap between the scope and aims of central management functions and the ones from functions on the operations level (e.g., at manufacturing sites) due to different routines and target systems (Rockefeller, 1979).
Not invented here syndrome	Distributed employees are responsible for integrating innovations in the field, for example at different manufacturing sites. If these are not be fully convinced by an idea, resistance or biases can undermine the effectiveness of central innovation management function (Katz and Allen, 1982; Ismail et al., 2023).
Limited outside perspective	Outside perspective is essential to innovation (Bradley et al., 2018). Historically, ideas emerged from within the corporation and little focus was put on external assessment of their quality. In the early 2000s the term “open innovation” was shaped and became an established part of today’s innovation management (Chesbrough, 2003). This applies to innovation and innovation management alike.
Efficient innovation management and budget allocation	Budgets in daily operations and manufacturing e.g. at manufacturing sites are clearly defined, structured, and reported. Budgets without clear purpose are avoided. As a result, there is little flexibility to spontaneously support promising but uncertain innovation projects (Keller et al., 2020). In contrast, dedicated innovation units require high innovation output to justify themselves against higher management. Low funding volumes of early-stage ideas make it crucial to not overengineer operations within the innovation unit.
Fuzziness at the front end of innovation	Fuzziness refers to the uncertainty in early stages of innovation. Within the creative innovation process it is not clear where and when ideas emerge and how innovation can best be ensured (Management of the Fuzzy Front End of Innovation, 2014).

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The relevance of each characteristic partially depends on the industry. As an example, the value chain of pharmaceutical product supply holds a high level of complexity. The end-to-end process is initiated by patient demand, which results in dedicated research and development activities. The successful identification of an active pharmaceutical ingredient is followed by the development and approval of a novel drug. From there, the drug manufacturing starts with the raw materials. Afterwards, the drug substance is synthesized and combined with excipients to form a final drug product. Following, the drug product is packaged, distributed, and made available to patients. Each part of this chain is essential and contributes towards overall value generation (Friend, 2011) (see figure 2).

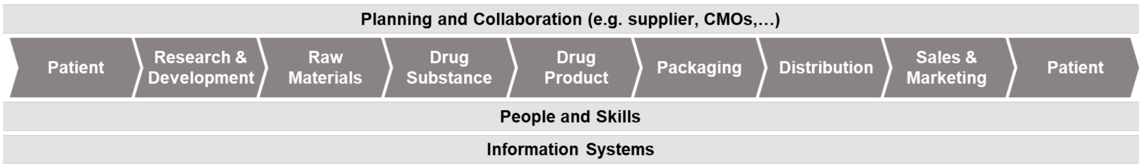

Figure 2: Schematic value chain of end-to-end product supply in pharmaceutical industry, adapted from (Friend, 2011).

With respect to the different dimensions and scope, CII design and management are complex. It remains desired to design a CII closely aligned with the specific needs and capabilities of central innovation functions. With an action research project in mind, the authors aim to answer the following research question:

RQ: How to design a corporate innovation initiative (CII) with respect to the characteristics of a corporate innovation management function?

To answer this question, this work is structured as follows. First, the action innovation management research-framework (AIMR-framework by Guertler et al. 2019) and the methods applied within the framework are described. Next, insights into several literature analyses are gathered, mapping various established CIIs, and identifying best practices. The extracted insights from literature are applied to propose an CII aligned with the characteristics of central corporate innovation management functions. Results are discussed and recommendations for management and avenues for future research are presented.

2 Methods

2.1 The action innovation management research-framework

Innovation management research can be triggered by academia or in practice, that is, by identifying a research gap or noticing specific industry needs (Kaplan, 1998; Mumford, 2001; Eikeland, 2006). Close scholar-practitioner relation can help to overcome the frequent perception of research being an activity isolated from practitioners (Flyvbjerg, 2001; Ven and Ven, 2007). Therefore, action research is a favorable method. Guertler et al. 2019 provided an overview of action research and described its high compatibility with technology and innovation management research. Action research and innovation management show similarities such as close practitioner contact and uncertainty in outcome, making the method highly compatible with innovation management (Frederiksen and Brem, 2017; Guertler et al., 2019). Subsequently, Guertler et al. formulated the AIMR-framework to specifically enable action research in innovation management (see Figure 3) (Guertler et al., 2020). The framework is already embraced, to promote rigor and diversity in innovation management (Ritala et al., 2020).

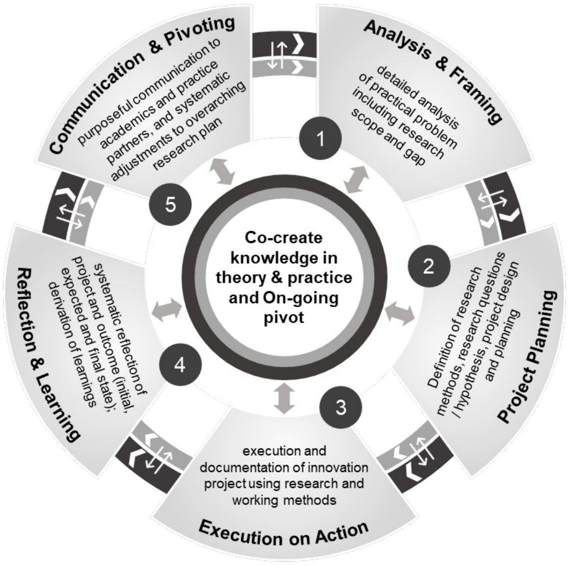

Figure 3: The action innovation management research - framework by Guertler et. al. 2019.

The AIMR-framework suggested by Guertler et al. 2019 was applied to guide the overall action research project. The different phases of the framework are briefly summarized in the following:

1. Analysis & Framing
The project is initiated, and general scope and framing are derived. Practitioner and scholarly goals and results are defined. When the researcher joins the practitioner, he holds the role of an academic-practice co-creator.

2. Project Planning
The project planning starts with extensive exchange to gain a detailed understanding of the practitioner's specifics. Afterwards a project plan is developed and research methods are selected (Mumford, 2001). Next, a basic literature analysis is performed to identify relevant literature steams and a suitable CIIP framework. From here, the characteristics of corporate innovation management functions are established (see Table 1).

3. Execution on Action
The execution phase includes the application of previously defined tasks and methods. Existing CIIs are systematically identified, prioritized and reviewed. During execution, agile iterations are possible by facilitating the "intra-project pivot" integrated in the AIMR-framework.

4. Reflection & Learning
Aligned with Guertler et al. the reflection and learning blends with the iterative approach during the previous phase. Overall insights are discussed in dedicated review meetings and aligned with overall scope.

5. Communication & Pivoting
Communication is split between tangible results for the practitioner and academic results. The practitioner results potentially including confidential information are handed over at the end the co-creation. The academic results are developed for public communication.

2.2 Applied methods within the AIMR-framework

Across its phases, the AIMR-framework recommends the application of different methods of primary and secondary research. The selected and applied methods are shown in Figure 4 and described in the following.

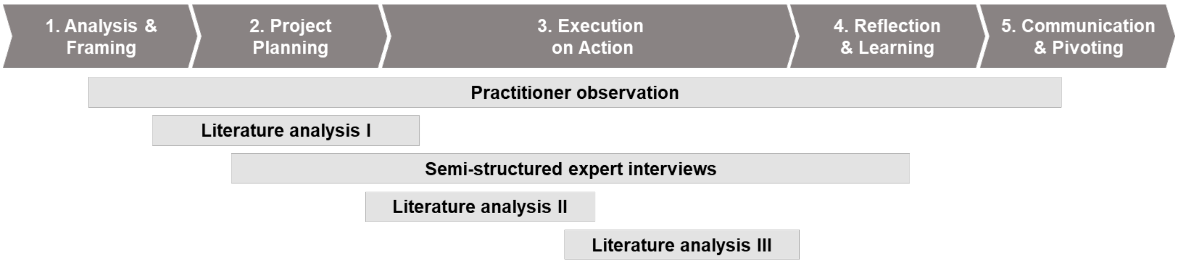

Figure 4: Applied research methods during the action research project.

2.2.1 Literature analyses

Three interconnected literature analyses are conducted over several months in different phases of the action research project. The initial literature analysis targets the identification of a structuring framework for existing CIIs. The second literature analysis focuses on CII case studies. CIIs are identified across various literature streams. The growing understanding during the action research project steadily influences the targeted literature streams. This iterative approach based on practitioners needs aims at a holistic screening of the heterogeneous literature. CIIs identified during the second literature analysis are categorized and prioritized by mapping in the framework of the first literature analysis. From there, respective literature streams are derived and further explored in the third literature analysis. The final analysis aims at extracting best practices for the later proposal of a CII aligned with the characteristics of a corporate innovation management function. Further details on the approach are summarized in Table 2.

Table 2: Overview of sequential literature analysis.

	1: Framework	2: Case Study	3: Best practices
Aim / Target	Holistic CV framework; literature reviews	CII case studies; research papers	Best practices within specific literature streams; literature reviews; research papers
Search approach / platform	Key words; high impact journals	Cross referencing from frameworks; key words; journals and conference papers	Cross referencing from selected CIIs; key words
Search platform	Google Scholar, webofscience	Google Scholar	Google Scholar
Selected Keywords	Innovation management framework, structure; corporate venturing framework;	Multinational innovation; internal corporate venturing; open innovation; case study; accelerator; incubator; internal crowdsourcing	Innovation project portfolio management; corporate venture capital; stage gate evaluation

2.2.2 Practitioner observation

Practitioner observation is applied to explore the practitioner's characteristics and existing CIIP. Participatory observation serves as a qualitative method of organizational research to develop understanding of the research subject through intensive interactions with people relevant to the research (Jorgensen, 2015). Key limitation of participating observation is that the intersubjective verifiability of the data obtained is limited due to the single source. In addition, the long presence in the field makes the method very time-consuming (Jorgensen, 2015). Furthermore, potential conflicts in confidentiality limit the extent of publicly sharing detailed insights during the phase of Communication & Pivoting. The possible restriction of objectivity due to the intensive cooperation was considered and accepted due to the chance of an in-depth understanding.

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3 Resulting insights

3.1 Frameworks for clustering corporate innovation initiatives

The landscape of CV research is fragmented and ambiguous (Phan et al., 2009; Gutmann, 2019; Heinzelmann and Baltes, 2019). The first innovation management literature analysis revealed six frameworks to structure CIIs. As one of the earliest, (Miles and Covin, 2002) present four forms of CV by differentiate between internal and external focus of entrepreneurship and direct or indirect investment resulting in a 2x2 matrix. Narayanan et al., 2009 and Selig and Baltes, 2019 later follow this differentiating between the source of innovation. Next to mention is Blume, 2020. Here, a specific focus is set on open innovation. In addition, CIIs are arranged regarding the maturity of the innovation projects. Enkel and Sagmeister, 2020 map CIIs to dynamic capability development. In a review of previous frameworks, Gutmann, 2019 derived the following seven dimensions: locus of opportunity, prioritization of objectives, ambidexterity, link to the corporate firm, level of investment intermediation, equity involvement, and the direction of innovation flow. Subsequently, Gutmann, 2019 presents a framework based on innovation flow and objectives, resulting in a 3x3 matrix. A novelty of this framework is the consideration of an "inside-in flow of innovation" as a distinct characteristic of the CIIP in MNCs (see Figure 5).

As of writing, none of the frameworks for clustering CIIs appears dominant. For this work, the framework of Gutmann 2019 was selected based on several criteria: As other, it is mutually exclusive and collectively exhaustive, allowing for a clear allocation of each identified CII. Furthermore, while early frameworks follow a 2x2 matrix (Miles and Covin, 2002), a 3x3 matrix allows for a higher degree of differentiation. Finally, the selected framework uniquely includes the inside-in flow of innovation connecting to internal open innovation initiatives and the conducted action research project. The framework can be seen in Figure 5. Detailed description regarding each category can be found in the respective publication (Gutmann, 2019).

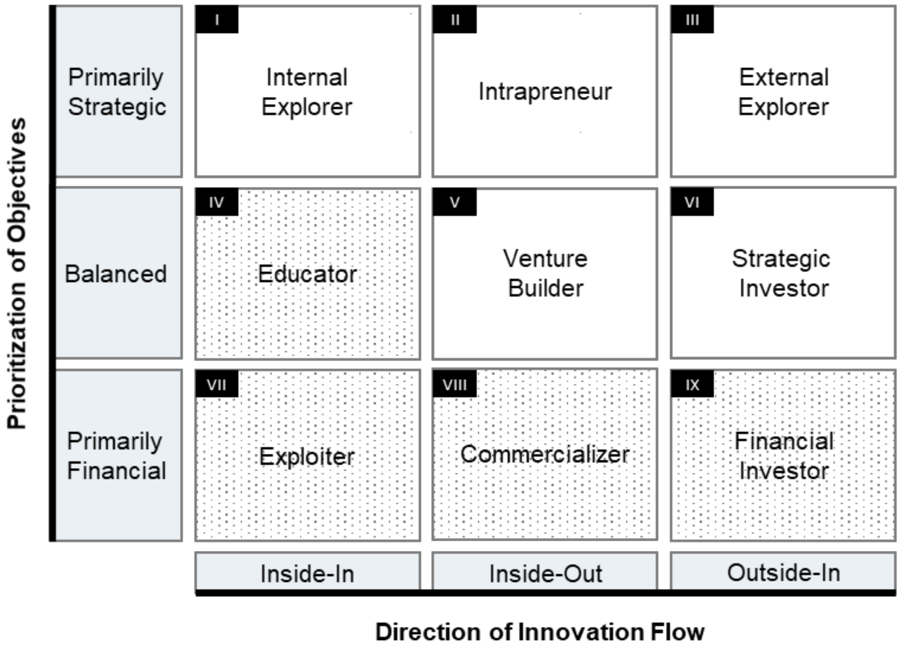

Figure 5: Gutmann's harmonized 3×3 framework for Corporate Venturing, figure adapted from (Gutmann, 2019). Highlighted modes of corporate venturing (IV, VII, VIII, IX) refer to exploitation, the others (I, II, III, V, VI) to exploration of innovation

3.2 Structured analysis of corporate innovation initiatives

During the second literature analysis 19 case studies on CIIs are identified. The CIIs are analyzed, summarized and specific characteristics of the CII are given (see Table 3). In addition, the CIIs are mapped in the related area of the presented framework of (Gutmann, 2019) (see Figure 6).

Table 3: Selected corporate innovation initiatives from literature, area in respect to the framework of (Gutmann, 2019).

#	Focus and key learnings	Area	Source
1	■ Selection process at an internal corporate venture unit of a major energy company ■ Differentiation between development risk of early-stage entrepreneurial initiatives and later risk for field adaptation	I, II	(Masucci et al., 2021)
2	■ Insights from an internal corporate venture capital unit at a large German industrial conglomerate ■ Inside-in flow of ideas applied over various business units	III, VI	(Grimpe, 2006)
3	■ Internal crowdsourcing of ideas at SAP to overcome information silos	I, IV	(Pohlisch, 2020)
4	■ Corporate venturing at Telekom ■ Iterative approach for validation of assumptions based on lean start-up approach (Ries, 2014)	V	(Breuer and Mahdjour, 2012)
5	■ Investigation of lean internal start-ups at software corporations ■ Top management support and cross-functional team as key enablers	IV	(Edison et al., 2016, 2018)
6	■ Internal corporate venturing in a large manufacturing company following a staged process ■ Entrepreneurial mindset and innovation culture	II, V	(Abrell and Karjalainen, 2017)
7	■ Success factors in internal corporate venturing at a multinational consumer goods company: Pragmatic, cross-functional support, internal visibility, risk taking	II, V	(Makarevich, 2017)
8	■ Crowdsourcing of new product ideas at Zeiss ■ Idea marketplace to prequalify ideas by employees	I	(Soukhoroukova et al., 2012)
9	■ External innovation competition at Cisco ■ Open crowdsourcing for new product development	V, VIII	(Jouret, 2016)
10	■ Strategic technology carve-outs at Thermo	VIII	(Powell, 2010)
11	■ Intrapreneurship in a knowledge-intensive industrial MNC ■ Risk tolerance, rewards, and top management support	II	(Skovvang Christensen, 2005)
12	■ Technology intelligence processes at Novartis at others ■ Complexity and learning ability of the company	V, VI	(Lichtenthaler, 2004)
13	■ Agile Stage-Gate Management for physical products ■ Benefits and challenges of agile culture	VII	(Edwards et al., 2019; Salvato and Laplume, 2020)
14	■ Large-scale paper manufacturing company ■ Quantitative selection model in new product development	VII	(Ma et al., 2020)
15	■ Front end idea evaluation at automotive OEMs ■ Focus on high customer relevance, strategic fit, ■ high communication potential and vision potential	VII	(Dziallas, 2020)
16	■ Internal corporate venturing at an electronics MNC ■ Focus on capability development not direct financials	I, IV	(Keil et al., 2009)
17	■ Internal crowdsourcing system design ■ Focus on structure, actors, technology, and projects	IV, VII	(Knop et al., 2017)
18	■ Open innovation in pharmaceutical drug development ■ High-value of outside-in innovation flow	VI	(Lee et al., 2019)
19	■ Intra-corporate crowdsourcing at an MNC ■ Idea marketplace for frontline employees	I	(Villarroel and Reis, 2010)

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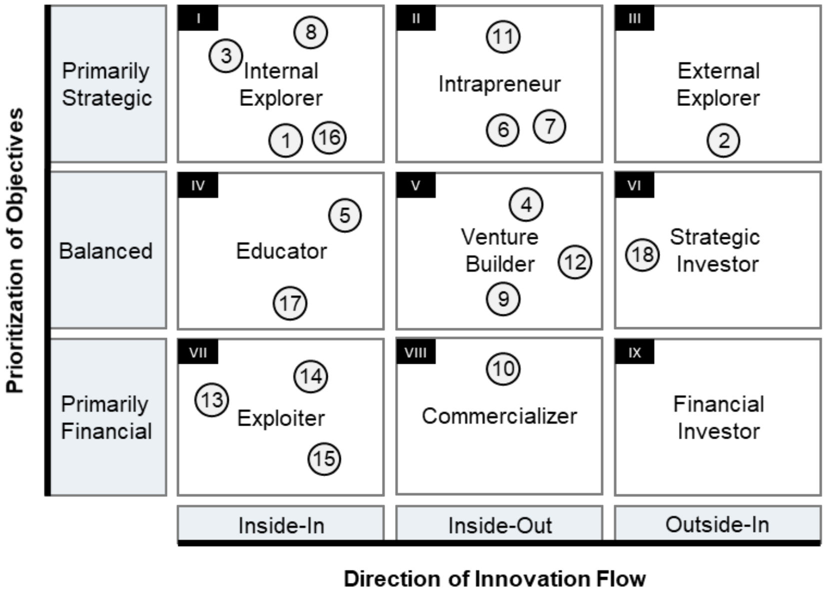

Figure 6: Corporate venturing framework of (Gutmann, 2019) including mapped corporate innovation initiatives identified from literature (see Table 3).

The research question focuses on the design of a CII harmonized with the characteristics of a corporate innovation management function. These concentrate on integration (outside-in innovation flow) of emerging technologies (primarily strategic objectives). This mainly correlates with the exploitation of innovation. Within this target area, nine CIIs are identified.

3.3 Best practices across different literature streams

In the third and final literature analysis, each framing, focus and literature stream of the nine identified CIIs is further explored. This allows the extraction and aggregation of best practices across different literature streams such as new product development, venture capital and innovation project portfolio management. Insights from 21 publications are mapped with the characteristics of a corporate innovation management function (see Table 4) and considered in CII proposal.

Differentiated risk analysis

Under the area new product development, multiple works of Cooper at al. present the Stage-Gate method (Cooper, 2008, 2019; Cooper and Edgett, 2014). Recent works focus on management of high uncertainty (Cooper, 2019). The presented expected project value takes the different phases of innovation projects into account. First there are the development costs and the associated risk of development. Later there are implementation costs as well as the associated implementation risk.

→ These insights contribute towards a differentiated evaluation of proposals.

Community approach

Best practices from (corporate) venture capital (VC) studies were gathered (Clarysse, 2005; Cavagnaro et al., 2016; Gompers et al., 2020). VC is focused on active deal generation and the process is divided into three phases: sourcing, selection, and post-investment management. A quantitative identification of key success factors remains challenging (Clarysse, 2005). A survey among 1110 VCs by Gompers, 2020 provides detailed insight. During sourcing >30% of proposals come from direct or indirect contacts of the VC management. 47% of survey participants rate the team as the most important factor. Others follow that assessment (Cavagnaro et al., 2016). This is followed by business-related factors at 37% (Gompers et al., 2020).

→ These insights contribute towards the phased structure of the CII, the roles for sourcing and execution within a network and community approach.

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Project lineage

It was shown that pharmaceutical organizations learn from continuous venture activities (Dunlap-Hinkler et al., 2010). These results where generalized by an empirical analysis of 257 firms (Kock and Gemünden, 2019). The authors showed that the factors innovativeness and risk taking both linked to entrepreneurial orientation positively moderate the relationship between managerial practices and performance of continuous innovation project portfolio management practices.

→ These insights contribute towards a repetitive and learning approach for projects and the CII itself.

Dynamic portfolio management

A risk-positive, entrepreneurial orientation can leverage the quality of innovation project portfolio management (Kock and Gemünden, 2021). This includes adjustments as rigor as project termination as uncertainty reduces over time (Kaufmann et al., 2021). Subsequently, performance measurements should focus on overall portfolio success (Bailey et al., 2019).

→ These insights contribute towards a dynamic portfolio design and risk-positive attitude.

The overall gained insights from literature were considered in the proposed CII which is presented in the following chapter.

4 Proposed corporate innovation initiative for integration of emerging technologies

In the first chapter of this work, specific needs of innovation management units in MNCs were identified from literature and practice (see Table 1). In subsequent literature analyses elements from CIIs and best practices from selected literature streams were collected (see chapter 3). Subsequently, these insights are combined. The characteristics of innovation management units in MNCs are addressed by selected features of CIIs (see Table 4).

Table 4: Features of proposed corporate innovation initiative aligned with characteristics of corporate innovation management functions.

Characteristics	Features of proposed CII including confirmation from literature findings
Complexity ■ Fast value chain ■ Many technologies ■ Many employees involved	Decentralized sourcing of ideas via employees (Soukhoroukova et al., 2012; Pohlisch, 2020) Interdisciplinary CII expert community to determine expected project value (Cooper, 2019; Edwards et al., 2019; Salvato and Laplume, 2020)
Ambidexterity ■ Exploitation of incremental innovation ■ Exploration of radical innovation	Clear focus on exploration of novel technologies (Andriopoulos and Lewis, 2008) Portfolio balancing via risk assessment (Sanchez et al., 2008; Antonczyk and Salzmann, 2012)
Ivory tower syndrome ■ Gap between central management understanding and operations needs	Sourcing ideas from front-line employees (Jouret, 2016; Abrell and Karjalainen, 2017; Makarevich, 2017) Ensuring operational need via project sponsor (Kock and Gemünden, 2021) Expert community for cross-functional exchange
Not invented here syndrome ■ Resistance or biases to fully embrace external ideas	Sourcing ideas from front-line employees (Jouret, 2016; Abrell and Karjalainen, 2017; Makarevich, 2017) Decentralized sourcing of ideas via employees (Soukhoroukova et al., 2012; Pohlisch, 2020) Ensuring operational need via project sponsor (Kock and Gemünden, 2021)
Limited outside perspective ■ Need for open innovation and external benchmarks ■ Applies to projects and CII	External scope is essential for application (Festel and Rammer, 2015; Lee et al., 2019) Funding focus on external resources (Festel et al., 2015)
Efficient innovation management and budget allocation ■ Little decentral innovation budgets ■ Low funding volumes in early-stage funding need to be in balance with CII management effort	Lean flow of information Valuation based on few selected quantitative parameters and focus on expert discussion (Cooper, 2017; Cooper and Sommer, 2020) Repetitive funding process to foster learning (Lichtenthaler, 2004; Kock and Gemünden, 2019)
Fuzziness at the front end of innovation ■ Unclear how and when invention starts	Open innovation approach: Exploring external ideas aligned with specific internal innovation needs (Villarroel and Reis, 2010; Kock and Gemünden, 2021)

The features in Table 4 guide the proposal of a CII, which is presented in the following. The description focuses on operations and corresponding roles. In essence, the proposed CII maintains a dynamic and rolling innovation project portfolio. The core process is a regularly triggered funding procedure including a screening phase, a selection phase, and an ongoing supporting phase. Regular project selection allows competence to build up and to learn from past funding rounds (Kock and Gemünden, 2019). Next to these events the community is continuously maintained to foster cross-functional exchange regarding novel emerging technologies and therefore potential new projects (de Jong et al., 2015; Garrett, 2015). The proposed setup includes five dedicated roles. Each role comes from a different area across the organization. To keep operations efficient, each employee involved contributes to the initiative as one of multiple responsibilities (Table 5).

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Table 5: Overview of roles for the proposed corporate innovation initiative (CII).

Role	Description
CII expert community	The CII expert community holds various expertise from various functional areas. They act as a cross-functional community to support the inside-in innovation flow. Individual expertise allows for project recommendation and evaluation. In addition, the community members leverage their network to collect additional proposals.
Project sponsor	The project sponsor ensures real operational need and later field implementation of projects.
Project initiator and manager	The project initiator is a frontline employee from across the value chain. If the project is selected, the role shifts to project manager, ensuring commitment and individual expertise.
Project partner (external)	The project partner is a mandatory part of every project. This external stakeholder provides the desired novel technology, either as a product or service.
Project customer (internal)	The project customer is the receiver of the project's results and the potential applicant of the technology (e.g., a manufacturing site or research unit)

After presenting these roles the specific operations of the funding process are described in Table 6.

Table 6: Overview of the proposed corporate innovation initiative's (CII) annual funding process.

Phase	Step	Content and key reference
Screen	**1**	In repetitive intervals the CII distributes a call for applications across functional areas. Applicants can apply until a certain deadline is reached. The guided application includes first descriptions and assumptions for determination of the expected project value. The network of the CII expert community is leveraged to extend the reach of the call for applications. → This leverages the learning by project lineage (Kock and Gemünden, 2019) and active idea sourcing from employees (Gompers et al., 2020).
Select	**2**	Members of the CII expert community pre-evaluate the received proposals through the lens of their area of expertise. Factors include team setup and value estimation following (Cooper and Sommer, 2020). → This leverages technology expert evaluation for optimal portfolio selection (Clarysse, 2005; Festel et al., 2015).
	3	High-priority projects are reviewed in discussion sessions. The cross-functional background of the CII expert community allows termination and transfer of ideas if they are already perused somewhere else in the organization or prior knowledge is available. Criteria follow → This leverages the inside-in innovation flow (Guertler et al., 2020) across the supply chain.
	4	Higher management selects the projects based on prior evaluation. → This leverages cross-functional and top-management approval to ensure project priority (Skovvang Christensen, 2005).
Sustain	**5**	Results are communicated and budgets distributed. To achieve tangible results projects, focus on proof of concepts, feasibility studies and minimal viable products (MVPs). → This leverages entrepreneurial orientation and lean start-up focus of the ideators (Breuer and Mahdjour, 2012; Kock and Gemünden, 2021).

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5 Discussion

This work describes an action research project proposing a CII based on strategic CV. First, practitioner needs are identified. Next, selected CIIs are analyzed across various literature streams and best practices are extracted. As result, a CII for integration of emerging technologies across a wide area of applications is proposed. The CII is characterized by idea sourcing from frontline employees, expert evaluation with cross-functional exchange, efficiency, and a rolling innovation project portfolio.

The systematic research approach is supported by the application of multiple frameworks. First, the AIMR-framework guides through the phases of the action research project. By 'intra-project pivoting', the framework allows for the necessary flexibility in operations. This scalability and flexibility make it a promising addition for innovation management research.
Next, for the systematic literature analysis, a framework for CV was applied to support structuring the heterogeneous research landscape. As a result, potentially otherwise overlooked best practices are included in the results. For example, multiple best practices from venture capital and new product development literature are incorporated. Also, the framework itself gave guidance, highlighting the inside-in flow of innovation.

The systematic approach in this work confirms the need for harmonized structures in CV research. Generally, initiatives are often not described in such a level of detail to be fully comprehensible in regard to complexity, operations, and motivation. While the applied framework of Guertler et al. 2019 was among the most sophisticated frameworks available, there are more characteristics to distinguish CIIs and that are relevant for CII design. Some examples for additional characteristics are budget, timeline, type of resource allocation and level of employee involvement.

The proposed CII is derived from multiple research findings. First, VC research shows advantages of community project selection. To better cope with the high level of uncertainty of early-stage innovation projects moderated open discussions are prioritized over individual complex quantitative scoring. Second, it is shown in literature that a lineage of work increases quality of outcome and characterizes innovation leaders. As a result, a repetitive process of portfolio assembly is proposed. Third, evaluation of innovation projects is aligned with positive research findings from new product development, the differentiation between technology maturity and implementation risk allows for a sophisticated discussion. Risk of technological development can be assessed by subject matter experts, while implementation risk is linked to project sponsor commitment and project customer need. After project assessment the portfolio is jointly formed balancing cost, risk, time, and expected benefit.

The proposed CII is aligned with the needs of corporate innovation management units responsible for pursuing CV across the organization. The presented characteristics were derived from academic literature and practitioner insight. The literature foundation lets the authors hope that the identified features of corporate innovation units are generally valid and that the proposed CII can support other CV functions in need of integration of emerging technologies in their respective CIIP.

6 Conclusion and Outlook

Central CV management functions aim at increasing the level of corporate innovation. Specific characteristics of these units and corporate structures in general challenge the integration of external emerging technologies. This work shows how strategic CV can be applied to address such specific innovation needs. It thus contributes to management and research in different ways.
First to mention are the several contributions towards management. The described action research project can serve as a template for practitioner-scholar interaction. The applied framework of Guertler et al. 2019 shall encourage practitioners to strategically assess their CIIP. This might reveal blank spots where innovation management can be further improved. Here the presented CIIs can serve as a starting point. Also, practitioners are advised to incorporate cross-functional communities from throughout the whole company, strengthening the inside-in innovation flow.
Second to mention are the scholarly contributions. The detailed application and discussion of the AIMR-framework strengthens its role in innovation management. The work confirmed it as an advantageous framework to follow scholar-practitioner cooperation in innovation management. Furthermore, a CII was designed and proposed based on practitioners' needs. The authors can confidently claim

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that they have found no identical CII within their literature research, making the proposed CII a potentially valuable addition.

The pursuit of cost-effectiveness across the whole value chain does not stop at innovation management. Here practitioners need pragmatic decision guidelines for CII and CIIP setups. In order to achieve this, CV research needs sophisticated multidimensional frameworks to cope with the fuzzy nature of innovation. Current research started with CII interactions analyzed (Heinzelmann and Baltes, 2019; Heinzelmann et al., 2020) and should continue towards CIIP analysis. Detailed specifications on different CIIPs might allow cross-corporation comparability and reveal blank spaces where novel CIIs are yet to be developed. Here, comparing studies between CIIPs of top performers and others would be of great scholarly and practitioner interest.

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JOURNAL OF
BUSINESS CHEMISTRY

Vol.22, Iss.1, February 2025
URN: urn:nbn:de:hbz:6-43998535719
DOI: 10.17879/43998525170

Practioner‘s Section

Daniel Eggart *, Arko Graf-Bürk **, Niklas Huber ***

Leveraging Generative AI for Rapid Competitive Landscape Analysis: A Feasibility Study in the Chemical Industry

Competitive analysis is a crucial yet challenging task for chemical companies as it requires synthesizing fragmented financial and market information to assess strategic positioning. Conventional methods are often time-consuming and labor-intensive limiting their scalability, efficiency and adaptability. This study explores the potential of generative AI to overcome these challenges by automating the extraction and interpretation of corporate financial reports and mapping product portfolios to end-user markets based on the Global Industry Classification Standard. By linking these markets to historical growth rates, the presented methodology maps competitive positions and reveals strategic opportunities as well as market risks for selected chemical companies. The AI-powered approach significantly accelerates competitive analysis while ensuring accuracy and reliability. The study concludes with an outlook on how generative AI can further enhance strategic decision-making in the chemical industry and beyond.

Introduction

The chemical industry is characterized by high complexity due to its diverse product portfolios, regulatory constraints, and entangled supply chains (Hiemer and Suntrop, 2017). In the past few years, the chemical industry has been undergoing significant transformation, driven by increasing competition, technological advancements, and regulatory pressures. As traditional business models become less effective in navigating these challenges, companies must adopt new analytical frameworks to sustain competitive advantages (Utikal and Leker, 2018). Historically, strategic analysis has relied on structured methodologies including, for example, expert interviews to derive SWOT (strengths, weaknesses, opportunities, and threats) analysis (Paul, 2010). However, interviews with industry professionals pose the risk of bias from subjective expert opinions and may also lack statistical validation due to limited sample sizes (Dorussen et al., 2005). This and other conventional approaches to competitive analyses in the chemical industry and beyond can be time-consuming and require extensive in-depth industry knowledge (Pleatsikas and Teece, 2001).

Generative AI (GenAI) has become an essential technology enabling automated industry comparisons and financial forecasting due to its capacity to rapidly analyze vast amounts of data (Kumar et al., 2025). While its huge

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Vol.22, Iss.1, February 2025
URN: urn:nbn:de:hbz:6-43998535719
DOI: 10.17879/43998525170

potential is recognized by most companies, the practical feasibility of applying GenAI to use cases in the chemical industry remains an open question (Konrad, 2024). This study demonstrates and evaluates the power of leveraging OpenAI's ChatGPT to enhance competitive and strategic analysis in the chemical sector.

In more detail, the authors developed a GenAI-supported approach to evaluate the strategic positioning of ten European chemical companies. Profitability and performance trends were calculated using financial metrics extracted from corporate financial statements by GenAI. Additionally, the algorithm mapped company activities to their corresponding end-user markets, which were then aligned with historical growth rates revealing strategic opportunities. The presented approach demonstrates the potential of using GenAI to efficiently generate competitive landscapes. With the framework at hand, the process can easily be re-applied, allowing for seamless re-evaluation and thus ensuring an up-to-date understanding of the competitive environment.

Future work could further enrich the presented results by incorporating additional information such as press releases on investments, acquisitions, and divestitures providing further insights into companies' strategic direction. Additionally, integrating frequently updated market reports and price forecasts could enable even more dynamic and forward-looking analyses. Finally, the framework could be applied to other asset-heavy industries, making it a scalable approach to future competition analysis.

Literature Review: GenAI for Competition Landscape Analysis

Recent advancements in GenAI enable new ways to conduct structured competition analyses within an industry including the interpretation of financial reports. Generally, there are multiple approaches to screen and interpret reports with GenAI. First, as used in this study, relevant documents can be directly uploaded to ChatGPT and subsequently analyzed. This direct approach is easily implemented while maintaining a robust performance.

Beyond this direct usage of documents, a study by Amazon Web Services demonstrated the benefits of fine-tuning LLMs for summarization and answering questions concerning complex financial documents (Amazon Web Services, 2024). Furthermore, a comparative analysis of retrieval-augmented generation (RAG) by Zou et al. identified the GPT-4 LLM as a leading model for data analysis of environmental, social, and governance reports (Zou et al., 2024). Compared to the approach within this work, LLM fine-tuning and RAG implementation might allow for even more granular results and answers.

Integrating additional sources beyond financial reports provides further opportunities for in-depth industry studies. A GenAI analysis of corporate news, reports and policies was shown to be valuable for stock analysis and investment recommendations (Teo et al., 2024). Similarly, Beckmann et al. found that unusual financial communication extracted with ChatGPT from earnings call transcripts correlates with a negative stock market reaction and can thus be used in stock and company analysis (Beckmann et al., 2024).

In all cases, communication with the GenAI model requires proficient prompts to enable optimal results. Therefore, establishing and fine-tuning prompts – called prompt engineering – has become an essential part of using GenAI. A recent work by Krause explored the capabilities and limitations of different LLMs in financial and company analysis, emphasizing the importance of well-structured prompts to maximize accuracy and relevance (Krause, 2023). The study highlights essential practices, such as iterative prompt refinement, adding domain-specific context, avoiding ambiguity, and cross-verifying AI-generated insights with conventional analytical methods. Additionally, the risks of excessive reliance on AI-generated outputs without human validation, such as the possibility of hallucinated information and challenges in factual validation of the GenAI output, are discussed. Furthermore, Sikha et al. highlighted structured prompting as a key technique to enhance AI interpretability and reliability, demonstrating how adaptive prompt engineering strategies refine AI responses through iterative optimization (Sikha et al., 2023).

Further improvements can be achieved by utilizing open questions and starting conversations with the algorithm. An example of advanced AI interactions is explored by Chukhlomin who introduces "Socratic prompting" as a technique to refine AI-generated responses. By structuring prompts within the question-driven approach, this method helps mitigate biases and improve the depth of AI-generated insights (Chukhlomin, 2024).

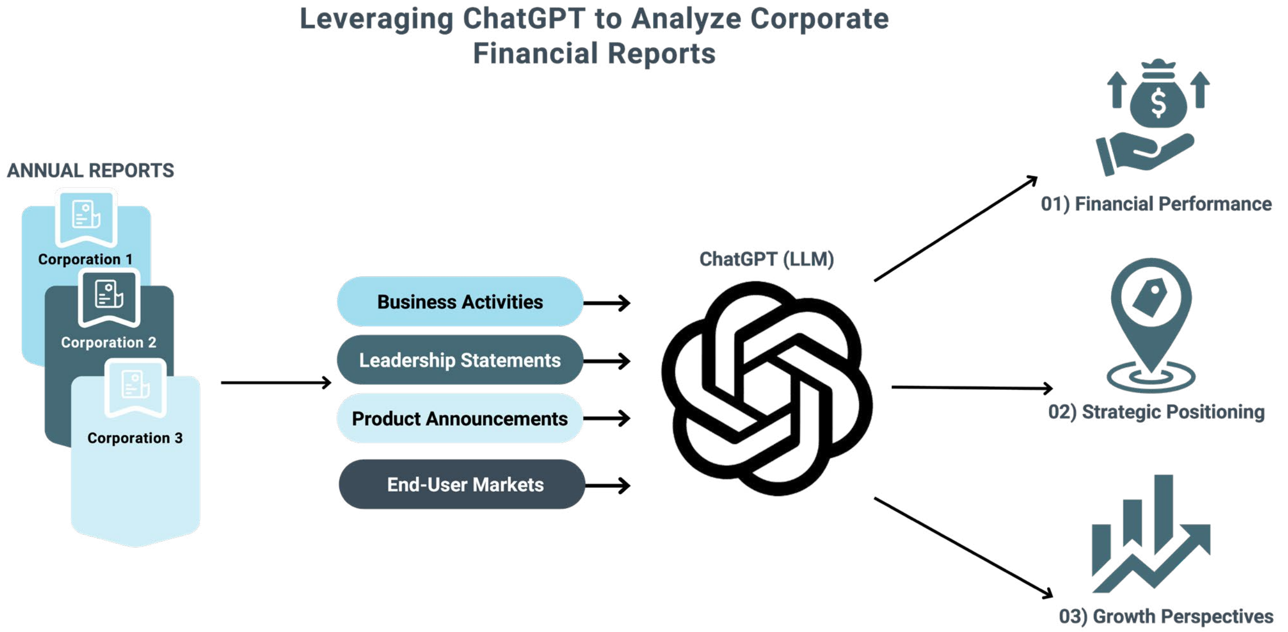
Besides providing output in natural language, GenAI can boost the process efficiency of text-processing tasks such as advanced categorization and pattern recognition. As an example, Rizinski et al. showcased the potential of natural language processing in automating industry classification for datasets, since established standards like Global Industry Classification Standard (GICS) traditionally rely on manual industry assignment by experts (Rizinski et al., 2024). In addition, the paper by Krause also discusses the advantages of AI in accelerating data processing and uncover patterns in vast financial datasets (Krause, 2023).

Overall, GenAI has the potential to minimize the need for manual data gathering, significantly enhancing process efficiency and allowing for rapid analysis of extensive datasets. The practical use case, described in the following sections of this paper, demonstrates these capabilities for competition landscape analysis while providing detailed instructions and showcasing exemplary results.

Methodology

This study deploys a structured analysis utilizing the large language model (LLM) of OpenAI's ChatGPT model 4o to interpret the financial reports from 2021 to 2023 of 10 selected European players in the chemical industry. Namely, these companies are Air Liquide, BASF, Bayer, Covestro, INEOS, Linde, Solvay, Syngenta, Umicore, and Yara. A schematic work and data flow is depicted in Figure 1. The methodology begins with automated data extraction and processing with ChatGPT where financial data is gathered from published annual reports.

Figure 1: Schematic overview of the automated analysis of corporate financial reports with ChatGPT.



For all steps, a dedicated series of prompts was developed. Results were improved by applying several prompt engineering techniques. This includes breaking the tasks of data extraction and interpretation into smaller work packages, automated verification of the extracted data, and giving virtual bonuses to ChatGPT for detailed and thorough extraction of data. Furthermore, the prompt was enriched with exemplary expected results providing validated examples and thus guidance to the LLM. To ease the subsequent analysis and visualization, the prompt also provided how to output the extracted information, i.e., tabular formatting and naming of columns.

For a comparative financial assessment of the companies, revenue and EBITDA figures were extracted from the reports for the fiscal years 2021, 2022 and 2023. Subsequently, the end-user markets, in which the sold products, chemicals and services are ultimately used, were identified. The LLM leverages natural language processing to scan, interpret, and match products with their relevant markets. For instance, in the classification process, the product „Chemicals for surface treatments and coatings for electronics" is automatically identified as being linked to the „Electronic Equipment & Instruments" end-user market. In addition, ChatGPT is asked to explain each mapping of product to end-user market enabling a fast way to validate the extracted data with additional expert knowledge.

The extracted end-user markets were then linked to an industry category of the Global Industry Classification Standard (GICS) system (S&P Dow Jones Indices and MSCI Inc., 2023). The standardized classification ensures consistency in the analysis across different players and allows for direct comparison between these companies concerning their strategic positioning in the end-user markets.

Furthermore, every GICS industry was matched to a published compound annual growth rate (CAGR) from 2019 to 2023 (Damodaran, 2024). Finally, all industry growth rates were categorized from low (<5%), medium (5% to 10%) to high (>10%), to provide a semi-quantitative and comparative assessment that enhances understanding of potential market opportunities and growth trajectories for the investigated companies.

Since the GICS industry names differ from the sector names of the published revenue growth rates, we matched the GICS industries with ChatGPT to the revenue growth sectors. The GICS classification comes with a detailed description for every industry. The industry descriptions for the revenue growth sectors were generated with ChatGPT by using the list of companies for each respective sector. The revenue growth sector descriptions were then matched with ChatGPT to the GICS industry descriptions.

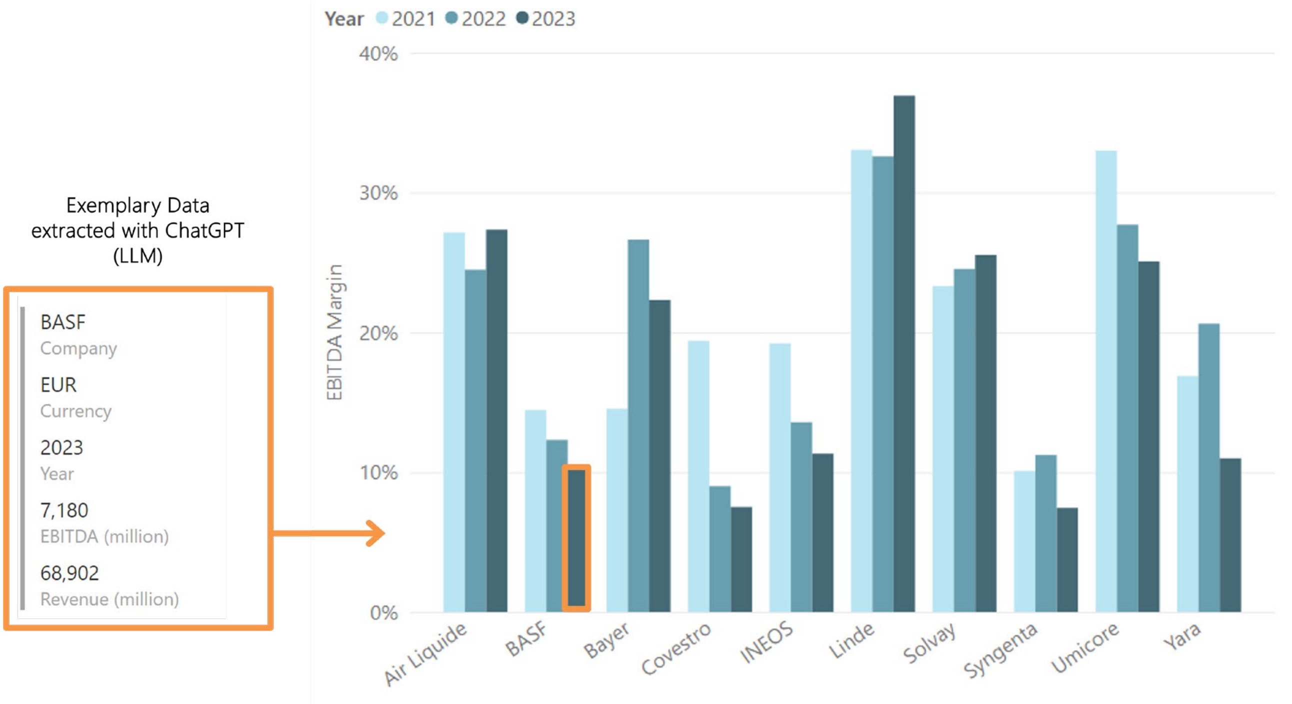
Results

As described in the methodology section, we chose ten chemical companies to demonstrate the potential of GenAI in competitive landscape analysis. Applying the above-described steps using ChatGPT yielded several key insights related to their financial performance, strategic positioning, and market opportunities. By processing publicly available financial reports and annual business statements, the tool successfully extracted financial information and identified end-user markets for each company's products. These comparative analyses provide an initial overview of the individual companies' strategic positioning and the industry's dynamics. The insights derived from this comprehensive analysis are synthesized into a comparative framework that highlights the strategic positioning of the selected chemical companies. This framework not only identifies market opportunities and shortcomings but also recommends strategic opportunities that companies may consider capitalizing in future.

Financial Performance

The GenAI-based approach effectively retrieved and processed the financial data of the selected chemical companies, demonstrating the model's ability to reliably and accurately handle complex financial statements and annual reports. A key metric is the EBITDA margin, which provides insight into each company's operational profitability before interest, taxes, depreciation, and amortization. Figure 2 depicts the results from the semi-automated report screening. This initial financial analysis sets a foundation for understanding both current performance and trends over

Figure 2: EBITDA margin comparison for ten chemical companies from 2021 to 2023 (light to dark blue) as extracted with GenAI from corporate financial reports. An example of raw data gathered by ChatGPT is shown in the orange box for BASF in 2023. The derived EBITDA margins (EBITDA divided by revenue) for all companies are plotted on the right.


Exemplary Data extracted with ChatGPT (LLM)

BASF
Company
EUR
Currency
2023
Year
7,180
EBITDA (million)
68,902
Revenue (million)

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URN: urn:nbn:de:hbz:6-43998535719
DOI: 10.17879/43998525170

the past three years.

As an example, in 2023 the data displays notable differences in the absolute EBITDA margins across the companies. Linde stood out with the highest margin at 37%, followed by Air Liquide 27%, and Solvay at 26%. These companies exemplify successful execution in niche markets and rank in leading market positions with specialized, high-value products. Among others, products such as industrial gases, advanced materials, and catalysts benefit from stable demand and premium prices. On the other hand, companies like BASF, Covestro and Syngenta reported lower EBITDA margins of 10%, 8% and 7%, respectively. While their diverse product portfolio provides resilience, larger shares of commoditized business areas in the portfolio limit overall profitability. In particular, competition from Asian producers and rising energy and raw material costs create more challenging business conditions while impacting margins for the observed period.

Examining the changes in profitability between 2021 and 2023 reveals varying trajectories among the companies. Linde, Air Liquide, and Solvay maintained relatively stable and high profitability throughout the period. Considering the geopolitical changes and disruptions throughout these years, the companies show high resilience and low volatility against economic fluctuations. In contrast, several companies such as BASF, Covestro, INEOS, and Umicore recorded notable and gradual declines in their profitability. This can be interpreted as a sign of a more cyclical product portfolio and overall higher price sensitivity.

While comparing EBITDA margins across companies and years is a basic analysis, the results establish a baseline understanding of financial health and profitability trends within the sector. To gain a more comprehensive view of growth trajectories and investment in potential opportunities, additional financial metrics could be integrated into the model. Metrics such as R&D-to-sales ratio, CAPEX trends, cash flow, debt-to-equity ratio, and ROE/ROA would offer valuable insights not only into current performance but also how well-positioned each company is for organic and sustainable growth. However, in this analysis, these metrics were not included due to an overall inconsistent reporting on the mentioned KPIs across the selected companies.

Strategic Positioning

Next, the ChatGPT framework was used to extract and categorize the companies' business activities and product applications in end-user markets. This approach allowed for a detailed mapping of each company's strategic focus across different subsegments, such as specialty chemicals, agricultural chemicals, and consumer products (Figure 3). The matrix highlights each company's relative allocation of identified end-user markets. The color intensity in each cell reflects the strategic focus based on qualitative data from the annual reports such as product announcements, leadership statements, or summaries of business activities. The model's capability to provide explanations for individual data points in the matrix was highlighted with two exemplary results (Figure 3, left), also allowing easy validation and deeper understanding of the data. Note, the assignment of products to their corresponding end-user markets is conducted through a fully automated process, significantly reducing the effort that a manual categorization would entail.

The analysis demonstrated the ability of GenAI to accurately distinguish between relevant and irrelevant GICS sectors for the displayed chemical companies. For sectors such as real estate, financials, and communication services, which are less aligned with the core operations of chemical companies, only few examples were found and are thus not shown here. This capability underscores the model's precision in focusing on sectors and end-user markets directly tied to the chemical sector, such as materials, consumer staples, industrials, and energy, ensuring results remain relevant and actionable.

A key insight from the heatmap is the contrast between companies that pursue broad diversification and those that adopt specialized strategies. Diversified companies, such as BASF and INEOS, display dependencies across multiple segments, with e.g., BASF balancing its portfolio towards materials, consumer staples, and consumer discretionary sectors. INEOS exhibits a similar approach, balancing its activities with commodity and specialty chemicals towards various end-user markets in construction, household products, and automotive. In contrast, the heatmap shows a more concentrated focus for companies like Syngenta and Bayer.

The analysis can further provide an indication of competition and leadership dynamics within certain subsegments. For example, Agrochemicals is an area where the matrix shows several companies such as Bayer, Syngenta, and Yara with highlighted activities, hinting at direct or distant competition in the market. However, such overlap also suggests opportunities for collaboration, especially in areas where shared interests align, such as improving efficiency, co-development & innovation, or advancing sustainability initiatives. By leveraging these common

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URN: urn:nbn:de:hbz:6-43998535719
DOI: 10.17879/43998525170

goals, companies could potentially reduce costs, accelerate development cycles, or address broader industry challenges collaboratively. Additionally the analysis also highlights leadership in specific markets with minimal competition between the selected companies. For instance, Linde's and Air Liquide's focus on industrial gases positions them with a limited direct overlap from other companies within the analysis.

The heatmap further highlights differences in dependence on cyclical versus non-cyclical industries. For example, companies with significant ties to construction materials, automotive, and manufacturing may experience more pronounced sensitivity to economic cycles, which can introduce volatility in short- and mid-term performance. In contrast, companies with a focus on agricultural products, consumer staple goods, and pharmaceuticals/healthcare operate in markets for which demand remains relatively stable over time. These markets are driven by factors such as population growth or food security needs. The model's breakdown can therefore indicate how portfolio composition and market activities result in different exposures to cyclical and non-cyclical business in the peer group.

The analysis demonstrates the model's ability to extract and categorize business activities, accurately map strategic priorities, and identify key elements of competitive positioning within the chemical companies at hand.

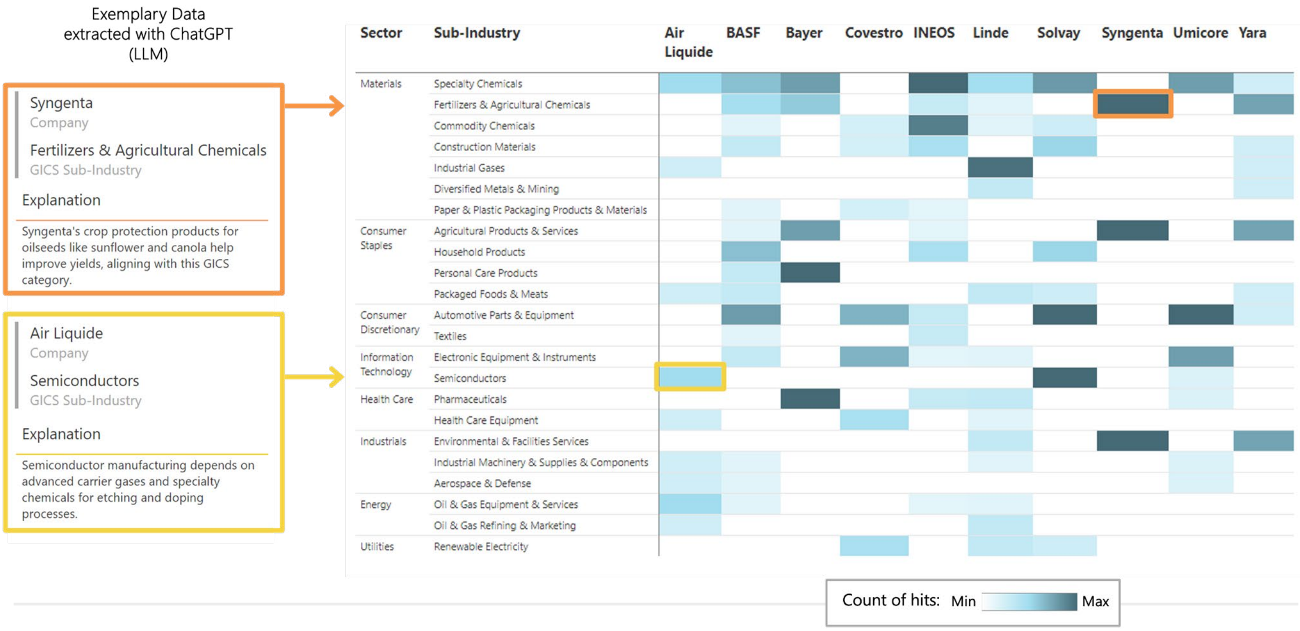
Market Opportunities & Risks

Next, the strategic focus of each company is linked to historical industry growth rates of the identified end-user markets. As described in the methodology section, each company's activities were linked to high-, moderate-, and low-growth sectors based on compound annual revenue growth rates (CAGR) from 2019 to 2023 (Figure 4). From dark to light blue, the data represents high-growth (>10% CAGR), moderate growth (5–10% CAGR), and low-growth segments (<5% CAGR). Identified sub-industries with high growth during past years are, for example, pharmaceuticals, agricultural products, and electronic equipment. While fertilizers, automotive parts, and building materials showed moderate growth, examples of sub-industries with low growth are household products, paper packaging, and agricultural machinery.

Mapping the end-user markets, as identified for each company's products into these three categories provides a detailed perspective on how chemical companies are aligned with growth opportunities across their portfolios (Viguerie et al., 2011). Furthermore, the graph shows the portfolio alignment of each company with growing markets, revealing notable differences in resource allocation and strategic focus. The data shows varying degrees of alignment with market trends, capturing opportunities, and insights into competitive positioning across the industry.

In more detail, the visualization reveals clear differences in strategic positioning across companies. Companies with a significant share of high-growth segments, like

Figure 3: Strategic positioning of key chemical companies across GICS industry sectors and sub-industries, highlighting the concentration of business activities. Darker colors indicate stronger focus areas within specific sub-industries. In the orange and yellow boxes on the left side, two with ChatGPT extracted exemplary data points of identified GICS industry and matching explanation of identified end-user market to GICS industry are given.



Syngenta's crop protection products for oilseeds like sunflower and canola help improve yields, aligning with this GICS category.

Semiconductor manufacturing depends on advanced carrier gases and specialty chemicals for etching and doping processes.

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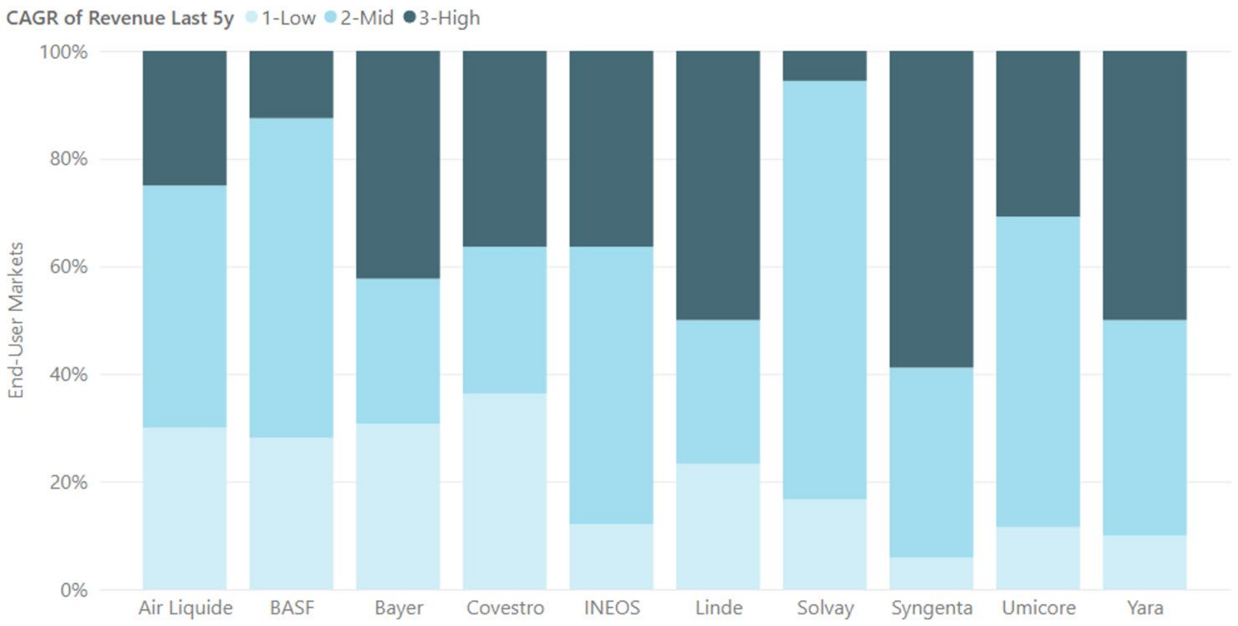
Syngenta and Linde, appear well-positioned to capitalize on expanding demand in fast-growing markets, such as semiconductors, pharma, and agriculture. This alignment may provide potential competitive advantages in capturing growing demands. In contrast, companies with significant activities in moderate- and low-growth segments, like Solvay and BASF, may face challenges in achieving significant growth, as these segments tend to experience greater market stability but lower growth potential. Such portfolio compositions could introduce strategic risks due to missing growth opportunities in the long run.

The analysis further provides insights into portfolio resilience. Companies with a balanced distribution across high-, moderate-, and low-growth segments could mitigate risks associated with volatility in individual categories. Firms blending high-growth opportunities with stable mid-growth markets might buffer against fluctuations while maintaining steady long-term growth. Conversely, companies focused heavily on high-growth markets may face greater exposure to market shifts, while those weighted toward low-growth areas risk stagnation without strategic adjustments.

By comparing this chart (Figure 4) with the heatmap of strategic focus (Figure 3), additional insights emerge. Companies heavily specializing in high-growth segments may also exhibit niche dominance in the heatmap, signaling deliberate alignment with emerging trends. As an example, Syngenta provides products to a few markets that however showed robust growth during past years. Conversely, firms balancing high-, moderate-, and low-growth areas often align with diversified strategies that emphasize risk mitigation. The balanced approach is identified, for example, for INEOS, which additionally enables products in many end-user markets. Identifying mismatches between growth opportunities and strategic focus provides valuable opportunities for companies to adjust their priorities or reallocate resources. Besides the positioning in growing markets, the profitability that can be achieved within an industry plays a crucial role in achieving high margins. While Syngenta and Linde both sell into growing markets (Figure 4), the specific profitability depends on the individual end-user markets. This also hints at differences in these companies in terms of EBITDA margin (Figure 2). Including the dimension of average profitability in each industry could enrich the analysis in future.

Overall, the results highlight the varying degrees of future readiness among chemical companies. Firms with a strong presence in high-growth segments appear better positioned to seize market opportunities, while others may need to adapt their strategies to address market dynamics. By linking growth potential with existing market focus, the tool enables a forward-looking perspective on competitive positioning and portfolio optimization. Next, the precision and reliability of the GenAI-based results are elaborated.

Figure 4: End-user market growth across key chemical companies. Three categories are defined with revenue CAGR in the industries during the last 5 years: Green represents high-growth segments (>10% CAGR), grey indicates moderate growth (5-10% CAGR), and red signifies low growth (<5% CAGR).



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Evaluating GenAI Output

To ensure the accuracy and reliability of the AI-generated insights, a thorough validation process was deployed. Firstly, by cross-checking selected financial metrics and the end-user market interpretations against the respective corporate annual reports, the prompts used for extraction and analysis were improved. This iterative process of improving the prompts and subsequently reevaluating the AI-generated insights ensures reliable data extraction. The output was then tested for consistency across multiple cycles. By running the tool on the same dataset multiple times, we ensured that it consistently produced highly similar insights each time.

The GenAI-extracted EBITDA and revenue figures were also compared against publicly available data. Thereby, significant outliers were identified in less than 5% of the extracted financial metrics. For this work, the outliers were manually corrected to ensure an accurate analysis of the financial performance.

The accuracy of mapping chemical products to end-user markets was further evaluated for two exemplary companies. Therefore, the end-user markets were additionally extracted using only corporate websites and mapped subsequently to the GICS industries. This was done by using the same prompts as within the ChatGPT analysis of the annual reports. Comparing both methods reveals a high overlap of the results: 87% of the GICS industries extracted from the annual reports were also found in the list of GICS industries from corporate websites. The remaining GICS industries from the annual reports were most likely not identified on the corporate websites, since not all business areas and projects are reported on the same level of detail in the annual reports and corporate websites. Furthermore, business focus might have shifted and thus business areas are not mentioned anymore on the corporate websites that were analyzed at the end of 2024, compared to the 2023 annual reports.

Besides the validation techniques used in this work, various further approaches can be applied. A more sophisticated way was used by Bouteraa et al. who conducted semi-structured expert interviews to gain insights on the banker's perspectives and willingness to use ChatGPT (Bouteraa et al., 2024). These expert interviews can provide helpful insights but can be time-consuming to set up and conduct. Furthermore, comparing AI-generated insights to published key performance indicators offers a quantitative means of validation (Moreno and Caminero, 2024). However, variations in calculation methods or underlying assumptions can introduce discrepancies between metrics. In a recent study from Apple, Mirzadeh et al. found no evidence of formal reasoning in LLMs. Moreover, minor changes to inputs, such as altering variable names or introducing irrelevant information, significantly affected the model accuracy (Mirzadeh et al., 2024).

These studies show that combining expert validation, quantitative comparison to KPIs from other sources, and stress testing of prompts as well as the generated output are essential in establishing a robust framework with GenAI-generated outputs that are trustworthy.

Limitations

While the tool demonstrated significant capabilities in generating detailed insights from financial and strategic data, several limitations were identified. As a language processing model, the tool relies exclusively on publicly available corporate reports and disclosures. These documents are prepared to meet regulatory requirements and communicate strategic priorities, which may not always include the full scope of a company's operational details. Consequently, the analysis is contingent on the level of transparency and granularity provided in these disclosures.

An additional limitation arises from the inability to quantify the revenue or profit contributions of specific segments due to the lack of detailed financial breakdowns in many public reports. While the tool can identify a company's presence in specific segments and assign them to end-user markets, it cannot assess the relative financial significance of these segments within the company's overall portfolio.

The tool's reliance on historical data further means that recent strategic adjustments or emerging trends are only captured if explicitly documented. While the mapping of end-user markets to GICS industries provides a standardized framework for comparison, inconsistencies may arise when corporate product terminology or definitions deviate from those established by the GICS system. These considerations emphasize that the analysis offers a structured and efficient approach to understanding competitive positioning and market alignment. It is most effectively applied as an initial framework, which can be supplemented with expert interpretation and additional validation to achieve a more comprehensive strategic assessment.

In terms of usability, the approach proved accessible for non-technical users, offering a practical solution for business analysts and decision-makers who need to quickly generate comparative insights. The automated nature of the tool

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URN: urn:nbn:de:hbz:6-43998535719
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reduces the need for manual data collection and synthesis, allowing companies to focus on strategic decision-making rather than time-consuming data processing. The tool significantly reduced the time required for comprehensive competitive analysis, which traditionally would have taken several weeks to perform manually.

Conclusion

This study demonstrates the potential of OpenAI's ChatGPT to automate and streamline competitive analysis in the chemical industry. The methodology presented serves as a framework for conducting detailed, data-driven assessments of industry players. By utilizing the prompts of this work, the approach allows for quick adjustments to new industries, alternative metrics, or evolving market conditions—overcoming the barrier of starting from scratch. The analysis of financial data, end-user market positioning, and industry growth rates enables a comprehensive, multi-dimensional comparison of companies. This not only provides valuable insights into each company's financial health and strategic positioning but also helps identify potential market opportunities and risks based on sector-specific growth trends. By correlating business segments with market growth rates, companies are assessed in their competitive position in growing markets.

In addition to its analytical depth, the reusability of the framework is one of its greatest strengths. Once the initial prompt system is set up, the model can be easily updated with new data and applied across different sectors, making it a scalable solution for competitive analysis in various industries. This continuous adaptability ensures that companies can maintain an up-to-date understanding of their competitive landscape without the need for costly and time-consuming manual analysis.

While the tool enhances the efficiency and speed of generating competitive landscapes, it is important to note that AI-driven analysis is dependent on the quality and availability of public data. In industries like chemicals, where strategic nuances and long-term vision are often complex, some qualitative aspects still require human interpretation and expertise. However, as a tool for rapid synthesis of quantitative data and strategic positioning, GenAI offers significant potential for augmenting human decision-making.

In conclusion, this feasibility study underscores the potential of GenAI to enhance strategic analysis in the chemical industry. The presented methodology offers an adaptable and efficient approach for competitive analysis. Future work could further enhance the results by exploring its predictive capabilities and expanding its application across other asset-heavy industries facing similar analytical challenges. By integrating AI-driven insights with established industry standards, companies can gain a deeper understanding of market dynamics, proactively identify risks, and strategically adapt to evolving challenges.

Declaration

During the preparation of this work the authors used GPT-4o in order to improve readability and refine language. After using AI-assisted revisions, the authors thoroughly reviewed and edited the content as needed.

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JOURNAL OF
BUSINESS CHEMISTRY

Vol.22, Iss.1, February 2025
URN: urn:nbn:de:hbz:6-43998534889
DOI: 10.17879/43998524091

Research Paper

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The illustrative case of the HYBRIT fossil-free steel production initiative in the perspective of industrial symbiosis and convergence

This article attempts to bridge the gap between the concepts of Industrial Symbioses (IS) and Industrial Convergence (IC) by arguing that the two concepts can jointly help to understand the role of industrial structures and value chains that embody transformation processes through which technologies evolve in response to transformation pressure. On one hand, IS with a focus on inter-firm collaborations and resource exchange has become a useful framework to understand and capture the mechanisms that foster sustainable industrial and technological development, while on the other hand IC has been used to analyze technological development that blurs traditional borders between firms in terms of innovations and business development. However, although interrelated the two concepts have been discussed separately. This paper is using the HYBRIT initiative as an illustrative case of a climate change mitigation and as such a "flagship" project in Sweden in an effort to replace the traditional blast furnace technology as the core unit processing technology in steelmaking. It is advocated that whilst many aspects of the conceptual models of IS and IC appear to be congruent with the on-going HYBRIT eco-industrial transformation process, the overall impression is that in future eco-industrial transformations, it could be of interest to develop and deploy a more specific transformation model adapted and capturing unique process-industrial conditions for product and process innovation.

1 Introduction

Industrial transformation processes are often characterised by the presence of both opportunities and challenges on actors that are structurally interconnected as argued by Dahmen (1950) more than half a century ago. As industries become increasingly interconnected, the traditional boundaries that delineate sectors are blurring, giving rise to a complex web of relationships that transcend company and industrial borders (Heo and Lee, 2019). Often, existing inter-industrial collaboration serves as a catalyst for synergistic efforts, fostering the exchange of knowledge, expertise, and resources across diverse sectors (Geum et al., 2016). This interconnectedness not only expedites the diffusion of technological advancements but also promotes the emergence of novel solutions to multifaceted common problems (Kim et al., 2015). In the context of climate change mitigation, where the imperative for rapid and profound solutions is paramount, inter-industrial collaboration has received heightened importance (Elia et al., 2020). The interconnected nature of industries from different sectors thus allows for co-creation of innovative technologies and

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Vol.22, Iss.1, February 2025
URN: urn:nbn:de:hbz:6-43998534889
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new corporate strategies that can address complex and common challenges associated with climate change. In this context, the two notions of Industrial Symbiosis (IS) (2012; Chertow, 2000) and Industrial Convergence (IC) (Bröring, 2010) have been proposed to capture potential implications for environment management and innovations.

This paper discusses IS and IC in the context of the process industries. Whilst both IS and IC can take place on a technology, corporate, and sectoral level (Curran and Leker, 2011), opportunities for IS on all levels may incentivize IC as well, and vice versa. Although different sectors of the process industries (e.g. chemical, steel, pulp & paper) share several characteristics related to their production systems and conditions for product- and process innovation, their production system characteristics significantly differ from assembly-based industries (Lager, 2017). The "family" of process industries is thus similar within itself, but dissimilar to other manufacturing industries (Lager and Chirumalla, 2020). In consequence, management of IS and IC in the process industries must not only be adapted to the idiosyncratic process-industrial environment in search of cross-industrial management and sectoral patterns, but individual sectoral experiences can in an organizational learning perspective be shared within this important cluster of industries. IS and IC are today fairly well-articulated and researched concepts. In the emergence of IS and "uncovering" of kernels for Industrial Symbiosis (Chertow, 2007), a profitable physical exchange of materials, energy, and/or by-products in-between companies from different sectors of the "family" of process industries has historically been a major driver (Chertow, 2000). The cause could most likely be grounded in the idiosyncratic process-industrial production system characteristics and associated inherent and contextual conditions for product- and process innovation. ***More specifically, the aim for this article is to review the knowledge base and understanding of the individual areas of IS and IC, and further explore their potential conceptual interrelationships and discuss related industrial cooperation and business opportunities. Moreover, to further explore how they could open up opportunities for sustainable development and novel eco-industrial transformation processes, particularly in a process-industrial context.*** Nevertheless, there seems , so far and to the authors best knowledge, to be a lack of useful eco-industrial transfer models designed and adapted to the specific process-industrial common conditions.

The process industries, being major contributors to greenhouse gas emissions, are facing transformation pressure to reduce their carbon footprints, which largely stems from their energy intensive production systems. The selected illustrative case, the HYBRIT fossil-free steel production initiative, draws on a transformative initiative in Sweden with the goal of producing steel in use of hydrogen in the involvement of 3 collaborating industrial actors, from three different sectors of the process industries. In use of this illustrative case of which we already initially could see relations to both IS and IC conceptual models, we intend to explore and test if and how different aspects of the IS and IC concepts, harmonize with the goals of environmental sustainability and broader company business goals, in an eco-industrial transformation case. Previous studies have analyzed this transformative initiative in use of a multi-level perspective (Öhman et al., 2022; Karakaya et al., 2018) while in this paper we use the lens of IS and IC. We argue that successful management of Industrial Symbiosis (Lombardi and Laybourn, 2012; Chertow, 2007) and its related transformation model(s) should be adapted to the idiosyncratic process-industrial environment in a search of advantageous cross-industrial management constellations and potential novel sectoral patterns. Furthermore, that emerging eco-industrial transformations within the process-industrial landscape, in an IC perspective (Kohut, 2019; Bröring et al., 2006b), is changing traditional sectoral boundaries, which ought to incentivize the studying of the process industries as one importance cluster of industries for the global economy. Apart from this introduction, this paper consists of six other sections. In the subsequent section, we briefly review the literature on the cluster of process industries and IS and IC conceptual models. Section 3 provides the research design and some methodology considerations while in Section 4 we briefly discuss the peculiarities and analyze some tentative characteristics the two industrial transformation models. In Section 5 we deploy those theoretical findings as a framework in the positioning of the illustrative case on both transformation models. The total results are discussed in Section 6, and finally, in Section 7 we conclude the paper and provide some implications and arenas for future research.

2 A frame of reference

2.1 The singularity of the "family" of Process Industries

For companies in the process industries, sustainability is not only emerging as an operational issue, but as a prime driver

Vol.22, Iss.1, February 2025
URN: urn:nbn:de:hbz:6-43998534889
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for eco-design of non-assembled products (Lager, 2024), and eco-innovation in general (Karakaya et al., 2014), and below we present a brief overview of the characteristics of the "family" of process industries. In the review of the process industries, both production system and delivered product characteristics are discussed, recognizing that in this group of industries corporate sustainability is not only related to product recyclability, but often to a large extent associated with sustainable production processes (Chirumalla et al., 2023).

One fundamental difference between companies in the "family" of process industries and those in assembly-based industries is that supplied and delivered products in the process industries are materials and not components (Simms et al., 2021; Frishammar et al., 2013); a fact which affects not only the upstream supply chain of incoming materials but also the downstream supply chain of outgoing products (Lager and Blanco, 2010). Because of the strong interrelationship between raw materials, production processes and finished products, successful product innovation needs to take a concurrent view on all these areas (Storm et al., 2013), which makes the development of non-assembled products, in reality, the development of new or improved process technology; the process encompasses the product (Lager and Liiri, 2023; Hullova et al., 2016).

Moreover, in assembly-based industries a new product is usually manufactured in a new production setup, whereas a new production system or technology in the process industries usually is integrated within an existing plant structure (Samuelsson et al., 2015; Samuelsson and Lager, 2019). If a company relies on captive (company-owned) raw materials, the characteristics of incoming materials will not only predispose the selection of unit processes and production system design (Frishammar et al., 2012; Aylen, 2013) but may also influence finished product properties (Linton and Walsh, 2008). Raw material variability will also sometimes influence the production system's receiving capability (Soman et al., 2004), especially in the food industries where raw materials are perishable (Van Donk and Fransoo, 2006).

An interrelationship between product and process innovation is often required for a successful development of non-assembled products in the process industries (Reichstein and Salter, 2006; Hullova et al., 2019), as well as an intimate collaboration with technology and equipment suppliers (Storm et al., 2013; Lager and Frishammar, 2012). Furthermore, the production yield in the process industries is dependent on both raw material characteristics (Finch and Cox, 1988) and production system capabilities. Meanwhile, products manufactured in the process industries are often next to homogeneous substances, but their inner structural characteristics largely determine their functionalities in B2B customers' production systems (Kuwashima and Fujimoto, 2023; Chronéer, 2005). The product innovation time cycles in many sectors of the process industries are often extended to protect customers from unforeseen difficulties (Pisano, 1997), requiring time-consuming pilot-planting or full-scale production trials (Lager et al., 2015; Frishammar et al., 2014). From conceptualization to industrialization, a number of alternative test environments are deployed (laboratory, pilot plants, demonstration plants), each one mimicking to a varying degree a forthcoming production process for a new or improved product (Lager and Simms, 2020; Lager and Liiri, 2023).

Apart from company main product families, there are usually a number of supplementary products that must be produced as a consequence of raw material quality and the production set-up (Lager et al., 2017; Lager and Samuelsson, 2018). A semi-finished product, which also could be denominated as an "intermediate product" (Taylor et al., 1981b; Taylor et al., 1981a), is a product that is discharged from the total production process and marketed and sold to other customers for further refining into other kinds of finished products. Low volumes of semi-finished products can thus be a missed market opportunity, since high volumes of semi-finished products may create interesting outlets for part of the volumes from the company's production system. On the other hand, a co-product is defined as a product that must be produced in association with the production of another kind of product. Both product types can be marketed and sold, but a low number of co-products (low volumes) often makes overall operations easier (Lager et al., 2017). Nevertheless, production levels and quality of semi-finished products and co-products are important product categories especially in the perspective of possible opportunities for Industrial Symbiosis. Finally, a by-product could be defined as a product or material (or non-product) that is an inevitable side effect of a select production process. ***Low production volumes of by-products is generally a favorable production position since many by-products, so far, often have to be turned into waste. However, by-products may generate substantial revenues after dedicated product innovation and marketing efforts possibly in a collaborative endeavor with a partner in a symbiotic relation.***

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2.2 Industrial Symbiosis (IS)

As one important part of the sustainability concept, industrial ecology (Ehrenfeld, 2004), views industrial systems in concert with its surroundings, and in a system perspective search for an optimization of the total material cycle from virgin materials, finished products and recycled products at a process technology, firm, inter-firm, and regional (global) level (Chertow, 2000). As an important part of industrial ecology, Industrial Symbiosis (IS) was earlier defined by (Chertow, 2007: p.313) in her seminal paper as:

Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity.

In a critical examination of IS projects in the USA, (Chertow, 2007) later on demonstrated that "uncovering existing symbioses" has had a higher success rate than purposely designed eco-industrial parks (EIP). In order to distinguish IS from general "resource exchange", the criterion for IS was proposed by Chertow to incorporate a minimum of three different organizational entities and minimum two different resources. It was further acknowledged that IS should provide environmental benefits, cannot occur in an individual company but in single industry dominated clusters, as well as in multi-industrial ones. Chertow (2007) further concludes that among drivers for IS endeavors, the most basic one is a desire of profitable business supplemented with regulatory, environmental and social drivers. There are today an abundant number of definitions of IS, which can be regarded as an essentially contested concept similar to the "circular economy" concept (Korhonen et al., 2018), and in an analysis of the above definition, Lombardi and Layburn (2012) have proposed some major redefinitions:

IS engages diverse organizations in a network to foster eco-innovation and long-term cultural change. Creating and sharing knowledge through the network yields mutually profitable transactions for novel sourcing of required inputs, value added destinations for non-product outputs, and improved business and technical processes.

In that respect, the proposed inclusion of eco-innovation by Lombardi and Laybourn (2012) in their novel definition of IS is sound, and they note that eco-innovation not only is a common output from IS but possibly also an important driver. They further conclude that the use of the term "traditionally separate industries" in a definition could restrict the usability of the IS construct, and that the assessment of IS possibilities should be "process based" and generally on a company or "facility level". The development of biomass production processes and related high value products could serve as an example on such emerging new industry segments and products embedded both in the IS and IC concepts (Nuur et al., 2012). Moreover, Lombardi and Laybourn (2012) recognize that company and industry boundaries tend to change over time, which in this article) has been a one incitement for the inclusion of the IC concept (Curran and Leker, 2011). The illustrative case of the development of fossil-free hydrogen-based steelmaking presented in this article can thus serve as an example on such changing industrial boundaries related primarily to the IC concept. Furthermore, Lombardi and Laybourn (2012) propose an exchange of the term "industry" with "organizations" as a broader construct; a suggestion which in a process-industrial perspective could facilitate the inclusion of, industrial intermediaries, suppliers of technology solutions and process equipment in the use of the IS concept. Nevertheless, it is vital to discriminate between IS and IC on a company level and on a sectoral level.

2.3 Industrial Convergence (IC)

The notion of IC refers to the integration of previously distinct industries characterized by separate technologies and markets and is defined by Bröring et al., (2006b: p. 488) as "the blurring of boundaries between formerly distinct industries due to converging value propositions, technologies and markets. IC was initially predominantly studied in the information and communication technologies (ICT) industries (Hacklin et al., 2009; Gambardella and Torrisi, 1998). One of the first studies related to the process-industrial cluster was sectoral convergence in the pharmaceutical, specialty chemical, and food industries (Bröring and Leker, 2007; Bröring et al., 2006a). For example, the emergence of a new converged sector was recognized as a new inter-industry segment, and the convergence was described as a "process", when supply-side convergence (input side) was distinguished from demand-side convergence (market pull). In a follow-up study of Nutraceuticals and Functional Foods (NFFF)/Cosmeceuticals, Curran and Leker (2011) concluded that when coping with increasingly permeable industry boundaries it is necessary to source the essential

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URN: urn:nbn:de:hbz:6-43998534889
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knowledge and experience from beyond one's own factory gate. Moreover, industries would be labeled as "converging", if they (or parts thereof) begin to merge with each other in a new field (Curran and Leker, 2011), and they recognize four levels of convergence in a sequential "convergence process" as: science convergence, technology convergence, market convergence, and, finally, industry convergence.

In a study of the dynamics of the final phase of an industrial convergence process Sick et al. (2019) conclude that convergence can take place with varying intensity and with varying length of the individual phases and could be technological or market driven. If an industry A starts to converge with industry B, a new inter-industry segment C occurs. If A+B=C is phasing out A and B they denominate this substitutive convergence, whilst if A and B remain (A+B=A+B+C) this is denominated complementary convergence, when the "core business" of the converging companies is not threatened (Sick et al., 2019). Geum et al. (2016) developed a taxonomy for industry convergence, including technology enhancer, policy-driven environmental enhancer, new business-driven product-service integrator, and service-integrated social business generator. In conclusion, when two industries converge, the dominant industry logic is subject to significant changes, and established firms need to position themselves adequately in the market, acquire new required competences and increase their awareness of partners (Kohut, 2019) and competitors from vastly distinct fields (Kohut et al., 2020). Indeed, in their analysis of IC in entire U.S. industries, Kim et al. (2015) show that significant transformation is under way in the economy, but industry convergence is not yet prevalent across entire industries. Because of that "early warning systems" are of interest and depending on the different stages (levels) of the convergence life cycle the measures could be number of scientific publications, number of patent documents, and number of newspaper abstracts over time (Bornkessel et al., 2016a). Further studies related to convergence in the process industries include functional foods (Bornkessel et al., 2016b), biotechnology (Aminullah et al., 2015; Aaldering et al., 2019), tablet Sub-sector Industry (Calvosa, 2021).

3 Research design

This article present the research results from one part of a research project related to the on-going industrial transformation process induced by the HYBRIT (Hydrogen Breakthrough Ironmaking Technology) initiative in Sweden.

3.1 Research approach

The research approach and the research process for the whole study has been of an abductive kind, going to-and-fro between theory and the empirical settings (van Maanen et al., 2007; Dubois and Gadde, 2002). Whilst a deductive approach starts with a select theory and hypothesis in a further deduction of new theory for a particular area (Popper, 1983; Popper, 1959) an inductive research approach (Glaser and Strauss, 1967) commences with the researcher's phenomenological perception of the topical area. On the contrary abduction, as a more recent approach in the philosophy of science, arguably is positioned in-between a deductive and an inductive approach (Alvesson and Sköldberg, 2009). Brodie and Peters (2020) argue that conceptual development lies in the heart of abduction and that both input and output from abduction is a successive refinement of concepts. As a foundation for inquiry, abductive research may begin with testing an existing theory, or in the application of a new conceptual framework (Kovacs and Spens, 2005):

Abduction also works through interpreting or re-contextualization individual phenomena within a contextual framework, and aims to understand something in a new way, from a new conceptual framework.

Abduction does not refute previous theoretical pre-conceptions (Alvesson and Sköldberg, 2009), and in a discussion of the alternatives of a "loose and emergent" or a "tight and pre-structured" framework, Dubois and Gadde (2002) suggest the latter since the "tightness" reflects the degree to which the researcher has articulated his "preconception". Moreover, they recommend that the framework should evolve when empirical observations inspire changes of the view of theory and vice versa.

3.2 Development of an integrated theoretical framework

Existing theory is generally the point of departure in case study research (Yin, 1994), and the further development of a theoretical framework will afterwards serve as a guidance in search of supporting relevant empirical evidence. IC and IS are in this study viewed as two related but different industrial concepts. In this study we have selected to use the term "concept" instead of "construct", as a more value neutral term in reference to Gioia (2013), describing or

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explaining a phenomenon of theoretical interest. As such, and even if the concept of IS now has been used over two decades (Chertow, 2000) it is still in a flux, and there are a number of proponents suggesting major redefinitions, see e.g, Lombardi and Layburn (2012). In today's societal interest in sustainability and on-going eco-industrial transformations, different definitions of the IS concept are often used in scholarly publications, and the conceptual clarity unfortunately thus tends to diminish. The topical area of IC is somewhat younger (Bröring et al., 2006b), and, so far, the number of publicans in this area are substantially less, and possibly because of that, the conceptual clarity is yet quite good. However, both concepts are still open for further discussions, improvements, possible extensions, or simplifications, until they can reach the level of a more strictly defined construct. Both concepts are, from different angles and perspectives, related to collaboration, intertwinement or exchange of resources, and even potential mergers between complementary companies on different organizational levels. However, one common denominator for both concepts is that company, and sometimes sectoral boarders, are crossed in use of different industrial transformation models. As a consequence, company internal perspectives on innovation, production technology, and products (and waste) are viewed in an outlook "outside company factory gates" (Curran and Leker, 2011).

In this study, each concept has been tentatively defined in use of a number of different characteristics, and if congregated, they can be regarded as embryos for "intentional definitions" (Foellesdal et al., 1990). However, the concepts are still in flux because of new research findings, and the individual concepts thus tend to still vary in scientific publications. The coherent state-of-the-art of conceptual definitions in academy (and industry), can be viewed as their convergent validity. In use of the publications in the literature reviews in the previous Section 2, a number of characteristics of the two concepts have tentatively been identified and presented in Table 1; Section 4. However, the congruence and clarity of each characteristic in each of the individual concepts varies considerably. Even if the concept of IC is of a fairly recent origin (not yet many publications), this concept appears to be of a fairly convergent nature; the individual characteristics are thus not too difficult to outline. On the contrary, the somewhat older concept of IS seems still to be much more in transition and there is still no general agreement on its inherent characteristics or definition. Concept validity could be described as how well a concept, and its related characteristics corresponds to the property one wish to measure or study. Convergent validity as a sub-type of concept validity, is thus related to how coherent alternative descriptions (definitions) of the individual characteristics (measurables) of a concept are depicted in literature. On the other hand, discriminant validity as a sub-type of concept validity, is related to how individual characteristics (measurables) differ between different concepts. In view and use of the information from the literature review of IS and IC, and in the perspective of a process-industrial context, a number of characteristics of the two different transformation models were tentatively identified. For each concept, each characteristic was further detailed in reference to a select number of references from the literature reviews. The discriminant validity of the IC and IS concepts were afterwards analyzed by the research team.

3.3 Deployment of an illustrative mini case

How well the individual characteristics of the IC and IS concepts could be applicable on an on-going industrial transformation project, that from an outside perspective seemed to share some aspects of both concepts, was afterwards tested as an "illustrative case" in a second step. This supplementary case study was carried out in order to test how well the two different concepts could fit a real-life industrial project. The holistic nature of case studies allows a multidimensional perspective, considering a variety of variables (more variables than cases) that may influence the phenomenon under investigation. This is especially pertinent in the study of innovation processes, where a multitude of factors, ranging from policy frameworks to market dynamics, can shape technological advancements. There are a number of rationales for the selection of a single-case research design and according to Yin (1994) a single-case design is analogues with an experiment; a situation which representatives from the process industries should be rather familiar with. One rationale for the deployment of a single-case design, is when it represents a critical case. The single-case study can then be deployed in order to confirm, challenge, or extend the theory, and in this perspective the theoretical foundations for both IS and IC were considered sufficiently well-formulated. Yin has stated that overall, the single-case design is justifiable under certain conditions where the case represents a critical test of existing theory (Yin, 1994), and Welsch et al. (2011) also recommend the potential use of case studies to challenge, refine, verify, and test theories.

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In use of the theoretical framework, the positioning of the HYBRIT project was thus reviewed and validated in a separate interactive exercise together with one representative from the HYBRIT board of directors (CTO of the SSAB and the HYBRIT champion). Furthermore, and during follow-up interviews with the other three individual members of the HYBRIT board and the previous CTO of the HYBRIT management team, the information related to the HYBRIT relationships with the different concepts were often discussed. The results were afterwards triangulated with published official documents and research reports from the project and the official websites from LKAB, SSAB, and Vattenfall. Moreover, the results were further analyzed by the research team in view of their in-depth knowledge acquired in this total study of the HYBRIT initiative. Even if the empirical results must be considered as tentative, the illustrative case can serve as a preliminary outlook on an on-going eco-industrial transformation process carried out when management lacked previous perspectives from any theoretical model and lacking knowledge of either of the IS and IC conceptual models.

4 A discriminant analysis of the IC and IS concepts

4.1 An integrated analysis of the two concepts

In Table 1, a number of important aspects on both concepts have thus initially been selected. In use of the information in Section 2.2 and 2.3, a number of characteristics of IC and IS have afterward been identified, in reliance of important references. Focusing on the discriminant validity of the two concepts, the research team afterwards tentatively positioned the characteristic of each model in the perspective of how strongly the individual characteristics generally are articulated in the overall definitions and descriptions of each conceptual model in publications. A three-point ordinal scale was selected as: Red = Strongly articulated, Yellow = Articulated to some extent, Green = Usually not articulated at all. The results are presented in a "heat map" for the facilitation of a further analysis of the discriminant validity of the individual concepts.

4.2 A preliminary synthesis of the findings from the discriminant analysis

With regards to the aspect of "eco-efficiency and sustainability targets", this is usually strongly articulated in most IS studies, and even if this generally not has been the driver so far for IC, it can certainly be so in the future. The second aspect of "openness for new collaborative partners after initiation of the collaboration", is also strongly articulated and sought for in IS, whilst in IC it is neither common nor advisable, but could yet be a possibility. In the perspective of "the physical location (proximity) of collaborating partners", it is articulated sometimes in IS, but is not a necessity with regards to the conceptual model of IC. "The diversity of collaborating partners" aspect is articulated to some extent in both concepts, and possibly even stronger in IC. There is, however, a rather big difference between the two concepts with regards to "the organizational structure between collaborative partners", and for the IS conceptual model a network structure is a necessity, whilst the organizational mode of operation must be contingent on project characteristics in IC. The characteristic "corporate product, process, or systemic innovation activities" differs strongly in-between the two concepts, and whilst this is the predominant driver for IC, it is not so in IS, even if new conceptual re-definitions this is emerging as a more significant aspect. In the perspective of "corporate profitability and business opportunities", this is a common ground for both concepts, even if it naturally is more strongly articulated in IC. The last but not least characteristic "corporate organizational configurations and corporate boundaries", and a to some extent often a final outcome from IC, this is not at all a desired outcome in IS, but certainly one for IC. In section 6.1 these findings will be further discussed.

5. The illustrative case of HYBRIT fossil-free steel production initiative

5.1 Introducing HYBRIT initiative

The HYBRIT initiative is one out of a large number of initiatives aiming at the development of future fossil-free steel making process routes. This initiative brings together 3 large and historically important industrial sectors in Sweden: LKAB, a state-owned mining company established in 1890 in the rich iron fields of northern Sweden which currently is producing a major part of the EU iron ore raw material. SSAB, established 1978, is a global steel producing

Table 1 A tentative analysis of eight characteristics of the IC and IS conceptual models, in use of a simplified "heat map" (Red = Strongly articulated; Yellow = Articulated to some extent; Green = Usually not articulated at all).

Conceptual models Model characteristics	Industrial Convergence (IC)	Industrial Symbiosis (IS)
Eco-efficiency and sustainability targets	🟩 Sustainability and eco-innovation are not necessarily drivers or targeted output. (Bröring et al., 2006b), (Aminullah et al., 2015); (Geum et al., 2016)	🟥 Strong focus on sustainability and as a tool for innovative green growth. Exchange of by-products rather common but not generally nowadays a necessity. (Chertow, 2007; Chertow, 2000)
Openness for new collaborative partners after initiation of the collaboration	🟩 Usually a "closed" system with a few numbers of select complementary collaborating partners. (Sick et al., 2019); (Bröring et al., 2006b)	🟥 Usually very "open" systems and with a desired inclusion of a growing number of collaboration partners. (Ashton, 2008); (Lombardi and Laybourn, 2012; Chertow, 2007)
The physical location (proximity) of collaboratinga partners	🟩 The physical location of collaborative partners is not usually of a major importance, but a proximity could diminish the mental distance among partners. (Bröring et al., 2006b)	🟨 Traditionally (but not necessary today) a strong focus on geographic proximity, especially if material, transport costs or energy are important aspects for the industrial network (Chertow, 2007); (Lombardi and Laybourn, 2012)
The diversity of collaborating partners	🟨 Usually partners from different industrial sectors and sometimes from an already existing supply/value chain. (Curran and Leker, 2011)	🟨 Traditionally partners from separate industrial sectors but a gradual transition into an acceptance of similar partners is today also common. (Chertow, 2000), (Chertow, 2007);(Lombardi and Laybourn, 2012);(Paquin et al., 2014);
The organizational structure between collaborative partners	🟩 Generally, a company-to-company emerging collaboration developing into a more strategic alliance among partners with complementary capabilities. (Bröring et al., 2006b); (Aaldering et al., 2019)	🟥 Generally, an emerging network structure with a large number of independent collaborative partners. (Chertow and Ehrenfeld, 2012); (Walls and Paquin, 2015);(Korhonen et al., 2004); (Posch et al., 2011)
Corporate product, process, or systemic innovation activities	🟥 Collaborative product and/or process innovation (sometimes radical) is generally the initial driver for collaboration. (Hacklin et al., 2009); (Bröring et al., 2006b)	🟨 Traditionally, innovation was not necessarily a prerequisite for establishing a collaboration, but incremental innovation is often a necessity. (Boons et al., 2013); (Lombardi and Laybourn, 2012); (von Malmborg, 2007)
Corporate profitability and business opportunities	🟥 A profitable business/market outcome is always the overall target (with equally distributed financial gains). (Bornkessel et al., 2016a)	🟥 Traditionally a "competitive advantage" (profitability) has been central (less costs for waste disposal is certainly also an attractive target). (Boons et al., 2013); (Paquin et al., 2014; Paquin et al., 2015); (Chertow and Lombardi, 2005)
Corporate organizational configurations and corporate boundaries	🟥 The final successful outcome is usually new industrial boundaries. (Gambardella and Torrisi, 1998); (Sick et al., 2019); (Bornkessel et al., 2016b)	🟨 New corporate structures or boarders are usually a rare outcome. (Boons, 2008); (Walls and Paquin, 2015); (Lombardi and Laybourn, 2012)

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URN: urn:nbn:de:hbz:6-43998534889
DOI: 10.17879/43998524091

company in Sweden, while Vattenfall is a state-owned utility company producing electricity, partly from hydropower in Sweden. This initiative is thus a collaboration between three Swedish companies from three different sectors of the process industries and is formally set-up as a Joint Venture. HYBRIT stands for "Hydrogen Breakthrough Ironmaking Technology" and thus includes three actors and incorporate a diversity of core-businesses, production technologies, and products. The initial role of the LKAB group was as a supplier of the primary raw material (direct reduction pellets), SSAB a steel processing company, and Vattenfall a supplier of "green" electricity. The HYBRITE initiative is a still on-going long-term industrial transformation process presently formally governed by a Board of Directors including one representative from each of the three different actors. Nevertheless, many operational development activities have so far been predominately carried out in use of the combined resources from the different mother companies, whilst final industrialization activities to a large extent will be carried out within each of the mother company operational organizations. In consequence, there are a multiple of organizational boundaries within the HYBRIT initiative, including the organizational interfaces between the HYBRIT initiative and each mother company, and the boundaries in-between each individual mother company organization.

5.2 Positioning the HYBRIT initiative on the IS and IC conceptual models, in use of the theoretical framework developed in Section 4

In use of the previously developed theoretical framework in Table 1, the HYBRIT initiative has been positioned on the IC and IS conceptual models in Table 2. The individual characteristics that are valid for the HYBRIT initiative have been marked with bold text in both conceptual models.

In view of the results in Table 2, only the two characteristics "eco-efficiency and sustainability targets" and "corporate profitability and business opportunities" in the IS conceptual model are coherent with the HYBRIT initiative. Nevertheless, the HYBRITE initiative follow the recommended 3 - 2 Chertow (2007) recommendations for at least three entities and two resources, since it includes three actors from different industrial sectors and two materials (electricity and pellets). In reference to Wittgenstein's concept of "family resemblance" (Wittgenstein, 1953), a concept or a construct must not necessarily share all characterizing attributes to be considered as a member of a "family", since few family members generally do. However, the HYBRIT initiative share a large number of IC characteristics, and position very well on the IC conceptual model with six out of eight characteristics and could certainly be regarded as an IC of a kind.

On the other hand, the outcome from the HYBRITE initiative is not of a traditional IC kind. In view of the present LKAB and SSAB intra-organizational supply-chains, one could characterize both the pellet product and the upcoming sponge iron product as semi-finished or intermediate products; a rather common situation in long process-industrial supply chains (Lager and Blanco, 2010). In consequence, and in view of the different outcomes from the IC conceptual model in Section 2.3, **the HYBRIT case is neither a "substitutive" or "complementary" convergence, but an industrial transformation that could be denominated as a "configurative" convergence, when an industrial boarder is relocated in a novel inter-organizational supply chain.**

Even if only two of the IS characteristics relate to the HYBRIT initiative, the authors would not hesitate to include the HYBRITE initiative as an IS in accordance with the Lombardi and Laybourn (2012) re-definition. Moreover, since those two characteristics often today are considered as two of the most essential attributes in the IS concept. This is also in accordance with the Kalundborg Industrial Symbiosis Institute definition of IS as *a collaboration between different industries for mutual economic and environmental benefit* (Posch et al., 2011: p.424).

6 Discussion

6.1 The discriminant analysis of the two conceptual models

In conclusion, and in view of all characteristics, the two concepts IC and IS appears to be rather different since a red color in one concept often has a green or yellow color in the other concept. The individual colorings also distinguish the use of IC as a more "market driven" conceptual model, whilst the IS concept more "sustainability driven". One can further envision that traditional technology and market drivers for IC, in the future will be complemented, or possibly even partly replaced, by emerging environmental drivers for convergence. This could emphasize the necessity of knowledge sharing on a process (technology) level, a facility level, and firm level, and even on an overall sectoral level.

Table 2 A tentative positioning of the HYBRIT initiative on the IC and IS conceptual models, in use of the theoretical framework and heat map presented in Table 1. The individual characteristics that are valid for the HYBRIT initiative have been marked with bold text in both conceptual models.

Conceptual models Model characteristics	Industrial Convergence (IC)	Industrial Symbiosis (IS)
Eco-efficiency and sustainability targets	Sustainability and eco-innovation are not necessarily drivers or targeted output. (Bröring et al., 2006b), (Aminullah et al., 2015); (Geum et al., 2016)	**Strong focus on sustainability and as a tool for innovative green growth. Exchange of by-products rather common but not generally nowadays a necessity. (Chertow, 2007; Chertow, 2000)**
Openness for new collaborative partners after initiation of the collaboration	**Usually a "closed" system with a few numbers of select complementary collaborating partners. (Sick et al., 2019); (Bröring et al., 2006b)**	Usually very "open" systems and with a desired inclusion of a growing number of collaboration partners. (Ashton, 2008); (Lombardi and Laybourn, 2012; Chertow, 2007)
The physical location (proximity) of collaborating partners	The physical location of collaborative partners is not usually of a major importance, but a proximity could diminish the mental distance among partners. (Bröring et al., 2006b)	Traditionally (but not necessary today) a strong focus on geographic proximity, especially if material, transport costs or energy are important aspects for the industrial network (Chertow, 2007); (Lombardi and Laybourn, 2012)
The diversity of collaborating partners	**Usually partners from different industrial sectors and sometimes from an already existing supply/value chain. (Curran and Leker, 2011)**	Traditionally partners from separate industrial sectors but a gradual transition into an acceptance of similar partners is today also common. (Chertow, 2000), (Chertow, 2007);(Lombardi and Laybourn, 2012);(Paquin et al., 2014);
The organizational structure between collaborative partners	**Generally, a company-to-company emerging collaboration developing into a more strategic alliance among partners with complementary capabilities. (Bröring et al., 2006b); (Aaldering et al., 2019)**	Generally, an emerging network structure with a large number of independent collaborative partners. (Chertow and Ehrenfeld, 2012); (Walls and Paquin, 2015);(Korhonen et al., 2004); (Posch et al., 2011)
Corporate product, process, or systemic innovation activities	**Collaborative product and/or process innovation (sometimes radical) is generally the initial driver for collaboration. (Hacklin et al., 2009); (Bröring et al., 2006b)**	Traditionally, innovation was not necessarily a prerequisite for establishing a collaboration, but incremental innovation is often a necessity. (Boons et al., 2013); (Lombardi and Laybourn, 2012); (von Malmborg, 2007)
Corporate profitability and business opportunities	**A profitable business/market outcome is always the overall target (with equally distributed financial gains). (Bornkessel et al., 2016a)**	**Traditionally a "competitive advantage" (profitability) has been central (less costs for waste disposal is certainly also an attractive target). (Boons et al., 2013); (Paquin et al., 2014; Paquin et al., 2015); (Chertow and Lombardi, 2005)**
Corporate organizational configurations and corporate boundaries	**The final successful outcome is usually new industrial boundaries. (Gambardella and Torrisi, 1998); (Sick et al., 2019); (Bornkessel et al., 2016b)**	New corporate structures or boarders are usually a rare outcome. (Boons, 2008); (Walls and Paquin, 2015); (Lombardi and Laybourn, 2012)

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URN: urn:nbn:de:hbz:6-43998534889
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6.2 Positioning the HYBRIT case in the perspective of the two conceptual models

The creation of the HYBRIT initiative was in reliance of a previous close customer supplier business relationship between LKAB and SSAB, and their close geographic proximity. The illustrative case thus support the view that Industrial Symbiosis often is facilitated by such contextual situations (Chertow, 2007). In use of the IC lens, the initial HYBRIT initiative could certainly initially be regarded as a "blurring" of industrial boarders (Bröring et al., 2006a). **Nonetheless, the final outcome of the HYBRIT initiative will certainly not be a "blurred" industrial boarder but a new well-defined corporate interface, within a novel fossil-free industrial supply/value chain from mine to metal.** In such a perspective, the IC definition is thus more of a characterization of the "industrial convergence process", than the characterization of its final outcome. In view of the organizational, and transformational operational procedures related to the HYBRIT case, the Joint Venture organizational solution is experienced to have fostered a fast development route which most likely could not have been possible with an "open" organizational network structure commonly deployed in IS Science Parks. On the other hand, such a "closed" Joint Venture could be dysfunctional in search of a more "open innovation" culture in future eco-industrial transformations.

6.3 A discussion of the industrial usability of the IS and IC conceptual models, in the perspective of future eco-industrial transformations in the process industries.

Whilst many aspects of the conceptual models IS and IC appear to be congruent with the on-going HYBRIT eco-industrial transformation process, the overall impression is that in forthcoming future eco-industrial transformations in a process-industrial context, it could possibly be of interest to develop and deploy a more specific transformation model. Because of that, the research team has dusted off and reviewed a rather early, but less utilized and configurated transformation model named the Development Block model (DB).

The Development Block (DB) concept was early introduced by Eric Dahmén (1950), who went beyond stylized facts and analyzed the mechanisms of industrial transformations. According to Dahmén, transformation processes necessities the evolution of both positive (opportunities) and negative (challenges) transformation pressures on stakeholders to find solutions (Dahmén, 1998; Dahmén, 1950). The positive transformation pressures are mitigated by the evolution of DBs which encompass interconnected sectors that play a pivotal role in industrial transformation and innovation processes. Thus, the synergy between sectors within DBs where advancements in one sector catalyze growth in another, creates a self-reinforcing cycle of a transformation process. In the context of climate change mitigation, the DB concept could be of interest to further explore and develop as recently discussed by (Chizaryfard et al., 2020). DBs are clusters of industries and sectors that exhibit characteristics of vertical and horizontal relationships that spur technological innovation and fostering development. These sectors are not isolated; they are interlinked, with advancements in one sector often benefiting others, creating a dynamic network of economic progress. The concept of Development Blocks could tentatively be defined as: *A Development Block (DB) is a cluster of industries (sectors) that are interlinked in vertical (or horizontal) synergetic relationship, when an advancement in one industry often benefit others, spurring technological development and innovation.* We believe that it could also be of interest to develop and discuss this conceptual model not only on sectoral, but also on a corporate level.

6.4 Theoretical contribution and aspects of generalization

Purposeful sampling (Patton, 1990; Palinkas et al., 2015) is commonly deployed if an extreme or unique case is selected (Ridder, 2017), and if rarely observably phenomena are investigated, and in reference to Corley and Goya (2011: p. 12) "theory is a statement of concepts and their interrelationships that shows how and/or why a phenomenon occurs". The main theoretical contribution from this study is the discriminant analysis of the related conceptual models and their potential use in eco-industrial transformation in a real-life process-industrial context. In a single case study it is not possible to make statistical generalizations of the research findings, and such a research design is furthermore less adaptable to theoretical generalizations than multiple-case research design (Yin, 1994). The research results can thus not be the foundation for discussing the transferability of the research findings but must provide sufficient contextual information to the readership to determine if this is reasonable. Such a contextual information is what Geertz (1973) name a "thick description". The presentation of the illustrative case is not as such an in-depth case study but

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URN: urn:nbn:de:hbz:6-43998534889
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provide sufficient contextual information for the reader to judge the external relevance of the case (Siggelkow, 2007).

7. Conclusions, implications, and suggestions for future research

The industrial landscape across the globe is undergoing a paradigm shift driven by the necessity to transform towards sustainable modes of production and consumption. These transformation processes often take place at the intersection of technological evolution and across industrial sectors and it is imperative to dissect and understand the intricate dynamics that characterize such transformative processes and their further advancements. The amalgamation of diverse technologies across industrial sectors are by and large underpinned by the presence of symbiotic relationships that influence industrial and technological trajectories. The convergence of once disparate or related sectors not only accelerates technological advancements but also open-up unprecedented possibilities for cross industry collaborations, novel business models, and reconfigured inter-and intra-industrial value chains. The establishment of symbiotic relationships within industrial ecosystems may be argued to amplify the resilience and adaptability of the overall system as this interconnectedness cultivates an environment conducive to sustainable growth, where the success of one entity contributes synergistically to the progress of others. It is from this context that this paper has put a fossil-free initiative aimed at producing steel in the context of the two conceptual models of IS and IC.

It is concluded that the two conceptual models are different, with regards to driving forces, partner structures, and organizational configurations. Nevertheless, both models related well, in an overall perspective, to the select real-life eco-industrial transformation case, pin-pointing a potential need to utilize both models into the development of a specific conceptual model adapted to the process-industrial contextual situation and to the intrinsic nature of product- and process innovation characteristics (Lager, 2024). In the illustrative case the three companies did not rely on any theoretical IC or IS frameworks or models, but jointly set up their organizational framework utilizing their inherent long-term experience of the development of primarily new process technology. Even so, one could suspect that the availability of a firmer foundation and theoretical framework, possibly could have been beneficiary in guidance of their still on-going innovation journey.

Acknowledgement

The authors wish to thank the informants and case-companies that took part in this study, offering their precious time, and providing valuable insight and feed-back in the further development of models and framework.

Vol.22, Iss.1, February 2025
URN: urn:nbn:de:hbz:6-43998534889
DOI: 10.17879/43998524091

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JOURNAL OF
BUSINESS CHEMISTRY

Vol.22, Iss.1, February 2025
URN: urn:nbn:de:hbz:6-43998534359
DOI: 10.17879/43998523309

Research Paper

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Environmental Impacts of Pyro- and Hydrometallurgical Recycling for Lithium-Ion Batteries - A Review

The growing demand for lithium-ion batteries (LIB) leads to an increasing importance of battery recycling. Given the scarcity of resources, effective material recovery is essential for the sustainable production of batteries. Therefore, understanding the environmental impacts of different recycling approaches is crucial. This review is the first to provide a comparative analysis of the environmental impacts across various impact categories for both pyro- and hydrometallurgical recycling processes of nickel-cobalt-manganese (NMC) batteries, including consideration of different data sources and their influence on the results. For global warming potential (GWP), hydrometallurgical recycling achieves an average reduction of - 25.5 kg CO2eq kWh^{-1}, corresponding to a 39% decrease in emissions from battery cell production. In comparison, combined pyro- and hydrometallurgical recycling reduces emissions by 27%. Additionally, the hydrometallurgical method demonstrates greater sustainability in terms of cumulative energy demand (CED), lowering the energy required for battery cell production by nearly 17%. Other environmental categories besides GWP and CED receive significantly less attention in the literature, although the benefits are often more significant. To guide future research, we present three key recommendations for further exploring the environmental impacts of battery recycling.

Keywords: Lithium-ion battery, Battery recycling, Pyrometallurgy, Hydrometallurgy, Environmental impact, Life cycle assessment

Introduction

Driven by growing interest in electric vehicles, portable electronics, and renewable energy storage systems, global annual demand for lithium-ion batteries (LIB) exceeded 1 TWh for the first time in 2023 and is expected to reach around 3 TWh by 2030 (Bürklin et al., 2022; Hettesheimer et al., 2023). At the same time, recycling of used LIBs is increasingly crucial, as improper disposal will cause environmental and safety problems threatening the ecological environment and human health (Islam and Iyer-Raniga, 2022; Zhenghe et al., 2022). Also, recycling helps to preserve critical materials, such as lithium, cobalt, nickel and manganese, which can contribute to a reduction of

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URN: urn:nbn:de:hbz:6-43998534359
DOI: 10.17879/43998523309

the environmental impact associated with battery cell production (Islam and Iyer-Raniga, 2022). On the other hand, recycling of LIBs involves complex processes that require substantial energy and chemical inputs, leading to questions about the overall net environmental benefits of the different recycling methods (Kim et al., 2021; Mohr et al., 2020).

Currently, three main recycling methods are used for LIBs: pyrometallurgical, hydrometallurgical and direct recycling (He et al., 2024). While hydrometallurgy and pyrometallurgy are already employed on industrial scale, direct recycling processes are at lower technological readiness (Davis and Demopoulos, 2023; van Hoof et al., 2023; Xu et al., 2023). In pyrometallurgical recycling, high-temperature processes are used to recover valuable metals from spent LIBs. The process is energy-intensive, can cause harmful emissions, and valuable metals, such as lithium, are not recovered (Gaines, 2014; van Hoof et al., 2023). The hydrometallurgical process involves the use of chemical reagents for the dissolution of valuable metals in aqueous solutions (Wang et al., 2022). This allows manganese and graphite, among other materials, to be recovered (Brückner et al., 2020). Direct recycling separates different battery active substances through physical processes, such as gravity separation and flotation (Jung et al., 2021). The principal distinction between direct recycling and pyro- and hydrometallurgical processes is that direct recycling preserves the crystalline morphology of the cathode (Gaines, 2018).

Apart from economic aspects, which historically have represented a central element in the evaluation of general waste treatment processes, the assessment of environmental impacts has been incorporated into decision-making. Several companies have announced the ramp-up of new recycling capacity, designed to treat different battery chemistries (Bürklin et al., 2022). Here, a sound understanding of the environmental impacts associated with different recycling approaches is key. Previous work has provided some insight into the environmental impacts of different recycling approaches (Lai et al., 2022; Li et al., 2023; Mohr et al., 2020). However, previous work falls short of providing a detailed comparison between different sources of primary data and its impact on the robustness of results. By presenting an up-to-date critical review about environmental impacts of battery recycling, we support industry and policy-makers in shaping their recycling strategies while also providing guidance for future research on battery recycling with low environmental impacts. LIBs with either lithium-iron phosphate (LFP) or lithium nickel cobalt manganese oxide (NMC) account for most of today's battery production volumes (Hettesheimer et al., 2023). Due to a generally higher cycling stability of LFP batteries, it is reasonable to assume that, at first, significant volumes of NMC batteries will have to be treated at end-of-life (EoL). Thus, in the present review we focus on different recycling strategies for NMC batteries.

The structure of the review is as follows: Section two provides technical background on different recycling processes. Due to the aforementioned drawbacks of pyrometallurgical recycling and the lower technological maturity of direct recycling, we focus here on hydrometallurgical and combined pyro- and hydrometallurgical recycling approaches. Next, in section three, we present publications that have conducted life cycle assessments (LCA) for battery recycling. Differences in data sources, system boundaries and technical battery parameters are addressed. Results from different publications are compared in section four, and possible explanations for variability critically analyzed. In addition, we develop an overview of blank spots in literature which could be subject of future research and provide recommendations to improve the consistency of LCAs for battery recycling.

2 Technical background for hydrometallurgy and combined pyro- and hydrometallurgy

Before NMC batteries are treated by pyro- and hydrometallurgical recycling, the battery packs must first be removed from the application, collected and dismantled (Slattery et al., 2021). The dismantling process is usually carried out manually or semi-automatically (Rajaeifar et al., 2021). Subsequently, the non-cellular material is shredded and further treated to recover aluminium, copper and steel (Accardo et al., 2021; van Hoof et al., 2023). In contrast, the battery cells are discharged and submitted to pyro- and hydrometallurgical recycling processes. The system boundary of our study with different treatment routes is shown in Fig. 1.

The hydrometallurgical recycling of LIBs is a widely adopted method in the industry and describes the use of aqueous solutions to recover valuable metals from spent batteries (Wang et al., 2022). This process comprises a number of key stages, including mechanical pre-treatment, leaching, purification and separation (Chen et al., 2019; Liu et al., 2019).

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The pre-treatment involves crushing and sieving of the batteries to produce the black mass, which contains valuable metals such as lithium, nickel, cobalt and manganese (Lee et al., 2024). Effective pre-treatment not only improves metal recovery rates, it also reduces environmental impact by minimizing the need for aggressive chemicals and energy during the leaching process (Li et al., 2018). Leaching represents a critical stage in the hydrometallurgical recycling process for LIBs, wherein valuable metals are extracted from the pre-treated battery materials through the use of acidic solutions. Widely used leaching agents include sulphuric acid, hydrochloric acid and nitric acid, often supplemented with hydrogen peroxide to increase metal recovery (Zeng et al., 2014). Ongoing research focuses on developing more environmentally friendly leaching agents to further reduce the ecological footprint (Milian et al., 2024). After leaching, the dissolved metals are purified and separated using techniques such as solvent extraction, ion exchange and selective precipitation. These processes ensure the recovery of high-purity lithium, nickel, cobalt and manganese suitable for reuse in new batteries (Chen et al., 2019; Li et al., 2013). Hydrometallurgical recycling of LIBs offers several key benefits. The most significant advantages of this process include low energy consumption, high recovery purity and a high extraction rate (Hua et al., 2020). Conversely, this recycling method faces the challenges of complex processes and long processing times. Furthermore, the consumption of expensive reducing agents and a considerable quantity of acids and alkalis results in the generation of highly saline organic wastewater (Hua et al., 2020; Yang et al., 2022).

The pyro- and hydrometallurgical treatment also includes the steps pyrolysis and smelting before hydrometallurgical treatment (Brückner et al., 2020; Rajaeifar et al., 2021). These sub-steps offer the advantage of increased throughput with a reduction in plant size and the removal of organic components. In addition, the technology is highly mature and suitable for the initial recovery of alloys by reduction and smelting (Yao et al., 2018). Subsequently, high-purity individual metals and compounds can be obtained through hydrometallurgical treatment. However, high energy consumption, additional processing of the intermediate products and the need for waste gas treatment are required. Despite these challenges, the combined approach remains a promising method for large-scale battery recycling, offering both efficiency and scalability (Brückner et al., 2020; Windisch-Kern et al., 2022).

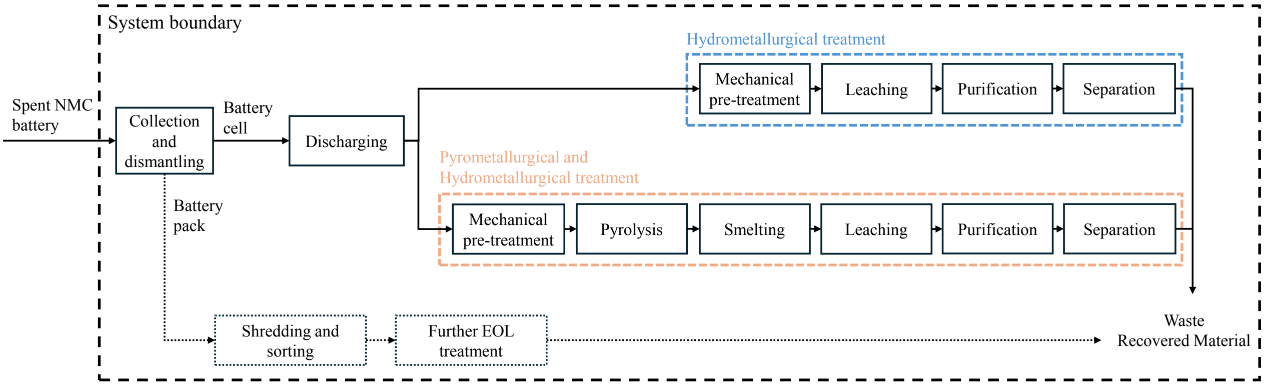

Figure 1: System boundary of this study.

3 Identified literature

The keyword-based search strategy applied in this review was conducted in Scopus and identified a total of 379 potentially relevant publications.[1] After reviewing the abstracts, a total of 64 potentially relevant studies were identified. These 64 studies were analyzed in detail for their relevance to the topic. Possible reasons for exclusion included consideration of a different cell chemistry (n=19), limited detailed LCA (n=13) or different recycling technology (n=8). Finally, 24 studies remained relevant to the environmental assessment of pyro- and hydrometallurgical recycling of NMC batteries. The results of the literature review are presented in Table 1.

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[1] Keywords used: (batter* OR lithium-ion) AND (LCA OR Life Cycle Assessment) AND (Recycling OR Recover OR Circular); Field of search: Titel, abstract, keywords; Focus: January 2019 – August 2024

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URN: urn:nbn:de:hbz:6-43998534359
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Table 1: Life cycle assessments of pyro- and hydrometallurgical recycling of lithium-ion based NMC Batteries.

No.	Name, Year	Functional Unit	Background Data, Impact Assessment Method	Energy density	Chemistry	Region
1	Cusenza et al., 2019	11.4 kWh Pack	PEF, Ecoinvent 3	65 Wh/kg	NMC*	Europe
2	Ciez and Whitacre, 2019	1 kg Cell	Ecoinvent, GREET	270 Wh/kg	NMC*	USA
3	Zhu and Chen, 2020	1 kWh Pack	Ecoinvent, GREET	n/a	NMC 622*	China, USA
4	Tao and You, 2020	1 kWh Pack	ReCiPe, Ecoinvent V3.6, GREET	181 Wh/kg	NMC 622*	n/a
5	Mohr et al., 2020	1 kWh Pack	ILCD midpoint, Ecoinvent 3.4	105 Wh/kg	NMC 811*	Europe
6	Sun et al., 2020	1 kWh Pack	CML-IA baseline V3.02, Ecoinvent 3.0, GREET 2018	115 Wh/kg	NMC 622	China
7	Xiong et al., 2020	1 kg Cell	EverBatt	164.37 Wh/kg	NMC 111	China
8	Accardo et al., 2021	1 kWh Pack	CML baseline, Ecoinvent 3.6	213 Wh/kg	NMC 111, NMC 622, NMC 811	China, Europe
9	Rajaeifar et al., 2021	1 kg Cell	Ecoinvent	150 Wh/kg	NMC 111*	China
10	Jiang et al., 2022	1 ton Pack	CML, Ecoinvent V3.6	n/a	NMC 111	United Kingdom
11	Chen et al., 2022	1 kWh Pack	n/a	228 Wh/kg	NMC 811	China
12	Kallitsis et al., 2022	1 kWh Pack	Ecoinvent	105 Wh/kg	NMC 111	China
13	Feng et al., 2022	1 kWh	ReCiPe 2016 Midpoint	120 Wh/kg	NMC*	China
14	Castro et al., 2022	569 g Cell	ReCiPe 2016 v1.1 Midpoint, Ecoinvent v3.6	65,2 Wh/kg	NMC	Europe
15	Quan et al., 2022	1 kWh Pack	CML2001, Ecoinvent, GREET	142.4 Wh/kg	NMC*	China
16	Wang et al., 2022	1 kWh Pack	ReCiPe, GREET	n/a	NMC*	China
17	Blömeke et al., 2022	95 kWh Pack	Ecoinvent 3.8	n/a	NMC 622	Germany
18	Rosenberg et al., 2023	1 kg Pack	CML2001, GaBi Professional Database	142 Wh/kg	NMC 111, NMC 811	Germany
19	Wu et al., 2023	1 kWh	EDIP 2003, CML IA-baseline, ReCiPe 2016, Ecoinvent3, PCF Database	n/a	NMC 811	China
20	Gutsch and Leker, 2023	1 kWh Cell	PEF 3.0, ReCiPe 2016, Ecoinvent 3.8	281 Wh/kg	NMC 811	USA
21	Haupt et al., 2023	1 kg	CML 4.8 2016, Ecoinvent	n/a	NMC 622	n/a
22	Yang et al., 2024	1 kg	PEF 3.0	n/a	NMC*	China
23	Gong et al., 2024	1 kWh	ReCiPe 2016, Ecoinvent 3.8	163 Wh/kg	NMC 811*	China
24	Ali et al., 2024	42.2 kWh Pack	Ecoinvent 3.8	n/a	NMC 622	Europe

*Other cell chemistries are analysed in addition.

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URN: urn:nbn:de:hbz:6-43998534359
DOI: 10.17879/43998523309

LCA has become a widely used method for evaluating the environmental impact of industrial products and complex systems (Dong et al., 2021; Guinee J. B., 2001). The procedure for a LCA is described in standardized form in ISO 14040/44 (International Organization for Standardization, 2009). Accordingly, an LCA consists of four parts: 1. goal & scope definition, 2. life cycle inventory (LCI), 3. life cycle impact assessment (LCIA) and 4. Interpretation. In the initial phase, the system boundaries and functional unit are defined (Unterreiner et al., 2016). For this study, we defined the grave-to-cradle approach as system boundary to examine the ecological effects of pyro- and hydrometallurgical recycling. Thus, the entire recycling process, including collection, dismantling, discharging, pyro- and hydrometallurgical treatment is considered. In the LCI phase, data are gathered and evaluated to ensure their accuracy, completeness, and consistency for subsequent use in impact assessments (Hauschild et al., 2018). During the LCIA step, inventory data are translated into indicators for environmental impacts categories using an impact assessment methodology (International Organization for Standardization, 2009). In this context, midpoint and endpoint characterization models are basically two different approaches. The midpoint approach treats environmental impacts in a problem-oriented manner and the endpoint approach in a damage-oriented manner (Dong et al., 2021). In this paper, we have focused on studies that use the midpoint approach to better understand the causes of environmental impacts. As shown in Table 2, 17 of the 24 relevant studies used ReCiPe (Huijbregts et al., 2017) or CML (Guinee, 2002) at midpoint level as impact assessment method.

Primary data are included in 11 of the 24 relevant studies (Blömeke et al., 2022; Cusenza et al., 2019; Feng et al., 2022; Haupt et al., 2023; Jiang et al., 2022; Kallitsis et al., 2022; Mohr et al., 2020; Rajaeifar et al., 2021; Sun et al., 2020; Yang et al., 2024; Zhu and Chen, 2020). Among these eleven studies, five LCAs are based exclusively on primary data (Blömeke et al., 2022; Haupt et al., 2023; Jiang et al., 2022; Yang et al., 2024; Zhu and Chen, 2020). Consequently, the remaining 13 studies rely on secondary data (Accardo et al., 2021; Ali et al., 2023; Castro et al., 2022; Chen et al., 2022; Ciez and Whitacre, 2019; Dai et al., 2019b; Gong et al., 2024; Gutsch and Leker, 2024; Quan et al., 2022; Rosenberg et al., 2023; Tao and You, 2020; Wang et al., 2022; Wu et al., 2023; Xiong et al., 2020). These findings are consistent with those of Bauer (Bauer et al., 2022) which further addressed the imbalance between primary and secondary data studies (Aichberger and Jungmeier, 2020; Degen and Schütte, 2022; Ellingsen et al., 2017; Peters et al., 2017). However, the proportion of studies that only use primary data is slightly higher for recycling (21%) than for battery cell production (12%) (Degen and Schütte, 2022). Looking at the links between the studies in Fig. 2, it is noticeable that the studies by Mohr (Mohr et al., 2020) and Dai (Dai et al., 2019b) are central in the literature. Mohr conducted a study based on primary and secondary data, as well as the Ecoinvent database. In contrast, the EverBatt model of Dai relied on secondary data and the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model (Argonne National Laboratory, 2018a, 2018b). The GREET model is from Argonne National Laboratory (ANL), providing researchers with great access to primary data on the production and EoL treatment of LIBs (Benavides et al., 2015; Dunn et al., 2015b; Wang et al., 2023). Approximately 45% of the relevant studies refer directly or indirectly through other studies to data from the EverBatt model of Dai et al. (see Fig. 2).

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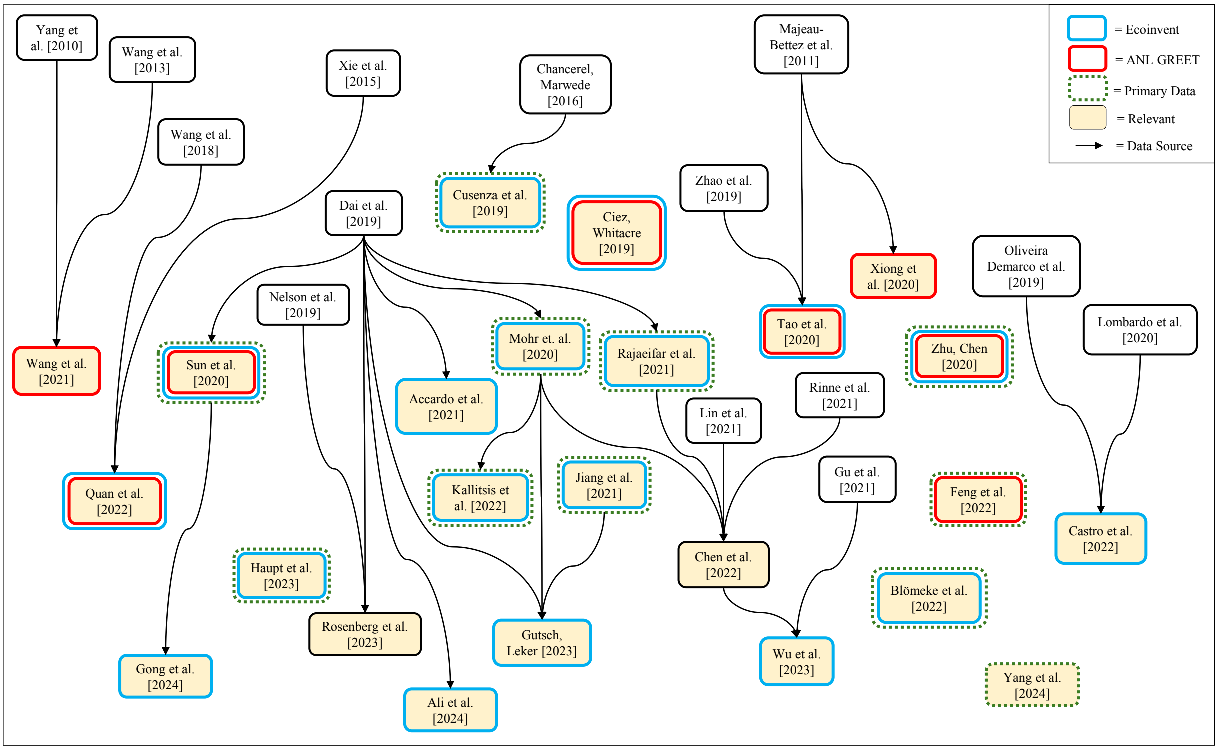

Figure 2: Relationships between LCA studies.

4 Results

To ensure the comparability of the reported results, the functional unit was set to 1 kWh battery pack. When data for the pack level were not available, the analysis was conducted at cell level. Studies where the functional unit differed from 1 kWh of battery capacity were adjusted based on the specific energy density.

4.1 Global Warming Potential

Global warming potential (GWP) is the most frequently investigated impact category for LCA in the field of battery cell production and reflects the influence on climate change by kg CO2 to air (Huijbregts et al., 2017; Peters et al., 2017). While 67% of the studies about battery cell production have assessed GWP (Peters et al., 2017), all considered studies on recycling have examined it. The total GWP impact is the sum of the GWP recycling credit and GWP recycling burden (see equation 1).

$$GWP_{total} = \sum GWP_{Credit}, GWP_{Burden} \qquad (1)$$

It was found that the GWP burden in all studies ranges for the hydrometallurgical treatment between 2.7 and 34.0 kg CO2eq kWh-1. For combined pyro- and hydrometallurgical treatment emissions are between 5.1 and 15.8 kg CO2eq kWh^{-1} (see Fig. 3). The discrepancies in the literature can be primarily attributed to variations in the content of nickel, manganese, and cobalt, as well as different production locations, since greenhouse gas (GHG) emissions resulting from a similar recycling process in China are higher than those observed in most European countries or the US (Xiong et al., 2020). Furthermore, studies based on the same primary data show consistent results (Chen et al., 2022; Gong et al., 2024; Mohr et al., 2020; Sun et al., 2020; Wu et al., 2023). This emphasizes the importance of collecting new primary data to gain new insights. With respect to GWP credit and GWP total impact, the study of Kallitsis (Kallitsis et al., 2022) differs from the remaining studies. This can in part be explained by the functional unit being set at pack level, allowing greater GWP benefits to be achieved through aluminum, copper and steel recovery (Kallitsis et al., 2022). If we compare the results of Mohr and Kallitsis, it is noticeable that the values for burden, credit and total from Mohr are only 53% of Kallitsis results. As the Mohr study was also conducted at the pack level, this alone cannot explain the discrepancies in the results. Another explanation would be that Kallitsis study was conducted in China, where the GWP benefits from the recovered materials are the highest, as production is related to high CO2 emissions (Kallitsis et al., 2022). However, these criteria were also applied in the studies by Sun (Sun et al., 2020) and Accardo (Accardo et al., 2021). One distinguishing characteristic is that the study by Kallitsis collected primary data from the industry in addition to secondary data. This indicates that the recycling process analysed was already further advanced, which also underlines the importance of collecting primary data.

The average burden of the examined studies for recycling of 1 kWh NMC battery with hydrometallurgical treatment is 9.5 kg CO2eq and for combined pyro- and hydrometallurgical treatment 11.9 kg CO2eq. In comparison, the production of 1 kWh NMC 811 battery releases 64.5 kg CO2eq (Gutsch and Leker, 2024). Thus, the CO2 emissions from recycling are about 15-19% of battery cell production. In the studies reviewed, the average total CO2 emissions associated with hydrometallurgical recycling are - 25.5 kg CO2eq kWh^{-1}. In comparison, the average total CO2 emissions associated with combined pyro- and hydrometallurgical recycling are - 17.5 kg CO2eq kWh^{-1}. This indicates that combined pyro- and hydrometallurgical recycling can reduce the GWP of battery cell production by 27%. Hydrometallurgical recycling can result in a reduction of GWP associated with battery cell production by 39%. By comparing the results of the hydrometallurgical approach with those of the combined pyrometallurgical and hydrometallurgical approach, it becomes evident that the studies conducted by Kallitsis (Kallitsis et al., 2022), Chen (Chen et al., 2022), Wu (Wu et al., 2023) and Yang (Yang et al., 2024) are particularly suitable for comparison, since both approaches were investigated under identical conditions. The slight differences in the average values for burden and total can also be observed here. Additionally, the study by Accardo (Accardo et al., 2021) in the context of the combined pyro- and hydrometallurgical approach is unique in reporting a positive value for the total GWP. Therefore, hydrometallurgy is more environmentally friendly in terms of GWP compared to the combination of pyro- and hydrometallurgy (see Fig. 3).

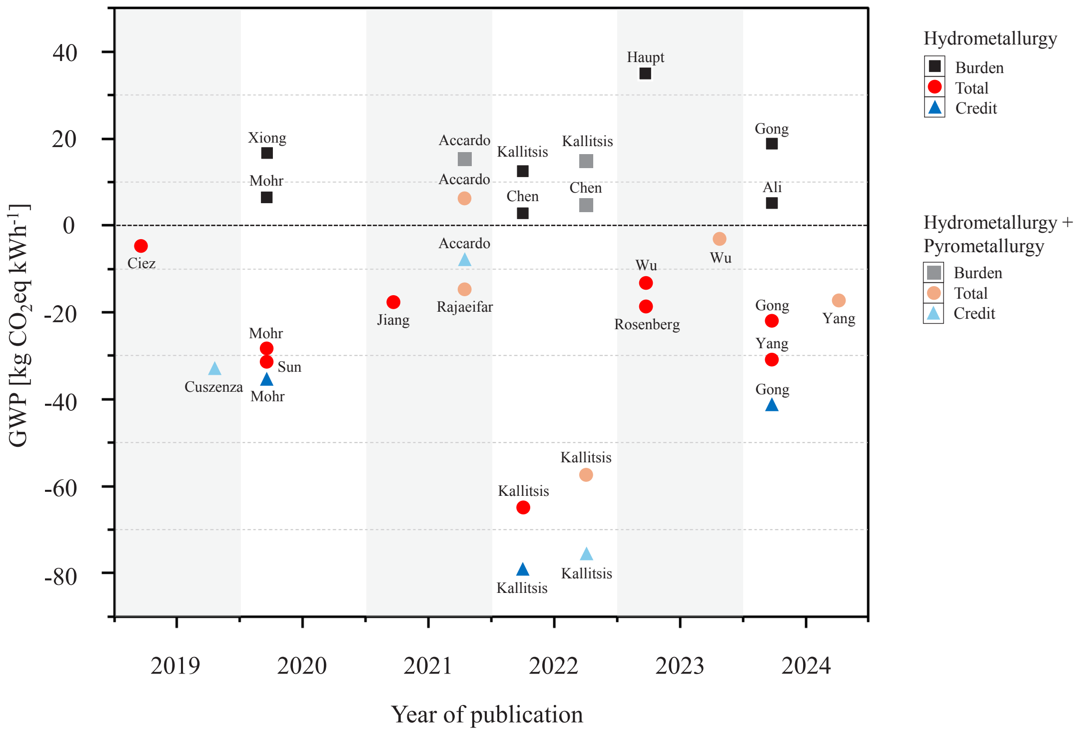

Figure 3: GWP from selected studies in pyro- and hydrometallurgical recycling of 1 kWh NMC battery cell or pack.

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4.2 Cumulative Energy Demand

According to Peters (Peters et al., 2017), cumulated energy demand (CED) is the second most frequently investigated impact category for LCA in the field of battery cell production and reflects the energy consumption in MJ. While 53% of the studies about battery cell production have evaluated CED (Peters et al., 2017), 54% of the considered studies have analyzed it. The total CED impact is the sum of the CED recycling credit and CED recycling burden (see equation 2).

$$\boldsymbol{CED_{total} = \sum CED_{Credit}\,, CED_{Burden}} \qquad \mathbf{(2)}$$

The analysis reveals that the total CED of all relevant studies ranges for the hydrometallurgical treatment between - 453.3 and - 62.9 MJ kWh^{-1} and for the combined pyro- and hydrometallurgical treatment between - 257.6 and 256.8 MJ kWh^{-1} (see Fig. 4). Specifically, the average value for the CED burden of hydrometallurgical recycling is 198.2 MJ kWh^{-1}. In contrast, the combined pyrometallurgical and hydrometallurgical recycling process exhibits a higher average value of the CED burden, with 228.2 MJ kWh^{-1}. A comparative analysis of the average recycling credit values reveals that hydrometallurgical recycling achieves a more significant reduction in energy consumption compared to the combined pyro- and hydrometallurgical recycling process. In particular, the hydrometallurgical process offers an average energy credit of - 492.5 MJ kWh^{-1}, whereas the combined approach yields a comparatively lower credit of - 326.1 MJ kWh^{-1}. This disparity highlights the greater efficiency of the hydrometallurgical method in reducing energy demands and demonstrates that the pyrolysis and smelting sub-steps are characterized by a high energy consumption (Accardo et al., 2021).

Furthermore, it can be determined that 83% of the studies demonstrate a benefit in total CED, establishing a general consensus within the research community. Therefore, the average total CED for hydrometallurgical recycling is calculated to be - 189.5 MJ kWh^{-1}. Hydrometallurgical recycling can reduce the CED by almost 17%, given that the production of 1 kWh NMC battery requires 1,126 MJ of energy (Dai et al., 2019a). However, the study by Accardo differs from this trend with a positive total CED, due to high energy requirements of the pyrometallurgical steps (Accardo et al., 2021). Nevertheless, Rajaeifar conclude that the combined pyro- and hydrometallurgical recycling process yields a net benefit (Rajaeifar et al., 2021). This can be attributed to the closed-loop approach, which is considered the best-case scenario, as it allocates optimistically high energy and environmental credits to the system. Additionally, since 2022, fewer studies have analyzed the values for recycling CED total and recycling CED credit (see Fig. 4). To gain a comprehensive understanding of the impact of recycling, it is essential to address these aspects in future research.

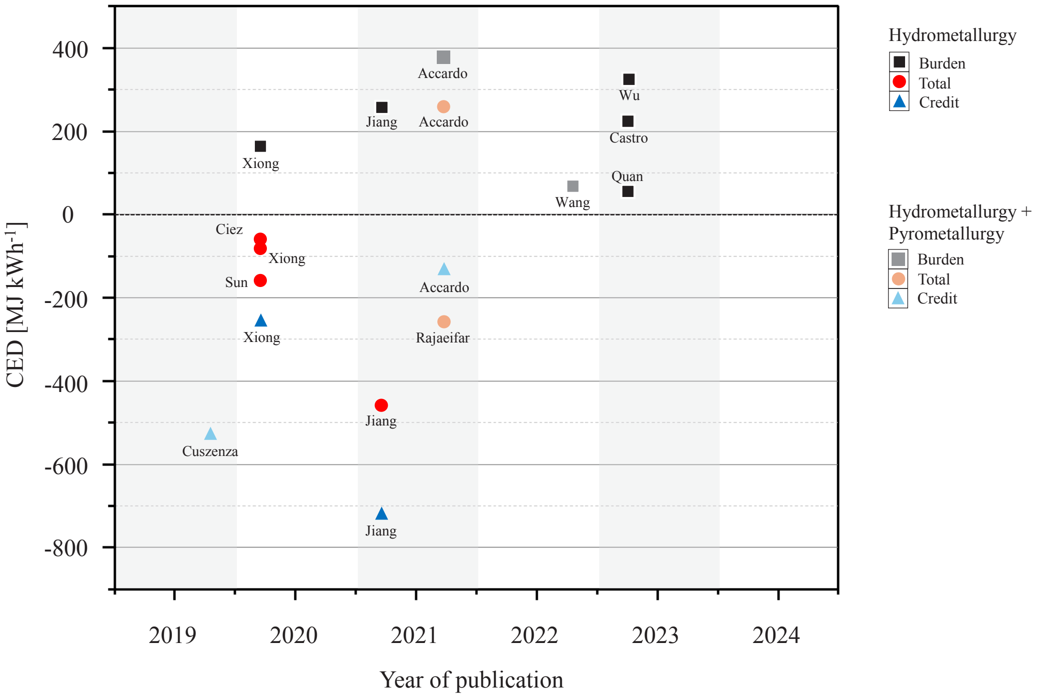
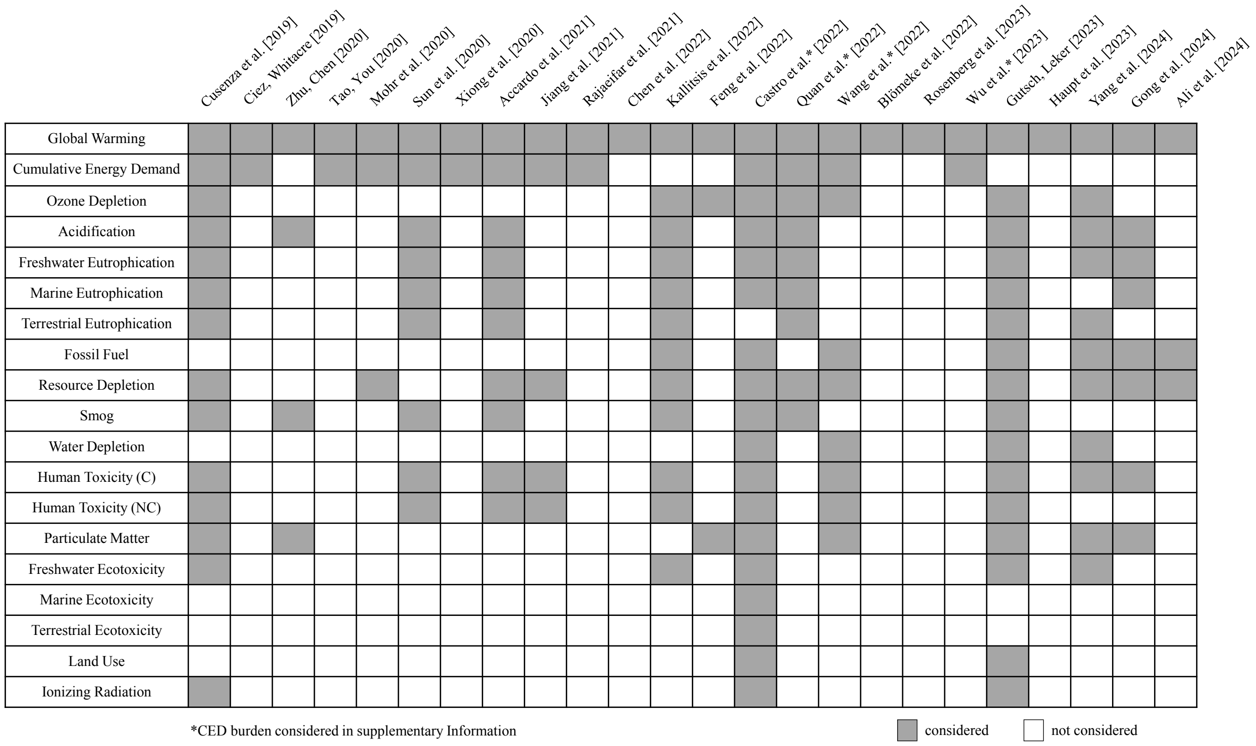


Figure 4: CED of selected studies in pyro- and hydrometallurgical recycling of 1 kWh NMC battery cell or pack.

5 Further Impact categories

The objective of a LCA is to quantify the overall environmental impacts of a system (International Organization for Standardization, 2009). Accordingly, in the LCIA phase exists a wide set of characterisation models and impact categories that can be used to evaluate the environmental impact (Finkbeiner et al., 2006; International Organization for Standardization, 2009). In the analyzed studies, the used impact categories consist of the frequently applied impact assessment methods ReCiPe (Guinee, 2002; Huijbregts et al., 2017), CML (Guinee, 2002) and the impact category CED. The matrix presented in Fig. 5 summarizes the considered impact categories in the relevant studies. However, looking at the impact categories, it appears that many studies consider only GWP and very few other categories in addition, while still referring to the concept of LCA. In particular, only the studies by Cusenza (Cusenza et al., 2019), Kallitsis (Kallitsis et al., 2022), Castro (Castro et al., 2022) and Yang (Yang et al., 2024) analyse a wide spectrum of impact categories. The study by Gutsch and Leker (Gutsch and Leker, 2024) employs a combined approach to assess a number of impact categories simultaneously. Furthermore, it is evident that since 2022, none of the analyzed studies have examined the impact category CED, including its burden, credit and total recycling values (see Fig. 5). This absence highlights a gap in the current research, as CED represents a crucial indicator for comprehending the total energy implications of recycling processes. This includes the energy conserved through material recovery and the energy consumed in the recycling operations themselves.



	Cusenza et al. [2019]	Ciez, Whitacre [2019]	Zhu, Chen [2020]	Tao, You [2020]	Mohr et al. [2020]	Sun et al. [2020]	Xiong et al. [2020]	Accardo et al. [2021]	Jiang et al. [2021]	Rajaeifar et al. [2021]	Chen et al. [2022]	Kallitsis et al. [2022]	Feng et al. [2022]	Castro et al.* [2022]	Quan et al.* [2022]	Wang et al.* [2022]	Blömeke et al. [2022]	Rosenberg et al. [2023]	Wu et al.* [2023]	Gutsch, Leker [2023]	Haupt et al. [2023]	Yang et al. [2024]	Gong et al. [2024]	Ali et al. [2024]
Global Warming	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Cumulative Energy Demand	■	■	☐	■	■	■	■	■	■	■	☐	☐	☐	■	■	■	☐	☐	■	☐	☐	☐	☐	☐
Ozone Depletion	■	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	■	■	■	■	■	☐	☐	☐	■	☐	■	☐	☐
Acidification	■	☐	■	☐	☐	■	☐	■	☐	☐	☐	■	☐	■	■	☐	☐	☐	☐	■	☐	■	■	☐
Freshwater Eutrophication	■	☐	☐	☐	☐	■	☐	■	☐	☐	☐	■	☐	■	■	☐	☐	☐	☐	■	☐	■	■	☐
Marine Eutrophication	■	☐	☐	☐	☐	■	☐	■	☐	☐	☐	■	☐	■	■	☐	☐	☐	☐	■	☐	☐	■	☐
Terrestrial Eutrophication	■	☐	☐	☐	☐	■	☐	■	☐	☐	☐	■	☐	☐	■	☐	☐	☐	☐	■	☐	■	☐	☐
Fossil Fuel	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	■	☐	■	☐	■	☐	☐	☐	■	☐	■	■	■
Resource Depletion	■	☐	☐	☐	■	☐	☐	■	■	☐	☐	■	☐	■	■	■	☐	☐	☐	■	☐	■	■	■
Smog	■	☐	■	☐	☐	■	☐	■	☐	☐	☐	■	☐	■	■	☐	☐	☐	☐	■	☐	☐	☐	☐
Water Depletion	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	■	☐	■	☐	☐	☐	■	☐	■	☐	☐
Human Toxicity (C)	■	☐	☐	☐	☐	■	☐	■	■	☐	☐	■	☐	■	☐	■	☐	☐	☐	■	☐	■	■	☐
Human Toxicity (NC)	■	☐	☐	☐	☐	■	☐	■	■	☐	☐	■	☐	■	☐	■	☐	☐	☐	■	☐	☐	☐	☐
Particulate Matter	■	☐	■	☐	☐	☐	☐	☐	☐	☐	☐	☐	■	■	☐	■	☐	☐	☐	■	☐	■	■	☐
Freshwater Ecotoxicity	■	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	■	☐	■	☐	☐	☐	☐	☐	■	☐	■	☐	☐
Marine Ecotoxicity	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	■	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Terrestrial Ecotoxicity	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	■	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Land Use	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	■	☐	☐	☐	☐	☐	■	☐	☐	☐	☐
Ionizing Radiation	■	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	■	☐	☐	☐	☐	☐	■	☐	☐	☐	☐

*CED burden considered in supplementary Information

■ considered ☐ not considered

Figure 5: Overview of the impact categories considered within relevant studies.

The Bauer commentary (Bauer et al., 2022) highlights that the EoL management of batteries is potentially harmful to the natural environment and human health. Moreover, the findings of the study by Kallitsis indicate that the recycling credits can be even higher in impact categories other than GWP and CED (Kallitsis et al., 2022). This is in line with the results reported by Accardo, who identified the greatest benefits from recycling in the impact categories of human toxicity and acidification (Accardo et al., 2021). Therefore, LCA about battery EoL treatment should examine impact

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categories like Human Toxicity Potential, Resource Depletion, Acidification Potential and Terrestrial Eutrophication Potential in addition to GWP and CED to address aspects of human health and natural environment. However, the analysis of the relevant studies shows that on average only 40% of these four categories are analyzed. Consequently, future research should prioritise a more comprehensive investigation.

6 Conclusions and outlook

This work provides an overview about the current state of research on the environmental impacts of pyro- and hydrometallurgical recycling of NMC batteries. It was found that most LCAs were conducted in China, followed by Europe and the United States. As background data, GREET (Argonne National Laboratory, 2018b, 2020; Dunn et al., 2014; Dunn et al., 2015a) and Ecoinvent (Wernet et al., 2016) are used by a large number of studies. We improved the comparability of relevant studies by analyzing the system boundaries and adjusting the functional units to a standard of 1 kWh battery pack. Our analysis results show that pyro- and hydrometallurgical recycling of NMC batteries is described in the literature with predominantly positive environmental effects. Combined pyro- and hydrometallurgical recycling can reduce the GWP of battery cell production by 27%. Conversely, hydrometallurgical recycling can result in a reduction of GWP by 39%. Furthermore, it can be summarised that the pyrolysis and smelting sub-steps are distinguished by a high level of energy consumption. Conversely, hydrometallurgical recycling can reduce the CED of battery cell production by almost 17%. The findings suggest that studies using secondary data generally show a high degree of consistency with those using primary data. In the literature, environmental categories beyond GWP and CED generally receive less attention, even though their benefits are often more significant.

When evaluating this study, it is important to acknowledge that it encompasses battery cells with varying compositions of nickel, manganese, and cobalt. Moreover, LIBs were analyzed at both the pack and cell levels, which can lead to variations in the results. Further research could investigate the EoL environmental impacts of other cell chemistries, such as LFP or Lithium nickel cobalt aluminium oxide (NCA), in terms of data sources and different environmental impact categories. Based on our findings, we offer three recommendations for conducting future LCAs:

- *Recommendation 1:* In addition to the total impact, it is advisable to include the credit and burden in absolute terms. This allows a more differentiated analysis and comparison of the individual recycling processes and ensures that both the benefits and the drawbacks of each process are clearly identified.
- *Recommendation 2:* To facilitate direct comparisons between studies, it is recommended to standardize the functional unit to 1 kWh at pack level. Additionally, given that the majority of current studies rely on secondary data, it is recommended that more primary data be collected to ensure the gathering of new insights.
- *Recommendation 3:* Besides GWP and CED, other impact categories are not regularly considered. To gain a comprehensive understanding of the impact on both humans and the environment, it is important to consider additional impact categories such as Human Toxicity Potential, Acidification Potential, Terrestrial Eutrophication Potential and Resource Depletion.

Funding sources

This research was partially funded and supported by the German Federal Ministry of Education and Research within the project ProRec [03XP0537A] and the Ministry of Culture and Science of the State of North Rhine-Westphalia within the project BIOSTORE [PB22-014].

CRediT authorship contribution statement

Luca Stegemann: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing.

Moritz Gutsch: Writing – review & editing, Supervision, Validation, Project administration.

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JOURNAL OF
BUSINESS CHEMISTRY

ISSN 1613-9623