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A cross-disciplinary, cross-organizational approach to sustainable design and product innovation in the aluminum industry

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Abstract

Aluminum is a promising sustainable and industrial resource that provides strong, lightweight structures with complex geometric possibilities, a high recovery rate in the recycling process, and low-emission production when produced by hydropower. Design and product innovations are enabling aluminum to increasingly replace steel in many industrial sectors (such as construction, automotive, and furniture), improving environmental (e.g., reduction of CO_2 emission in transport) and financial (e.g., increased circularity and value creation) performance. However, key knowledge of the aluminum value chain is concentrated among the different actors. For instance, downstream actors possess a high level of technical expertise in the metallurgical properties and processing of aluminum, and they are typically situated a long distance from the end market or end user are unaware of the end user's current and future needs. Investments in and investigations of new aluminum alloys, treatments, and machines are accompanied by high financial and time risks. Cross-disciplinary, cross-organizational collaborations might facilitate design and product innovations, including value creation and sustainability aspects and reducing financial and time risks. There is limited literature on how the different actors in the aluminum value chain should collaborate and which methods they should apply to increase sustainable design and product innovation. Therefore, this study applies a multiple case research approach to identify the benefits, enablers, and barriers of sustainable design and product innovation. Based on the findings, a sustainable design and product innovation framework was developed, highlighting actors, collaboration, and methods applied at different innovation project stages. The introduced approach supports the actors in the aluminum value chain to efficiently introduce sustainable design and product innovations to new and existing markets.

Keywords: Design and product innovation; sustainability; framework; triple diamond; aluminum;

1. Introduction

Advances in material and manufacturing technology make aluminum a promising sustainable and industrial resource, thereby supporting companies in moving their value chains toward a green transition. The poor environmental and high-cost reputation of aluminum due to energy-intensive production has for a long time hindered the introduction of design and product innovations and prevented its use in several markets [1]. Increased external environmental pressure has been a major driver for the development of radical innovations in this industry [2].

Geographical conditions, long-term investments, and collaborations have helped Norway to have one of the lowest environmental footprints in primary aluminum production thanks to hydropower [3]. Aluminum is a metal suitable for recycling, and used aluminum has financial value through the collection and reverse logistics. Furthermore, aluminum provides significant energy savings, up to one-fifth of the savings of secondary production [4]. While in the past aluminum was mainly appreciated for its high strength-to-weight ratio, good formability, and high corrosion resistance [5], today, aluminum can be considered an environmentally friendly resource and applied in a variety of products. Hence, aluminum is increasingly replacing steel in many traditional

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industrial sectors (such as construction, automotive, and ship building), improving their environmental (e.g., reduction of CO_2 emission in transport), financial (e.g., increased circularity and value creation), and social (e.g., improved ergonomics reducing fatigue of operators) performance.

However, while the global demand for aluminum has seen significant growth in recent years [1], product innovations in the aluminum industry are progressing slowly. The characteristics of the aluminum industry have been hindering this process. The aluminum industry is highly capital intensive, and investment decisions must be made well in advance. For instance, new technologically enhanced aluminum frames that are extruded need to be intertwined within the existing aluminum production system and infrastructure [2]. Such implementations and integrations are connected with high costs and significant time efforts. Further, key knowledge of the aluminum value chain is concentrated among the different actors. For instance, downstream actors possess a high level of technical expertise of highly specialized machines for producing aluminum, and these actors are typically situated a long distance from the end user and are unaware of the end user's current and future needs. Therefore, investments and investigations in new aluminum alloys, treatments, and processes are accompanied by high financial and time risks.

To reduce these risks and increase product innovations in the aluminum industry, a research project was established to support industry and research collaborations. Several approaches have been studied, applied, and extended in the course of the project—including industrial design practices and methodologies, as well as divergent and convergent phases, as emphasized in the Double Diamond by the British Design Council [6]. Further, Verganti's [7] perspectives on broad innovative networks are driven by social trends and technology. However, these approaches do not appropriately cover the metal production and processing aspects of product innovation or the complexity of changing social structures, nor are they adapted to include the circular economy aspects. Therefore, this study applies a multiple-case study approach to identify the benefits, enablers, and barriers of sustainable design and product innovation. Based on the findings, a framework for sustainable design and product innovation was developed, highlighting actors, collaborations, and methods applied at different stages in innovation projects. The introduced approach supports the actors in the aluminum value chain to efficiently introduce sustainable design and product innovations to new and existing markets.

The rest of the paper is organized as follows: Section 2 reviews the literature on sustainable design and product innovation approaches. Section 3 explains the applied research method, including case selection and analysis. The next section describes the six case studies. In Section 5, we introduce the sustainable design and product innovation framework. Section 6 discusses the insights of the multiple case study and how the introduced framework can be applied to support the aluminum industry. We conclude the study with recommendations for future research.

2. Theoretical background

Innovation plays a central role in creating value and sustaining competitive advantage [8, 9]. Design methodologies support companies in discovering new opportunities for innovation that are prompted by a deep understanding of people's needs. These innovations start with the primary goal of creating offerings that are desirable for users and meet their needs, thereby possessing user value. Creating offerings with more user value, in turn, raises the economic and business value of the offerings [10]. Rational methods for designing have been developed since the 1960s–1970s. The motivation for studying design processes has been to externalize the design way of thinking and creation, supporting non-designers to participate [11]. Over the last few years, several concepts and approaches have been introduced to achieve design and product innovations. One of the most prominent approaches has been the Double Diamond design model. The model has the phases "discover," "define," "explore," and "develop," which help to define the problem (doing the right thing) and develop the solution (doing things right) [12].

Incorporating concerns of sustainability and circularity into design practice is important. However, user-centric approaches have the tendency to reduce the priority of circularity initiatives and environmental sustainability [13]. Therefore, sustainability-oriented innovation should include systems and societal perspectives and an awareness of multidimensional targets. According to Wilkerson and Trellevik [13], problem definition can be improved by combining design thinking and systems. Furthermore, eco-design strategies have been developed to increase the sustainability performance of products and companies [14]. Eco-design strategies aim to reduce the environmental impacts of products and services throughout the whole life cycle while assuring similar or improved services for the end customer. However, only a few studies provide eco-design techniques and tools compatible with product development processes [15]. There is a need to equip novice designers with the skills to facilitate a sustainability-focused future while collaborating with industry to implement these concerns into contemporary design practices [16]. However, both academia and industry have had difficulties in developing approaches for product innovation balanced with environmental, financial, and social sustainability. Close collaboration and arenas for knowledge transfer have supported increasing circularity initiatives and environmental sustainability in design processes [17]. There is a need to develop methods and frameworks to support academia and industry collaboration to succeed with sustainable design and product innovation.

3. Method

Case research was conducted to achieve the current study's aims and fill the gap in the literature. This research approach is suitable for investigating a real-life phenomenon when the associated variables and complexity are not sufficiently understood [18]. The growing frequency and magnitude of changes in technology and managerial methods require researchers to apply field-based methods [19]. The multiple-

case study approach enables a deeper comparison of the similarities and differences between different contexts than other approaches [20, 21]. Hence, the insights and findings of the multiple-case study approach would support the development of a framework for sustainable product and design innovations.

To discover insightful findings to build on, case selection plays a vital role in this research approach. We focused on the replication logic rather than the sampling logic [22]. Therefore, our strategy is based on achieving theoretical replication using information-rich cases that produce diverse results and maximum variation, although for predictable reasons [23, 24]. Therefore, six cases were selected from the shipbuilding, energy, and construction sectors (two cases from each sector).

In case research, triangulation is an essential factor in increasing research validity: it is the process of corroborating evidence from different individuals and types of data (such as theory, interviews, observations, documents, and field notes) to reflect the same phenomenon [18, 25]. In the current study, multiple semi-structured interviews and workshops with experts were conducted, and project documents and reports were collected. The data were analyzed using Mayring's [26] recommendations for content analysis.

4. Case descriptions

4.1. Electrical Urban Water Shuttle

Many cities are seeking alternative options to reduce road traffic, carbon emissions, and infrastructure costs while improving the connectivity of urban areas, air quality, and value chains. The electrical Urban Water Shuttle is a system of energy-efficient, zero-emission passenger vessels for 150 passengers and 20 bikes in densely populated areas located close to rivers, lakes, or seas. The innovation process was driven by workshops and knowledge transfer between different partners of Norway's maritime cluster (including a shipbuilder, an aluminum supplier, and other technology suppliers). Energy providers, universities, and research centers supported the design process to maintain sustainability aspects. Aiming for an all-aluminum vessel, the project reduced the risk of failure by identifying several challenges at an early stage of the project, systematically transforming the challenges into innovations supporting environmental sustainability in particular. For instance, one of the crucial parts was the development and production of the aluminum gearbox. Aluminum gearboxes have faced cast production challenges regarding surface quality, cracks, and fatigue. Mechanically processed gearboxes shaped out of aluminum blocks cause a long processing time and a high amount of material waste. The innovation for this component enabled a new lightweight form cast near net shape, thereby reducing significant material waste and production time.

4.2. Whale Safari Boat

Catamarans are preferred boats for high passenger comfort and a great nature experience. Traditionally, whale safari boats are made of oak and use petrol-powered engines, resulting in a rather heavy boat with low flexibility in design due to structural load restrictions. Using a strong, lightweight material, such as aluminum, can reduce the environmental footprint. Working closely with industrial experts enabled the introduction of a completely new design in aluminum. Moreover, an optimized hull design and a hybrid engine (with an electrical engine and a mechanical one as backup) were developed. The collaborative design and product development process facilitated a more environmentally sustainable catamaran. It supported changes in propulsion technology for increased comfort and large windows for high visibility of marine wildlife and scenery. The collaboration also supported the development of an aluminum superstructure to include batteries, engines, large windows, reduced weight, and minimal resistance in the water. Another aspect is that parts of the Whale Safari Boat can be made of recycled aluminum, drive electrical, and have a strongly reduced environmental impact.

4.3. Transmission tower

For decades, steel and concrete have been the dominant materials for transmission towers, with well-developed standards and supply chains. However, there is a high environmental footprint due to the transportation of heavy materials and components, among others, with helicopters throughout the entire life cycle of the transmission towers. Efforts have been made to increase interest among representatives of this traditional, linear supply chain to investigate the use of aluminum in transmission towers. Knowledge-sharing activities among industrial actors and researchers have been carried out, focusing on the impacts of lightweight constructions. The lightweight properties of aluminum can significantly improve transportation activities. For instance, the number of deliveries performed by helicopters can be reduced, on-site assembly time with helicopters can be reduced due to easier handling. The aluminum properties of corrosion resistance can additionally reduce the transportation activities of materials and operators due to the low maintenance activities needed. A life cycle analysis was carried out, comparing aluminum towers to standard steel towers over the entire product lifetime (ore mining, material processing, design, production, transportation, construction, maintenance, dismantling, and recycling). The study concluded that the aluminum towers resulted in half the CO2 emissions. Furthermore, the research-based innovation project developed a construction principle with a point of departure in aluminum properties, instead of focusing on steel constructions.

Several prototypes were tested, and a demonstrator of a full-scale transmission tower was built and provided knowledge to move transmission towers toward environmental sustainability.

4.4. Power mast

Power masts in cities or towns are often made from wood and impregnated with creosote. Creosote is poisonous, and in 2001, the European Commission recommended banning its use in industrial applications [27, 28]. Further, woodpeckers damage wood masts, resulting in high-maintenance activities and high costs of maintenance due to power failures.

Cocreation arenas facilitated rethinking the value chain of wooden power masts. The high recovery rate of aluminum provides a basis to create circular value chains and move away from linear ones. Substituting poisonous wooden masts with extruded multifunctional masts of aluminum allows the recapture of the value of used ones. Co-design activities resulted in a new extrusion profile that makes it possible to create a range of products and provide a product family, including lighting mast or charging posts for electric vehicles. Starting with a circular vision allowed the introduction of design and product innovations and provided the opportunity to enter new markets.

4.5. City bench

The construction industry is one of the largest contributors to Europe's carbon footprint and waste [29]. Sustainable product and design innovations are needed to change the construction industry. A cross-disciplinary, cross-organizational collaboration provided a platform to focus on slimmer and lighter construction that reduces energy consumption, CO_2 emission, and maintenance activities. Aluminum was not a suitable material for the reinforcement of concrete structures due to the high alkaline pH corroding aluminum. However, with a good strength-to-weight ratio and increased environmental focus, aluminum became a component worthy of investigation. Joint industrial and academic research efforts resulted in the development of a new type of concrete with a significantly lower alkaline level, resulting in a pH that aluminum can withstand. Further, using aluminum for concrete reinforcement provides design innovation opportunities. Due to aluminum's corrosion-resistance properties, the aluminum structure can be visible and be used as a decorative effect, providing added functionality. In this case study, a city bench was designed and produced to demonstrate the aluminum and concrete combination. The aluminum reinforcement has a hexagonal structure that flushes with the upper surface of the bench. The aluminum structure goes beyond the length of the bench, providing a natural place to store wastebaskets, umbrellas, and so forth.

4.6. Aluminum long-span bridges

Aluminum has been used in bridge structures for decades; however, no significant breakthrough in substituting steel has been achieved. Long-span bridges, in particular, are still mainly made from steel. The advantages of aluminum's properties—its lightweight property, ductility for crashworthiness, formability, corrosion resistance, and visual appearance—have not convinced bridge builders to change bridge construction or the value chain. Not even potential cost savings have had a significant impact on decision-makers in bridge construction. Several bridges are planned for the fjord crossing on the west coast of Norway, concerning the ferry-free E39 program. A project exploring aluminum for the Langenuen suspension bridge, with a span of 1,235 m, showed that the cost of an aluminum alternative, meeting all relevant design criteria, is quite similar to a benchmark steel option. While the aluminum girder bridge itself is slightly more costly, it can offset some of the costs for the main elements of the tower, hangers, and main cables. The strong pressure to improve the environmental footprint is forcing the construction industry to increasingly include environmental impact in the decision-making processes. Workshops across industries and collaboration with research centers reduced the acquisition time of crucial environmental aspects in construction activities and processes. Further, these efforts explore cost savings from lower maintenance activities, structural design innovation for higher appeal, manufacturing design innovation for ease of assembly, and reusability of aluminum alloys.

4.7. Case summary

A summary of the cases highlighting sustainable design and product innovations, sustainability benefits, and knowledge creation and transfer can be found in Table 1.

Table 1. Case summary

Case	Design and product innovation	Sustainability benefits	Enablers for knowledge creation and transfer	Innovation barriers
Electrical Urban Water Shuttle	Passenger vessel with electrical engine and high number of aluminum components	High recovery rate, low manufacturing waste	Cross-disciplinary, cross-organizational collaboration; co-development of ideas; prototyping; testing.	Several components with high innovation risk
Whale Safari Boat	Catamaran with a hybrid engine and aluminum superstructure	Low CO_2 emission with high passenger comfort	Collaborative innovation, close dialogue between designer and project owner, 3D visualization, prototyping	Several components with high innovation risk
Transmission tower	Extruded struts for improved transportation and ease of assembly at high heights	Low CO_2 emission	Cross-disciplinary, cross-organizational collaboration; co-development of ideas; prototyping; testing	Reluctant industry; industrial standards are mainly developed for steel
Power mast	Masts with a large sustainable product family	High recovery rate, low maintenance	Cross-disciplinary, cross-organizational collaboration; workshops; prototyping; testing	Scepticism towards recycled materials; resistance to change
City bench	Aluminum reinforcement structures for concrete and increased functionality	Low CO_2 emission	Cross-disciplinary, cross-organizational collaboration; prototyping	Short project period hinders to investigate long time impacts
Aluminum long-span bridges	Structural design innovation	High recovery rate, low maintenance	Cross-disciplinary, cross-organizational collaboration	Low longtime knowledge of recycled materials in constructions

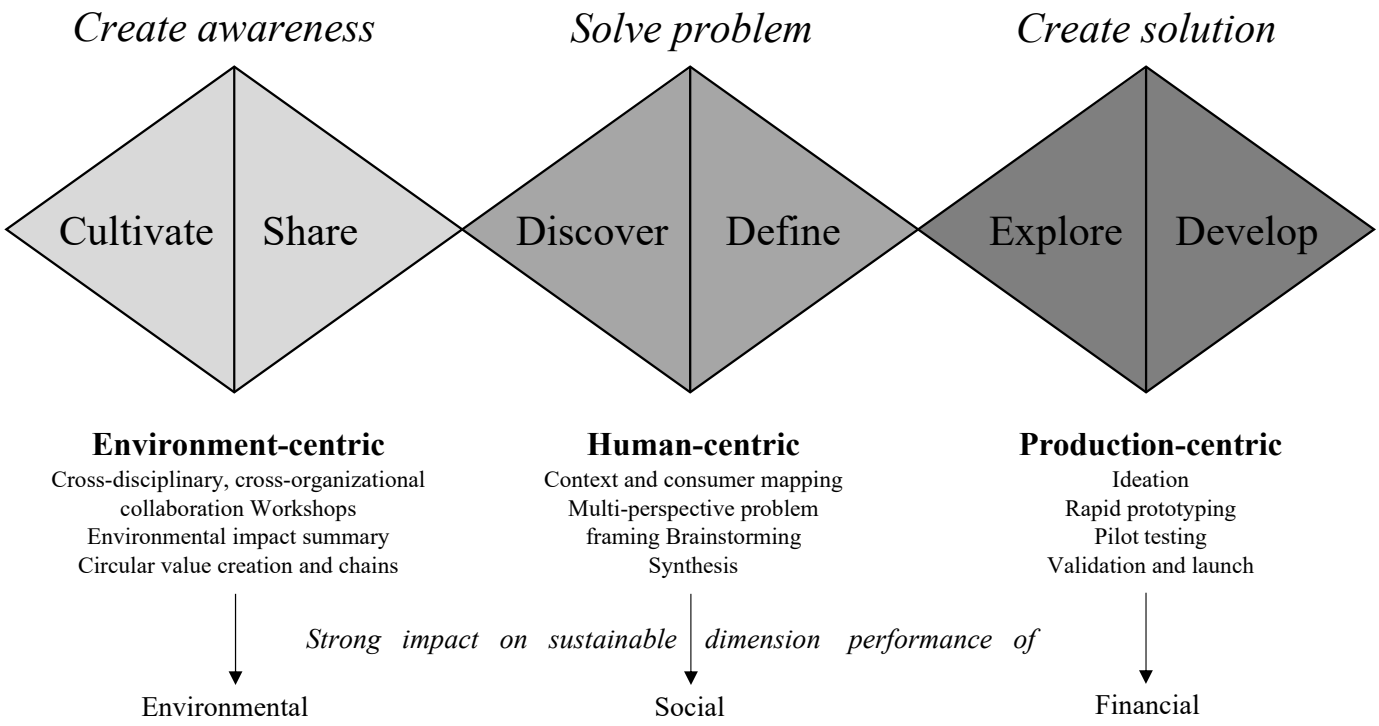

Fig. 1. Sustainable design and product innovation framework

5. Framework

With increasing interest to infuse circularity and have balanced environmental, social, and financial sustainability in product innovation processes, both industry and academia are seeking to introduce new or enhanced approaches. The case studies presented demonstrate that cross-disciplinary, cross-organizational collaborations are highly valuable in cultivating knowledge for sustainability and value creation in the aluminum industry. Substituting traditional material supply chains with sustainable ones is often criticized or considered with skepticism. Therefore, it is important to create an awareness of circular value chains and sustainability for decision-makers, sharing insights and co-developing knowledge and solutions focusing on sustainability and value creation. Furthermore, environmental analyses, such as life cycle assessment, of initial supply chains can quantify potential environmental impact.

By analyzing the case studies in terms of benefits, enablers, and barriers, a pattern of sustainable design and product innovation approach could be identified. The traditional approach focuses on solving problems and creating solutions with a human or production-centric perspective. The case studies highlight that it is crucial to create awareness with an environment-centric focus. This can be established by cultivating and sharing knowledge about circular value creation and sustainable value chains. Some of the case studies emphasize aluminum as a recycle-friendly material, making it a suitable material in a circular economy. Cross-disciplinary, cross-organizational collaborations supported providing the input of lessons learned and instructive insights. Workshops and cocreation arenas supported to focus on specific markets. As a result, this study has extended the Double Diamond design process with an increased focus on environmental sustainability and hence provided balanced sustainable performance in the design and product innovation process. The insights of the multiple case study supported the development and introduction of a framework for sustainable design and product innovation (Fig. 1).

6. Discussion and conclusion

The UN Sustainable Development Goals were launched in 2015, covering environmental, economic, and social sustainability. The circular economy is seen as a promising tool for sustainability by reducing, reusing, recycling, and recovering materials [30]. However, in manufacturing, a clear link between a circular economy and the triple bottom line in sustainability is missing [31]. Indeed, the linear pattern of “take-make-use-dispose” does not provide producers with sufficient incentives to make their products more circular. According to the European Commission, 80% of products’ environmental impacts are determined in the early stages of the design or innovation process [32, 33]. Concerning sustainability impact, the triple bottom line is suggested as a lens to turn the focus on aluminum processing—starting with an environmental perspective (in which is the largest impact) and moving toward human-centric aspects (fulfilling needs in society), and finally, the economic aspects (securing efficient value chains).

The case studies presented started with establishing a basis for sustainable aluminum innovation and focused on building the next design approaches and product development. The aluminum industry has, for many years, invested and put great effort into improving reverse logistics. However, this knowledge is often concentrated in the different actors in the supply chain. Cultivating knowledge through cross-

disciplinary, cross-organizational collaboration and sharing knowledge in workshop and cocreation arenas has significantly contributed to creating circular value chains. This approach has helped the aluminum industry to introduce sustainable design and product innovations.

The case studies revealed that traditional methods need to be further evolved. The introduced framework for sustainable design and product innovations builds on the triple bottom line approach and greatly improves environmental performance, potentially supporting a shift toward a circular economy.

Future research should investigate the applicability of the introduced framework in other industries. Further, guidelines for workshops and cocreation arenas with an environment-centric focus should be developed.

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