

# Modularity for circular economy: Four circularity pathways for industrial firms

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## ABSTRACT

Transitioning toward improved circularity is a complex challenge for industrial firms, where modularity is emerging as a promising strategic approach. Although modularity has been acknowledged in prior circularity research, the current understanding of the specific practices industrial firms can adopt and the corresponding capabilities they must build to support modularity is limited. Addressing these gaps, this study adopts a multiple case study with data from 47 informants in 11 Southeast Asian power sector firms and their ecosystem partners. The analysis identifies two modular strategic orientations: traditional modularity architectures and complex modularity practices. It also identifies two capability-building approaches named: internally driven capability development and ecosystem-enabled capability enhancement. By examining the interlinkages among these, we propose a framework comprising four circularity pathways, modularity innovation pathway, alliance-driven pathway, organizational embedding pathway and circular leadership pathway, that offer novel insights into how varying configurations shape circular benefit realization. These findings contribute to circular economy literature by conceptualizing modularity as a strategic orientation and articulating how diverse pathways support circular transformation. It further extends modularity research by linking it to capability building and circular benefits beyond traditional operational domains. The study offers actionable managerial implications for managers engaged with circularity, sustainability and operations in traditional industrial firms seeking improved circular benefits.

## 1. Introduction

In response to the call to intensify efforts to achieve the UN 2030 Agenda of Sustainable Development Goals (SDGs) (United Nations, 2015), traditional industrial firms are seeking ways to embrace circular economy (CE) to improve business performance, comply with regulations and create positive externalities (Santa-Maria et al., 2022). The CE has emerged as perhaps the dominant frame or “paradigm” for improving sustainability because it helps to realize a net-zero and climate-resilient economy by minimizing waste, promoting resource efficiency, and fostering sustainable production and consumption (Haque et al., 2024). During this transformative journey, traditional industrial firms often face significant challenges to improve circular benefits (Santa-Maria et al., 2022). By circular benefit we mean, the positive outcomes for firms adopting circular economy practices,

categorized under economic, environmental, and social dimensions (Rosa et al., 2019). Traditional industry refers to energy-intensive firms with high resource consumption and significant environmental impact. These firms often operate under entrenched linear models, characterized by a “take-make-dispose” logic, that deprioritize sustainability (Frishammar et al., 2025; Santa-Maria et al., 2022). Their size and structural complexity further complicate the swift adoption of circular principles, making transitions challenging (Frishammar et al., 2025). Additionally, firms from traditional industries seldom sell to end customers, being situated in supply chains with multiple actors and stakeholders, which can also create inertia (Amir et al., 2023). Combined, a cap is often placed on both the speed and scope by which circular benefits can be improved (Frishammar and Parida, 2019).

Improving circular benefits necessitates trying out strategic orientations, which means comprehensive approaches that defines how a firm

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plan to achieve its long-term goals and maintain a competitive edge (Bocken et al., 2016). Developing specific strategic orientations, for example digital transformation (Giganti et al., 2024), lifecycle extension (Santa-Maria et al., 2022), closed-loop supply chain (Amir et al., 2023), as examples of circular practices have become advantageous for industrial firms (Quttainah et al., 2025).

Against this backdrop, modularity emerges as a novel and underexplored strategic orientation with the potential to consolidate and amplify the benefits of previously studied circular strategies. While modularity has been defined as a “strategy for organizing complex products and processes efficiently,” with emphasis on independence, similarity, and standardization (Gershenson et al., 2003, p. 300), its full potential in supporting circular transitions remains insufficiently theorized. Although recent studies have begun to recognize modularity as a driver of circular benefits (Romano et al., 2023), most discussions are still fragmented and lack empirical depth. Much of the existing work focuses on product-level modularity, such as enhancing disassembly and repair (Baldwin and Clark, 1997; Mertens et al., 2023), without sufficiently addressing how modular thinking can shape operational and organizational design. Likewise, while examples such as modular solar panel systems or modularized maintenance in power generation illustrate practical circular gains (Zhuang et al., 2023), systematic frameworks that connect modularity with capability-building in traditional industries are lacking. Given the high degree of specialization in such firms (Simms & Frishammar, 2024), the potential for experimenting with modular configurations and complementing capabilities remains an important, yet underexplored, research avenue.

In this context, the purpose of this study is to explore what types of modular strategic orientations traditional industries need to adopt for enhancing circular benefits, and how they can build the corresponding capabilities. Our study contributes to the existing literature on the CE and modularity, addressing three gaps. First, our study broadens the CE literature by positioning modularity as a strategic orientation for improving circular benefits. While several studies identify circular practices such as slowing, closing, and narrowing resource loops (Bocken et al., 2016), modularity is typically treated as an operational concept focused on efficiency in product and process design (Campagnolo and Camuffo, 2010; Huikkola et al., 2022; Machado and Morioka, 2021). Our study departs from this view by exploring how modularity, when elevated to a strategic level, can guide traditional industrial firms toward organizational transformation for circular benefits. Although prior conceptual work has linked modularity to CE (Clemente et al., 2019; Machado and Morioka, 2021), empirical research remains limited. Second, while capability-building is acknowledged as key to circular transitions (Parida et al., 2019; Santa-Maria et al., 2022), we extend this discourse by identifying how modular capability-building unfolds internally and through collaboration. This includes innovation in modular design and leveraging ecosystem partners to access complementary knowledge (Antonio et al., 2009). Third, addressing the fragmented and slow adoption of CE (Quttainah et al., 2025), we propose four actionable pathways that integrate modular orientations with specific capability-building approaches for realizing circular benefits. The paper is structured as follows: section 2 provides the theoretical background, section 3 outlines the research methods, section 4 presents findings and discusses the framework, and section 5 presents the implications. Finally, section 6 considers the study’s limitations and future scope.

## 2. Theoretical background

### 2.1. Circular economy implementation among industrial firms

Firms in traditional industries operate under distinct dynamics and face unique challenges in navigating sustainability transitions (Frishammar et al., 2025). While advancements in manufacturing have enabled mass production, greater product availability, and cost

efficiency, they have also intensified emissions, waste generation, and environmental degradation (Parida et al., 2019). With natural resources being finite, these firms increasingly contend with risks related to resource scarcity, price volatility, and tightening environmental regulations (Quttainah et al., 2025). Scholars have, therefore, called for deeper insight into how firms practically implement CE principles (Frishammar et al., 2025).

The CE concept, rooted in Pearce and Turner’s (1990) work, emphasizes the cyclical interrelationship between resource use and waste reduction. It promotes a make-remake-use-return logic aimed at minimizing resource inputs and outputs through a systems-oriented approach (Ellen MacArthur Foundation, 2013). For industrial firms, CE offers a pathway to close material loops and narrow resource flows, applying the 3Rs: reduce, reuse, and recycle (Frishammar et al., 2025). CE initially focused on waste management but has since expanded to address energy efficiency, product longevity, service life, and new business model configurations (Nian et al., 2022).

To overcome implementation challenges, firms must develop and deploy adequate capabilities (Falcone and Fiorentino, 2025). From a capability perspective, firms adapt to dynamic environments by reconfiguring routines to sense, seize, and transform in response to emerging opportunities and threats (Teece, 2007; Zhuang et al., 2023). These capabilities are critical for fostering organizational change and driving circular transitions (Santa-Maria et al., 2022). Beyond their existing internal capabilities (Huikkola et al., 2022), traditional firms require access to ecosystem capabilities to enable innovation, enhance profitability, and deliver circular benefits (Frishammar and Parida, 2019; Giganti et al., 2025). These external capabilities are often developed via collaboration with suppliers, service providers, and customers, forming the backbone of effective circularity initiatives (Amir et al., 2023). However, as Giganti et al. (2025) highlight, these ecosystem dynamics are shaped by institutional quality and digital coordination mechanisms, which influence how such capabilities are accessed and integrated. There is no universal approach, therefore, firms must tailor their capability-building efforts to their specific modular strategies.

Although the literature recognizes the dual importance of internal and external capabilities, it lacks clarity on how firms actually cultivate, access, and operationalize these capabilities in practice (Falcone and Tutore, 2025). Moreover, as Falcone and Fiorentino (2025) suggest, while connections between circular benefits and capability are acknowledged, we still lack insights into the capability-building approaches that support modularity as a strategic enabler of CE. Together, these contributions underscore the need to study how traditional firms configure modularity and capability-building approaches remain largely unexplored.

### 2.2. The role of modularity as a strategic orientation to improve circular benefits

Traditional firms are increasingly strategizing to transform their businesses in accordance with circular parameters (Giganti et al., 2024; Santa-Maria et al., 2022). Modularity principles promote interchangeability and flexibility, thus supporting circular benefits such as recyclability, maintainability, upgradability, and reusability (Mignacca et al., 2020). The concept of modularity is grounded in the idea of modules, defined as “physical or conceptual groupings of components that share some characteristics” (Campagnolo and Camuffo, 2010), which function as cooperative sub-systems within product and operational designs.

Prior literature illuminates several benefits of adopting a modular strategic orientation for circular benefits. Components in traditional industries can be designed to be structurally independent yet interoperable (Mertens et al., 2023). For instance, power electronic converters (PEC) become more amenable to reuse, repair, or replacement through modular design (Romano et al., 2023). This approach enhances material recovery, reusability, and recyclability (Zhuang et al., 2023), supporting

the circular strategies of narrowing, slowing, and closing loops (Machado and Morioka, 2021).

Moreover, integrating digitalization into operational design, like traceability and data-sharing mechanisms, can further support these modular strategies, particularly in managing product lifecycles and value retention (Giganti et al., 2024). In parallel, aligning modular initiatives with internal governance routines and performance metrics allows firms to institutionalize circular benefits more effectively. It also allows the fostering of behavioral alignment for sustainability transitions (Falcone and Fiorentino, 2025) and allow firms to “redesign their internal organization” (Baldwin and Clark, 1997, p. 91; Campagnolo and Camuffo, 2010).

While modularity appears closely linked to capability development, few studies have systematically theorized this connection. For instance, Spanellis et al. (2021) explored the relationship between modularity and dynamic capabilities in the service sector, focusing on IT management and knowledge interventions for sustainability (Shen et al., 2024; Roy

et al., 2023). In manufacturing, Antonio et al. (2009) examined how design modularity and internal integration influence competitive capabilities such as product innovativeness, quality, delivery, and flexibility, highlighting how modularity supports sustainable advantages in dynamic production contexts.

Despite these insights, the specific relationship between modularity and capabilities in achieving circular benefits remains underexplored (Panda et al., 2025). It is likely that traditional industrial firms adopt different combinations of modular strategies and capability-building approaches, both internal and ecosystem-driven, to meet circular objectives. The selection of modular orientations is often shaped by the availability of internal resources and existing capabilities (Nian et al., 2022). Increasingly, firms are turning to network-enabled capabilities through ecosystem collaboration to overcome resource constraints and embed circular benefits more effectively (Huikkola et al., 2022), thereby supporting their long-term competitiveness and sustainability goals.

In summary, we assume that the extent to which circular benefits can

**Table 1**  
Details of respondents for in-depth interviews.

Country	Firm	Standard Industrial Classification	Sector (Type)	Capacity	No. of employees	Total no. of respondents	Designation of respondents (experience in years)	Duration of interview -in minutes approximately (round)
India	A	NIC (2008)40	Public (Power generation)	6450+ MW: thermal, hydro, solar and wind power	1600+	3	Senior Operating Officer (19), Senior Executive SE (System Engineering) (5), Plant Manager (18)	57 (R1), 43 (R2), 52 (R3)
India	B	NIC (2008)40	Private (Power generation, transmission, distribution)	13,900+ MW: thermal, hydro and renewable power	21500+	5	Senior Executive Engineer (21), Module Team Leader (6), Senior Distribution Manager (11), Operations Lead (19), Senior Strategic Analyst (9)	27 (R1), 56 (R1), 53 (R2), 30 (R2), 57 (R3)
India	C	NIC (2008)40	Private (Power Generation)	16000+ MW: thermal, hydro and wind power	3100+	5	Sustainability Officer (6), Power Plant Specialist (4), Area Maintenance Manager (11), Senior Sustainability Officer (10), Head – Business Development and Growth (21)	60 (R1), 29 (R2), 23 (R2), 37 (R2), 50 (R3)
India	D	NIC (2008)40	Public (Power Generation)	8200+ MW: hydro, thermal and solar power	6000+	3	Regional Manager – Transmission & Distribution (10), Offshore Business Strategy Expert (9), Area Maintenance Manager (8)	28 (R1), 45 (R2), 58 (R3)
India	E	NIC (2008)40	Public (Power transmission)	3500+ transformers and reactors, 290,000+ transmission towers, 174100 circuit km transmission lines	8000+	4	Operations Lead (10), Plant Head (7), Area Lead-Renewables (10), Regional Generation Manager (9)	53 (R1), 37 (R1), 50 (R2), 50 (R3)
India	F	NIC (2008)40	Private (Renewable energy generation -solar, small hydro, biogas, biomass, waste-to-energy)	5300+ MW thermal power	3550+	2	Project Manager (10), Senior Business System Analyst (16)	52 (R1), 37 (R2)
Malaysia	G	MSIC (2008) 351	Private (Power generation)	2200+ MW: coal-fired thermal and solar power	4000+	2	Senior Manager –Generation (8), Director – Projects (7)	52 (R1), 37 (R2)
Malaysia	H	MSIC (2008) 351	Public (Power generation)	3400+ MW: renewable power	2000+	1	Senior Strategic Advisor (18)	33 (R1)
Indonesia	I	KBLI (2020) 35115	Private (Power distribution)	20,000 km of power distribution lines	22000+	3	Senior Energy Advisor (5), Business Head –Power Projects (12), Area Executive Engineer (20)	30 (R1), 42 (R3), 21 (R3)
Indonesia	J	KBLI (2020) 35115	Private (Power generation)	9200+ MW hydro, solar and thermal power	4000+	1	Advisor – Power Projects (16)	55 (R1)
Philippines	K	PSIC (2008) 351	Public (Renewable energy generation)	8600+ MW: wind and solar power	800+	0	NA	NA

SIC: Standard Industrial Classification, NIC: National Industrial Classification, MSIC: Malaysia Standard Industrial Classification, KBLI: Klasifikasi Baku Lapangan Usaha Indonesia, PSIC: Philippine Standard Industrial Classification.

be achieved is partly contingent on how traditional firms utilize capability-building approaches along with modular strategic orientations. Based on the literature review, we mobilize the concepts of capability-building approaches (internal and external) along with modularity (product, process, or at the organizational level) and use these as sensitizing concepts to guide our multiple case study, to which we turn next.

### 3. Research methods

#### 3.1. Research approach and empirical setting

To explore how modularity contributes to improving circular benefits, we employed an exploratory multiple case study. Case studies are particularly suitable for examining complex, contemporary processes in real-world settings (Quttainah et al., 2025) and are well-suited for theory development, especially in underexplored domains (Eisenhardt, 2021). This approach aligns with our focus on traditional industrial firms in the power sector adopting modular strategies to enhance circular benefits.

Our sample includes 11 power sector firms and 5 ecosystem partners across Southeast Asia (see Table 1), enabling rich, context-specific insights. We selected the power sector for its strategic relevance to circular transitions in the Global South. As one of the most energy-intensive sectors, it contributes approximately 35 % of global and 40 % of Southeast Asia's GHG emissions (IEA, 2023; Fallin et al., 2023). This environmental burden, coupled with rising regulatory pressures and sustainability commitments in countries like India, Malaysia, Indonesia, and the Philippines (Kuah and Wang, 2020), makes the sector a prime candidate for modular experimentation aimed at reducing waste and extending asset lifecycles (Hossain et al., 2022; Nian et al., 2022).

To guide our case selection, we applied three screening criteria. First, we prioritized firms with large installed generation capacity and ongoing reliance on fossil fuels (Chen and Mauzerall, 2021). Second, we selected firms with publicly documented modular circular practices, as evidenced through websites, sustainability disclosures, or public reports. Third, we included firms that were actively involved in regional collaboration platforms such as the ASEAN Power Grid and BIMSTEC Energy Initiatives, which reflect emerging interdependencies in infrastructure and energy governance (ERIA, 2024).

We began with Indian firms due to their regional scale, institutional visibility, and early experimentation with modular approaches. As of January 2025, India's installed power capacity stands at 466.26 GW (Rao, 2025), positioning Indian firms as technological benchmarks across Southeast Asia. Initial access was facilitated through pre-existing author networks and ongoing collaborations with Indian institutions. Moreover, many Indian firms participate in cross-border infrastructure and policy initiatives, providing a strategic lens to examine how modularity and circular benefits diffuse regionally (Setyawati and Nadhila, 2024).

While Indian firms contributed valuable insights into internal capability-building and modular integration, they demonstrated relatively limited engagement in inter-firm collaboration and community-level initiatives (Kapoor, 2023). To capture a broader perspective, we therefore included firms from Malaysia, Indonesia, and the Philippines. These firms offered complementary practices, such as public-private partnerships, ecosystem-enabled capability enhancement, and structured knowledge-sharing platforms (Giganti et al., 2025; Falcone and Tutore, 2025), which are less prevalent in Indian firms but vital for systemic circular transitions. Aligned with case study logic (Eisenhardt, 2021), we ensured within-sample variation by selecting public and private firms, covering value chain segments (generation, transmission, distribution), and capturing firms at different stages of modularity adoption. For example, Firm A had recently initiated modular pilot projects, Firm B was refocusing after limited past experience, and Firms C and D had implemented modular systems but faced scaling challenges.

This diversity enabled us to trace varied trajectories and challenges in aligning modular strategies with circular goals.

#### 3.2. Data collection

The data were primarily collected in two steps; individual interviews first, followed by focus group discussions with participants who were senior and top managers involved in making decisions related to circular and sustainable initiatives. Individual interviews were conducted from March 2021 to May 2022, followed by focus group discussions from September 2022 to March 2023.

We have collected data from 47 respondents through in-depth interviews and focus group discussions. We developed a semi-structured interview guide (see appendix) and interviewed 29 respondents. This format allowed us to explore aspects like modular architecture and capability building in depth, while also giving respondents the freedom to elaborate on topics of particular interest or expertise (Lobe and Morgan, 2021). The initial interview guide was developed based on themes from the literature on modularity, CE, and capability building (Campagnolo and Camuffo, 2010; Agrawal et al., 2021; Clemente et al., 2019). Following the iterative nature of data analysis, we continuously refined the interview guide as new information and themes emerged (Haque and Panda, 2024; Panda et al., 2024). This approach allowed us to begin analysis while still collecting data, ensuring the guide evolved to capture product and process modularity as well as capability-building activities. Initially we contacted the sustainability managers at each firm for an interview. They were asked to suggest another 2 to 3 key informants for subsequent interviews. A total of three rounds of interviews were conducted (See Table 1). All interviews were recorded and transcribed verbatim. Strict measures were implemented to safeguard participant confidentiality, retaining only essential information from the transcripts.

We conducted four focus groups, with 16 informants in the first 3 groups and 10 in the fourth (see Table 2). Eight participants from the first 3 focus groups, including 3 ecosystem partners, joined the fourth focus group based on their expertise. Focus groups, conducted after the in-depth interviews, served to validate and deepen the insights gathered during earlier stages. They facilitated cross-learning among participants and enabled the testing of emerging themes, ensuring the capture of diverse perspectives and enhancing the overall validity and reliability of findings. This iterative engagement process added robustness to the study. Participants selected for focus groups were those who had been especially engaged and insightful during interviews. Instead of rigidly structured questions, we used semi-structured prompts drawn from prior insights, for example: "Can you discuss how your company practices product and process modularity to enhance circular benefits?" or "How does your firm communicate modularity initiatives to internal and external stakeholders?" While the discussions were guided by these prompts, they remained largely respondent-led, with the facilitator's role limited to ensuring thematic continuity. Multiple sessions were necessary to explore and cross-validate all key themes. The final two focus groups served to validate the study's emerging findings. Additionally, data triangulation was applied through secondary sources such as websites, reports, and archived documents (Bans-Akutey and Tiimub, 2021). For instance, Firm A's mention of GaBits software was substantiated in its annual report, while Firm B's reference to smart-grid technologies was confirmed through reported performance improvements.

#### 3.3. Data analysis

The data analysis followed a thematic approach, as outlined by Braun and Clarke (2006), to identify patterns in the data while ensuring empirical accuracy. The process unfolded across six iterative phases: familiarization, initial coding, theme identification, theme review, refinement, and reporting. MAXQDA software was used to efficiently manage codes, quotations, and data segments. The research team began

**Table 2**  
Details of the respondents in focus group studies.

Rounds	Total no. of respondents	Firms	Designation of respondents (experience in years)	Duration of interview (in minutes) approx.
First Focus Group	5	F, G, H, J, K	Senior Staff Engineer (6), Senior Technical Engineer (7), Sustainability Consultant (9), Region Project Manager (11), Plant Manager – Head (17)	60
Second Focus Group	7	A, B, F, G, H, K, EP1: Battery manufacturer	Senior Staff Engineer (6), Senior Power Electronics Design Engineer (8), Senior Technical Engineer (7), Sustainability Consultant (9), Engineering Head (10), Region Project Manager (11), Divisional Head (11)	85
Third Focus Group (For validation)	4	A, B, EP2: Startup: Solar panel manufacturer, EP3: Cement industry	Senior Power Electronics Design Engineer (8), Engineering Head (10), CEO and Founder (7), Project Manager (4)	45
Fourth Focus Group (For validation)	10	A, D, E, F, K, EP1: Battery manufacturer, EP2: Startup: Solar panel manufacturer, EP3: Cement industry, EP4: Steel manufacturer, EP5: Principal financial institution	Senior Staff Engineer (6), Senior Technical Engineer (7), Area Sustainability Consultant (4), Senior Technical Engineer (7), Region Project Manager (11), Divisional Head (11), CEO and Founder (7), Project Manager (4), Engineer (3), Assistant Manager (5)	60

EP: ecosystem partner.

by reading transcripts and listening to audio recordings, capturing initial insights and notable patterns. The first stage involved open coding, resulting in descriptive first-order codes that reflected the essence of firms' modularity practices and associated capability-building efforts. For example, enhancing the efficiency and lifespan of underperforming assets through process modularity was one such activity.

In the second stage, these codes were grouped into second-order themes, such as "traditional modularity architectures," which encapsulate product and process modularity activities. These themes were then collapsed into aggregate dimensions, including "modular strategic orientations." To structure this process, we followed the Gioia methodology (Gioia et al., 2013), which visually maps the progression from first-order codes to second-order themes and aggregate dimensions.

The analysis remained iterative throughout the study, evolving with the emergence of new insights. We drew on relevant literature on modularity and capabilities (Mignacca et al., 2020; Machado and Morioka, 2021; Huikkola et al., 2022) to ground our themes theoretically and align them with empirical observations. Multiple researchers participated in the analysis to enhance rigor, with discrepancies addressed through iterative discussion and reconciliation (Miles et al., 2014). Additionally, focus groups were conducted to validate the coding structure, refine thematic boundaries, and ensure that the final themes accurately captured the multidimensional nature of the data (Panda et al., 2022). The overall research process and methodological flow are summarized in Fig. 1.

## 4. Findings and discussion

This section describes how traditional industrial firms achieve circular benefits by utilizing modularity as a strategic orientation and various capability-building approaches (Refer to Fig. 2). Following the coding structure's order of aggregate dimensions, the findings of the research are presented below.

### 4.1. Modular strategic orientations

Our sample industrial firms confirmed that they adopted modularity in two distinct yet complementary categories: traditional modularity architecture and complex modularity practices. The concept of traditional modularity architecture encompasses both product and process modularity. Product modularity involves the design of product modules or components, while process modularity enhances operational flexibility and streamline workflows, minimizing disruptions (Lange and Imsdahl, 2013; Zhuang et al., 2023). On the other hand, complex modularity practices are deeply ingrained in the firms' culture, influencing their communication strategies, governance models, and

performance evaluation metrics. Firms embrace these two practices with the aim of redefining their identity as organizations dedicated to sustainability (Falcone and Fiorentino, 2025). This underscores their commitment to eco-friendly practices and adherence to CE principles, emphasizing a holistic approach toward resource efficiency and minimizing environmental impact.

#### 4.1.1. Traditional modularity architectures

Establishing a fundamental understanding of the essential principles of modularity is regarded as the foundational component. Analysis of the data indicated that traditional firms generally initiate their modularity journey by adopting product-process-oriented modularity. This is characterized by a focus on both the **structural and functional independence between modules for product modularity**. Such a strategy helps in the assembly of idiosyncratic products composed of unique but interrelated subsystems. The aspect of independence is pivotal in modularity because it provides the advantages of flexibility, simplicity in replacing or upgrading modules, and system robustness. According to the operations lead in firm B, "The development and installation of mini grids with smart transformers allow single-phase LT voltages to be optimized for local conditions. We designed these systems to be modular, so they can operate independently from the main grid .... each mini grid can autonomously regulate and stabilize its own voltage, ensuring reliability and efficiency, even in remote or isolated areas."

Apart from independence, firms ensured **structural and functional cohesion within modules for product modularity**. Cohesion within modules stipulates how modules interact and work cohesively when assembled into the final product. It is necessary for the product to operate as an integrated whole, ensuring that the intra-module interactions enhance the overall system performance. The area executive engineer of firm I explained, "Our SCADA system, exemplifying structural and functional cohesion within modules, showcases its capabilities. By integrating our Advanced Distribution Management System with SCADA, we've improved our response strategies for power distribution and outages, elevating service reliability. This cohesion is intentional, enabling us to promptly collect and analyze outage reports, ensuring efficient incident resolution. This underscores our commitment to uninterrupted power supply and customer satisfaction". Both practices facilitate circular benefits through repairability and maintenance by reducing waste and improving resource consumption effectiveness.

The next architectural component in the data is process modularity – a technique to achieve flexibility, operational efficiency, and reduced time to market. Most case firms implemented this as an architectural approach combined with product modularity. **Enhancing the efficiency and lifespan of underperforming assets through process modularity** is such an activity mentioned by the respondents. These systems optimize

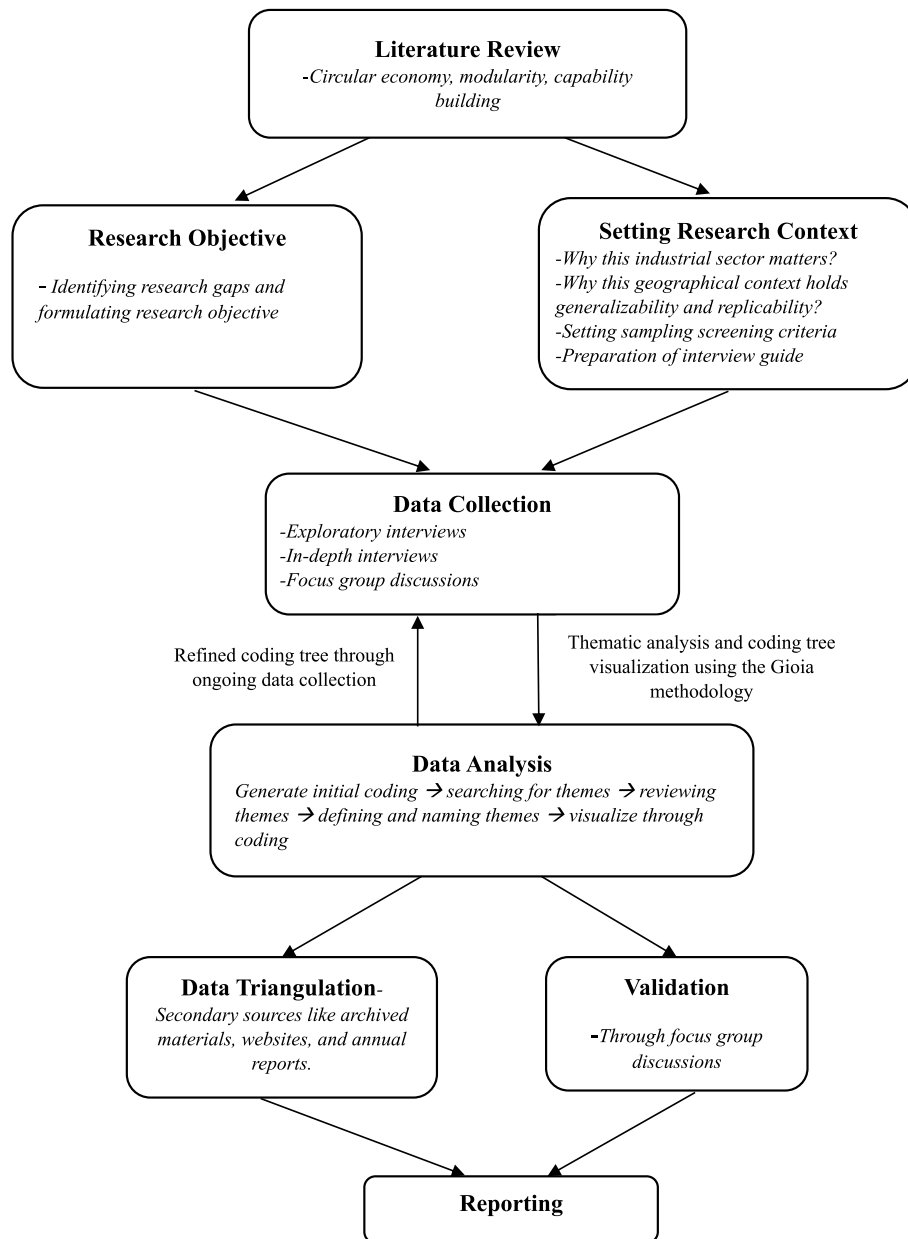


Fig. 1. Research methodology process.

the performance of each modular component, reducing disruptions and enhancing both efficiency and the lifespan of the overall process. According to the technical advisor–head of firm E, “... we have reliability centered maintenance of transmission assets with asset management dashboards and asset health indexing software. It automatically fetches and evaluates, suppose the circuit breaker data, and assigns a health index figure to it based on the extent of deterioration.” This activity adds circular values by minimizing waste, promoting longevity, and optimizing resource usage. Finally, firms discussed the **monitoring and maintenance through advanced analytics for process modularity**. This refers to the use of highly automated technology to track the performance and condition of equipment or systems remotely without a physical presence. The plant manager of firm J commented: “We offer modular practices like the installation of a portable dew point meter in instrument header lines for online dew point monitoring and compressor performance for our ecosystem partners. We have a dedicated power system control centre for complete remote monitoring of the distribution network for any abnormalities and corrective measures to be taken.” Through these business practices, firms achieve

circular benefits by reducing downtime, improving energy efficiency, and enhancing overall operational efficiency.

#### 4.1.2. Complex modularity practices

After achieving product–process modularity, traditional firms seem to prioritize modularity practices. Traditional industrial firms adopting modularity at this level often seek to communicate various modularity approaches, standardize governance, and utilize performance metrics to rebrand themselves as sustainable, circular organizations, strengthening their customer base and conferring competitive advantage (Falcone and Fiorentino, 2025). The first activity firms mentioned was **communication about modularity through annual reports, certifications, and awards**. According to the sustainability consultant of firm F, “It’s not just about the internal gains anymore; it’s about showcasing our commitment to sustainability. This strategic move aligns perfectly with the changing preferences of our stakeholders towards more sustainable and circular solutions.” Certifications, while not directly tied to modularity, signify quality and progress toward circular benefits, indirectly highlighting the benefits of

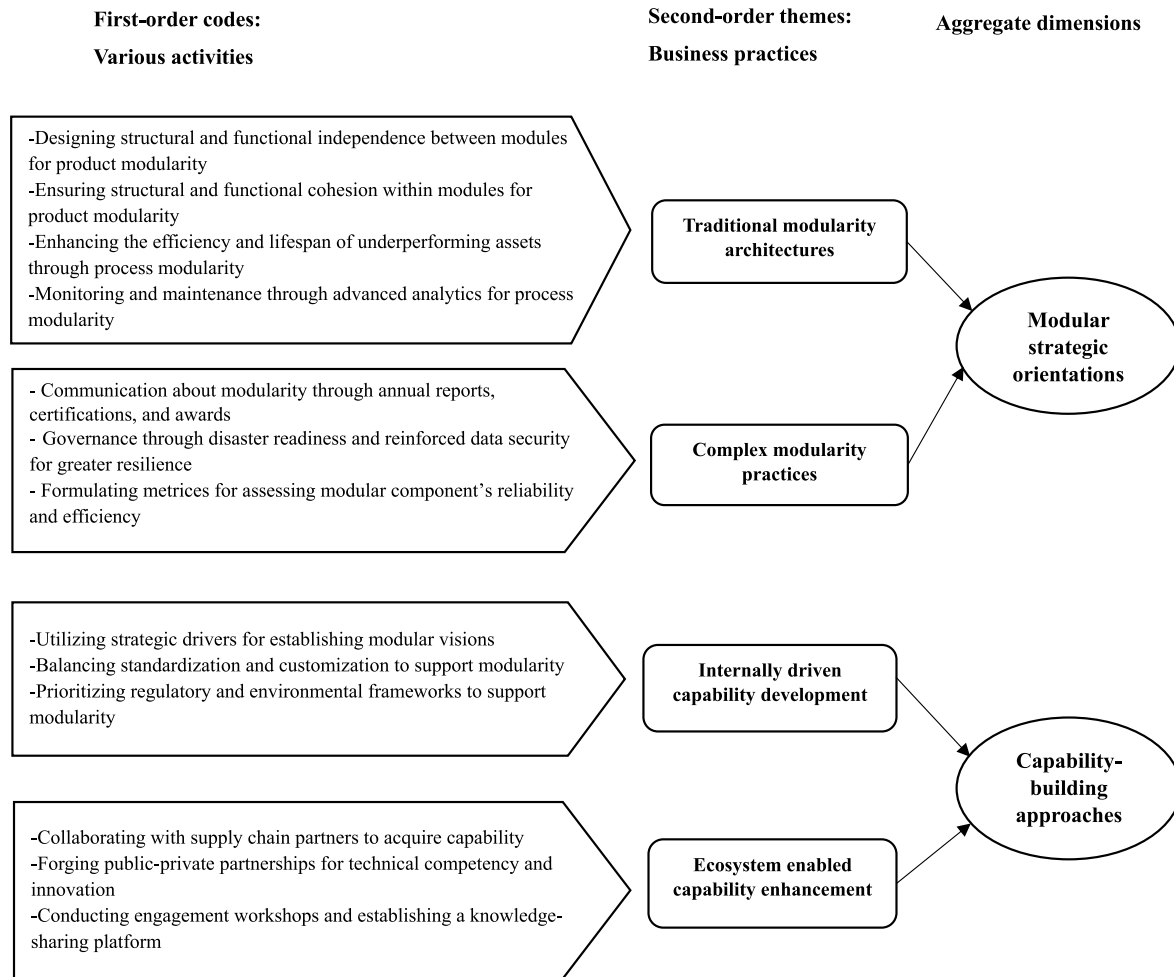


Fig. 2. Coding tree.

modularity. For example, firm A has achieved ISO-9001:2015, ISO 14001:2015, ISO45001:2018, ISO 50001:2018 certifications for maintaining the best quality at manufacturing plants. This initiative signifies the firm's sensitivity to circular endeavors within and beyond the sector, contributing to the establishment of industry leading practices.

The next activity manufacturing firms explored was establishing **governance through disaster readiness and reinforced data security for greater resilience**. By proactively addressing potential disasters and bolstering data security measures, firms minimize disruption and enhance their adaptability. This practice aligns with modularity principles by providing a safety net that enables the smooth functioning of modular components, even in challenging circumstances. It aligns with circular principles by not only safeguarding critical operations but also contributing to the overall sustainability and resilience of the organization faced with unexpected events. The region project manager of firm K explained: *"We take disaster preparedness and data security very seriously ... Our Business Continuity and Disaster Management Plan, certified to ISO 22301:2012 standards ensures that we are well-prepared for any unforeseen events. Our workforce is regularly trained through mock drills and exercises to handle emergency situations effectively ...."* Beside this, many firms highlighted their ongoing practices of **formulating metrics to assess modular component's reliability and efficiency**. These metrics serve as objective benchmarks, enabling traditional firms to fine-tune their modular systems for optimal performance. By consistently measuring these parameters, firms enhance operational reliability, control disruptions, and extend the lifespan of modular components, contributing to CE. The senior business analyst of firm F offered an example: *"We*

*routinely assess various parameters such as boiler efficiency, turbine cycle heat rate, HP heater performance, and more. By continuously optimizing these aspects, we not only enhance the overall efficiency of our modular systems but also contribute to our sustainability goals by reducing resource wastage and operational costs."*

#### 4.2. Capability-building approaches

Traditional firms often embark on a journey to build capabilities for implementing modularity. Some opt for internal resources, focusing on developing in-house expertise to foster modularity practices (Lange and Imsdahl, 2013). Concurrently, firms are exploring the avenue of enhancing capabilities through strategic partnerships within the ecosystem (Mignacca et al., 2020; Romano et al., 2023). This dual approach allows firms to harness their internal strengths while benefiting from external expertise, creating a comprehensive trajectory for successful modularity implementation (Amir et al., 2023). It is a dynamic blend of internal development and external collaboration that propels firms toward modularity excellence.

##### 4.2.1. Internally driven capability development

Our data suggests that traditional firms developed their internal capability through three different activities. The first activity they highlight is **utilization of strategic drivers for establishing modular visions**. For traditional firms, the drivers are the motives for achieving a targeted circular goal by implementing modularity. These drivers reflect a mix of market response and strategic foresight to collectively steer

organizational efforts toward modularity. After summarizing all the responses, three driver types were identified. The first activity firm discusses is customer expectations. “Customers today expect products that can adapt to their changing needs. Modularity allows us to provide that flexibility,” shared the plant manager of firm A. This sentiment aligns with the growing demand for personalized products to which firms respond by increasingly adopting modular designs. The business head – power projects of firm I commented: “We’ve entered an era where the customer is the co-creator of the product ... our modular design strategy directly responds to the growing trend of personalization. Customers want to feel that their product is uniquely theirs, and modularity makes this possible.” Besides customers, firms mentioned manufacturing and circular goal-related expectations. These align with lean manufacturing to swiftly adapt to market demands and handle the pressing need to enhance circular benefits by aiding inventory and schedule management. This enables firms to adjust production volumes with minimal reconfiguration, optimizing time, and resources. A senior business system analyst from firm I stated: “Our commitment to modular design is really about agility and scalability in power generation. It resonates with our lean principles, allowing us to efficiently pivot as market demands shift, and scale operations with ease. This strategic approach has been a cornerstone of our operational resilience and competitiveness.”

In pursuit of modularity, firms often find themselves at the crossroads of standardization and customization. While industry benchmarks and best practices provide valuable guidance, they may not align perfectly with a firm’s unique operational context. **Balancing standardization and customization to support modularity** become paramount as firms strive to develop internal modular capabilities for circular benefits. This delicate equilibrium allows firms to adopt industry standards while making targeted customizations to their processes, ensuring that modularity aligns seamlessly with their specific operational goals. The third business activity to develop modular capabilities that these firms revealed was **prioritizing regulatory and environmental frameworks to support modularity**. It is exemplified by initiatives aimed at compliance with stringent emission regulations. For instance, firm B invested in developing internal capabilities to reduce greenhouse gas emissions to meet environmental standards. Implementation can involve cleaner technologies, process optimizations, and renewable energy integration. By aligning their internal capabilities with regulatory and environmental requirements, such firms not only achieve compliance but also are positioned for greater modularity in their operations, enabling them to adapt to changing environmental standards and market demands. A senior design engineer of firm A explained: “We’ve invested in advanced emission control technologies that comply with stringent environmental regulations while enhancing the modularity of our power generation processes.”

#### 4.2.2. Ecosystem enabled capability enhancement

The industrial firms we studied enhanced their capabilities by means of innovative ecosystems employing three business activities. Firms mentioned that, by **collaborating with supply chain partners to acquire capability**, they can easily integrate inputs from external suppliers and partners into their workflows. This approach to building capabilities improves flexibility, allowing each unit to rapidly adjust to new information or materials. It promotes collective innovation and responsiveness in the supply chain, contributing to the journey toward CE. According to the area lead – renewable of firm E: “Our collaboration with firm A is proof to the power of joint inventory management. It is a type of vendor-managed inventory ... This modularity allows us to focus on core competencies, while this partner ensures module component availability, based on real-time data. They are separate functionalities working synergistically and ensuring correct inventory while guaranteeing uninterrupted power supply.”

The second aspect highlighted was **forging public-private partnerships for technical competency and innovation**. This allows resources and expertise to be shared in a targeted manner, aligning public sector

objectives with the nimble, market-driven approaches of private entities, thus catalyzing innovative solutions to complex challenges. For example, an offshore business strategy expert from firm D stated: “We collaborate with 65 + global technology companies, institutions, and funding agencies to transform the power sector. Our partnership with mostly private entities in the grid resilience coalition is a testament to our commitment to drive excellence in services.” This collaboration enables traditional firms to gain the necessary technological expertise, including advanced analytics, cloud computing, and other emerging technologies, for circular benefits. In addition, we found that many firms are **conducting engagement workshops and establishing a knowledge-sharing platform**. These activities serve as critical nodes in a modular process network, facilitating the dissemination of insights and best practices. For example, senior strategic advisor of firm H mentioned: “In the digital age, our knowledge exchange platforms are dynamic hubs for sharing insights, best practices, and the latest modularity trends in the power sector.” The operations lead from firm B explained it thus: “We sponsor hackathons on modular design concepts regularly to promote innovative ideas from young minds. We also hired brilliant interns from universities and colleges for designing modular products and scale processes to achieve modularity.” For some case study firms, it is a form of consultancy service to help ecosystem partners distribute and transmit energy efficiently. According to senior technical engineer from firm G: “Our modularity workshops and related knowledge dissemination seminars for ecosystem partners to equip teams with the skills and insights needed to harness modularity within the power sector.” Another example is firm B organizing “demand response events” where smart meter and automatic meter readings are adopted to maintain the stability of the power system. This is achieved by reducing or shifting the peak load, which helps consumers to reduce their energy costs. The firm-wise mapping is presented in Table 3.

#### 4.3. Discussion: pathways to improve circular benefits through modularity

Circular benefits include positive environmental, economic, and societal outcomes (Ellen MacArthur Foundation, 2013). However, realizing these benefits in practice requires traditional industrial firms to rethink both strategic orientation and operational structures (Frishammar and Parida, 2019). This shift often demands targeted capability-building—internally and through ecosystem collaboration (Falcone and Tutore, 2025). While prior studies have explored specific circular practices (Agrawal et al., 2021) and capability-building mechanisms (Santa-Maria et al., 2022), limited attention has been given to how modularity and capabilities co-evolve in enabling circular benefits.

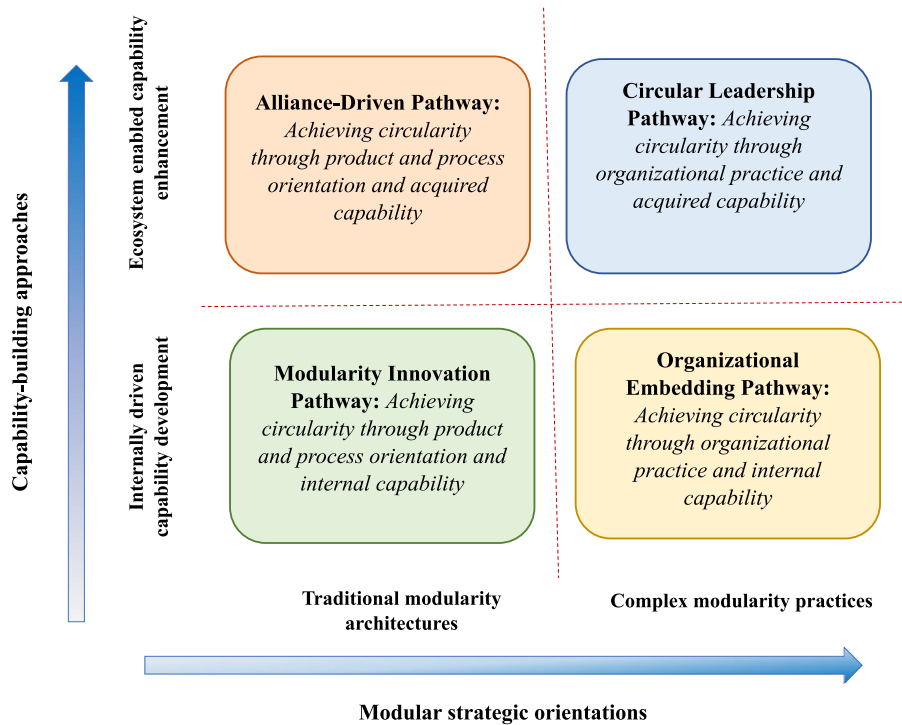
Circular transformation does not follow a linear or one-size-fits-all path (Frishammar et al., 2025). Firms in our study shared the goal of enhancing circular benefits but differed in their modular strategies and capability-building efforts (see Table 3), shaped by their maturity, orientation, and ecosystem access (Santa-Maria et al., 2022). In response, we propose a framework (Fig. 3) outlining four distinct pathways combining modular strategies and capability approaches to explain variation in circular benefit outcomes. By “pathway”, we mean four distinct routes – rather than a step-by-step track – each utilizing unique strategies to incorporate circular benefits into a firm’s operations.

The first pathway, “modularity innovation pathway” was adopted by traditional firms (public firms A, H, K) often in the early stages of their circular transition journey and relied primarily on internal resources to establish modular architectures. These firms implement modular product and process designs to improve reparability, upgradeability, and component reuse. Unlike prior research that assumes modularity is a mature capability (Campagnolo and Camuffo, 2010), our findings show that even novice firms can use modularity as an entry point. However, their efforts typically remain at a component or product level, and the lack of ecosystem support constrains their ability to scale (Hossain et al., 2022). Firms in this category may build a technical foundation but must expand collaboration or internal alignment to deepen their impact.

**Table 3**  
Firm wise mapping between modular approaches and capability approaches.

Aggregate dimensions	Second-order themes	First-order codes	A	B	C	D	E	F	G	H	I	J	K	
Modular strategic orientations	Traditional modularity architectures	Designing structural and functional independence between modules for product modularity	+	+	+	+	+	+	+	+	+	+	+	
		Ensuring structural and functional cohesion within modules for product modularity	+	+	+	+	+	+	+	+	+	+	+	
		Enhancing the efficiency and lifespan of underperforming assets through process modularity	+		+	+	+	+	+	+	+		+	+
	Complex modularity practices	Monitoring and maintenance through advanced analytics for process modularity	+		+	+	+	+	+	+	+		+	+
		Communication about modularity through annual reports, certifications, and awards	-	+		-	-	+	+	-	+	+	-	
		Governance through disaster readiness and reinforced data security for greater resilience related to modularity	-	+	-	-	-	+	+	-	+	+	-	
Capability-building approaches	Internally driven capability development	Formulating metrics for assessing modular component's reliability and efficiency	-	+	-	-		+	+	-	+		-	
		Utilizing strategic drivers for establishing modular visions	+	+		+	+			+	+		+	
		Balancing standardization vs. customization to support modularity	+	+	+	-	-			-	+	+	-	+
	Ecosystemenabled capability enhancement	Prioritizing regulatory and environmental frameworks to support modularity	+	+	+	-	-	-	-	+	+	-	+	
		Collaborating with supply chain partners to acquire capability	-	-	-	+	+	+	+	-	-	-	+	-
		Forging public-private partnerships for technical competency and innovation	-	-	-	+	+	+	+	-	-	-	+	-
		Conducting engagement workshops and establishing a knowledge-sharing platform	-	-		+	+	+	+	-	+	-		

Note: “+” indicates the practice was present, “-” indicates the practice was informed as absent, and blank spaces indicate practice could have been present or absent, though not concludable with available data.



**Fig. 3.** Modularity pathways to improve circular benefits.

The second pathway, “*alliance-driven pathway*”, was followed by traditional firms like public firms D, E, aim to develop modularity by strategically engaging with ecosystem partners. These firms often lack advanced in-house capabilities but compensate by collaborating with suppliers, consultancies, or research institutes to co-develop modular solutions. Their approach aligns with studies highlighting the growing relevance of external capability acquisition in circular transition

(Giganti et al., 2024). Unlike the previous pathway, this pathway recognizes that modularity is not just a design challenge but also a networked capability. Through alliances, they are able to embed modularity principles into broader system design and value chain coordination. While firm’s maturity in modularity may still be evolving, their ecosystem orientation accelerates circular benefits, particularly when internal capabilities alone are insufficient (Huikkola et al., 2022).

The third pathway, “*organizational embedding pathway*” was pursued by private firms B, I with advanced internal capabilities and established modularity architectures. These firms have historically embedded product-process modularity and are now formalizing their approaches through internal KPIs, roadmaps, and organizational routines. This reflects a shift from ad hoc to institutionalized circular practices and corresponds to Miguel’s (2005) call for systematic performance metrics in modularity strategy. Unlike earlier stages where modularity is primarily technical, these firms use modularity design as a strategic logic that informs decision-making across functions. They often serve as benchmarks for other firms, similar to the “mimicry” logic proposed by Frishammar and Parida (2019), where industry laggards emulate the standardized practices of frontrunners. This pathway focuses on internally driven but outward-looking approach, shaping circular narratives within and beyond their sector.

Finally, some firms (private firms C, F, G, J) followed the fourth pathway, “*circular leadership pathway*” to combine internal modular maturity with advanced ecosystem collaboration for integrating modularity into core organizational practices. These firms not only co-develop modularity solutions with partners, but also embed modular thinking into governance, capability planning, and sustainability reporting. They operate with a dual orientation: drawing on external expertise while aligning circular benefits with internal processes. This group extends the notion of capability orchestration (Falcone and Tutore, 2025) and positions modularity not merely as a product design tool but as a platform for systemic innovation. Their ability to boost circular benefits lies in the integration of both architecture and governance, building on findings by Machado and Morioka (2021) that link modularity to long-term CE strategies such as slowing, narrowing, and closing resource loops.

Altogether, the four pathways provide a nuanced understanding of how industrial firms advance toward circular benefits. Rather than serving as a fixed maturity model, the framework reflects the fluidity with which firms can shift between pathways—responding to learning, technological change, or evolving partnerships. Each pathway illustrates a viable route to CE transition by combining internal development and ecosystem collaboration in different ways. While grounded in the power sector, the framework is applicable across various industrial contexts where aligning design, operations, and innovation with sustainability goals is essential. Importantly, the framework offers academic and managerial value by clarifying the interdependence between modular strategic orientations and capability-building approaches. Firms can use this framework as a flexible guide to assess their position, identify capability gaps, and choose strategic levers—such as KPI alignment or external partnerships—to enhance circular benefits.

## 5. Implications and conclusion

### 5.1. Theoretical contributions

The theoretical contribution of this study is multifold. Firstly, we advance CE literature by highlighting modularity as a strategic orientation for circular benefit realization. While previous studies have emphasized circular strategies like slowing, closing, and narrowing (Bocken et al., 2016) and practices such as leasing or resilience (Agrawal et al., 2021; Santa-Maria et al., 2022), the role of modularity has been largely overlooked (Zhuang et al., 2023). Modularity has traditionally been framed as an operational concept, yet we find that traditional firms increasingly rely on product and process modularity to progress along the learning curve towards CE. These modular strategies enable key circular benefits—such as maintenance, upgrading, extended lifespans, repairability, and reusability—demonstrating their broader strategic value in industrial circular transitions (Hossain et al., 2022).

Second, we concur with prior studies that capability building is a critical activity (Santa-Maria et al., 2022) for circular transformation of industrial firms. We extend the current dialogue on CE capabilities by emphasizing the role of ecosystem partners in enhancing modular

capability-building. Huikkola et al. (2022) highlight how integrating internal and ecosystem-enabled resources can yield substantial sustainability benefits. Similarly, Frishammar and Parida (2019) demonstrate how collaborative linkages support the scaling of circular business models, while Falcone and Tutore (2025) identify tactical capabilities needed across intra- and inter-firm networks. Building on this, our study illustrates how traditional firms develop modular capabilities internally and, more critically, enhance them through collaboration with partners, suppliers, and stakeholders (Amir et al., 2023). Such integration supports the implementation of modular initiatives and enables closed-loop systems that strengthen firms’ strategic positioning (Machado and Morioka, 2021).

Third, our study contributes to the CE literature by identifying four distinct pathways that reflect how traditional firms combine different modular strategic orientations with capability-building approaches to achieve circular benefits. These pathways account for variations in how firms adopt either product-process modularity—representing traditional modular architectures—or complex modularity practices that extend to organizational routines, governance, and stakeholder engagement. In parallel, firms either build capabilities internally or enhance them through collaboration with ecosystem partners. We show that the degree of circular benefit realization depends on the interplay between modular orientation and capability-building, shaped by firm-specific factors such as size, structure, and complexity. This extends current CE research, which has yet to fully theorize the modularity-capability intersection (Agrawal et al., 2021; Clemente et al., 2019).

Finally, we advance the modularity literature by moving beyond its traditional grounding in operations management (Romano et al., 2023), showing how modularity contributes to circular transformation. While past research has focused on product and process efficiency (Campagnolo and Camuffo, 2010; Mertens et al., 2023), our findings reveal how modular thinking is now being embedded in governance systems, performance metrics, and environmental compliance (Miguel, 2005). Empirical contributions such as ours are essential to deepen our understanding of how modularity supports CE transitions (Machado and Morioka, 2021).

### 5.2. Managerial implications

Our study offers several critical managerial implications for senior leaders, sustainability officers, and operations managers in traditional industrial firms navigating the transition toward circular benefits. Firstly, the findings emphasize that adopting modularity for circular benefits is a gradual, capability-driven process. Firms progress along a maturity spectrum, beginning with the use of traditional modular architectures to optimize efficiency and enable foundational circular practices. As firms evolve, they increasingly collaborate with ecosystem partners to co-develop modular systems, enhance capability depth, and accelerate their circular outcomes. At advanced stages, modularity becomes deeply embedded in organizational routines, accompanied by strategic alignment through firm-wide communication, KPIs, and benchmarking. This phased approach allows firms to tailor modularity to their current capability levels while steadily advancing their circular transformation.

Secondly, the study underscores the importance of proactive engagement with external stakeholders, including policymakers, consultants, and supply chain partners, to institutionalize modularity and maximize its impact. Firms reaching high modular maturity must prioritize transparency and signalling through standardized reporting, certifications, and awards. In doing so, they not only reinforce competitive advantage but also unlock access to sustainable finance mechanisms, such as green bonds and ESG-linked loans, that can fund circular modular initiatives. Aligning modularity with governance systems and embedding it in organizational culture is essential for long-term legitimacy and resilience.

Thirdly, we recommend managers to create dedicated roles to scan

and integrate ecosystem partners to ensure the firm is well-equipped to exploit future circular opportunities. Such a unit can help firms stay attuned to emerging modular solutions, such as renewable integrations and smart analytics, while ensuring alignment with long-term circular goals. The case of Firm E illustrates how ecosystem-enabled modularity enhances innovation and positions firms for leadership in the CE. Managers should institutionalize such functions to continually expand their capability base and reinforce modular systems that enable sustainable growth.

## 6. Limitations and suggestions for future research

This study has several limitations. First, it focuses on the power sector as a proxy for traditional industrial firms. While the findings offer transferable insights, sector-specific dynamics, like modularity intensity or ecosystem engagement, may vary. Generalization should therefore be approached with caution. Future research could explore other sectors or national contexts to capture broader variation. Second, the framework highlights different levels of circular benefits but does not assess performance outcomes. Investigating the performance implications of different pathways offers a valuable avenue for future research. Third, the qualitative nature of this study limits generalizability. Mixed-methods approaches could strengthen validity by integrating quantitative assessments of environmental, economic, and social outcomes. Finally, future works may explore how modularity as circular design strategy interface with sustainable finance tools (e.g., green bonds, ESG-linked loans) and how regulatory frameworks can incentivize inter-firm collaboration and capability-sharing for accelerating circular transitions through modularity.

### CRedit authorship contribution statement

**Debadrita Panda:** Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Shamima Haque:** Writing – original draft, Validation, Software, Methodology, Data curation, Conceptualization. **Johan Frishammar:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **Vinit Parida:** Writing – review & editing, Supervision, Software, Methodology, Funding acquisition, Formal analysis, Conceptualization.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Appendix

Questionnaire for in-depth interviews.

- Can you please share your name, position within the company?
- How many years of experience do you have in this industry?
- What key sustainability initiatives has your company implemented so far?
- What circular initiatives are currently being implemented within your company?
- Do you believe modularity is an effective approach for developing circular benefits? If so, why?
- How does your company use modularity in product design for circular benefits?

- How do your company implement modularity for circular benefits, especially when it comes to flexibility in operations?
- What role does digital technology play in keeping modular parts working well for circular benefits?
- How does your company communicate its modularity practices, those aim to improve circular benefits, to stakeholders?
- How does your company track the contribution of modular systems for circular benefits?
- What criteria or metrics are used to assess modular systems in terms of circular benefits?
- What skills and resources are required to implement modularity, and how does your company build them to enhance circular benefits?
- Which external actors (e.g., suppliers, partners) influence your modular strategies and long-term planning for circular benefits?

-How does your company collaborate with external partners to improve modularity and achieve circular benefits?

### Data availability

The data that has been used is confidential.

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