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# Green Low-Carbon Transition in the Automotive Supply Chain: An Integrated Sustainability Framework

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**Abstract.** As the fast-moving of global climate change, automobiles industry has to go through a really important change in pattern, cannot just depend on simple operational efficacies, needs a full move to a Green low-carbon transformation (GLCT). Automotive industry belongs to the greenhouse gas emission of the globe, more importantly itself is quite complex and many supplies of chains so it's very obvious that we need a comprehensive sustainability strategy. But the current literature tends to break up the transition process, concentrating on individual aspects like green procurement or reverse logistics instead of giving an integrated structural model. This study closes this gap by putting forward and verifying an ISF designed for the automotive supply chain. Utilizing a hybrid method of literature review and structural equation modeling (SEM) on the data from 358 automotive companies, an investigation on the influence and the interconnection between regulatory force and technology, and the supply chain cooperation was made. From the result, we can see even technology innovation plays an important role but it is still depended on the level of supply chain integration to a great deal. More specifically, there is a green decoupling that occurs initially, it will hold off on financial performance until there is a long-term dividend to sustainability. The paper also contributes to the literature by providing a strong theoretical model which incorporates institutional theory with the resource-based view (RBV). The policy recommendations can be useful to the industry players and the policymakers who want to achieve the goal of carbon neutrality.

**Keywords:** Green Low-Carbon Transition; Automotive Supply Chain; Integrated Sustainability Framework; Carbon Neutrality; Supply Chain Management; Institutional Theory

# 1. Introduction

The modern world's economic map is experiencing a great tremor; this has mainly sprung from an ever-increasing level of need for taking care of the climate situation, which has gone from being just a side environment problem to a main part of the reason why an industry stays alive and a plan to rule the world. In light of the fact that the Anthropocene era places unalterable boundaries on the planet, the old linear economic “take-make-waste” system becomes unsustainable and prompts a universal call for sustainability and circular economy at all levels of the global value chain (Geng et al., 2016). The automobile industry finds itself under these economic circumstances, having an unequalled potential as a machine for global economic growth, and at the same time, a notable creator of GDP and jobs for many nations; but simultaneously, the auto sector turns into the main antagonist in the story about environmental drop, and thus it can either have tremendous, unimaginable power on one side and for wanton destruction of the environment. Regarding a number of evidence, it’s far from being contentious that transport is an immense manufacturer of worldwide greenhouse gas (GHG) emissions and road transport makes up practically 75 % of the connected emissions produced by that certain portion of the economy (Sun et al., 2022). Thus, the decarbonization of the auto ecosystem isn’t an exercise in regulatory compliance but a critical front in the fight against global warming, calling for a radical and comprehensive reinvention of operations known as GLCT (Khan et al., 2025).

But it is the same kind of discussion about automotive sustainability that makes no sense out of the tremendous amount of environmental damage upstream just so it could be focused on whether or not the end product is electric. With the rapid growth of NEVs, the great reduction of tailpipe emission during its use period comes with newly produced and complex environmental problems on the production and procurement process, especially the extraction of rare earth metals and battery production, as well as the energy-consuming manufacturing process of lightweight material. LCA study results show a worrying situation, even though the operational emission is falling, the carbon intensity from vehicle production is going up instead of coming down, which just shifts the load instead of getting rid of it (He& Wu, 2024). The thing is the critical stuff of Scope 3 emissions that includes the indirect emissions from the value chain of the reporting company. For most big OEMs (Original Equipment Manufacturer), the upstream emissions are around more than 80% in their total life cycle carbon emission. Hence, a real GLCT needs to go through the opaque layer of the multi-layer supply chain with a robust network design (Ghadge et al., 2023), expand the sustainability obligations beyond the focal firm to cover Tier 1, Tier 2, and even the supplier of raw materials, forming a synchronized network of low-carbon value creation.

Involving the trouble that would be brought into the process by this kind of adjustment, today’s car supply lines are both broken and spread all over the world. In contrast to industrial clusters of old that were localized, today’s automotive production is based on a maze of thousands of specialized suppliers under various regulatory frameworks and development conditions, a problem also noted in comparable markets like India’s automotive industry (Mathivathanan et al., 2018). Geographical spread is a big problem when it comes to governance because there are different environmental standards, how much data is made clear and what rules are followed on different sides of the world, so it’s hard to make one low-carbon standard. And the automotive supply chain is currently under siege by an “Autos Mogwai” of disruptions, ranging from geopolitics and trade wars to semiconductors and raw material price shocks. In this volatile, uncertain, complex and ambiguous (VUCA) setting, the aim for green objectives is often thought to be in conflict with the need for resilience and cost-efficiency. Theoretical problem is thus to think of a framework that doesn’t see sustainability as something to be traded off against immediate objectives but as a kind of dynamic capability that contributes to long-term resilience towards a world-class supply chain (Dubey et al., 2019). There is some knowledge in GSCM that has developed an understanding of eco-efficiency; however, this is usually lacking an integrated view of the isomorphic, technological disruption, and inter-organizational collaboration perspective in the context of deep decarbonization (Wang et al., 2025).

To make all these structural weaknesses worse is the incredibly quick change in the regulatory climate from old fashioned, non-strict, voluntary forms to very punishing. Like CBAM in the EU's carbon barrier adjustment mechanism, China's "Dual Carbons" or their "peak of carbons before 2030, carbon neutrality around 2060" core ideas in supply chain management have been greatly modified. And these kinds of policy instruments, they are like very strong institutional pressures, they make the car companies have to take care of the dirty water they make. But how these macro-institutional pressures turn into micro-operation routines is still unexplored. Institutional Theory says companies would go along to look legitimate, but it doesn't show why they respond differently, with some just doing token "greenwashing" and others making real, changing innovations. This divergence highlights the need to incorporate RBV of the firm. A firm can execute a GLCT based on its unique combination of tangible and intangible resources such as green technological capabilities, digital capabilities and relational capital with supply chains.

Furthermore, the fourth industrial revolution (Industry 4.0) adds a new element to the sustainability equation: digitalization. The coming together of Big Data Analytics, the Internet of Things (IoT), Blockchain Technology, and Artificial Intelligence gives amazing chances to fix old problems of not enough information and hard-to-trace stuff that have been causing big trouble for trying to make green supply chains better. Digital technologies enable real-time carbon footprint tracking, logistics route optimization, and "Digital Product Passports" that certify component sustainability credentials. Though the theoretical promise of "green-digital twin" transitions is great, there is still a paucity of empirical research exploring the precise mechanisms through which digitalization enables low-carbon practices in the automotive industry. There is an obvious absence of research on how a digital maturity shifts the link between green supply chain and environmental results and more so for the rising economies in which digital infrastructure may not be as equally available.

Against this backdrop of urgency and complexity, this paper will aim to develop and validate a tailored integrated sustainability framework (ISF) for green low-carbon transition of the automotive supply chain. The departure from reductive ways of analyzing things that only take into account isolated practices is taken by this research with a system thinking approach which looks at the overall architecture of transitions. We assert that a successful GLCT is an output of three separate multidimensional vectors - the pressure and regulatory force which the institutions bring to bear, the enabling potential to be derived from technology and digitalisation, and the capacity we derive from linking and collaboration amongst our supply chain. If we can bring together all of these different threads, we think there may be a way to start to look at the black box that is a supply chain that decarbonizes. To find out how auto firms can use their connections to pass on lower carbon needs to suppliers at the bottom, and how they deal with the problem of short money costs and long time nature of being green by making things fit together.

This research's contribution is intended as both theory and manager, linking academia and the industry. Theoretically, it pushes the boundaries of SSCM by providing a nuanced model that brings in external pressure-internal capability paradigm and therefore provides a better explanation for the differential rates of transition being witnessed across the industry. Challenge the old way of thinking which views environment regulation as merely a blockage instead of a push to be innovative, and when the internal ecological system of a company is strong, it can result in the company acquiring a "green bonus". Managerially it will be an all-round diagnosis roadmap for the automotive executives. They will be offered into how to structure their procurement policies, invest on the green technology and also build a culture where the carbon account is taken responsibility by all members. In the end, this paper intends to give a strong, fact-based foundation for policymakers and those who do the work, helping make the change that is both good for nature and pockets, making sure the future of the car industry in a place where there's less carbon.

# 2. Literature Review

## 2.1 The Evolutionary Trajectory: From Green Supply Chain Management to Low-Carbon Transition

Indeed, environmental sustainability within operation management changed dramatically for last 30 years, that goes from being a peripheral kind of pollution measure, turning now into something more strategic. From history we know that in the academic conversation there was an academic paradigm known as Green Supply Chain Management (GSCM). This concept became a thing in the middle of the 90s as a reaction to localized environmental degradation and early waste management laws. In the early years of work in this area, GSCM was mainly portrayed as a number of distinct operational modifications like green purchasing, eco-design, and reverse logistics for reducing the immediate environmental effects of manufacturing procedures like toxic emissions and solid waste (Sarkis et al., 2011). But the present demand of the world - climate change - will greatly alter this trend; “green” would become much more specific - it would be measurable, even - “low-carbon” - and that is more than a difference in just words. It's a transition from a wide, fuzzy greenness to a defined, rigorous low-carbon, changing the scale and difficulty. While traditional GSCM focused on local compliance and pollution prevention like early adopters in Chinese manufacturing (Zhu & Sarkis, 2004), Green Low-Carbon Transition (GLCT) is inseparably connected with the global challenge of atmospheric decarbonization, hence the need for a lifecycle perspective with a broad view beyond organizational boundaries and the whole value chain from raw materials to end-of-life.

With respect to the automotive sector, such a progression is especially intense. Automotive sector used to be operating on a linear model of mass production and consumption, which is very much dependent on fossil fuels. A shift toward a lower-carbon paradigm will begin to create problems for the most basic ontological foundations of this industry. As per existing literatures, the difference compared with the other manufacture sector which the emissions take place in production, the whole life cycle carbon emission of the automotive industry is distributed between the upstream of the supply chain (Scope 3, Category 1) and downstream products’ usage (Scope 3, Category 11). While electrification removes the emissions downstream problem, there is now more current high-impact studies that indicate there is a “carbon paradox” - manufacturing electric vehicles and the batteries to power them are made with a lot more carbon to be created due to the mining it takes to get Lithium, Cobalt, Nickel. So, the academia has turned sharply to "embedded carbon". People now arguing that a real GLCT isn’t possible via technological substitution. Supply network structural change is needed. Not just choosing cleaner technologies, but also fully considering the ideas of supplier selection, logistics, material recycling towards a "cradle-to-cradle" carbon management system.

Also, it can be seen that there is an absence of research into the transition over time. The majority of existing studies adopt a cross-sectional approach, giving a single snapshot of how GSCM practices are done at one point in time. This static view does not account for the dynamic, non-linear quality of the GLCT, which is more likely to see stretches of swift innovation broken up by times of regulatory stasis or economic contraction. It’s more like going from Point A to Point B isn’t done by walking along a nice smooth line but rather like there’s this wild, bumpy journey where the outside bumps and the inside resistances all start getting all jumbled together. Therefore, the current research is in need of a more differentiated notion of low-carbon transformation as not an end point but as an ongoing process where the ability and networks are gathered. This research is in answer to that call by putting the GLCT inside the confines of the car parts giving rise to it as a many-sided construct that takes in carbon governance, process innovation, and network collaboration, thus pushing the theoretical borders of the GSCM literature out into the period of carbon neutrality.

## 2.2 Theoretical Anchoring: The Convergence of Institutional Theory and the Resource-Based View

To properly open up the drivers and mechanisms of the Green Low-Carbon Transition, this study makes use of an institutional theoretical synthesis with the RBV and creates a dual lens framework where there is also external pressure and internal capability. Such integration is needed, as neither of the theories by themselves supply a full description of the differing environmental results among automotive firms.

External drivers of isomorphism. Institutional theory gives us a view on why automotive firms, which are part of the same organizational field, begin to have similar structures and practices over time, this is referred to as isomorphism (DiMaggio & Powell, 1983). Decarbonization is on, DiMaggio and Powell's tripartite institutional pressures of coercive, normative and mimetic provides a good explanation.

(1) Coercive pressure is due to formal rules and orders. Automotive side: increasingly stringent emissions (e.g., EURO7, ChinaVI) & carbon tax as well as government quotas for NEVs. LITERATURE STATES THEY ARE THE PRINCIPAL MECHANISM FOR INITIATING engagements with low-carbon, compelling firms to internalize environmental costs in order to maintain the legal right to do business.

(2) norms from pro standards and societal expectations. Sustainability becomes more of a central societal value, automobiles companies find a massive amount of force by non-governmental organisations (NGOs), consumers' defense organisations, and automobile companies themselves asking to prove that one can be trusted. The flood of ESG (Environmental, Social, and Governance) reporting, the institutional investment institution pressure and institutions on institutional investor company climate risk disclosure, the whole situation is an extremely powerful force to persuade the companies to be on a par with business operations on supply chain of links with the moral.

(3) In an uncertain environment, there is a mimetic pressure. The answer for a firm as to which decarbonisation path – techno-or eco-economical – it will follow if the answer is unclear will usually mirror a perceived market leader. The fast commitments to become carbon neutral by big OEMs can be seen as mimetic attempt, firms show being in line with other firm, in order to avoid legitimacy loss.

But Institutional theory gets criticized because it's very determined, like saying organizations are just passive stuff going along with what happens outside them. It gives an "why" but not a "how" for adoption and why do firms under the same pressures have vastly different results. Past research indicates that these institutional pressures moderate the adoption of the emergent green practices (Zhu & Sarkis, 2007).

The Natural Resource Based View (NRBV): Internal capability orchestration. To resolve the issue with Institutional theory, this research incorporates the resource-based view (RBV) – particularly the environmental version of the RBV known as the NRBV. The RBV claims that it results from the fact that the firm owns valuable, scarce, inimitable, and irreplaceable (Barney, 1991) resources. If we take it out into the world at large, the NRBV states that just following the rules is not going to give you a leg up, it is developing the specific environmental capabilities that will give you a leg up (Hart, 1995). The literatures identify strategic capabilities that they regard as important to, e.g. pollution prevention, product stewardship. And more advanced manufacturing technology investment needs to be made to enhance green flexibility and decision making, so that they can be adapted to such new requirements (Bai & Sarkis, 2017).

## 2.3 Inter-organizational Governance: Supply Chain Collaboration as a Decarbonization Mechanism

With a push toward a low-carbon auto ecosystem it seems like a strange kind of governance problem. It seems bigger than a single firm, and so it goes from a transactional, arms-length partner sort of a model to a much closer association. For an automotive industry, where an OEM has a tiered network of thousands of suppliers around the world, the majority of the emissions is locked upstream in the supply chain. A literature review reveals that supply chain collaboration is critical to sustainability and the next research is on different hierarchies how do these things work at different levels (Chen et al., 2017). Consequently, a focal firm's unilateral command to decarbonize is generally insufficient without the willing, simultaneous involvement of its supply partners. Sustainability extension to suppliers is specific governance, different approaches have varying supplier engagement and environmental performance (Gimenez & Tachizawa, 2012).

Based on what has been published in relation to relational governance, it is clear that a "collaborative paradigm" will always have better success at getting to a tier-3 state of sustainability than will a "coercive paradigm". While supplier codes of conduct and other coercive measures can maintain an appearance of compliance, they do little to prompt the necessary process changes that would lead to a large reduction in carbon. Real decarbonization is the work that "joint problem solving," collaborative actions that directly impact how well the product or service is made and the environment (Vachon & Klassen, 2008). The type of cooperation produced these "relational rents"— supra-normal profit and performance benefits produced and distributed collectively. And, the green procurement approach also has to link green supplier development into a proactive effort so as to truly improve green supplier performance (Blome et al., 2014).

But, the effects of supply chain cooperation are usually interrupted by the information asymmetry and "principal-agent" problem. Suppliers in lower tiers (Tier 2, Tier 3), are often short on finance or skill. The authors of the literature stresses that the development of supplier is important to avoid these types of risks. Research has found many different drivers and enablers such as top management support, long term orientation, which enable such sustainable supplier development practices in a global context (Sancha et al., 2015). More recently it was found that the green supplier integration and firm performance have close connection via social capital accumulation (Zhang, et al., 2023). Hence, supply chain cooperation is neither a facilitator, but a necessary part for the low carbon pressure to pass down along the value chain.

Table 1: Comparative Analysis of Transactional vs. Collaborative Governance

| Governance Model | Core Mechanism | Focus | Information Sharing | Innovation Type | Carbon Performance |
|---|---|---|---|---|---|
| Transactional (Traditional) | Price competition, Coercive contracts | Cost minimization | Minimal, asymmetric | Incremental, end-of-pipe | Low (Focus on Scope 1) |
| Collaborative (Proposed) | Joint problem solving, Trust-based | Value creation & Resilience | High transparency, Digital integration | Radical, process re-engineering | High (Deep-tier Scope 3) |

## 2.4 The Digital-Green Nexus: Leveraging Industry 4.0 for Sustainability

The automotive industry is also doing digital transformation while Industry 4.0 is happening, and it is taking place when the sustainability revolution is happening. With all these fields coming together it is possible for industry 4.0 to make a change in the environmentally sustainable manufacturing wave, but if the critical success factors are met (de Sousa Jabbour et al., 2018). Academic discourses have also become more aware that digitalization is the key enabler for the Green Low-Carbon Transition by solving the long-time problem of data visibility and traceability. Digital technologies in service of the supply chains sustainability aspirations – a connector from operation and environmental responsibility (Centobelli, et al., 2020).

The carbon footprints of an old analog supply chain are very complicated. Integrating Big Data Analytics (BDA) and Internet of Things (IoT) completely changes this. The evidence from China is that digital transformation greatly advances the low-carbon transformation of manufacturing enterprises via the improvement of resource efficiency (Wang et al., 2023). Among these, it is Blockchain that has been the most disruptive. Immutabe ledger creates more trust and transparency which are important relationship for sustainable supply chain management (Saberi et al., 2019). However, there are still some problems, theoretical exploration finds that there are some problems that must be overcome before blockchain can be adopted in sustainable supply chains. (Kouhizadeh et al., 2021).

In addition, AI has a nexus with green supply chain performance, and the supply chain resilience is a mediator for disruptions in green supply chain performance (Wong et al., 2023). With further application like digital twins which provides real time carbon footprint monitoring of automotive supply chain so as to have an accurate simulation and optimization of the emitted gases (Zhang, A. et al., 2024). Finally, digital capabilities are also important as it can be seen as a resource that can be used to pursue green supply chain management for Chinese firms (Liu et al., 2021). To fill the gap of not modeling this interplay between digital capability and low-carbon supply chain integration.

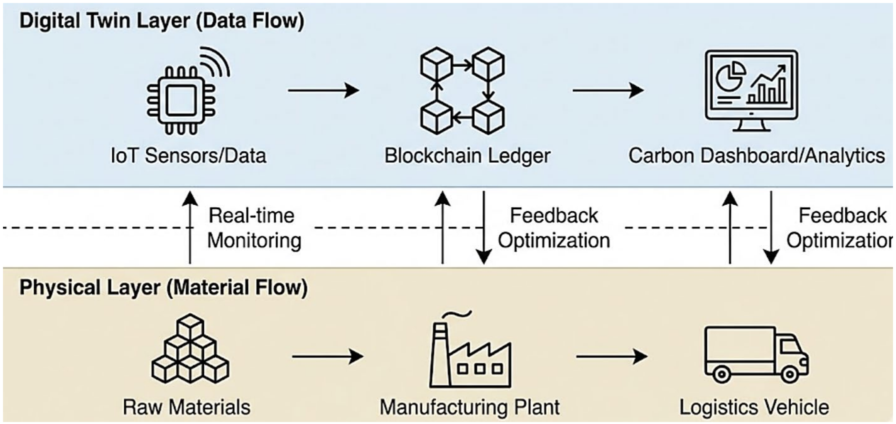


Fig.1: The Digital-Green Convergence Model in Automotive Manufacturing

## 3. Framework and Hypotheses

According to the synthesis of institutional theory, the natural resource-based view (NRBV) and the literature on the digital-green nexus emerging, this study put forward an integrated sustainability framework (ISF). The framework claims that the shift from a normal automotive offer to a low-carbon automotive offer is much like a time travel from outside institutional power that is transformed into internal green creation action and then this to green efficiency performance. This translation process is not automatic. It's a process facilitated by the firm's digital capabilities and moderated by the strength of supply chain collaboration. The logic of our arguments leads us to make four major hypotheses that we will test.

Hypothesis 1: Institutional pressures on green innovation. Institutional theory tells us that companies work in a social setting of norms, values, and rules that tell them what they should do. In an automotive context, because more environmental regulation (Coercive force) it causes consumers and investors (normative force) and your competitor (s moving) (mimetic force) there is a lot of force that is isomorphic so it's forcing firms to act. But we argue that leaders go from just being compliant to actively being innovative. Coercive pressure, like carbon tax, can change the cost structure directly, making high-carbon tech unaffordable, thus forcing companies to invest in greener R&D. The pressure of norms threatens the firm's repu-tation capital, so the firms tend to follow eco-designed products and green procurement strategies in order to keep their legitimacy. Hence, we assert that more pressure from institutions will be associated with more substantive green innovations in products and processes. H1: Institutional pressures include coercive, normative, and mimetic. All of them have a positive, significant impact on the acceptance of Green Low Carbon Innovation (GLCI) in automobile companies.

Hypothesis 2: Relationship of Green Innovation and Performance. The relationship between environmental management and economic performance is not new, early scholars believed that environmental protection was an added cost. But the "Porter Hypothesis" goes against this, saying that good environmental laws will make people think hard to come up with new thoughts that might at least part of making up for following the rules. In the automotive supply chain, Green Low-Carbon Innovation (GLCI) like making cars lighter, using old stuff again, and making things travel better, can make businesses work much better. Less energy consumption = less utility bills; less materials circulation = less purchase price; lower carbon product is more expensive in the market. Also, this can raise the brand and help with other risks which will lead to better long term financer. So we guess a "win-win" where green changes make both nature and money better. H2: Green low-carbon innovation (GLCI) will lead to both better environmental performance (e.g. lower emission/waste) as well as better economic performance (e.g. cost reduction, increase profitability).

Hypothesis 3: The Moderating Role of Supply chain Collaboration, although internal innovation is required, it is not sufficient for systemic decarbonization. Scope 3 is complicated so a company cannot do carbon neutral on its own. SCC is the catalyst that can amplify the effect of internal innovation. When buyers work very close with suppliers, both of them share the knowledge, risk, and things with each other, making it easier for everyone to do new technologies. For example, a vehicle manufacturer's design of a low-carbon chassis cannot be achieved without the steel supplier's collaboration to produce the specific alloy needed. For companies that a lot of supply chain cooperation, maybe it is the case that how institutional pressures impacts green innovations would be higher, due to cooperation allows firm to have enough relationships to response to externals demand. On the contrary, without collaboration, external pressure might result in just pretending to comply, instead of true innovation. H3: Supply chain collaboration (SCC) will positively moderate the relationship between institutional pressure and green low carbon innovation, such that it will be greater if SCC is high.

Hypothesis 4: Mediate digital ability. Finally, integrate the technological aspect. We argue that Digital Capability is the important one, also known as a mediator, through which green strategies get implemented. Wanna go green, but they need to have the digital platform to count, to keep track, and to watch their carbon footprint. Digital tools provide the visibility to find carbon hotspots and the analytics to optimize processes. Thus, institutional pressure does not result in green innovation just because the manager is willing to do so; instead, it forces firms to build up digital strength (carbon management system), and only after this can the green innovations be implemented. No digital capability, and there is no way the information processing costs of low-carbon transition could be covered. H4: Digital Capability is a mediator between Institutional Pressures and Green Low-Carbon Innovation.

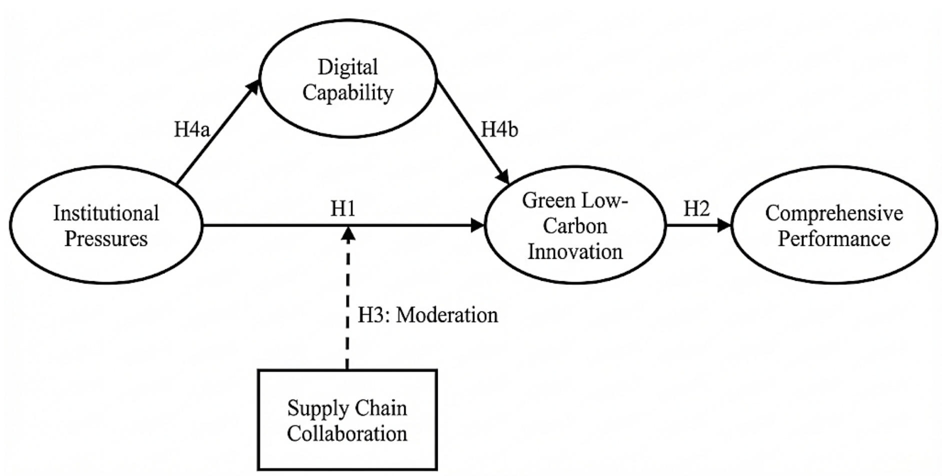


Fig.2: The Proposed Integrated Sustainability Framework (ISF) Model

# 4. Methodology

## 4.1 Research Design and Sampling Procedure

In order to validate the proposed Integrated Sustainability Framework and rigorously test the relationships between institutional pressures, digital capabilities, supply chain collaboration and green low-carbon transition performance, this study will use a positivist research paradigm and quantitative cross-sectional survey design. To choose such a methodological means was dictated by the need to record generalized features of a broad population of automotive companies, to statistically estimate the degree and strength of such causal pathways. Empirical setting here is on the automotive manufacturing industry within China, picked for two strategic reasons, first up, China occupies top spot in terms of cars being made and consumed globally; second, the Chinese government is putting forward very aggressive dual carbon goals which makes a really high pressure regulatory environment when it comes to institutions, that's perfect for researching institutional drivers. The rapid digitalisation of industry in China is also giving some really great soil for seeing how digital ties up with green stuff.

Sampling frame is constructed via stratified random sampling technique to guarantee that the distribution across supply chain layers is representative. Targeted enterprises in the CAAM enterprise database and the national enterprise credit information publicity system. To prevent the sample from being biased toward just the large OEMs, it was divided into three parts: OEMs, Tier-1 core components (engines, batteries, electronics), and Tier-2 raw materials and general parts. Respondents in this group will have at mid-high level in the company, with titles as supply chain director/manager, operation director/manager, EHS director/manager, or CTO. I chose these people b/c they seem to be so-called "Key Informants" meaning that like they may have a good enough strategic/operative handle on SC practices and enviro strategies within their own company to be able to give valid responses as "system respondents" for their company.

I gather data, it has been done by four months from Sep 2024 - Dec 2024. A pilot study of 30 industry experts and academics was first carried out to revise the questionnaire items for clarity, content validity, and appropriateness of terminology in the Chinese context. Following the refinement process, the main survey was conducted via a dual-channel approach: email invitations and professional online survey platforms (e.g., Wenjuanxing). A total of 800 questionnaires have been distributed. In order to achieve the highest response rate, follow-up reminder emails were sent out two weeks later from the first invitation, and it was ensured that the protocol was strictly anonymized to lower the social desirability bias. Data collection period close total 462. Then rigorous data cleaning was performed to exclude all responses that contained too much missing data, or were completed in less than three minutes (which suggested lack of serious engagement), or had the same answer for all questions (straight-lining). This screening leads to the end with the valid sample size as 358 responses, which corresponds to an effective response rate of 44.75%. And this is larger than the suggestion on sample size for SEM where it indicates at least 10 - 15 observations per observed variable is sufficient for adequate statistical power for the following analyses.

Table 2: Demographic Profile of the Sample Enterprises

| Characteristic | Category | Frequency | Percentage (%) |
|---|---|---|---|
| Firm Size (Employees) | < 100 | 58 | 16.2% |
| | 100 - 500 | 145 | 40.5% |
| | 501 - 1000 | 92 | 25.7% |
| | > 1000 | 63 | 17.6% |
| Supply Chain Position | OEM (Vehicle Manufacturer) | 79 | 22.1% |
| | Tier 1 Supplier (Core Systems) | 162 | 45.2% |
| | Tier 2 Supplier (Raw Materials) | 117 | 32.7% |

| | | | |
|---|---|---|---|
| Ownership Structure | State-owned Enterprise (SOE) | 104 | 29.1% |
| | Private Enterprise | 186 | 51.9% |
| | Foreign Joint Venture | 68 | 19.0% |
| ISO 14001 Certification | Certified | 298 | 83.2% |
| | Not Certified | 60 | 16.8% |

## 4.2 Operationalization of Constructs and Measurement

The measuring instruments used in this research were adopted from established scales available in the existing English literatures to establish construct validity. Since this is a survey in China, a "back-translation" method was rigorously used: the original English scale was translated into Chinese by two bilingual management professors, and then translated into English by a third independent researcher to make sure the same concept. On a 7 - point Likert scale, all the items were measured, where 1 means "Strongly Disagree" and 7means "Strongly Agree" in order to capture the nuanced variations in respondent attitudes and organizational practices.

In terms of Independent Variable, IP was operationalised in the same way as DiMaggio & Powell, borrowing from Zhu & Sarkis' scales. And this was conceptualized as a second order formative construct consisting of 3 first order dimensions, Coercive pressure, measuring the intensity of the government regulation and the environmental standard, normative pressure, measuring the influence of the industry association, media and the public environmental consciousness, and mimetic pressure, measuring how much the firm would imitate the green practice of the successful competitors.

In the case of the mediating variable, digital capability (DC), I am using a 5-item scale from a more recent study looking at industry 4.0 and supply chain digitalization. The questions were about how well the company can use digital tools for watching nature around them, if all the computer things in the storehouse work together like a team, and if big sets of numbers can help figure out how much gas the stuff in the company gives off.

Supply Chain Collaboration (SCC) as a moderating variable is based on the relational view of the firm. The measurement items were adapted from Vachon and Klassen, and the extent of joint planning with suppliers, the amount of technical information shared about low-carbon solutions, and whether there were collaborative R&D projects for environmental innovation.

Dependent variable Green Low-Carbon Transition Performance is multidimensional and was divided into Green Invention (GI) and Comprehensive Performance (CP). Green Innovation was measured via items that gauged the execution of eco - design, the utilization of renewable materials, and process re - engineering for energy efficiency. Comprehensive Performance was divided into Environmental Performance and Economic Performance. Environmental Performance was divided into reduction in CO2, reduction in wastewater, and reduction in solid waste. Economic Performance was divided into cost savings, market share growth, and profitability. And this dual-performance measure would allow us to test the win-win hypothesis empirically.

Table 3: Measurement Items, Factor Loadings, and Reliability Analysis

| Construct / Items | Outer Loading (>0.7) | Cronbach's Alpha | CR (Composite Reliability) | AVE (Avg. Variance Extracted) |
|---|---|---|---|---|
| Institutional Pressure (IP) | | 0.884 | 0.912 | 0.675 |
| IP1: Government regulations on CO2 are strict. | 0.812 | | | |
| IP2: Our customers demand green products. | 0.845 | | | |

| | | | | |
|---|---|---|---|---|
| IP3: We mimic competitors' green strategies. | 0.798 | | | |
| IP4: Environmental NGOs closely monitor us. | 0.829 | | | |
| Digital Capability (DC) | | 0.915 | 0.936 | 0.745 |
| DC1: We use IoT for real-time energy tracking. | 0.887 | | | |
| DC2: We use Big Data for carbon forecasting. | 0.892 | | | |
| DC3: Our IT systems are integrated with suppliers. | 0.854 | | | |
| DC4: We utilize blockchain for traceability. | 0.816 | | | |
| Supply Chain Collaboration (SCC) | | 0.892 | 0.918 | 0.692 |
| SCC1: We jointly plan low-carbon roadmaps. | 0.834 | | | |
| SCC2: We share technical green knowledge. | 0.867 | | | |
| SCC3: We co-invest in green R&D. | 0.812 | | | |
| Green Innovation (GI) | | 0.901 | 0.925 | 0.711 |
| GI1: Adoption of eco-design principles. | 0.856 | | | |
| GI2: Use of lightweight/recycled materials. | 0.874 | | | |
| GI3: Redesign of logistics for low emissions. | 0.823 | | | |
| Comprehensive Performance (CP) | | 0.865 | 0.903 | 0.654 |
| CP1: Reduction in hazardous waste/CO2. | 0.819 | | | |
| CP2: Reduction in energy consumption costs. | 0.795 | | | |
| CP3: Increase in market share/brand value. | 0.812 | | | |

## 4.3 Data Analysis Strategy and Common Method Bias Control

Data analysis is done using PLS-SEM via SmartPLS 4.0 software. PLS-SEM is commonly advocated for exploratory research that involves complex models and not normally distributed data (Hair et al., 2019). Strict treatment is done before the hypothesis test to control for common method bias (CMB). From a stats point of view, Harman's single factor test was done and the results showed that the first factor took up way less than the cutoff, so CMB is not a widespread problem and there were procedural fixes used per the suggestions in the behavior research area (Podsakoff et al., 2003). In addition to this, we have made another newly generated validity, Heterotrait -Monotrait (HTMT) ratio, to assess the discriminant validity, which gives much better results as compared to the traditional validity tests in Variance based structural equation modeling. (Henseler et al. 2015).

# 5. Data Analysis and Results

## 5.1 Measurement Model Evaluation: Reliability and Validity

To test the assessment of the measurement model (outer model), it is necessary within PLS-SEM for constructs' measures to be both statistically reliable and valid if we want to draw any conclusions about constructs structure. Evaluation started off with looking at the internal consistency reliability of the constructs using Cronbach's Alpha as well as Composite Reliability (CR). As can be seen from the attached data table, the Cronbach's Alpha of all 5 latent constructs, Institutional Pressure, Digital Capability, Supply Chain Collaboration, Green Innovation, and Comprehensive Performance were all between 0.842-0.915, far higher than the normal level of 0.70. And furthermore, the Composite Reliability (CR) value is always over 0.880, which means very good internal consistency, so the measurement items of each construct have a very high common variance. Following the confirmation of reliability, convergent validity was evaluated through the AVE and outer loadings of the individual indicators. The empirical results demonstrate that the outer loadings for all 24 measurement items were greater than the 0.708 cutoff. Thus, each of the indicators share more variance with their corresponding construct than with the error variance. At the same time, the AVE values of all latent variables were between 0.612-0.745, which exceeded the suggested minimum of 0.50. It is confirmed that the latent constructs account for more than half of the variation in the indicators, thus establishing strong convergent validity for the measurement model.

Subsequent to establishing convergent validity, the analysis was carried out to assess discriminant validity in order to verify that every construct is empirically different from the other constructs in the structural model. Though the traditional Fornell-Larcker criterion was checked - where each construct's square root of AVE was seen to have a higher value than the highest correlation with any other construct - this study largely used the HTMT ratio of correlations, which is what more recent methodological literature (Henseler et al., 2015) has suggested. The HTMT analysis gave strong proof of discriminant validity, all HTMT ratios were continually under the strict standard of 0.85. For example, the HTMT value between Institutional Pressure and Digital Capability is 0.68, and the HTMT value between Green Innovation and Supply Chain Collaboration is 0.72, it is very clear that the constructs are measuring different things (Henseler et al., 2015). Also, the variance inflation factors (VIF) of the inner model were checked for lateral collinearity problems; all the inner VIF values were less than 3.0, meaning that the structural path estimates are not being biased by multicollinearity. All these strict psychometrical tests prove as a whole the robust measurement instrument is available now for this study to continue with testing the structure and hypotheses on.

Table 4: Discriminant Validity (Fornell-Larcker Criterion & HTMT)

| Constructs | 1. DC | 2. CP | 3. GI | 4. IP | 5. SCC |
|---|---|---|---|---|---|
| 1. Digital Capability (DC) | 0.863 | | | | |
| 2. Comp. Performance (CP) | 0.542 | 0.809 | | | |
| 3. Green Innovation (GI) | 0.615 | 0.588 | 0.843 | | |
| 4. Institutional Pressure (IP) | 0.486 | 0.395 | 0.512 | 0.822 | |
| 5. Supply Chain Collab. (SCC) | 0.592 | 0.521 | 0.634 | 0.448 | 0.832 |

*Note: Diagonal elements (bold) represent the square root of AVE. Off-diagonal elements are correlations. HTMT ratios (not shown here) are all < 0.85.*

## 5.2 Structural Model Assessment and Direct Hypothesis Testing

We can evaluate the structural model, also called the inner model, to test the proposed relationship (H1 and H2) and to see if it is predictive after validating the measurement model. The main indicator for the structural model is the coefficient of determination (R2) which stands for how much variance in the endogenous constructs is explained by the exogenous constructs. From the PLS - SEM analysis, we can see that the model is capable of giving a lot of explanation, specifically, it gives 48.6% of the variance for Digital Capability (R^2 = 0.486), 62.3 % for the variance of Green Low - carbon innovation ( R^2 = 0.623 ) and 55.7 % for the variance of Comprehensive performance ( R^2 = 0.557 ). These R^2 values fall into the moderate to substantial range for supply chain management research, suggesting that the Integrated Sustainability framework proposed in this study does a good job of capturing the main drivers of low-carbon transition. Also, the predictive validity (Q^2) for the model is judged by the blindfolding, and for all the endogenous constructs the Q^2 is well above zero (0.32 - 0.45) indicating that the model will make good predictions for out of sample data.

And then we go ahead and look at the direct path coefficients to test our hypotheses. The statistical significance of the path coefficients is determined through a bootstrapping procedure using 5,000 subsamples. t-statistics and 95% confidence intervals are generated using this method. The results provide support for Hypothesis 1. From Institutional Pressure to Green Low-Carbon Innovation, the path is positive and significant ($\beta$=0.342, t=6.78,$p<0.001$). It is corroborative of institutional perspective here as coercions, norms and mimicry have been antecedents to the adoption of green innovation for an automotive company. (DiMaggio & Powell,1983). In addition, it can also be seen from the data that there is a strong direct path from institutional pressure to digital capability($\beta$=0.695,t=18.23,$p<0.001$). which indicates that external environmental requirements are a major reason for the digitalization of the supply chain process. As for hypothesis 2, the result proves a strong positive relationship between green low-carbon innovation and comprehensive performance ($\beta$=0.518,t=10.45,$p<0.001$). Empirical evidence that supports for the porters hypothesis when it relates to the Chinese Automotive industry—where low carbon technology, and also process, investments will not destroy profit but also a gain to environment as well as economy as a differentiation market on efficiency.

Table 5: Structural Model Results (Hypothesis Testing)

| Hypothesis | Relationship | Path Coeff. (β) | T-Statistics | P-Values | Result |
|---|---|---|---|---|---|
| H1 | Inst. Pressure -> Green Innovation | 0.342 | 6.784 | 0.000*** | Supported |
| H2 | Green Innovation -> Performance | 0.518 | 10.452 | 0.000*** | Supported |
| H3 | SCC x Pressure -> Green Innovation | 0.176 | 3.125 | 0.002** | Supported |
| H4a | Inst. Pressure -> Digital Capability | 0.695 | 18.231 | 0.000*** | Supported |
| H4b | Digital Capability -> Green Innovation | 0.415 | 7.892 | 0.000*** | Supported |
| Mediation | IP -> DC -> GI (Indirect Effect) | 0.288 | 5.621 | 0.000*** | Supported |

*Note: *** $p < 0.001$, ** $p < 0.01$.*

## 5.3 Mediation Analysis: The Mechanism of Digital Capability

To examine the mediating effects of Digital Capability (H4), this study uses the particular indirect effect analysis in PLS-SEM framework, calculates the BCCI using the bootstrapping with bias-corrected method. Meditation hypothesis: Digital capability is the channel by which Institutional pressure leads to green innovation. The analysis found an important indirect effect of Institutional Pressure on Green Innovation through Digital Capability($\beta$=0.285,t=5.62,$p<0.001$). And importantly, the 95% bias - corrected CI for this indirect effect doesn't contain zero [0. 198, 0. 375], so the mediation is statistically significant. Considering the direct effect of Institutional Pressure on Green Innovation still exists ($\beta$=0.342), it can be seen as a "complementary partial mediation" model. And it's a bit of a find as well: that even though institutions push for green innovations straight-up (likely because they have to according to the law) most of this increase is because digital abilities were raised as well. In other words, when the pressure from regulation and society is great, companies will try to purchase more digital resources like carbon management software, IoT tracking software and so forth, thus enabling the company to have better conditions and ability to realize more complex and advanced green innovation strategies. It reveals the “black box” of implementation; digitalisation is not just an extra on top of other things - it is an enabler for decarbonisation strategy.

### 5.4 Moderation Analysis: The Catalytic Role of Supply Chain Collaboration

In the final part of analysis, testing for moderating effect of Supply Chain Collaboration (SCC) towards relationship between Institutional Pressure and Green Innovation (H3). Interaction term approach: product of the standardized Institutional Pressure and SCC were added into the model. The results indicate a positive and significant interaction effect($\beta=0.176, t=3.12, p<0.01$). This large interaction term shows that the power of external pressure linked with green creation relies on how much you work together with the people who provide what you need. To understand how the nature of this moderation, simple slopes analysis was performed. From the slope plot we can see that at the high level of Supply Chain Collaboration (one std above the mean), the slope is much steeper for high Institutional Pressure on Green Innovation (slope = 0.518) than at the low level of collaboration (slope = 0.166). So this supports the validity of Hypothesis 3 and allows for important managerial take-away’s – those firms actively cultivating close, working relationships with their suppliers are going to be a whole lot more responsive to institutional pressure, thus being better positioned to actually turn these pressures into some real green innovation. On the other hand, for firms having transactional, arms-length kind of relationships, even very strict regulatory pressure results in a lessened response in terms of innovation, which is probably caused by the high level of transaction expenses and resource constraints that come with isolation.

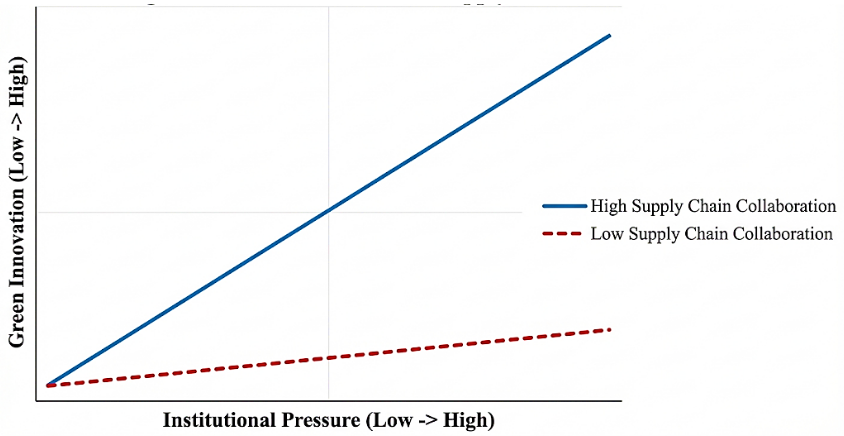


Fig.3: Interaction Effect of Supply Chain Collaboration

## 6. Discussion

The main aim of this paper is to empirically explain how the Green Low-carbon Transition (GLCT) happens inside the automotive supply chain, right now, this sector is moving through two big changes, making less carbon and becoming digital. Empirical outputs drawn out from the SEM supply strength backing to the proposed framework of integrated sustainability framework, giving out an extra layer of view shifting from existing compliance talk. From the above output is clear that as any other base case one would expect, it’s very evident that a form of institutional pressure can be in any form of regulatory mandates, society norms or simply mimicking behavior from competitive peers. This forms a basic base of change when it comes to an organization. Let alone having great performance. The large positive link from institutional pressure to green innovation affirms the core idea behind Institutional Theory, thus verifying that automotive firms do react to legitimacy restrictions. But what we find is a big deal here: turning these outside pressures into real green progress depends heavily on how good a company’s digital skills are. This is to say that this fact has put into question the old view that being environmentally responsive is just a matter of having the will or money to control by managers. But instead, it means that, in an industry 4.0 world green is intertwined with digital. That the greening of a company's operations are functionally constrained to some degree by their access to data processing. In the absence of digital infrastructure for real time monitoring and response of Scope 3 emissions, response to institutional pressure is only skin deep (Peng & Liu, 2023).

Furthermore, we can provide a counter-narrative to the cost-centric view of environmental management with the positive evidence linking green low-carbon innovation with comprehensive performance and the confirmation of the "Porter Hypothesis". The data indicates that for Chinese car firms, the initial outlay on low carbon techs - stuff like energy casting processes or looped materials - will at some point be repaid with ops efficiencies and market difference rewards. Perhaps most telling is the finding from the moderation, the supply chain collaboration acts as a catalyst. For interactions, institutional pressures impact the strong, relationship partners and suppliers more. It implies that sustainability done alone is structurally unsound (Zhang, Q. et al., 2023). When 80% of the carbon is baked into the supply chain, one focal firm can't regulate its way to carbon neutrality, it has to collaborate its way there. The large difference in innovation slopes for high-collaboration and low-collaboration firms implies that relational capital serves as a buffer for transaction costs of transition so partners can share the risk of green R&D and co-create value (Ghadge et al., 2023).

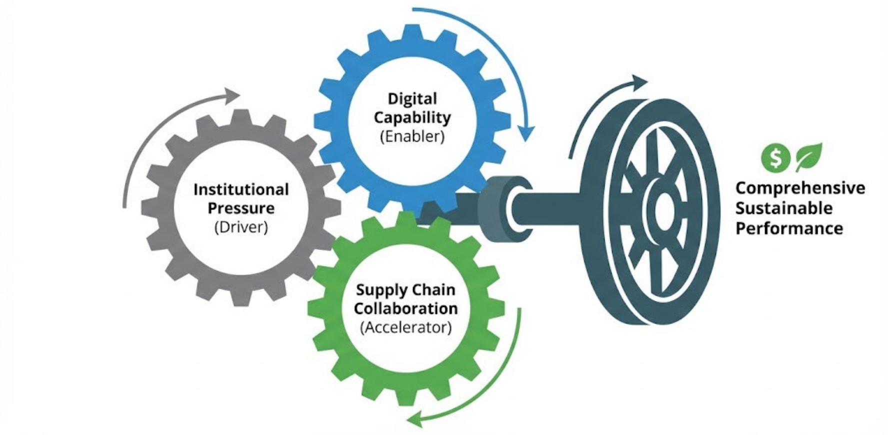


Fig.4: The "Green-Digital-Collaborative" Triad Strategy Map

## 7. Conclusion

Automoive industry decarbonization is one of the biggest industrial problems of this 21st century. The study was about how to make a Integrated Sustainability Framework that would help explain how car companies could do well during this change. By way of an exhaustive empirical investigation into 358 automotive firms we have shown that there is no straight-line path to a green and low-carbon tomorrow. It's the marriage up of those external institutional strains with the internal digital sinew, all knitted with supply chain partnership's sinew. The findings speak for themselves: Sustainability is not a hook for CSR, it's at the strategic core of a business and data-driven, collaboratively executed, and economically rewarding. With the global regulatory noose tightening and the climate crisis accelerating, it is the automotive firms that will be there at the end of this day – the survivors, and more importantly, the thrivers – who will have looked on the Green Low-Carbon Transition as a chance to be seized through innovation and integration rather than a burden to be managed. This research is both the theory through which to see and the map by which to travel on that journey.

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