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Manufacturing sustainability: Institutional theory and life cycle thinking

1. Introduction

From an ontological viewpoint, sustainability pressures are multi-scalar, and comprise of macro-systemic (global), meso-systemic (country/industry), and micro-systemic (organisation) pressures towards conformity and legitimacy (Koh et al., 2016; Seuring and Müller, 2008). From regulatory perspective, there are mounting *pressures* on companies by governments and supra-national bodies to account for the social and environmental impact of business operations, in addition to economic bottom-lines. Dubbed as "sustainability agenda", the need for regulatory pressure was ushered into mainstream management and academia through the widely cited Brundtland report on "Our Common Future", as a means of ensuring a multi-stakeholder approach to resource efficiency that tempers corporate decision-making and performance assessment with the agency of profit, people, and the planet. In 1992, United Nations convened an Earth Summit in Rio de Janeiro, Brazil. A number of sustainability policies were rectified by over 178 governments (e.g. Agenda-21, Sustainable Management of Forests). A follow-up United Nations Conference on Sustainable Development was held 20 years later and produced a series of Sustainable Development Goals to end poverty, protect the planet, and ensure that all people enjoy peace and prosperity (UN, 2018).

Likewise, there are also mounting *normative-pressures* from customers/media, as well as *peer-pressures* to mimic industry best practices, which has resulted in progressively higher nuanced transparency and reporting requirements (Gupta et al., 2017; Simpson et al., 2012).

In terms of normative and mimetic pressures towards sustainability, a report suggests that 66% of global consumers, would willingly pay more for environmentally sustainable products (Nielsen, 2015). However, the downside to normative-mimetic drivers is corporate greenwashing; or corporate attempts at misrepresenting a firm's sustainability profile. An early example was Chevron's pricy 1980-advertisement campaign tagged "People Do", which was costly to produce/broadcast. A more recent report was the 2016 Earth-Day slogan, in which manufacturers were portrayed as "the face of positive change" for using less virgin plastic. In reality millions of tons of plastic are landfilled or swept in the ocean yearly (Earth Week, 2016). Regulatory pressures on the other hand, could inadvertently facilitate the agency problem, wherein the differing or conflicting objectives of principal and agent would usually materialise as transaction costs by way of opportunism with guile (Ciliberti et al., 2011; Kauppi, 2013; Yang et al., 2018). For instance, in 2015, the Environmental Protection Agency announced that Volkswagen; had installed "defeat devices" in certain models to bypass the stringent 2008 anti-pollution standards. The fallout from this scandal was the forced recall of nearly 11million vehicles, dozens of lawsuits in several countries, and a £4.8 billion shortfall to the company in recall, reputation, and lawsuit costs (BBC, 2015). Similarly, Takata a Japanese automotive supplier of airbags suffered what was arguably the largest automotive safety recall in history, involving 19 large automakers, billions of dollars in liabilities, a bankruptcy filing by the firm in the US and Japan, and human penalties totaling 17 deaths-over 100 injuries (Reuters, 2017). Non-compliance to any of these institutional pressures could result in multi-scalar penalties such as meso-level penalties on brand loyalty, micro-level fines or lawsuits, and macro-level penalties on resource efficiency (Glover et al., 2014).

Institutional theory states that the environment and social surrounding could significantly affect the development of formal structures in an organisation, which is frequently stronger than pressures from the market. It is concerned with the deeper features of social structure reflecting impact of norms, rules and routines as imposing-guidelines in an organisation (Kauppi, 2013). In the field of sustainable development, most studies tend to directly or implicitly draw on resource-based and transaction-cost assumptions (Hitt et al., 2016; Huang and Badurdeen, 2018; Meinlschmidt et al., 2018). This has led to an incomplete understanding of the modalities through which institutional pressures drive firms to either conform to sustainability regulations or put up behaviours that create sustainability norms or mimesis. The automotive industry provides an important context to study the impact of institutional pressures in shaping the sustainability agenda because of the industry's accelerated growth curve in new sustainability initiatives in the last decade. For example, several countries have announced an intended ban on the sale of petrol and diesel vehicles in the future. France and UK declared that fossil fuel vehicles would be banned by 2040 (Bennett and Vijaygopal, 2018). There are many other countries considering implementing similar sustainable policies (e.g. Netherlands, Norway, Germany). To meet the new challenges of producing high-quality and eco-friendly vehicles, manufacturers are constantly exploring cutting-edge technologies that facilitate energy efficiency, cost reduction and improved vehicle performance. A primary focus in this regard is the use of composite materials such as Carbon Fibre Reinforced Polymer (CFRP), which are 5-times stronger, 3-times lighter, and stiffer compared to steel (Zhu et al., 2018). Over the last 60 years, composite materials have become increasingly essential and used as alternatives to conventional metals in a number of different industries (Kidalova et al., 2012; Moors et al., 2005). Focusing on CFRP could help manufacturers in building more futuristic-lightweight, fuel-efficient vehicles with the objective of tabling weight with strength/resilience advantages. The material benefits from a very high strength-to-weight ratio (10%weight-reduction save 8%fuel-consumption). CFRP has been used more frequently in the aerospace, military, and supercars/sporting goods sector, where cost is not a primary driver of choice. Timmis et al. (2015) carried out a Life Cycle Assessment (LCA) on the Boeing-787-Dreamliner-fuselage, and found planes using CFRP architecture had lower $CO2$ (14-15%) and NOx a result of reduced fuel burn. It is forecasted from 2020, CFRP used across different products/sector will comprise a market worth of \$35 billion, with automotive accounting for \$6 billion (LUX, 2016). As such, with cost reductions as the only prerogative, a widespread use of CFRP in different parts of the vehicle is a matter of time, and key automotive players are aiming to help make such changes and are adapting innovative approaches (alternative-materials and advanced-manufacturing).

Nonetheless, there appears to be institutional factors at play that increase the difficulty in integrating the sustainability agenda and the adoption of new innovations like CFRP into a comprehensive target (Yang et al., 2018). Consequently, manufacturers struggle to justify and capture the social and environmental benefits of such sustainability investments in a consolidated bottom line statement beyond reporting (Gong et al., 2018; Moktadir et al., 2018). Therefore, they resort to resource-based and transaction-cost rationales for such sustainability initiatives without unpacking how the institutional dynamics of the industry might constrain such sustainable initiatives.

Progressing the use of alternative materials/operations is a significant task, which involves looking at all the different stages of product life-cycle. Previous studies have demonstrated the role of LCA in aiding such a decision support (Koh et al., 2016; Koh et al., 2017). Therefore, it is important to understand how institutional pressures might constrain the life-cycle thinking of sustainability to better inform material selection and substitution decisions.

This research attempts to address this gap by advancing institutional theory alongside life-cycle thinking with regard to sustainability decision assessments (for material substitution in automotive). The study examines the combined institutional effect and life-cycle impact of substituting new materials in product development by using two empirical instances of aluminium and CFRP LCA models to explain why and how regulatory, normative-peer and peer-normative pressures affect material substitution life-cycle decisions. The aim is to bridge resource perspective (additive-manufacturing/hybrid-materials) with stakeholder and institutional theory considerations to provide a more comprehensive understanding on life-cycle thinking. From a business viewpoint, this could reduce triple-bottom-line risks for manufacturers in selecting new-materials/manufacturing-processes. By including the different LCA stages, managers could make more informed decisions before investing resources in futuristic products. This study could guide policymakers in effectively framing rules in a given institution, by mirroring the trajectory of institutional pressures as they move from regulatory (organised laws) through normative (organised behaviour) to mimetic (copied behaviour). As such, the main objective of this study is to advance a novel approach to life-cycle thinking. This represents a pioneering attempt to link life-cycle thinking and institutional theory in a single research framework.

2. Literature review

Supply chain management studies have progressively evolved from a focus on focal firms to dyadic relationships as the fundamental unit of exchange for understanding the dynamics of networks (Jonsson and Myrelid, 2016). However, this fails to account for the influence of a third significant link (buyer/supplier) that alters the balance of dyadic relations (Elking et al., 2017; Maestrini et al., 2018). Instead, triadic view of the fundamental strategic building block of networks is relevant for understanding the dynamics at play with regards to sustainable manufacturing; as buyer–supplier supplier–supplier relationships present different levels or degrees of the three types of institutional pressures that wield a significant impact on the sustainability outcome of SCs (Fahimnia et al., 2015). In recent years, automotive suppliers and their roles have significantly changed. One of such changes, concerns the amount and value of information and resource exchange between auto manufacturers and parts suppliers (Pagone et al., 2020; Wilhelm et al., 2016). As a result, a powerful network of suppliers is emerging, with the top 10 global automotive suppliers making a combined $315.44billion revenue in 2017 (Autonews, 2018). In addition, the recent trends in electric vehicles and advanced materials, is likely to further transform the future suppliers (Lyu and Choi, 2015).

Nevertheless, advanced manufacturing and use of sustainable/hybrid materials has its own challenges. Some authors have attempted to address such concerns by developing multi-criteria decision analysis in assessing sustainability in manufacturing systems (Malek and Desai, 2019; Pagone et al., 2020). For instance, Shankar et al. (2016) used Analytical Hierarchy Process (AHP) and found quality to be main driver for advancement in sustainable manufacturing systems. Others have found it a complex task to use multicriteria-decision making to select/prioritise different aspects of TBL in sustainable manufacturing. For instance, Malek and Desai (2019) found economical and managerial as most significant barriers in successfully adopting a sustainable manufacturing strategy (also considered organisational, social, environmental, technological among other barriers). However, they found multicriteria decision making difficult as the selection was greatly influenced by contextual settings (expert opinion).

Vehicle components depending on the type of material and the environment they operate in (e.g. high-humidity/temperature) could have varying functional performance. The chemical/physical changes (material-ageing) could have detrimental impacts on the properties of the material (loss of design function) (Szeteiová, 2010). Material properties of components could be directly linked to the design function. Therefore, the design of components is intended to maintain material properties within a bounded region of acceptability for a pre-defined time/operation; this could be more challenging when new materials/manufacturing processes are introduced (e.g. dynamic factors in use phase).

The design of the vehicle components, and the material structure/properties, thus creates a complicated trade-off between environmental, social, economic considerations (costs, mechanical/physical performance, environmental regulations, customer perception/satisfaction) (Bringezu and Bleischwitz, 2017; Malek and Desai, 2019; Yang et al., 2011). More often, such attributes are interdependent (environmental-regulations vs.

design/manufacturing catalytic-convertors). Some studies have also attempted to analyse drivers and metrics-based approaches to evaluating sustainable manufacturing however, most utilised resource-based and transaction-cost assumptions (Huang and Badurdeen, 2018; Pagone et al., 2020; Pang and Zhang, 2019).

LCA is a method that quantitatively assesses the environmental impacts related to the different stages of a product's life-cycle. It incorporates a number of environmental and cost factors throughout a product's life-cycle (Guinée, 2002; Pullman and Wikoff, 2017), and has been widely adopted in the automotive industry (Ehsani et al., 2018; Hawkins et al., 2013). A joint report between UN's Environment Programme and The Society of Environmental Toxicology and Chemistry, identified 92% of the major automotive brands were undertaking LCAs or Design for Environment studies (Koellner et al., 2013). LCA assesses the environmental impact of all the inputs (energy/material) and outputs (emissions) of a product system (Maestrini et al., 2018). It could be used to compare/investigate the effect of a product life-cycle against multiple environmental across various SCs.

The European Union sustainable initiatives (80% CO2 reduction by 2050), and more specific pieces of legislation setting mandatory emission reduction targets for new vehicles (e.g. 2021 target-fleet average 95grams of CO_2/km), are challenges the automotive industry cannot ignore (EC.Europa.EU, 2016; EU, 2050). As such, a number of studies have highlighted the economic and environmental savings of transforming conventional and high energy intensive manufacturing processes to more innovative processes using hybrid material (Ibn-Mohammed et al., 2016; Ibn-Mohammed et al., 2017; Pang and Zhang, 2019).

2.1 Research Gap

There is a strong drive to understand a products lifecycle impact across the chain, ensuring the end of life of products are environmentally acceptable. As reviewed, majority of studies have adopted resource based and transaction cost assumptions, in evaluating sustainable manufacturing. However, there is a lack of understanding on why resource hotspots exist and how these hotspots influence Supply Chain (SC) sustainability performance. In overcoming such challenge, this study extends the life-cycle thinking to explain the causes of the resource hotspots through institutional theory.

3. Life cycle thinking and theoretical lenses

Elkington (1997) first used the term “triple-bottom-line” (TBL) to describe the three integral elements of sustainability; economic prosperity, environmental quality, and social justice. This view of corporate accounting entails that managers carry out sustainability audits to assess the contribution of social and environmental bottom lines in addition to conventional financial bottom line reporting, with a view to understanding the full scale of value-added and the associated challenges faced by companies (Baumgartner and Ebner, 2010; Paulraj and Blome, 2017). The TBL approach is often operationalised using one of at least four interrelated multi-agency initiatives, including the UNEP/Sustainability’s biennial benchmarking reports, KPMG’s triennial surveys of practice, the Global Reporting Initiative (GRI), Dow Jones Sustainability Index reporting, and accounting awards like ACCA.

However, it has been argued that the institutionalisation of TBL by these agencies has likened it to corporate social responsibility and diminishes the emphasis on social/ecological sustainability (Milne and Gray, 2013). This is in part because corporate sustainability underpinned by the TBL provides very little by way of guidance on how to operationalise the inherent principles in practice. Furthermore, the aforementioned international guidelines that are used to deconstruct the elements of corporate sustainability into measurable performance indicators have been reduced to corporate compliance measures wherein firms focus on specific areas at the expense of others (Meinlschmidt et al., 2018). The UN Global Compact is the world’s largest global corporate sustainability initiative consisting of ten principles under four broad areas (human-rights, labour, environment, and anti-corruption) to help companies

in their sustainability commitments. However, some key shortcoming has been reported on how UN Global Compact outlines and deconstructs the key corporate sustainability principles and has a global reach; it does not offer a binding code of conduct with explicit performance criteria that can be monitored (see Rasche, 2009).
The LCA under this study complies with the procedures in the ISO-14040 series of standards. The European standard ISO-14040:2006 describes the principles and framework for LCA including: definition of the goal and scope of the LCA, the life-cycle inventory analysis (LCI) phase, the life-cycle impact assessment (LCIA) phase, the life-cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements. The intended application of LCA or LCI results is considered during definition of the goal and scope, but the application itself is outside the scope of this International Standard.

It is noted that performance measurement systems are generally designed to be needs-led (stakeholders-need), audit-led (institutional-needs), or model-led (organisation's prescribed theoretical model) (Beer and Micheli, 2017; Koh et al., 2016). Irrespective of a firm's chosen approach, performance measurement for all intents must be designed to ensure the alignment of suppliers' and customers' performance goals and expectations with the overarching goals and objectives of the firms (Hassini et al., 2012). Anderson and McAdam (2004) noted that traditional financial measures reflect past actions, focus on the short-term, encourage local optimisation, and could raise misguiding signals for continuous improvement and innovation because they are usually internally focused. As such, non-financial or operational performance measures of quality, speed, dependability, flexibility, cost, and innovation are necessary to compliment financial measures and support firms' long-term sustainable competitiveness across a broad spectrum of KPIs (Chavez et al., 2015; Moktadir et al., 2018). Similarly, in terms of manufacturing sustainability in the automotive industry, the environmental and social issues that impact automotive SCs are boundary-spanning and multi-scalar; thus focal firms (OEMs) must account for the holistic corporate performance of their industrial ecosystem (Pagone et al., 2020). To enhance collaborative performance measurement, some have suggested supplier evaluation provides the purchasing firm a better level of understanding on which of its suppliers are doing well and does that are not (Carr and Pearson, 2002; Fahimnia et al., 2015). This would enable the buying firm to effectively identify suppliers which could benefit most from supplier development initiatives.

Overall, suppliers are often evaluated based on three key assessments: (a) Product and delivery assessments (e.g. on-time delivery, correct quantity); (b) Capacity assessment (e.g. flexible-capacity); (c) Knowledge-based assessments (e.g. Information sharing and new product development capabilities). However, the business environment for automotive suppliers is rife with competitive pressures arising from increasingly complex and multi-regional operations and the expanding scope of value creation for suppliers due to product modularity and component commonality. In addition, suppliers need to make decisions regarding uncertain demand and fluctuating tastes as well as exploit the opportunities presented by a varied portfolio and shorter product cycles. They also need to effectively manage the trade-offs between innovation and product commonality requirements of the OEMs, in concert with the development needs of second tier suppliers.

Despite the recognition of the complex triadic relationships and increasingly important role of suppliers in the automotive SC, OEMs are still predominantly responsible for dictating procurement/sourcing best practices due to their higher level of sourcing maturity brought about by the institutional dynamics (pressures) of the industry (e.g. Best-cost-country sourcing strategies, advanced IT systems, high negotiating power, and systematic supplier management protocols). This could imply greater control over savings per-unit of spend and access to innovative capabilities. The sourcing maturity gaps between OEMs and key part suppliers add a degree of nuance to corporate sustainability assessments, because suppliers are in a constant uphill struggle to retain as much value as possible whilst concurrently meeting the sustainability requirements imposed by OEMs.

Predominant sustainable manufacturing frameworks focus more on the resource areas (carbon regimes focusing on emission, fuel efficient technologies, and weight reduction); however, this does not consider the extended boundary of the company and the suppliers that are involved. This draws in different stakeholder views on the same issue/problem, thus a strictly resource agenda would not necessarily work. For this reason, under this study the performance measurement for sustainable manufacturing is multifaceted covering the following theoretical lenses:

A) the resource perspective (normative-peer pressure): Observing the actual technicalities of sustainable development in the automotive industry. The majority of manufacturers tend to focus on this factor, since it helps them meet a variety of green/sustainable agenda/objective (i.e. looking for supplier that give you appropriate/sufficient resources). Based on the institutional theory, we posited the term normative-peer pressure, where normative pressure is stronger than peer pressure to describe the resource perspective lens.

B) The stakeholder view (peer-normative pressure) – within a sustainable manufacturing framework, the needs of key stakeholders should be met. For automotive manufacturers this starts from mining companies that extract rare earth material, to suppliers that focus on advanced material manufacturing/development (e.g. additive-manufacturing). Logistics and freight operation, a key cost for automotive manufacturers particularly with the rise of outsourcing of manufacturing activities to low-cost countries, tax, liabilities and uncertainties. Automotive manufacturers are under pressure to consider the end of life of their products. Under institutional theory, here we coined the term peer-normative pressure, where peer pressure is stronger than normative pressure to describe the stakeholder view lens.

C) Institutional theory (regulatory pressure) – the third prong of the theoretical lenses is where regulations come into account, knowing what regulation to meet, and the right ones to pursue. What is measured as sustainability performance depends on what manufacturers peg their indices to. If they are not following or do not have their upstream SC aligned to an appropriate set of measures, mismatches happen and different certifications are awarded (i.e. some adopt green GS1 measures others use ISO), which influence the final product price and quality, and result in inconsistency of sustainability outcomes. This regulatory pressure acutely describes the institutional theory lens.

It is argued that companies wanting to achieve sustainable manufacturing should align key suppliers within their SC to the right set of institutional frameworks. Therefore, if there is a mismatch between the above three objectives (resource, stakeholder, and target/institutional objectives), stakeholders could demand something that may not be aligned with the resource capabilities of the company. In such settings manufacturers may look quite sustainable in areas such as their resources, and not so much when it comes to supply strategies that could result in catastrophes (e.g. Toyota's recall incorrect/out-of-place driver's side floor-mat). To address this major gap, this research proposes a new framework (figure 1) that combines institutional theoretical lenses with life-cycle thinking for sustainable manufacturing to:

1. Understand the impact of institutional pressure on sustainable material choices to build on extant studies that directly/implicitly assume a resource based and transaction-cost theoretical lens to explain sustainable choice.
2. Link life-cycle thinking with institutional theory (at times where adopting life-cycle approach is becoming popular).
3. Bridge the resource perspective with a stakeholder and institutional approach to provide a more robust understanding of life-cycle thinking.

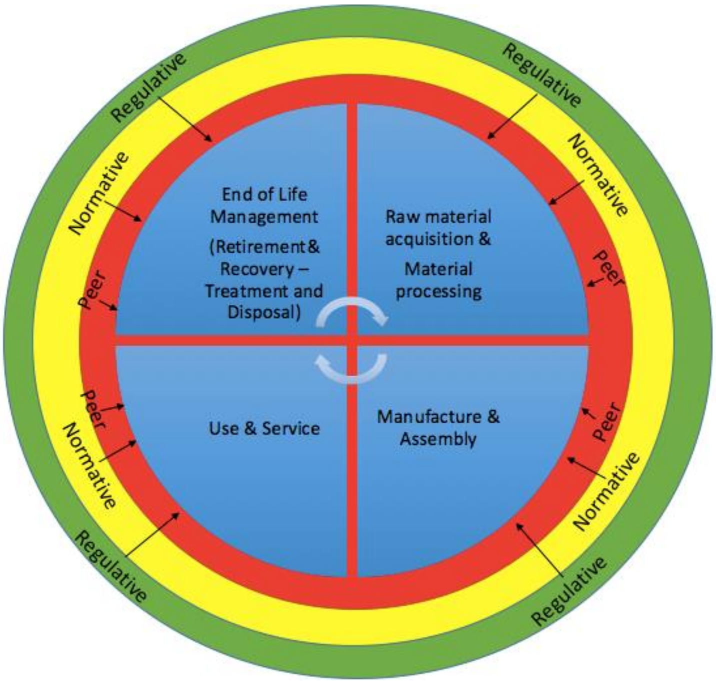

Figure 1. Life-cycle thinking-institutional theory framework

4. Research Methodology

Primary data from a global automotive manufacturer were gathered on two critical components (Aluminium and CFRP). The company in question faced material selection dilemma in understanding the institutional sustainability impacts of the substitute material (selection) beyond efficiency considerations (i.e. engineering cost and quality). It has been noted that the automotive industry is faced with increasing regulatory pressure, stiff global competition and complex triadic supply network, thus making the case example an ideal choice and representative to explain the new institutional lenses and life-cycle thinking.

4.1. LCA procedure

Extensive literature exists on LCA methods, and the main two are known as process based LCA, and environmental input-output (EIO) LCA (Ibn-Mohammed et al., 2016). The Supply Chain Environmental Assessment Tool intelligence (SCEnAT*i*), established by Koh et al. (2013), combines the two methods based on a five-stage framework, 1) SC mapping, 2) carbon calculations, 3) low carbon intervention, 4) SC performance evaluation and 5) informed decision making. Using this hybrid approach this study was able to evaluate the complete supply chain and deliver a more robust outcome (Lake et al., 2015; Suh et al., 2004). A number of companies have managed to successfully reduce their environmental impacts using this tool (Koh, et al. 2013).

4.1.1 System boundary

The assessment begins raw materials acquisition, and manufacturing. Experts in the automotive manufacturer suggested a service life of 200,000 km for the vehicle design life. This LCA not only includes emissions at use stage (200,000 km), but also emissions for fuel production (oil exploration/refining). Finally recycling, reusing, remanufacturing or landfilling at the end of the vehicle life is also included in the LCA. The functional units for the LCA models are 1-unit of the original aluminum and 1-unit of the CRFP respectively.

The system boundary is summarised in Table 1.

Included	**Excluded**
• Upstream raw material production • Upstream energy production • Mechanical part production • Part assembly • Use • Service (repair and replacement) • End-of-life disposal	• Overhead of manufacturing facilities • In-plant transportation • Human labour • Transportation of manufactured parts • Transportation of raw materials, finished products and parts, for service activities

Table 1. System boundary

4.1.2 Impact categories

The environmental impacts in this study were extracted from the ECOINVENT database (version 3.5) and used as the method of comparison between the two components. The impacts chosen were based on several discussions with experts in the automotive industry. The most significant impact categories that could affect different institutional pressures, were identified and taken from the CLM 2001 database; global warming potential (GWP) 100a, regulatory-organised law), acidification potential (Average European-SO2, normative - regional laws), human toxicity (HTP 100a), depletion of abiotic resources, stratospheric ozone depletion (ODP 40a), and freshwater aquatic ecotoxicity (FAETP 100a). In this study, cost is considered a peer – mimetic pressure.

4.1.3 Life-cycle inventory (LCI) and Life-cycle impact assessment (LCIA)

The life-cycle inventory (LCI) aggregates the mass-energy flows throughout the identified product life-cycle. At the centre of the LCI is a process flow of the product life cycle, identifying key process, material and energy inputs, and emissions to air, land and water. The data captured is relevant to the pre-identified functional unit of analysis.

This research has attempted to capture as much data relating to the product processes from primary sources. Where primary data was not obtained, secondary datasets were used (e.g. ECOINVENT), which utilises sectorial, national or regional averages. LCIA aims to make sense and describe the impacts of the environmental loads quantified in the LCI. Thus, the purpose is to turn the inventory results into more environmentally relevant intelligence in the form of effects of substances on the environment as shown in figure 2.

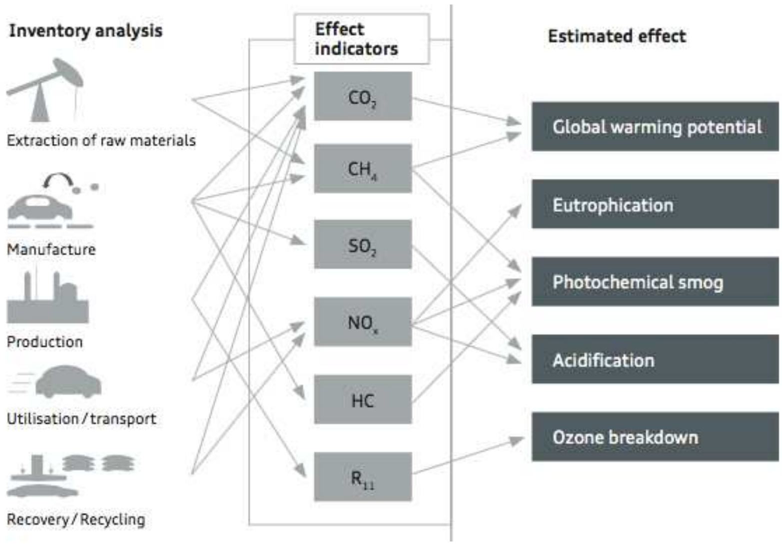

Figure 2. Effect of substances on the environment

4.1.4 Developing the LCA models

The results of the carbon accounting module of the above two components are estimated and translated into a SC carbon map to identify carbon hotspots and quantify their impacts, which can aid manufacturers in designing lower carbon products (components) and SCs. The following scales within SCEnAT*i* were used in the ranking: Very High (red, emissions> 10% total life-cycle-emissions); High (orange; 5-10%); Medium (yellow; 1-5%); Low (green; below 1%).

5. Results and discussions

The two LCA models are presented in figures 3 and 4 respectively. They demonstrate the significance of considering the use phase, and how such process could make alternative materials attractive (i.e. identifying components with identical/better functions)

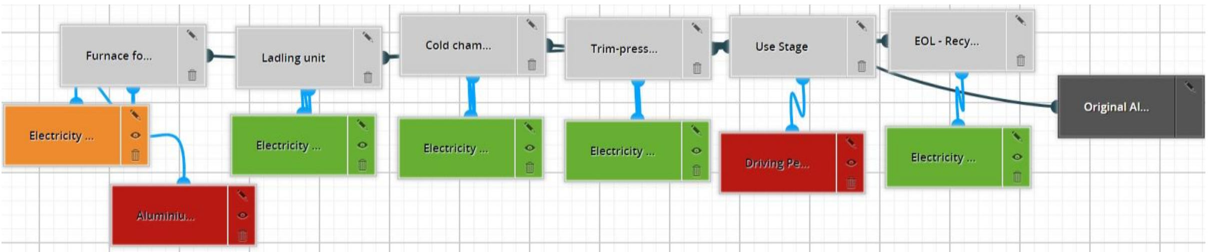

Figure 3. LCA-map Original-aluminium-design

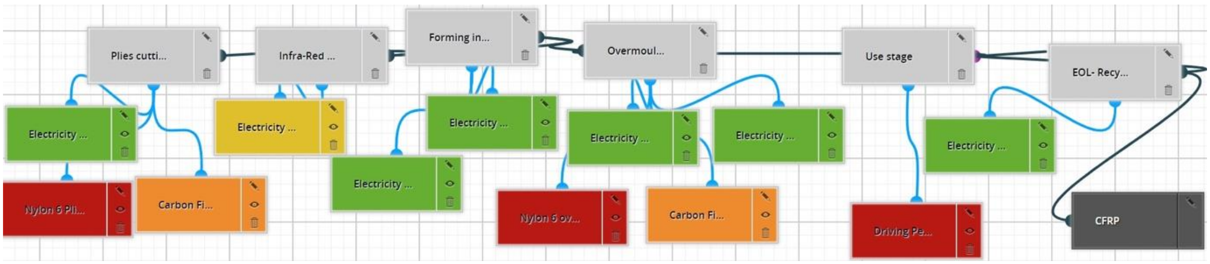

Figure 4. LCA-map CFRP-design

As illustrated in figure 3, an early stage life-cycle hotspot for aluminum design, is the material itself. Aluminium reported the highest emission intensity (12.1) and accounted for 77% of the total life-cycle emission. By substituting this conventional material with hybrid CFRP the early stage life-cycle hotspot changes to the Nylon used in overmoulding becomes the highest emission intensity (5.31) and accounts for 55.1% of the total life-cycle emission (figure 4). In addition to Nylon, recycled carbon fibre is also mixed to produce CFRP and has the third highest emission intensity (1.431), accounting for 14.9% of total life-cycle emission. Furthermore, expanding the above example and comparing the two products different manufacturing processes, an early stage life-cycle hotspot was the electricity needed for heating the furnace reported 5.4% of total life-cycle emission (emission intensity 0.852). Using advanced manufacturing (overmoulding 3D printing), significant reductions can be witnessed in the electricity usage. The main hotspot for electricity usage was in the infra-red heating process 1.4% of total life-cycle emission (0.132 intensity).

Table 2 compares and summarises the environmental impact between the aluminum and CFRP designs. As reported in table 2, significant reductions in global warming potential (15.72 to 9.63kg CO_2-Eq), freshwater aquatic ecotoxicity (8.01 to 0.82 FAETP 100a) and total human toxicity (19 to 1.26 HTP 100a) can be witnessed. Not much change can be observed in total depletion of abiotic resources (0.16 to 0.18 kg antimony-Eq) and total stratospheric ozone depletion (0.01 to 0kg CFC-11-Eq); however even such small changes could become significant when the numbers are scaled up to the entire fleet of production.

Aluminum-design vs. CFRP	Calculation summaries	
	Original Aluminum-Design	CFRP-Design
Global warming potential	15.72kg CO_2-Eq	9.63kg CO_2-Eq
Total cost	9.12£	13.67£
Total acidification potential (average European)	0.08kg SO_2-Eq	0.05kg SO_2-Eq
Total freshwater aquatic ecotoxicity (FAETP 100a)	8.01kg 1,4-DCB-Eq	0.82kg 1,4-DCB-Eq
Total human toxicity (HTP 100a)	19kg 1,4-DCB-Eq	1.26kg 1,4-DCB-Eq
Total resources (depletion of abiotic resources)	0.16kg antimony-Eq	0.18kg antimony-Eq
Total stratospheric ozone depletion (ODP 40a)	0.01kg CFC-11-Eq	0kg CFC-11-Eq

Table 2. Environmental impact summaries comparing Aluminum vs. CFRP designs

Comparatively analysing the hotspots, manufacturers can decide which of the indices/pressures to focus/prioritise on reducing. The main institutional pressure (regulatory) is on GWP, however focus also needs to be on acidification potential, water toxicity, resource depletion, which are strong normative pressures (could transform into regulations). For instance, European-led legislations such as Restriction of Hazardous Substances (RoHS) have set their own stringent toxicity expectation in comparison to the rest of the world (regulative and normative pressures differ based on region), and there are no institutional pressures forcing manufacturers to use or replace a certain material if they are operating in global SCs (outside regional jurisdictions). However, it has become norm for major manufacturers to switch to lighter weight materials i.e. CFRP (peer-pressure), without a regulation forcing them because it could help them tackle regulatory pressures like GWP. The findings from this study explains the interaction between life-cycle thinking and institutional theory especially observing the normative-peer pressure, peer-normative pressure and regulative dynamics in the automotive SC.

The findings could also show diverging from energy intensive manufacturing and conventional materials, to additive manufacturing (CFRP) could be justified through sustainable investment in lightweight, fuel-efficient vehicles, environmentally friendly manufacturing processes. Currently such change does not come cheap, by comparing the two models a significant cost increase (peer pressure) is observed from the original aluminum (£9.12) to CFRP (£16.37) design. In an industry where manufacturers are getting heavily implicated for damaging the environment, knowing which environmental impacts to choose (and at what cost) becomes a necessity when picking a certain manufacturing route. As reported, advanced materials and manufacturing processes could be costly (when scaled), however using a life-cycle approach could assist automotive manufactures in viewing/selecting sustainable process/materials across their SC. Signs of toxicity could be highlighted at the earlier design stage, which could be extrapolated over a few years to see what it could cost the business in the long term if they did not make a certain change.

In this study we also paid attention to the vehicle use phase, and the opportunities for vehicle manufacturers to reduce emissions and save costs. By excluding the use phase clearer/focused process-based solutions could be presented to the manufacturers for both the original and the new hybrid design. For instance, using weight saving design such as CFRP, the findings show efficiency at drive and fuel consumption operations prevailed. Reducing vehicle weight (mass), as well as advancements in aerodynamics, could result in less tractive effort (e.g. less rolling resistance from the tires) to drive the vehicle. Nevertheless, because such pressures are peer-normative and no regulations mandate the use of particular material, adopting life-cycle approach to identify hotspots and the type of pressures they fall under (peer, normative, regulatory) is novel. An automotive manufacturer could have found a lighter material substitute; however, the problem might be disposing of such material and the impact it would have on the environment. In most cases the problem would be a financial one, but other times it could be related to the chemicals used in the process of making the material, which comes secondary to regulatory requirements (i.e. strength of vehicle, safety, horsepower and etc.). It is argued that the interplay between the three levels of rulemaking creates institutional pressures around what is known as the industry and identifying them at different life-cycles can help automotive manufactures in deciding to invest or move away from a particular peer/normative pressure. The point is when automotive manufacturers examine their SCs, they would need to know where each of these hotspots fall, and whether the pressure associated is a regulatory (can be tackled/managed faster), or normative (how normal is defined in different regions) or peer (mimetic) or peer-normative or normative-peer.

Because of global alternates of environmentally friendly designs and the significant relationship between GWP and CO_2 emissions, the scrutiny on sustainable manufacturing processes are on the rise. As such this study attempted address this important gap by providing a comparative LCA for Aluminium and CFRP Design. This research in line with other related studies on conventional and hybrid materials, offers valuable ecological intuitions into futuristic designs (Pang and Zhang, 2019; Szeteiová, 2010; Zhu et al., 2018). It also establishes the basis for extra explorations into the sustainability and environmental profile alternative/hybrid/new materials. As presented above there are financial and technical challenges for migrating from lab scale production to entire fleet/industrial production, which the use of our novel framework could help in this regard. The methodological framework adopted under this study would be beneficial for the environmental profile assessment and LCA of other emerging processes/technologies/products in early stages of the study and prior significant design decision are taken.

6. Conclusions and managerial implications

This study provides a new framework by combining life-cycle thinking with institutional theory for manufacturing sustainability. Empirical data from a global automotive manufacturer was used, and two LCA management models were set to compare the results. Framing of new normative-peer and peer-normative pressures were introduced in conjunction with regulatory pressure under the institutional theory lens to discuss the complex interactions in the automotive SC in particular on its sustainable manufacturing practice. The two examples demonstrate the sustainability advantages in CRFP compared to aluminium design. However, the cost associated to CRFP and the advanced manufacturing operation is significantly higher. This framework can be used by automotive manufactures to map out the different institutional pressures affecting their product life-cycle and help them identify where emerging normative pressures are past being mimetic, and direct investment on normative pressures and make asset specific investment. It also helps understand the life-cycle impact from the interactions with peer and normative, and the interplay with regulatory pressures. LCA begins with the mapping of the SC, and the scenario modeling (different material/manufacturing processes) before selecting a particular material (substitute/integration into production) could be insightful. By including all the stages of the LCA automotive managers can make more informed decisions before investing the resources in future generation vehicles.

The majority of the materials used in the vehicle industry are from the metal groups (e.g. steel/iron, non-ferrous, special-purpose metals), however polymers and process polymers are becoming even more popular and viable material solution to future fuel saving efforts (weight reduction) required in the electric and autonomous vehicles market. As such, major automotive manufacturers have been active in forming joint venture partnerships with large carbon-fibre producers in order to conduct research and move automotive CFRP closer to large scale commercial reality (e.g. Carbon-Nexusan). Such firms are actively investigating in new pilot production lines to decrease the cost of carbon fibre composites and work in collaboration with top global automotive producers (e.g. VW, BMW and Audi). Such partnerships have also improved suppliers throughout the value chain, growing in capacity size and produce faster/effective equipment, resins designed for vehicle CFRP, and scalable CFRP recycling methods. Nevertheless, there still remains uncertainty and it could take until mid-2020s for it to be economically and technically feasible (scalability) for vehicle OEMs to produce mainstream vehicles that would be using large amount of CFRP. There are other additional factors in the industry that could affect the adoption (i.e. whether, when, how) of CFRP technology, and its use in vehicles. For instance, in the case of BMW, the manufacturer celebrated the 100,000 production of its i3 that features a monocoque produced from stiff, light, and expensive CFRP just last year. This was a big milestone since carbon fibre was still reserved for racing and supercars. However, the i3 was not a luxury sports car, and the fact that CFRP was used so extensively in this line of car, was a sign of intent that large OEM was investing $1Billion in its SC to commercialise carbon fibre. By expanding the use of hybrid materials, the manufacturer replaced heavy-steel with lighter-gauge-steel/aluminum and created a multi-material approach trough ‘intelligent light-weighting’. Therefore, the key to a successful future scalable use of CFRP is designing strategies that enable integration of carbon fibre into the traditional process. The above example demonstrates the relevance of how various normative and peer pressures interplay with each other.

This study can assist in this decision-making process and enable manufacturers prioritise between regulations and economics (e.g. cost, scalability, and technology). The tipping point between regulations and economics is what creates peer and normative pressures, that is why cost is a key peer pressure (i.e. production costs, legal suits). In other words, it resembles a mirror reflection of the institution driving the actual life-cycle as project moves from mimetic to normative to regulatory. However, there are so many different indices/measures to choose from, making it difficult to prioritise. Therefore, it is important for manufacturers to know exactly where the hotspots are at each stage and use that intelligence to assist in prioritising the measures that they focus investments on. In the case of BMW, the company took the cost (mimetic pressure) on itself and directed their investment in CFRP and its SC. In such case the manufacturer assumed that such mimetic pressure was about to complete the cycle (become norm) and positioned itself as a frontrunner with CFRP (i.e. focused investment not on norm - but on chasing that peer-normative pressure). Whether the focus is on hybrid material or advanced manufacturing most companies have to trade off on cost, which is mimetic pressure. All basic mimetic/peer pressure starts off at cost, sometimes in the transition between one phase to the other cost still outweighs the benefits. In the above case lighter materials started off very costly, and gradually with technological investments in upper tier SCs, became more feasible. Therefore, it is important for manufacturer to know when competitors are turning from cost to waste, as a business they have to be either be on top of the game or follow the regulation.

Combining life-cycle thinking with institutional theory could also be used to frame company, national, and industry level policies. There a number of institutions guiding the automotive industry (e.g. materialise, manufacturing, design) and for far too long, policy recommendations have been guided by norms and regulations without considering the role of mimetic pressures. If modern vehicles are changing the shape/positioning of their seats/steering-wheel (self-driving), experts working on smart designs require capturing the mimetic pressures earlier on and include them into automotive design process. Such experts have in place regulatory requirements for example, chassis and suspensions required to meet stringent requirements for road roar, noise and vibration in tyre and agility-without compromising on active safety. There also norms in place such as interior quietness, or lack of noise vibration harshness (NVH) felt by drivers. However, as highlighted above more focus needs to be paid to mimetic pressures (e.g. using new materials for shock-absorbers). They are the beginning of the transition to regulations, so whatever regulations an industry has pegged long-term should effectively anticipated mimetic forces. Therefore, before such pressure turns into norms, its already a fitting regulation and the members in that industry could willingly adapt it (more sensitive policy making).

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