A MULTI LEVEL PERSPECTIVE ASSESSING ALTERNATIVE CELLULOSE ADDITIVES IN PAPER PACKAGING

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Paper is a ubiquitous product integrated into nearly every global industry. While the paper packaging industry has made strides toward closed loop chemical recovery, fundamentally the conversion of plant matter into paper requires 3 times more water, produces 63% more emissions, and requires about twice as much material than compared to recycled paper fiber (Balea et al. 2020). At the current scale, corrugated cardboard and paperboard represent an ideal high performance product with high fiber recovery that could benefit from increased recycled fiber utilization.

Over 92% of cardboard is recovered making it the highest recovered recyclable of any material by far (*AF&PA*, 2020). Due to cardboard's physical consolidation along the supply chain and the fibers' high mechanical performance, Old Corrugated Cardboard (OCC) is recycled and then reintegrated into the manufacturing process. OCC fiber accounts for roughly 50-60% of all pulp used to make cardboard and using these fibers reduces raw material cost, energy consumption, and effluent/emission release (*DOE*, 2006). Since cardboard makes up 54% of all paper production, OCC reuse is vital to limiting negative impacts in an industry that accounts for 20% of all toxic US air emissions and 6% of global energy expenditure (*EPA*, 2017; Jobien et al., 2013). To maintain cardboard quality, the other 40-50% of pulp must be 'virgin' fiber derived from the Kraft process. The Kraft or sulphate process produces mechanically strong cellulose fiber from raw plant matter; however, with a yield of 30-70% by weight, the constant introduction of Kraft pulp creates an open loop system that accounts for the majority of energy expenditure, toxic emissions, and effluent releases in paper production (Vakkilainen et al., 2012). These are underlying technical processes governing current paper manufacturing practices; in addition geopolitical, economic, and market factors that influence paper packaging manufacture.

Disruptive external forces - in the form of stricter recyclable importation policies enacted in China - combined with increased market demand spurred by the rise of e-commerce have caused price and demand dislocations for recycled and 'virgin' paper fibers. Beginning in 2017, China dramatically reduced importation of recovered recyclables from the United States and Europe. Known as the National Sword Policy, China enacted a new contamination limit at 0.5-1.5% which caused decreases in imports of waste plastic by 99% and waste paper by 33% (Resource Recycling, 2018). This rapid shift caused price disruption in recycled material commodities.

Meanwhile, environmental policy initiatives in the EU have created a “technology-push” for sustainable, biobased products in the packaging industry by implementing a collaboration with the Biobased Industries organization in Europe (BBI-JU, 2020). In addition to this €3.7B private-public sponsored fund, “market-pull” instruments such as the single use plastic ban for select products to go into effect in 2021 have generated supply chain shifts initiated by large stakeholders like Fast Moving Consumer Goods (FMCG) companies such as Adidas and Ikea (Kramm et al., 2018; Rankin, 2019).

The formation of policy support structures that drive market readiness must create collaborative environments that mobilize and motivate industrial producers and entrepreneurs in order to comprehensively integrate sustainable paper packaging technology into production (Hasenauer et al., 2016). This balance of politically led capital injection, external market trends, and industry cooperation relies on promoting technological and manufacturing readiness and distributing value across stakeholders economically, environmentally, and socially.

The STS topic investigates early stage emergent paper packaging additives that transition to commercial deployment and the sociotechnical structures that support these transitions. Two cases studies are presented with each technology offering improved paper sustainability practices but originating from different levels of the sociotechnical domain described - Microfibrillated Cellulose (MFC) from regime level industry leaders and switchgrass grass fiber (Creapaper) from niche level entrepreneurs. A Multi Level Perspective (MLP) lens, developed by Geels & Schot in 2007, demonstrates how the sociopolitical environment and market forces (landscape) apply pressure for sustainability to the paper industry (regime) which are met via technological innovations both outside (niche) and inside the industry. The overarching MLP lens will be bolstered by two granular lenses identifying linear product innovation fomentation in the context of the unifying MLP analysis. Technological and Market Readiness Levels (TRL/MRL), a concept built upon by Hasenauer et al. in 2016, provide a framework for holistically assessing impact and likelihood of innovation commercialization within paper packaging by applying qualitatively quantified rankings and dissecting technological manufacturing barriers juxtaposed with market appetite. Additionally, the concept of Technology/Product Oriented Movements (TPMs) developed by Dr. David Hess in 2005 will explore the involvement of affiliated social movements (SM) in MRL that inform and influence both regime and landscape priority and examine how niche entrepreneurial paper additive innovations like Creapaper are fostered directly by TPMs.

Landscape Pressures Defining Paper Packaging

Cellulose is the most abundant biopolymer on the planet, and is a natural, biodegradable material that is currently integrated into large industries such as packaging. 35% of all packaging in the United States is cellulose based. External, landscape pressures from consumer preferences, e-commerce, and geopolitical shifts suggest that cellulose packaging will gain increased market share in response to petroplastic reduction agendas (Bukowski et al, 2018). Paper production is projected to grow from 422M metric tons in 2019 to 495M metric tons in 2030. (*Statista*, 2020) With the increase in e-commerce, packaging has undertaken a dominant role as the primary form of physical customer interface, and customers' perception of sustainable packaging has impacted FMCG brands. DHL, a multinational express mail service company in Germany, conducted a survey of their largest 800 partners and found that demand for sustainable packaging and public awareness of packaging waste were the top trends shaping packaging strategy (*DHL*, 2020). Similarly, FMCG companies such as IKEA, Adidas, and Colgate-Palmolive have announced plans to transition entirely to recyclable, biobased packaging by 2024-2025 (*DHL*, 2020). Not coincidentally, all of these companies are european based and this apparent market shift has been galvanized by technological-push and market-pull strategy enacted by the EU.

Regulatory changes in the EU, such as the reduction of fossil-fuel subsidies and polluter based tariffs, represent landscape pressures which exert increased MRL and encourage private industry to adopt more sustainable practices through regulatory penalization (Geels & Schot, 2007; Hasenauer et al., 2016). These actions represent policy enabled market-pull strategies adopted to guide packaging industry actors. Other less formal market-pull forces are related to FMCG companies' shifts toward purchasing packaging that align with consumer demand for more efficient and sustainable materials spurred by environmental SM activism and campaigns. Environmental SM organizations like the Ellen MacArthur Foundation's campaign surrounding marine petro-plastic waste or digitally viral incidents like the galvanizing video of the sea turtle wounded by a plastic straw have influenced consumer consciousness and can have significant influence in a sociotechincal landscape for paper packaging (MacArthur, 2017). In the aforementioned DHL survey, the two top trends shaping packaging were demand for sustainable packaging followed by public awareness of packaging waste are the result of public awareness from SM activism. These market-pulls, enacted by companies and politicians which respond to demand raised from SM activism, have preceded and helped drive the strategic technology-push by the EU. This has led to political coalition creating increased investment in biobased industries wich raised public funds of €3.7B for the development of raw materials for the biobased economy with the explicit aim to: foster biomass feedstocks that did not compete with food, optimise the economic viability of flagship biorefineries, and develop biobased products implementable into the market (BBI-JU, 2020).

In conjunction with EU initiatives, recyclable importation tightening through the National Sword policy exacerbated the need for paper packaging innovation. China - which burned high volumes of recyclables - cut importation of waste paper by 33% and an oversupply of OCC dropped prices from the high of $180 per ton to historic lows under $25 per ton. (EcoTechnology, 2018; Katz, n.d.; Resource Recycling, 2018) This policy change exposed recovered recyclables' reliance on exportation for economic viability. With depressed OCC fiber cost and increased prevalence of a more sustainable raw material, this sudden geopolitical shift by China created a window of opportunity, otherwise known as a market opportunity, for paper innovations that utilized circular deployment of OCC fiber to industrialize and integrate into manufacturing. In addition to the EU's market-pull initiatives, the oversupply of OCC fiber served to further increase the MRL for paper packaging innovations that could reduce environmental impact by utilizing OCC. These market-pull policies and external geopolitical events paired with the adequate capital injection offered to the regime paper industry, created a suitable environment to overcome technical challenges for sustainable paper packaging innovations to reach commercial deployment.

Regime Response - MFC Commercialization Spurred by Increased TRL/MRL

The first case example of paper packaging innovation deployment materialized via the Exilva Project through the BBI-JU partnership between incumbent players supported by sustainable landscape level policies in the EU. Exilva was a €44M project spearheaded by the multinational biorefinery conglomerate Borregard and represented a collaboration among some of Europe's largest paper producers (Stora Enso and BillerudKorsnäs) to produce MFC at an economically industrial scale (Exilva, 2020). MFC is a nanoscale cellulose fiber discovered in the 1980's and is similar morphologically to BNC. It is derived from wood pulp through energy intensive mechanical shearing and chemical treatment (Lu et al., 2008). When introduced to paper in proportions as low as 1% dry weight it exhibits properties such as increased (+25%) tensile strength; however, the high cost of production has historically kept MFC reserved to lab scale experiments and a lower TRL than was needed to justify industrial development (Xiang, 2017).

Level	Market Readiness
1	Unsatisfied needs have been identified
2	Identification of the potential business opportunities
3	System analysis and general environment analyzed
4	Market research
5	**Target defined**
6	Industry analysis
7	Competitors analysis and positioning
8	**Value proposition defined**
9	**Product/service defined**
10	**Business model defined coherently**

Level	Technology Readiness
1	Fundamental research
2	Applied research
3	Research to prove feasibility
4	Laboratory demonstration
5	Technology development
6	Whole system field demonstration
7	Industrial prototype
8	Product Industrialization
9	Market / sales certification

	TRL < 5	TRL > 5
MRL > 5	Market available, no technology => MARKET RISK	Market & Technology coherently mature
MRL < 5	Market & Technology in coherence, but not mature	Technology available , No Market TECHNOLOGY RISK

Figure 1: *Top left* presents criteria for determining Market Readiness Level (MRL) indicating market receptiveness toward adopting a new technology to meet a need or challenge. *Top right* presents criteria for determining Technology Readiness Level (TRL) determining technology barriers and pathway for successful deployment. *Bottom* identifies a matrix for aligned and unaligned MRL vs TRL (Hess et al., 2016).

TRL was originally developed by NASA as a numerical scale (1-9) to illustrate the technological readiness pathway from concept to infield deployment; see assessment criteria illustrated in *Figure 1* (Wheeler, 2010). Hasenauer specifically adapted this concept to apply beyond technological readiness to include market readiness. Ideally, both TRL and MRL are in nearly coherent, concurrent steps, but empirical data demonstrated that innovative technology adoption was most successful when MRL was one or two levels higher than TRL, meaning that potential customers are willing to purchase an fledging innovation that is still under development. Based on the criteria in *Figure 1*, MFC represents a TRL of seven with prototype development but no product industrialization, and a MRL increase from seven to eight with a clear value proposition aligned with EU sustainability incentives and packaging purchasers (Hasenauer et al., 2016). Both of these readiness levels are relatively high on the scale signifying the incredibly high level of assurance and market-pull that industries with as large of infrastructure as paper manufacturing require for new product technology implementation. On this note, MFC deployment through the Exilva Project represents an ideal innovation to take forward by the paper industry since: BBI-JU provided capital resources for development, MFC is derived from a vertically integrated woodpulp feedstock, and MFC production uses a majority of existing equipment infrastructure.

Tom Egenes, Director of Strategic Sourcing at Elopak (drink carton manufacturer partnered with Stora Enso), says, "By using MFC, we get the maximum yield out of the raw material and thus more packaging material per ton of board. Important properties, such as stiffness and internal strength, are maintained, with less weight. **Within Europe, there are various incentives and regulations to reduce the weight of packaging material.** The partnership with Stora Enso makes it easier for us to reach these targets." (Songer, 2017)

Jarle Wikeby, Exilva Project Coordinator, says, "For Exilva, the backing of an organisation the size of **BBI JU has strengthened our confidence in the project and boosted support from our board**." (Songer, 2017)

Mats Hjrnevik, marketing manager of Borregaard (lead company for Exilva project), says, "**I think the support the BBI JU brings is a key risk mitigator**; with the EU showing that they really stand behind us, and truly mean it when they say they want to support more sustainable technologies. That's key for companies like us to be able to succeed."
(Songer, 2017)

Figure 2: Displays quotes from key executive positions within regime level companies explicitly mentioning the significance that the BBI-JU and Exivla project had in MFC commercial development.

With the capital incentive of the Exilva project, MFC incorporation into packaging is now undergoing trials with Stora Enso producing 500,000 tonnes of paperboard containing MFC that will be converted by BillerudKorsnäs into lightweight milk cartons representing MFC technology crossing the TRL eight and nine thresholds (Williamson, 2017). Additionally, monetary incentives offered by the EU to reduce weight and increase recycled fiber content in packaging (both technical qualities that MFC possess) represent market-pull strategies that: create value for all stakeholders in the distribution chain, increase market appetite, and forward technological development (Williamson, 2017). *Figure 2* shows quotes from key positions within these companies highlighting the effect that landscape support has had on the development of this industrially intensive regime level project (Songer, 2017). Particularly, notice that the bolded sections explicitly state that the capital afforded to these industry leaders combined with the increase in MRL from market-pull EU strategies created the incentive for the monoliths of this industry to overcome the TRL needed for market deployment of a sustainable paper packaging innovation. Together the market-pull, technology-push mechanisms enacted by the EU and other external landscape pressures served to overcome technological lock-in impeded for 40 years to see MFC industrialization.

Niche Response - Creapaper Development Assisted by TPMs

The BBI-JU has also created opportunities for capital investment in innovations outside the loci of incumbent actors. While industry regimes possess large networks of technical capability and social capital, other niche networks that produce technological innovation exist as well. Hess introduces the concept of TPMs in which entrepreneurs create technology in conjunction with SMs like the focus toward sustainable materials (Hess, 2005). TPMs are a subset of SMs described above in which less emphasis is placed on the politics of protest but instead focused more on diffusing and developing alternative technologies to challenge regime level industry actors. Whereas typical SMs aligned with more sustainable packaging might influence the regime through activism to modify consumer behavior like campaigning against excess packaging or political coalition led policy like styrofoam bans; TPMs, like the one that supported Creapaper, challenge regime authority through technological design alternatives through a network of inventors, industrial reformers, and research organizations.

Creapaper is a small company that utilizes switchgrass locally grown on economically unproductive, fallow land to create an alternative cellulose feedstock for paper. Sourcing raw material locally cuts down on supply chain emissions and creates additional revenue streams and jobs for rural farmers and landowners. This social value combined with the fact that Creapaper fiber production uses: 75% less energy, no chemicals, and 1% of the water required for traditional wood fiber processing earned Creapaper a €2M grant from the BBI-JU (Creapaper, 2020; Terlau, 2017). However, breaking into this position was not without barriers described by Hasenauer.

These barriers known as “rules of the game” by Hasenauer are imposed by regulatory bodies and industry actors that can prevent new innovations from entering the market. In Creapaper’s early stage development, no paper producers would use their fiber since it didn't have material certifications, and it was feared that the new material would damage their machinery. This represents Creapaper’s fiber fitting a TRL of three/four with research validating claims and some demonstration but requiring further technology development. D’Agnone, the founder, utilized the TPM network and established a relationship with Bonn University to garner technological credibility. Through this relationship, Creapaper was then able to break into the paper industry with initial sales to companies that broadly supported the sustainable packaging mission of the TPM which demonstrated a defined target with a MRL of five. Through the capital injection from BBI-JU and reliance on the TPM network, Creapaper fiber has become listed as a standard material on the european paper index which coincides with crossing TRL eight and nine. Now 26 factories currently use their fiber since emission reductions offer EU incentives for paper producers and grass based paper generates positive sentiment from consumers (Jurgs, 2017).

Creapaper fits what is described as an entrepreneurial private firm, and Hess hypothesizes that the TPM pathway for a private sector symbiosis dictates that successful innovations produced by social movement led entrepreneurs are eventually so influential they become integrated into industry practices; the same industries that these TPM led product stood to rebuke (Hess, 2005). In this assimilation, Hess notes the tendency for the established industry to absorb these practices or technologies. This notion is congruent with MLP theory that suggests one route for sociotechnical conflict between the regime and niche levels is that regime level actors will incorporate niche technology (Geels & Schot, 2007). However, these industries may alter the technological design to be more consistent or complementary with current incumbent infrastructure, practices, or corporate profitability. Given strong current and projected EU incentives to minimize environmental impact for paper packaging, Creapaper looks to be an ideal technology for acquisition or licensing by larger incumbent players in the industry. With reduced supply chain length, increased land productivity, and reduced resource expenditure for processing, it is unsure how regime integration could lead to a decoupling of Creapaper's technological implementation from it's TPM foundational values. The aforementioned environmental qualities of Creapaper, like MFC technology, are desirable for incumbent paper manufacturers whose infrastructure is closely aligned with these paper packaging fiber innovations. Comparatively, biorefineries and pulp plants have higher technological lock-in costs since Creapaper fiber or MFC fiber conversion may require different equipment.

Conclusion - Synthesis and Synergy Among MFC and Creapaper

Between these two case studies exist overlapping and reinforcing interests. Currently, the grass fiber content of paper packaging is limited due to mechanical performance, and MFC has been demonstrated to improve tensile strength (Creapaper, 2020). The addition of MFC could allow for an increase in grass fiber content creating value for stakeholders like: rural farmers, entrepreneurs, biorefineries, distributors, and consumers while exhibiting a lower environmental impact that aligns with current EU initiatives for creating sustainable paper packaging. This sociotechnical transition is still ongoing with major considerations such as scale up of infrastructure, timeline, and market performance have yet to be determined.

Short term non vertically integrated paper packaging producers may be better positioned to adapt and integrate these innovations. Long term, the scale up for both MFC and Creapaper fiber will be required and instrumental to widespread adoption that will give clearer refinement for business models and economic sustainability. While both have crossed the threshold for TRL deployment certain large scale manufacturing criteria (defined by Manufacturing Readiness Level) are unmet. Currently, both Creapaper and MFC represent a narrow fraction of the total amount of fiber used for paper packaging (exact numbers are unknown as deployment performance is ongoing and clandestine for proprietary concerns). Also what is currently unknown is the quality of recovered Creapaper fibers of the effects of switchgrass fiber entering into fiber recovery in large quantities. Lower quality OCC made from Creapaper could result in higher concentrations of Kraft pulp or MFC additive required to maintain mechanical performance and could disrupt the balance of bottom lines and lessened environmental impact.

Overall, this research analysis has demonstrated that the EU has conducted an effective policy led incentivization structure utilizing the mechanisms of technology-push efforts through proper capitalization of industry incumbent leaders and niche level entrepreneurs as well as market-pull efforts to increase sustainable packaging evident through sustainability commitments made by large FMCG companies like Adidas and IKEA. These market-pull efforts are the result of specific policies addressing single use packaging waste partially reflected by environmental SMs in the EU that have consolidated political influence and representation. With the reduction of wasteful packaging through diminished resource expenditure and pollution, paper packaging provides an obvious, already deployed, and market expandable replacement for a myriad of plastic packaging options. Touting the highest recovery rate of any recyclable, cardboard stands to gain significant enhancement in sustainability by extending the utility of recycled fiber or OCC. Additionally, geopolitical landscape forces from China’s recycle import ban created a surplus of a more sustainable material while decreasing costs representing another external pressure on the regime to develop sustainably minded paper packaging innovations that leverage and extend OCC.

With the BBI-JU policy support through capitalization and increased market demand represented by higher levels of MRL, paper strengthening fiber innovations such as MFC, generated by the paper packaging regime leaders, overcame TRL challenges to see the deployment of scientific discoveries unearthed 40 years ago into industrial production and sale. Additionally, the BBI-JU helped fund niche level entrepreneur led innovations that focused on technological alternatives which were fomented through TPM networks of industrial research and purchase from early stage adopters. Both industrial research and early stage adopters respectively increased the TRL and MRL, and created institutional support and integration for a fiber additive that reduces resource expenditure and sprawling supply chains. Each of these innovations, although originating from different levels defined in MLP represent products that increase value for downstream stakeholders. TPM and MLP theory hypothesize that integration of these two technologies are possible, and given the complementarity of the two technologies it seems likely. However, in an industry as large as paper packaging - increased scaling, infrastructure adaptation, product performance, and business model refinement still pose major questions to the underlying profitability and sustainability benefits afforded from these technologies. It is sound to say that the increased EU policy adopted to facilitate the technology-push and market-pull mechanisms have produced accelerated outcomes for achieving activation energy needed to introduce sustainable innovations to the paper packaging industry.

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