sustainability

Article

Supplementary Information A.

Table S1 shows the literature findings grouped according to research approaches explored.

Table S1. Main findings in the circular economy literature.

	Approach/Topic	Author	Main contribution
Circular business innovation – concept	Providing a definition of BMI	(Amit & Zott, 2012)	BMI refers to changing "the way of doing business" and not only "what you do". […] it is not only about products and services but **encompasses a wider scope.**
		(Johnson & Suskewicz, 2009)	BMI involves *"shifting the focus away from developing individual technologies towards **creating new systems**"*
		(Wells & Seitz, 2005)	Four archetypical closed-loop value chains for BMI were identified. The archetype closest to the PaperChain demo cases is the "post business loop" in which material is **an exchange between different companies.**
	CBMI definition	(Nußholz, 2017)	Talks about Circular BM and that implementing circular strategies often requires more holistic and radical changes **beyond the boundary of a company**.
	CBMI related to system	(Antikainen & Valkokari, 2016)	CBMI is **networked and entails collaboration**, communication and coordination within complex networks of interdependent but independent actors/stakeholders. The main challenge is then to find a "win-win-win" situation in which the self-interest of the different actors is respected
	CBMI reference framework	(Lewandowski, 2016)	**"Triple fit challenge"** to facilitate the transition from a linear to a circular business model and reduce the inevitable uncertainty when designing a new model: 1) from linear business model innovation: value proposition fits the customer segments; 2) the cost structure fits the revenue streams; and 3) how the changes a company implements towards a more CBM, and adoption factors (internal and external), can hamper the process.
	System	(Poutiainen, 2015)	A system thinking approach is recommended to optimise the whole circular business model: seven and nine blocks of BM Canvas can be affected by the circularity character of the model.
New refer-	Design for Sustainability (DfX) & CBM	(Moreno, De los Rios, Rowe, &	**Circular Design Framework**: there is a need to provide design practitioners, industry stakeholders and product developers with recommendations as to how to think about particular design strategies for different circular business models.

		Charnley, 2016)	
	Sustainable Circular Business Model	(Antikainen & Valkokari, 2016)	**Extension of the classic BM canvas**. **Three strategic levels:** 1) Business level, which includes similar building blocks to the BM Canvas; 2) Business Ecosystem level, which includes macro factors such as trends/drivers (economical, geopolitical, legal, etc.) and external stakeholders (NGOa, media, public bodies, etc.); and 3) Sustainability impact level, which enables the sustainability and circularity of the model to be assessed.
	Circular Business Model Canvas	(Lewandowski, 2016)	An adapted version of all BM Canvas' dimensions taking into account the CE principles and two new constructs: **Take-Back-System** (the design of the take-back management system including channels and customer relations related to this system) & **Adoption factors** (transition towards a circular business model must be supported by various organisational capabilities and external factors).
Business case for sustainability	Critical elements	(Schaltegger, Lüdeke-Freund, & Hansen, 2012)	Besides the most cited critical elements, special attention should be paid to proactive strategic management – to address many business case drivers strongly and continuously, which results in the regular creation of business cases for sustainability; attractiveness as an employer (indirect influence); innovative capabilities (indirect influence)
		(Stubbs & Cocklin, 2008)	An SBM draws on Economic, Environmental and Social Aspects of Sustainability in Defining an Organisation's Purpose. An SBM uses a TBL Approach to Measure Performance. An SBM considers the needs of all stakeholders rather than giving priority to shareholders' expectations.
		(Witjes & Lozano, 2016)	Sustainable Public Procurement – collaboration for Sustainable Business Models: includes technical, non-technical and socio-cultural specifications that are co-developed and decided between the government agency and the potential suppliers
		(Giurco et al., 2015)	Key Success Factors – Implementation: Governmental structures providing long-term and consistent support frameworks, enabling circular economy activities; Legal and regulatory support (e.g., product and material eco-design); Availability of investment capital (e.g., for new infrastructure)

Supplementary Information B. The system dynamics causal diagram

Derived from systems thinking, SD combines the theory, methods, and philosophy needed to analyse the behaviour of systems in numerous research fields, such as management, environmental change, politics, economic behaviour and engineering (Hjorth & Bagheri, 2006).

It is worth highlighting some of the main premises of SD, especially:

1. The models created by applying SD focus on modelling the behaviour of the system as a whole, rather than modelling the behaviours of actors within the system (Harrison, Lin, Carroll, & Carley, 2007, p. 10).
2. At a system level, these models simulate the processes that lead to changes in the system over time (Sterman, 2000).
3. Although all the models portray simplified representations of reality, aiming to provide a better understanding of it, SD allows to understand how the interrelations between the elements of the system originate unexpected or side effects over the system as a whole (Sterman, 2000).
4. SD, as a modelling technique, should support the process of strategic development (Kunc & Morecroft, 2007).

After performing an in-depth analysis of the potential interactions, the feedback interactions and overall dynamics of the key variables that intervene in the dynamic process for creating a sustainable circular economy model of industrial symbiosis is portrayed in Figure S1.

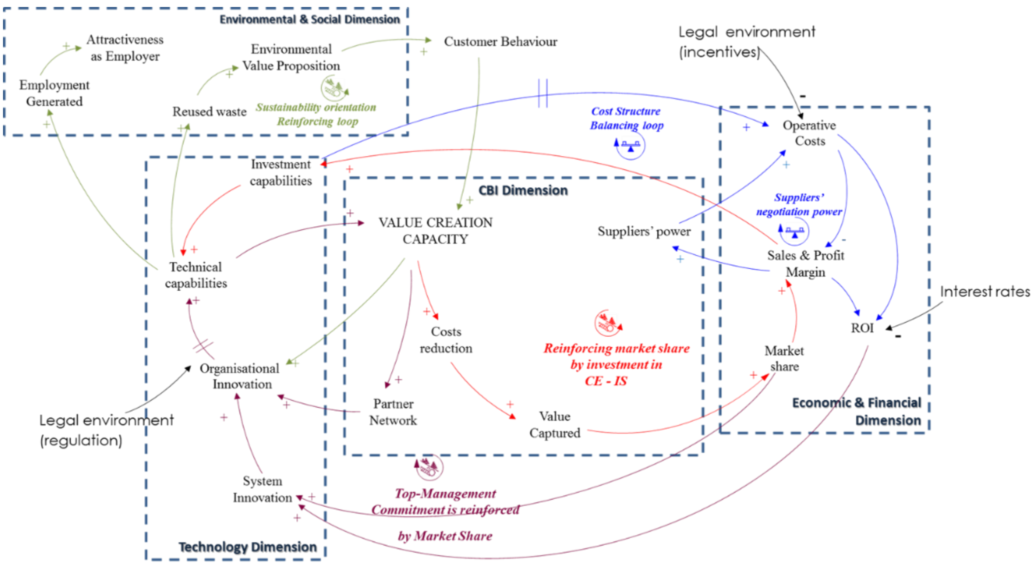

Figure S1: Causal Diagram of the circular economy model

This SD causal diagram helps to better understand how the new technological capabilities interact with the elements of circular business innovation at different stages of the process. Three reinforcing loops dominate the behaviour of the system: *'Reinforcing market share through investment in CE-Industrial Symbiosis'*; *'Top management commitment reinforced by Market Share'; and, 'Sustainability Orientation reinforcing loop'*. The positive effect of these three feedback loops is controlled by two main constraining forces, namely new or raised operative costs, which will have a negative impact on sales and profit margin, and the potential increase of suppliers' power (for the Pulp & Paper Industry), which in turn also increases operating costs. These restricting forces are strong enough to control the system and mean that capabilities or profit will not grow indefinitely. In addition, two external forces were discovered which, could delay the positive growth of the system, as expected as well as provoke the reduction of cost structure:

- Legal regulation: whose role could be to stimulate the circular economy by setting limits to waste treatment that affect reuse or foster innovation. However, regulation could also hinder CE if it is complex or fragmented;
- Legal incentives: fiscal and financial incentives that could reduce operating costs once the investment in capabilities is implemented.

Supplementary Information C. Detailed information of the industrial circular cases

A relevant contribution to this research came from our interaction with industry. More specifically, industry participated in various discussions via virtual web-based and face-to-face meetings at several European locations. This interaction was intended to result in a complete characterisation of the five demo cases.
This section includes a brief summary of the five CEMs including the context (waste to be valorised, the need, the solution, innovation and the result) and the stakeholders involved in the value chain.

1. Construction sector as end-user: precast concrete and asphalt

The circular case in which the demand side is represented by the construction sector portrays a resource-efficient partnership in Portugal (Europe) involving the Pulp and Paper Industry (PPI) and companies from the construction sector with the aim of valorising caustic waste from the PPI (i.e. lime ash, dregs and grits, green liquor dregs) as Secondary Raw Materials (SRM) in two technical pilot demonstrators: a trial with two precast concrete structures produced for a set of porticos (lime ash is used as a mineral aggregate in cement-based materials for the building industry), and an asphalt road stretch (dregs and grits are valorised as alternative raw materials incorporated in a bituminous mixture for the construction of a road stretch (≈250 m)). Figure S2 illustrates the direct and indirect stakeholders participating in this CEM graphically.

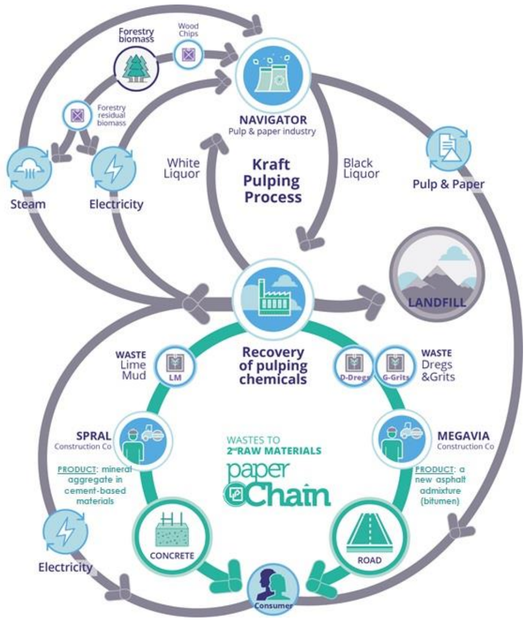

Figure S2: Circular case study 1 - lime ash in pre-cast concretes and new aggregate-bituminous mixtures ("green asphalt") in Portugal.

The stakeholders directly involved in the CEM are the PPI company, waste manager, road construction company, concrete construction company and research & development centre; while the indirect stakeholders are certification bodies and public departments in the sectors involved (Portuguese road authority, National Civil Engineering Laboratories).

2. Transport infrastructure sector (road stabilisation) as end-user

The proposed alternative in the transport infrastructure sector is a circular renewability and recycling model to produce new hydraulic road binders. It aims to valorise Waste Paper Fly Ash (WPA) produced during PPI waste energy recovery (Spain) as an alternative binder for soil-stabilisation works in road projects. The WPFA substitutes cement and lime in the Hydraulic Road Binder (HRB) used in sub-base and subgrade layers and recycled pavements. Three demo cases have been run to test the usability of WPFA for road layer binders and demonstrate its technical and environmental performance as a suitable replacement for cement and lime. In total, a valorisation of around 220 tonnes of WPFA, which replaced 150 tonnes of cement, was achieved, with 114 tonnes being employed in the soil cement layer

In this circular model (Figure S3), the stakeholders directly involved are the PPI company, a large construction company, which is responsible for adapting current construction procedures to the alternative binders, with technical support for dimensioning, structural calculation, modelling, testing and monitoring being provided by a national university; the indirect stakeholders are certification bodies and public regional entities in the transport sector, which support the demonstration activities.

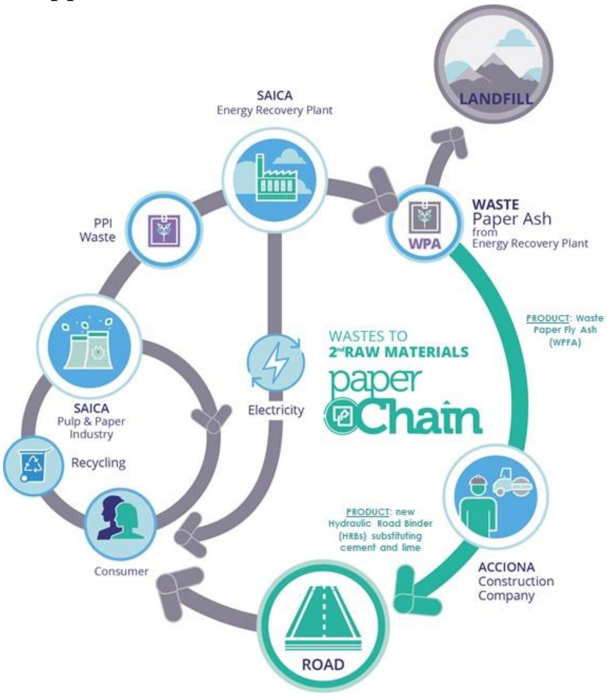

Figure S3: Circular case study 2 - Product-Service System (hydraulic binders as SRM & soil stabilisation) in Spain.

3. Transport infrastructure sector (slope stabilisation in railway infrastructure) as end-user

The pilot site in Slovenia allows the possibility of using two secondary materials from the PPI, namely wastepaper ash and deinking paper sludge (mixture of PSA and DPS), to be used as a composite material for slope stabilisation in railway infrastructures. The composite material, known as MUDIPEL®, is used as a backfilling material that can be applied in several contexts, for example as a back-fill material behind the retaining wall structures in open-pit mines.

As Figure S4 shows, the stakeholders involved directly are a producer of newsprint and coated graphic paper (PPI), a wholly state-owned enterprise that provides maintenance and management for public railway infrastructure, rail traffic, and transport of passengers and goods on public railway infrastructure at the national level and provides the demo site with an identified landslide problem, and a research institute that has accredited laboratories for testing the recycled material in the earlier phase and performs third party control of the whole geotechnical structure at the construction site. Slovenian technical approval was granted for the new composite, thus allowing it to be used as a construction product in Slovenia.

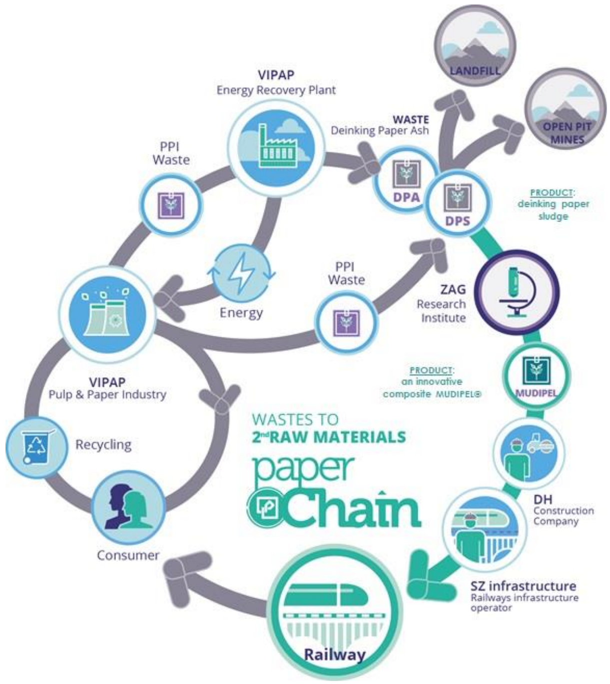

Figure S4: Circular case study 3 - New composite material for use in slope stabilisation in Slovenia.

4. Chemical sector as end-user

This circular case study showed the potential use of wood fibre sludge as a feedstock for the production of bio-based ethanol derivatives in the chemical industry built upon the partnership between a sulphite mill, chemical plants and an R&D centre in an industrial symbiosis scenario located in Sweden. It targeted the valorisation of fibre sludge waste generated by the pulp industry to produce bio-ethanol as raw material for secondary ethanol derivatives for the chemical industry. The end-product of this circular renewability and recycling model is Bermocoll, a high-grade, water-soluble polymer that can be used as a paint thickener and binding agent in the construction industry.

A biorefinery with a wide range of products, all based on renewable and traceable raw materials, which provides the ethanol; a firm specialised in refining biofuels and green chemicals that converts the bioethanol into ethyl chloride; a leading global paint and specialty chemical company that uses the bio-based ethyl chloride to produce Bermocoll; and a research industry that oversees the project's implementation and supports its completion were the main stakeholders participating in this circular case study (Figure S5).

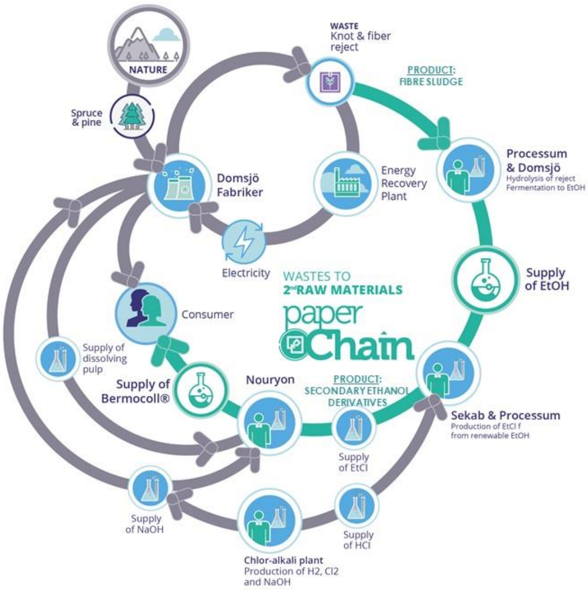

Figure S5: Circular case study 4 - Fibre sludge as raw material for secondary ethanol derivatives in Sweden.

5. Mining sector as end-user

In this CEM, residual Green Liquor Dregs (GLDs), which are produced as a by-product during the Kraft process for pulp manufacture, are used to produce a sealing layer for acid rock drainage mitigation in mine waste rock deposits. The stakeholders directly involved in this circular model (Figure S6) are: a mining company that provides the demo site and technical assistance in relation to mining procedures and requirements for soil cover, mining waste provision and handling recommendations; a national university that, in addition to planning and evaluating the demo case, provides support for dimensioning, testing and monitoring the heavy metals content; and, finally, a research institute that coordinates the circular case, performing material characterisation and monitoring of the demo; the indirect stakeholders are a privately held corporate group involved in waste management, environmental services and recycling.

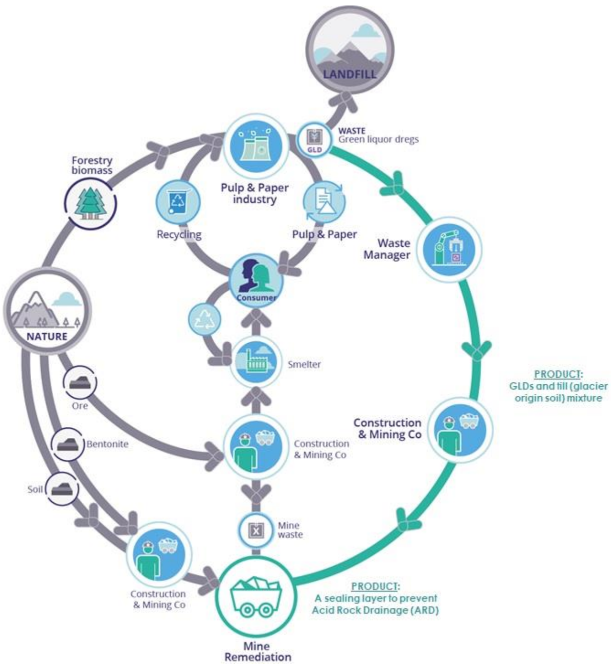

Figure S6: Circular case study 5 - By-product mixed with till and applied as a sealing layer in Sweden.