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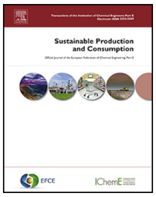

Perspective article

Exploring the circular economy through coatings in transport

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ABSTRACT

Coatings are widely used in a range of aesthetic, protective and durable applications, often leading to extension of the in-service period of many components. There is sizable demand for coatings in the transport sector across road, rail, marine and air. However, the issue of materials circularity with consideration of their surface treatment is an under researched and often overlooked area. The aim of this paper is to explore challenges and enabling factors that can catalyse industrial growth of a new material, technology, or process by investigating coatings within the transport sector. We do this by studying six new or novel approaches that have garnered significant research interest in the last decade, set against system-level drivers and enablers of circularity. Our findings highlight the complications, assumptions and benefits of a circular transition. We conclude that policy and regulation play a key role in supporting or hindering the transition, and further consideration of material 'lock-in' is required to understand how materials can be phased out from a design standpoint.

1. Introduction

A coating is a layer, or layers, of material that is applied to the surface of an item (known as the substrate) for aesthetic, functional, or informational purposes (Weiss, 1997). Cars, trains, ships, and even bicycles use coatings to protect surfaces and keep products functional for their design life. Whilst manufacturers now utilise more plastic and fibre-reinforced composite parts (Blanco et al., 2021), the quantity of painted and coated components has also been increasing (Sokol, 2022). Considering the transport sector, many raw material suppliers and manufacturers already recognise that coatings need further attention to reduce their impact on the environment (driven by corporate social responsibility or sustainability drivers). Current approaches include using water or environmentally benign solvents and biologically derived resins as binders (Buisman, 1999) instead of synthetic polymers. For many examples, these solutions do not consider end-of-life, issues of practicality or economic recycling of waste (Paruta et al., 2021). We therefore suggest a systems-level perspective is required, coupling responsible design and manufacturing with end-of-life waste and pollution removal, but in an economic model that enhances business resilience whilst mitigating external market risk.

Circular Economy (CE) has been gaining increased traction with academia, industry, and policymakers. Whilst CE has many definitions and practical applications, they all try to move beyond a linear take-make-waste model, to one where waste is designed out and materials are kept in use for as long as possible (Alexander et al., 2018). CE theory borrows a key principle from industrial ecology, in that natural systems (or ecosystems) serve as a template for designing new industrial systems, allowing biological or technical 'nutrients' that can be repeatedly cycled (Hobson and Lynch, 2016). Regenerative practices look to "reverse and recuperate from the negative impact of humans on the environment" (Mehmood et al., 2020). Another key part of CE is the role that actors and their respective societies play in these transitions, limiting negative effects and providing benefit for all (Deutz, 2009). Therefore, from a materials and design perspective, we can reduce toxicity of materials that we use, aim to recycle and re-use components that have already been made, and look to select raw materials that can be generated from renewable methods (an example would be to select bio-derived polymer materials rather than those generated from by-products of oil) so that nutrients can be returned to the soil after use. However, adoption of CE techniques in manufacturing environments is particularly complex and potentially disruptive. Mismatch between shifting demand, supply, and the value of used components causes uncertainty about costs and return on investment (Lopes de Sousa Jabbour et al., 2018). There is also a lack of understanding around system-level enablers that support transition towards a CE and how they can be used to ensure solutions can be successfully implemented.

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The motivation behind this research is to further explore the issue of materials circularity with consideration of their surface treatment. The transport sector provides an interesting case in which to discuss opportunities and challenges surrounding implementation of new concepts. Firstly, they provide an example of how products have evolved to contain complex material systems (coating layers often include pre-treatment, protective layer, primer, basecoat and clear coat which are less than one millimetre thick). Environmental concerns of solvent emissions (Goodship and Smith, 2008) and contamination (Paruta et al., 2021) from paint have been well documented, however, these multi-layer coatings are currently challenging to separate and difficult to recycle. Secondly, materials and production usually involve complex, global supply chains. Thirdly, it is an under researched and often overlooked area (Brown and Job, 2019) that is almost entirely based on concepts that date back to the industrial revolution. Existing research on these material systems has focussed on recyclability of substrate materials, or on a coating material alone, rather than a combination of the two, as found in commercial application. The changes required to overcome technology lock-in and system-level paralysis are therefore considerable. The aim of this paper is to explore challenges and enabling factors that can catalyse industrial growth of a new material, technology, or process by investigating coatings within the transport sector. We do this by studying six new or novel approaches that have garnered significant research interest in the last decade, set against system-level drivers and enablers of circularity. Although there is not scope within this paper to discuss each related piece of research in detail, we provide references to signpost the reader.

2. Methodology

We use a retroductive method to compare and contrast new and novel innovations with principles from CE and systems-level adoption theory (Ragin, 1994). This includes an analysis of the nature and dynamics of technological change (Gao, 2015; Geels, 2006). We draw on a wide range of sources to explore technological evolution (Utterback and Abernathy, 1975), theory of dominant design (Anderson and Tushman, 1990) and consider the influence of system level challenges and enablers.

Our observations are grounded in coatings in the transport sector (as one case), comparing multiple applications in this context. Fig. 1 illustrates our framework for case selection. Qualitative case-based research is a useful approach for applied in-depth research on a phenomena or process in a real-world setting (Yin, 2009; Yin, 2018). Richness, rather than discrete observations, is used in this exploratory study which lends itself to more open-ended questioning (Alasuutari et al., 2008). Beyond transparency, accessibility, and convenience, we chose and framed our case study based on its ability to provide detail and nuance (Silverman, 2013) to the specific aspect of implementing new materials, technology, or processes in relation to an overarching CE theory.

Even though they may share common raw materials, the supply chains of each transport segment function independently. There are, however, considerable potential benefits that might be realised if CE principles were adopted throughout these supply chains. Therefore, the transport sector was specifically chosen to provide insight to how and why actors, actions, and contexts within a single sector could influence a cascading chain of materials supply.

Based on a thorough comprehension of one case, a foundation is built for appreciating other comparable circumstances (Eisenhardt and Graebner, 2007; Gerring, 2004), without generalising to other situations. As a result, the analysis of the researcher(s) and evaluation of data used are essential in applied research. We employ problematization as a process for interrogating the assumptions that underpin not just others' but also our own perspective, and construct new research questions as a result (Alvesson and Sandberg, 2013).

Data was collected from multiple sources, including academic literature, industry reports, patent searches, alongside informal collaboration with stakeholders through discussions and emails. The data was structured by logically tying it to a collection of recurring elements, and then analysing the resulting information. This method allowed for the collection of insights on emergent themes. The ability to relate the data to their respective components simplified the work of understanding the case study findings.

3. Background and recent innovations in coatings

In the early 1900s, the industrial revolution brought in new markets for paints and coatings. Today paints and coatings are used in large quantities across a wide range of products to decorate, preserve, and prolong the life of items. This emergence of a single technological design that gains market dominance is referred to as "dominant design" in the product innovation literature (Utterback and Abernathy, 1975). The introduction of a dominant design is a significant turning point in the history of an industry, and it has altered the way businesses compete (Anderson and Tushman, 1990). A dominant design is a major technical element that has become a custom or convention that has risen to the

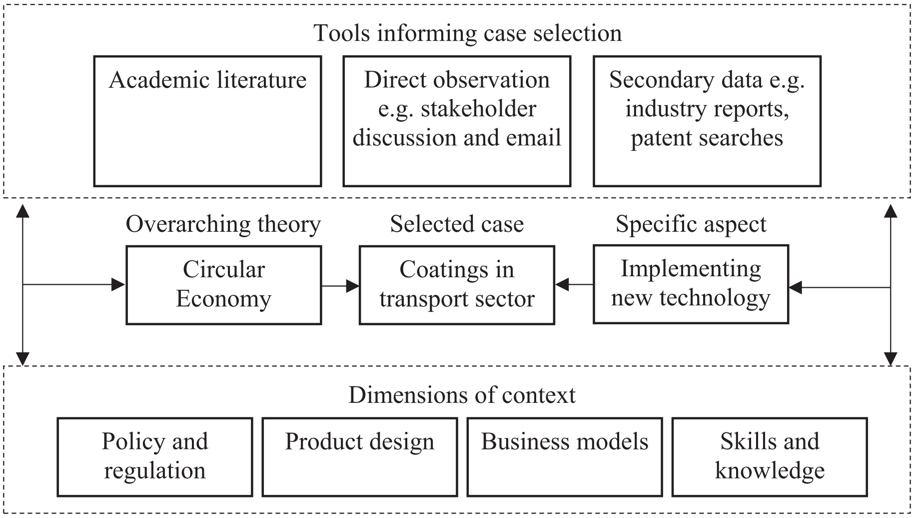

Fig. 1. Framework for case selection.
Inspired by (Poulis et al., 2013).

top of the market due to public approval or market adoptions (Utterback, 1996).

Innovation has long been acknowledged as a key factor in economic recovery and long-term competitiveness (Pisano and Shih, 2012). Different stages of the process innovation lifecycle have been identified in previous research (Kurkkio et al., 2011). Early work in this area does not discriminate between product and process innovation, implying that both should be approached in the same way (Utterback, 1971). Others view process innovation as a subset of product development or emphasise the two mutual benefits (Hayes et al., 2011). Some firms, for example, are said to produce goods and production processes at the same time using design-build-test cycles, where both are imagined and tested until a final design is obtained (Hayes et al., 2011). Similar to product innovation, technological process innovation has been highlighted as a facilitator of competitive advantage, making it a critical component to coordinate product and process development (Porter, 2011). However, innovation adoption is known to be challenging, and a recent study found that only 30% of European firms have introduced a new or considerably enhanced product or service within a three-year period (Hollanders and Es-Sadki, 2017). In terms of innovation adoption, the link between new product and processes has been examined in the literature in relation to the life cycle concept (Utterback and Abernathy, 1975). Although, the process of promoting new product value concepts from a market viewpoint has been extensively researched (Geiger et al., 2014; Dubuisson-Quellier, 2013; Callon, 2007), market innovations triggered by environmental issues are less well known and have been identified as an area that requires additional research (Goulet and Vinck, 2015; Le Velly and Goulet, 2015).

Paints and coatings are now so mainstream they are almost invisible to customers, and manufacturers frequently do not consider the conventions, before incorporating them in their products. For example, automotive paint represents 10% of worldwide paint consumption, or 5.5 million tonnes. According to a recent estimate, 28% (equivalent to 576 k tonnes of plastic) of all paint used in the automotive industry, would end up in the environment (Paruta et al., 2021). Raw material suppliers and coatings manufacturers are starting to analyse the environmental performance of materials and processes to drive measurable improvements. Consequently, thirty-one chemical firms have formed a joint initiative and global network. The aim is to deliver global improvements for environmental, social and governance performance of chemical supply chains (Together for Sustainability Initiative, 2021). Approaches that have been explored for making more circular coatings include replacing volatile organic chemicals (VOCs) with water or environmentally benign solvents, using biologically derived resins as binders instead of synthetic polymers, and using UV-curable monomers instead of synthetic binders (so that VOC solvents are unnecessary). Future options could include further advances in formulation, to organic solvents or biodegradable resins, or updating products and processes so that less coating is required.

There is also significant work focussed on the recyclability of the substrate material. Even if a component is made of a recyclable material, its recyclability may be compromised if it is coated in a different material that is less recyclable. For example, there is a current trend towards using thermoplastic materials for components, because these can be remoulded and recycled when heated. However, if a thermoplastic material is coated in a thermoset (which cannot be remoulded) then an energy-intensive separation step is required to remove the coating before recycling. Further consideration of the combination of the coating material and substrate (as found in commercial applications) is required (Brown and Job, 2019). We present a brief review of six approaches that have sparked substantial academic interest in the previous decade and can help with either a CE transition or a fundamental systemic transformation. For the purpose of this paper, a transition is defined as 'the process or a time of shifting from one state or situation to another', whereas a transformation is defined as 'a significant change in form, nature, or appearance'.

3.1. Biodegradable and bio-derived coatings

Formulation of a coating traditionally includes a carrier fluid, colourant, and binder resin. As the name suggests, the purpose of the binder is to bind the colourant to the substrate being coated; the binder forms the film coating and is usually polymeric. For more environmentally friendly coatings, then, it is useful to examine binder materials (Buisman, 1999). These may exhibit improved circularity by being derived from biomass ('bio-derived' rather than from the petrochemical industry) (Helanto et al., 2019) or by containing reactive chemical functional groups that make them biodegradable. In practice, these two approaches are linked, because many polymers derived from biomass also contain increased chemical reactivity (compared to oil-derived polymers such as polyethylene, which are highly chemically stable). It should be noted that common polymers used in coatings (such as polyurethane and epoxy) can also be made from bio-sourced feedstock without being inherently biodegradable.

However, replacing 'petro' plastics with 'bio' plastics is not a new phenomenon, especially in the automotive sector; the most well-known material used for this purpose so far is polylactic acid (PLA), which can withstand operating temperatures of 140 °C (Notta-Cuvier et al., 2014). This operating temperature range allows it to be useful for a wide range of operational parts, rather than just car interiors and so on. For example, a group of University students even demonstrated a car whose whole chassis and interior were made from a bioplastic material (Eindhoven University of Technology, 2018).

For transport applications, not all biodegradable polymers are suitable, because their increased chemical reactivity can also lead to lower durability. For example, starch-based polymers, although biodegradable, can also be highly hygroscopic and their tendency to absorb water is highly undesirable for transport coatings. However, this does not hold true for all bio-derived polymers; some can be exceptionally durable and moisture-resistant. Durable biopolymers tend to require different conditions for biodegradation- they may need to be industrially managed (European Environment Agency, 2020) rather than breaking down naturally in atmosphere. This means that materials can be returned to the biosphere in a regenerative process. Effective collection methods and infrastructures need to be in place to separate biodegradable materials at end-of-life and ensure they are sent for suitable reprocessing.

3.2. Vitrimers

There is an important distinction between thermoplastic materials (composed of polymer chains with no permanent interchain linkages, so that when they are heated, they can be remoulded) and thermoset materials (composed of crosslinked polymer chain networks that cannot be remoulded even when heated). For recycling, there is a clear advantage in using thermoplastic materials; however, thermosets do have advantages as coatings, in terms of their physical robustness and scratch-resistance. In the 2010s Ludwik Leibler and colleagues invented and named a class of materials that they termed 'vitrimers' in a nod to their glass-forming properties (Montarnal et al., 2011). Vitrimers are crosslinked, covalently bonded networks that can behave like thermoset materials at the desired operating temperature of the component; however, they incorporate some labile chemical functional groups that can break and re-form at elevated temperatures so that the topology of the crosslinked network can change, as shown schematically in Fig. 2. As the material is heated, labile bonds between polymer chains can break and re-form, giving the material some ability to flow. By contrast, in an associative bond transfer the 'new' bond would be formed before the 'old' bond is broken, leading to a constant concentration of crosslinks. Thus, when heated these materials can exhibit thermoplastic and self-healing properties, and they bridge traditional thermoset and thermoplastic classes of material.

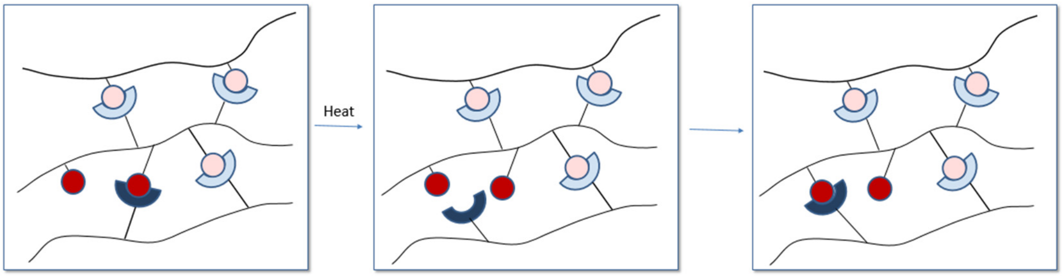

Fig. 2. Schematic to show a dissociative bond transfer in a dynamic polymer system.
Illustration inspired by (Krishnakumar et al., 2020; Yang et al., 2021).

The potential recyclability of vitrimer networks makes them attractive candidates for various industrial applications; the available chemistries of vitrimer networks, and their applicability in industry, has been the subject of some recent reviews (Alabiso and Schlögl, 2020; Krishnakumar et al., 2020; Liu et al., 2020). Vitrimer networks which do not require added catalyst are desirable, because of potential toxicity of the catalyst. Several catalyst-free vitrimer chemistries have been demonstrated (Debnath et al., 2020; Li et al., 2020b; Lessard et al., 2019). Furthermore, if the starting materials can be generated from biochemical rather than petrochemical sources, then the circularity of the vitrimer network is further enhanced (Lessard et al., 2019; Debnath et al., 2020). This field is not merely of academic interest but is also the subject of various patents (Li et al., 2021; Tellers et al., 2021; Li et al., 2019) and is beginning to be commercialised.

3.3. Depolymerisable polymers and chemical recycling

We have already discussed macromolecular networks that can become mouldable when heated above a transition temperature. A related field of research focuses on polymers that can be completely broken down into their component monomers, when acted on by a trigger (heat, light, or a catalyst). Ideally monomers could be re-used to form recycled polymeric materials (Schneiderman and Hillmyer, 2017; Sardon and Dove, 2018; Zhang et al., 2018). This process is termed 'depolymerisation' or 'chemical recycling' (Hong and Chen, 2016). This type of approach could potentially revolutionise our use of plastic materials, making true 'closed-loop' processes possible for the first time in this field. Current plastic recycling techniques focus on mechanical processes such as shredding and re-moulding used plastic; these processes heavily rely on plastic being sorted into separate types before recycling and tend to produce material that is of lower quality than new plastic (Goodship, 2007). However, if the plastic material could be chemically converted back to component monomers at components' end-of-life, then they could be 'repolymerised' with no loss of quality. This could be a significant step towards ending current issues being faced with discarded plastic materials causing major worldwide pollution.

A significant achievement in the chemistry of depolymerisable polymers has been the development of 'self-immolating' polymers, where a bond-breaking reaction at one end of the polymer chain behaves as a trigger for further bond-breaking further down the chain. This field was reviewed by Yardley et al. in 2019 (Yardley et al., 2019). For 'closed-loop' recycling of these polymers, the most interesting materials have chemistries that allow reversible depolymerisation and repolymerisation; examples include poly(benzyl ether)s and polyphthalaldehydes. Thermoset materials have also been demonstrated where the macromolecular structure can be broken down chemically (Oh et al., 2020). Some manufacturers are already using chemical recycling processes in commercial applications. SABIC's TRUCURCLE™ portfolio and services, for example, offer certified circular polyethylene and polypropylene polymers made from pyrolysis oils generated from recycled mixed plastic (Sabic, 2021).

3.4. Structural colour

Traditional paints and coatings are coloured using dyes or pigments that absorb some wavelengths of light. However, it has been known for some time that many animals and plants are highly coloured without the presence of pigments (Prum and Torres, 2003); their surfaces incorporate small regular structures that can interfere physically with incident light. The physics of structural colouration is rather well-understood, relying on optical phenomena such as thin-layer interference, light scattering, and photonic crystals (Kinoshita et al., 2008). In nature, however, combinations of these may be present and give rise to complex and striking colouration (Sun and Tong, 2013). For CE, if aesthetic coatings could be made artificially using structural colour, then recyclability and circularity would be enhanced, because toxicity often associated with certain pigments and dyes would be reduced. If the small structures required for structural colour could be made from the same material as the bulk component, then no extra recycling steps would be required.

For artificial small-scale structures to interfere with light, they need to be of the correct lengthscale, monodisperse, and to be arranged in regular patterns. Recent advances in the fabrication of colloidal particles allow the first two of these criteria to be satisfied; the challenge then is in arranging colloidal particles satisfactorily in repeating structures, using methods that can be scaled up (Liu et al., 2019). Research interest in this field is high and ongoing, with some intriguing work also being done on making 'intelligent' surfaces using structural colour (Shang et al., 2019; Huang et al., 2014). As mass manufacturing techniques develop, processes that mimic small scale surfaces for controlled surface are enabling smaller and smaller resolutions to be achieved (Saha et al., 2015; Walsh et al., 2021).

3.5. Peelable coatings

In addition to the 'chemical' approaches described above for recyclable coatings, it is also possible to adopt an approach where the coating can be physically peeled off the substrate once the coating has reached its end of life. The coating can then be recycled separately from the substrate without creating a mixed waste stream. Approaches for the creation of peelable coatings have very recently been reviewed (Wagle et al., 2021). The essential characteristics that distinguish these coatings from standard coatings are their flexibility, sturdiness, and non-permeability. Binders, pigments, solvents, and additives are all included in peelable coatings, the same as in conventional coatings. The release agent, on the other hand, is an essential element that assists in the simple removal from the substrate. In addition to testing for standard qualities required in coatings, the peelable coating must be tested for its peelable properties. The adhesive force is required for the longevity of the coating, whilst the cohesive force is required for simple removal. As a result, the appropriate balance of cohesive and adhesive forces in a substrate-film combination is critical for easy peeling. These coatings are effective for smaller items and may be sprayed using low-cost spraying equipment. This approach has mostly been used in the packaging industry, however, could have potential in transport, for example anti-bacterial surfaces to help to reduce the spread of microbes (Ro, 2020) or peelable colour coatings as a removable paint and protection solution (American Coatings Association, 2021).

3.6. No coating

In terms of investment, material cost, and manufacturing resilience, the removal of an entire production step is a significant benefit. It has long been recognised that removing the necessity for a finishing phase would open up a significant market potential for lower production costs (Goodship and Smith, 2008). Eliminating an entire coating stage would save energy usage and emissions, as well as simplify product designs to encourage component recovery and reuse for a CE.

4. System dynamics that influence change

Despite widespread support, the CE has experienced minimal implementation so far (Kirchherr et al., 2018). The idea is extensively circulated as an ideal, with application across a range of stakeholders, scales, and sectors, nevertheless, practicalities and real illustrations are limited and fragile. Initiatives often have a technical focus, with little consideration of the socio-ecological challenges (Calisto Friant et al., 2021) or consideration of system boundary limits (Korhonen et al., 2018). Although we have examined some of the technical elements that may influence implementation, we must also consider the role and consequent impact of cross-cutting levers such as product design, business models, policy, and skills, in reducing the gap between ideal circularity and application.

4.1. Policy and regulation

The concept of a CE has been guiding the governance of resource use and waste management worldwide, resulting in extensive innovation of policy instruments. Since the 1970s, closed-loop thinking has progressively affected evolving policy frameworks due to concerns about global resource depletion (Fitch-Roy et al., 2020). Some have argued that policies have been established without clear debate or consideration of system boundary constraints (Inigo and Blok, 2019; Korhonen et al., 2018) and that policy measures to date seem to solely encourage circulation of materials rather than to hinder legacy issues of a linear economy (Corvellec et al., 2021). Since 1975, when the Waste Directive (or Waste Framework Directive) was first introduced, the EU has controlled the narrative for resource use and waste regulation (Backes, 2020). Waste law is an essential tool for promoting the transition to a circular economy, however the implementation of waste regulation might also obstruct new circular solutions due to additional administrative or financial obligations (Gabriela Argüello, 2019). In 2014, the European Parliament introduced a further Directive 2014/95/EU which required companies with more than 500 members of staff to disclose on relevant and useful information including environmental and social matters. Companies have therefore reacted through new 'sustainability' initiates, formed new collaborations and associations to comply with various Sustainable Development Goals (SDGs) (Deutz, 2009; Deutz and Frostick, 2009).

The transport industry has also seen targeted governance to manage waste (Karagoz et al., 2020) including the European Directive 2000/53/EC on end-of-life vehicles (ELV) which promotes reuse, recycling and recovery (Seitz and Peattie, 2004) alongside a ban of hazardous materials (UK Government, 2015). Similarly, the rail vehicle manufacturer industries are working towards developing a unified process for declaring data regarding environmental performances of rail vehicles (International Organization for Standardization, 2019; Silva and Kaewunruen, 2017). The EU laws on ship recycling went into effect in December 2013 (The European Parliament and the Council of the European Union, 2013). The Basel Convention of 2003 stipulates that ships should be recycled using conventional shipbreaking procedures in compliance with technical criteria for environmentally sound management (Secretariat of the Basel Convention, 2011). The electrification of transport requires the integration of materials and technologies that would traditionally fall under the WEEE directive (Cherrington and Makenji, 2019) and therefore, retrieval of secondary raw materials through re-use, recycling and other forms of recovery becomes increasingly important when they are in high demand across sectors. This highlights interesting interactions with the waste electrical and electronic equipment (WEEE) directive which involves the collection and appropriate handling of WEEE, as well as the setting of collection, recovery, and recycling objectives (Goodship et al., 2019).

In March 2020, the European Commission adopted the new CE action plan with new legislative and non-legislative actions aimed at key areas (including plastics and chemicals) where intervention might contribute significant benefit (Fitch-Roy et al., 2020). There is a widely researched link between transport and economic growth (Vlahinić Lenz et al., 2018) that historically has caused a conflict between growth-oriented policies, which tend to increase consumption, and environmental policies, which call for emission reductions. However, to disrupt deeply established, unsustainable production and consumption patterns will require further integration of policy concepts across sectors (Fitch-Roy et al., 2020). To achieve the system-wide levels of social, economic, and technical transformation required by the CE, more radical approaches to policy design is needed.

4.2. Product design

Some CE initiatives have focussed on closing material loops (Velis and Vrancken, 2015). Considering waste as a resource, may inadvertently raise waste demand rather than reduce waste quantities (Greer et al., 2021) and individual product efficiency gains are counterbalanced by an increase in material consumption and use (Zink and Geyer, 2017). There are some design strategies from a materials point of view in terms of dematerialization (using fewer materials whilst offering the same functionality) and material selection (where recycled or materials with lower environmental burden are selected). However, a true CE strategy should address how we deal with existing embedded material stocks as well as radical new designs that disrupt the present system.

There are several circular strategies worth highlighting from a design perspective. Refurbishment is the process of returning old items to useable condition with a guarantee that is less than that of a freshly created object (Souza, 2013). Remanufacturing is a process that restores old items to usable condition with a guarantee and quality that is at least as good as that of a new product (Sundin, 2018). Both highlight opportunities for dismantling and recovering materials at end of life, which is one of the core methods within CE to maintain a product or component at its greatest usability and value (Webster, 2017). One of the most relevant strategies in the context of this paper considers the use of a "component passport" with information on the materials contained in the product to understand suitable next stage recycling or reuse processes (Kang et al., 2016). It is possible that further new technology will appear, however, any CE model must be adaptable to a range of existing processes and solutions within the supply chain. Engagement with internal and external stakeholders from across the ecosystem can also help to scale up innovation. This is particularly beneficial to leverage data to develop new applications. Data analytics provides the opportunity to generate value from data collected throughout the value chain, allowing companies to develop efficiencies, improve performance, increase productivity, and reduce costs. For example, options to reduce emissions or material consumption can be optimised through data analytics.

The push towards zero emission vehicles to improve air quality has seen an increase in the research surrounding materials, technology, and supply chains. Lightweighting using alternative materials can lower the usage-phase environmental effect of vehicles and assist original equipment manufacturers (OEMs) in meeting their low-carbon emission objectives (Tisza and Czinege, 2018). Steel traditionally contributes approximately 70% weight of a car, and consequently specific materials must be utilised to achieve true weight reduction (Han, 2020). Lightweight structural components composed of high-strength steel, titanium, magnesium, aluminium alloys and have been widely researched (Li et al., 2020a). Polymers, fibre reinforced polymers (FRPs), composites, and multi-material systems are also actively investigated (Blanco et al., 2021). Designing for the CE must consider the variety and performance of a diverse range of materials within a component, alongside the design complexity of parts (Aguilar Esteva et al., 2020). The materials required to support a low carbon transition for both the vehicles and infrastructure (whether this is personal or public transport) has recently been debated due to the limited availability and production capacity, concentrated in few countries (Elshkaki, 2020). It is likely that we will need a better understanding of the materials within components, where they are sourced, along with product life cycle scenarios to understand both the application of CE and synergistic effect on climate change. Innovations in the road transport industry are likely to flow over into other forms of transportation, since the technical skills and materials needs are similar (European Commission, 2017).

4.3. Business models

An effective recycling or reuse strategy for coatings would need to fulfil some basic criteria in a system that is still prominently locked into a linear model. It must firstly be technical feasible; the process would also need to be cost-effective (competing with incineration gate fees and landfill tax) and finally its impact on the environment would be required to be less than the current process (Partridge and Medda, 2019). Given the supply constraints, price volatility, inferior quality, contamination, legacy substances, and other inherent uncertainties in secondary resources, it is difficult to see why any business would want to use waste as a resource rather than the well-functioning value chains with primary resources (Johansson and Krook, 2021). There are some economic constraints to these new circular business models that still exist in specific industries, such as capital requirements, high starting expenses, or unclear return and profit (Linder and Williander, 2017).

Despite their inefficiency, linear technologies tend to maintain their market position, whilst circular ideas are difficult to scale up (Corvellec et al., 2021). As a result, transitional innovations often fail to address the underlying causes of the chronic resource problems that they are meant to alleviate, particularly in globally fragmented and distributed value production networks (Köhler et al., 2019). CE practises may also result in continuous expenditures because of increased management needs when companies engage in more horizontal and vertical connections at the same time. The current concept of investment recovery is typically predicated on rising resource costs due to increased scarcity or uncertain consumer purchasing behaviour. Small and medium-sized businesses (SMEs) may find it difficult to fund investments and apply CE practises, and there may be further need for consideration of market-based regulatory mechanisms, loans (Mathews and Tan, 2011; Pan et al., 2015) or preferential taxes (Liu et al., 2017). However, an initial assessment from industry has found that chemical recycling aimed at recycling mixed automotive plastic waste may be superior to energy recovery from both a financial and environmental perspective (Kolb, 2021). This study was focussed on increasing the recycled content of components requiring strict safety, heat resistance, and quality requirements. Future designs which decrease material contamination may also support the incorporation of recycled content.

Manufacturing is a global market, resulting in huge resource transfers across the world. Few items today are made, acquired, disposed of, and recycled in the same geographic region. Data and digital technologies are likely to play a key part in transform the manufacturing industry (Pagoropoulos et al., 2017) and understanding the impacts of substitutions and monitoring material flows within supply chains (Lopes de Sousa Jabbour et al., 2018), with some examples in the literature of successful commercial implementation (Ranta et al., 2021; Charnley et al., 2019; Moreno and Charnley, 2016). Data-driven manufacturing is fast becoming a widespread aspect of our economy, in which data obtained from diverse sources is used to produce new kinds of value through data analytics. These data-driven procedures are altering how goods are made, sold, and utilised across the value chain in the manufacturing industry (Rüßmann et al., 2015). Despite significant research into manufacturing technical advancements, much of it has focused on productivity, flexibility, and responsiveness (Babiceanu and Seker, 2016). The concept of industrial symbiosis is offered as a practical approach for achieving circularity inside and across value chains (Sacchi and Remmen, 2017). Companies that operate together in a symbiotic manner, sharing materials and by-products, is the most common example (Södergren and Palm, 2021). Similarly, the sharing economy (also known as collaborative consumption) is an economic paradigm that enables individuals to obtain or offer access to goods and services through a cooperative peer-to-peer method (Yu et al., 2020). Combining the use of data analytics with concepts of a CE has the potential to alter the industrial environment and its relationship to materials and finite resources, generating new value for the manufacturing industry (Ellen MacArthur Foundation, 2016).

4.4. Skills, knowledge, and capabilities

Manufacturing has declined as a percentage of the economy in most developed and developing countries during the previous two decades (McKinsey Global Institute, 2017). Most businesses in Europe are small and medium-sized, with little capacity and capability to implement innovative technology. Industrial SMEs typically lack the knowledge, experience, and skills, as well as the training, resources, strategy, and confidence (Maier, 2017). Research in business model innovation has also highlighted that companies may not have the ability to adopt new strategies based on the CE (Corvellec et al., 2021). However, SMEs are more likely to initiate investment in research, development, and innovation if they receive outside support (Audretsch and Belitski, 2020).

Communicating CE can be challenging and it is often used as a narrative to tell a bigger story which can lead to confusion, misinformation and incomplete or biased analyses (Becque et al., 2016). Public perceptions, attitudes and behaviours relating to CE principles is currently limited (Rogers et al., 2021). Knowledge of CE is currently fragmented across supply chains and there is a lack of environmental understanding among management (Liu and Bai, 2014) which leads to investment in short-term business goals (Andrews, 2015). As a result, securing senior management support for CE efforts remains challenging, as managerial reward systems place a premium on achieving short-term goals rather than long-term organisational transformation. A mix of design-specific knowledge and transdisciplinary abilities is required to engage in problem solving for CE practises utilising a broader viewpoint (De los Rios and Charnley, 2017).

Employer investment in skills is heavily influenced by the government. Rather than addressing inequities in access to learning that reflect previous business investment patterns, policy is increasingly reinforcing them in the UK (Clayton and Evans, 2021). Investment in work-based learning for adults, including apprenticeships, should include basic skills for lower-level learning along with developing higher-level expertise. Further investment in professional skill development to repurpose individuals who are now employed in industries that will decrease as the CE takes hold, such as conventional manufacturing is required (Greater London Authority, 2015). This is especially true for low-skilled people, who will be able to access high-quality and better-paying jobs.

5. Barriers and opportunities for industry adoption

The shift from a linear value chain to a circular one will need innovation in recycling, reuse, design and chemistry (Stuchtey et al., 2016). Each coating approach and technology presented is currently at a different stage of innovation, and may have a different route to implementation. In the process of scaling up to widespread use, new technology passes through numerous stages (Utterback, 1971). Most of these technologies are at early stages either with niche applications or pre-commercial early adoption (Geels, 2011). There is still a cost and performance gap that policy and regulation could help to close (Corvellec et al., 2021). Others are more mature and have potential for commercial adoption. New ideas arising from experience could also have the potential as a future disruptor. Table 1 presents each technology solution, alongside potential challenges, opportunities, innovation stage, timescales for technology integration and applicability to either systemic transformation (Hopkinson et al., 2020) or transition (Chen et al., 2020) within the current system.

The feasibility of chemical recycling is being tested in pilot plants and is seen as a solution to meeting the legal recycling requirements stipulated by European waste legislation (Zeller et al., 2021). An initial assessment from industry has found that chemical recycling aimed at recycling mixed automotive plastic waste, may be superior to energy recovery from both a financial and environmental perspective (Kolb, 2021). Some manufacturers are already using chemical recycling processes in commercial applications (Thiounn and Smith, 2020). It is the closest to commercial application, however requires high investment and additional transport and storage are needed.

Some of these the technologies are further from commercialisation and may require transformative systemic change. For example, implementing biodegradable coatings may be problematic for transport applications (Nayak, 1999). Not all biodegradable polymers are suitable, because their increased chemical reactivity can also lead to lower durability (Chang et al., 2020). There are now several types of biopolymers available that are suited for automotive applications in the engine compartment and underbody, as well as the inside of a car (Barillari and Chini, 2020). For coatings, strength, durability, resistance to moisture of the biopolymer will be crucial, to compete with the traditional materials used in transport applications (Luckachan and Pillai, 2011).

Peelable coatings, although still niche in application, have already been applied in the automotive industry to provide surface protection (Wagle et al., 2021). These coatings are also effective for smaller items and may be sprayed using low-cost spraying equipment (Menze, 2009). Structural colour is the most suitable CE solution, where colour is built into a substrate by either/or a combination of materials and manufacturing (Mehta, 2018; Parker, 2000). For a thermoplastic substrate this would be a simple recycle process in-line with current uncoated components (Goodship, 2007). Although most plastics may be mechanically recycled with little loss of quality, the value of the raw material is typically much lower, making the practice commercially unviable (Stuchtey et al., 2016). Investments that allow for the production of high-quality recycled materials at low costs and in large quantities will help to retain value in the system (Geng et al., 2019).

The emergence and evolution of radical breakthroughs occurs at the micro level where niche innovations occur (Geels, 2002). The commercial responsiveness to an opportunity can be considered as anything from stagnant, slow, medium to fast changing (Utterback and Abernathy, 1975). In some cases, these may occur all at the same time, it is simply dependant on the actors selected to study (Anderson and Tushman, 1990). It may also be acting either synergistic, disruptive, or ineffective to others in the cycle. For example, niche technology in automotive manufacture may have no impact on the aerospace sector or even high-volume automotive technology. There is a complex micro-environment in which key players across the supply chain interact to implement innovations. The material technologies discussed here all have the opportunity to breakthrough to commercial use, however, it

Table 1
Perceived challenges and opportunities for implementation of alternative coating systems.

Technology	Challenges	Opportunities	Innovation stage and timescales for integration	Transformation or transition
No coatings	Requires radical systemic innovation	Provides an opportunity to simplify design and complexity of materials (Goodship and Smith, 2008)	Potential future disruptor. Widely used in consumer electronics and recent examples of brushed steel cars (English, 2021)	Transformation
Biodegradable coatings	May result in problematic contaminants in conventional plastic recycling streams (Ren, 2003) Classification of 'biodegradable' is not consistent (Kale et al., 2007).	Made from renewable resources (Helanto et al., 2019). Opportunity to reduce contamination in natural environment when unintended leakage occurs.	Niche (in transport market) Increasingly used in single-use packaging (Wu et al., 2021).	Transition
Peelable coatings	Longevity and durability are not widely reported (Wagle et al., 2021).	Consists of the same components as traditional coatings (Gao et al., 2021). Currently used in the protection of automotive parts, therefore there is existing supply chain (Wagle et al., 2021). Low-cost spray equipment used (Menze, 2009). Coating can then be recycled separately from the substrate without creating a mixed waste stream (Singh and Bharti, 2021).	Niche (in transport market)	Transition
Structural colour	May require additional investment in equipment (Parker, 2000).	Simple recycle process in-line with current uncoated components (Singh and Bharti, 2021).	Pre-commercial (Mehta, 2018)	Transformation
Vitrimers	Mechanical performance remains a significant problem (Xu et al., 2021). Long relaxation times not compatible with current process systems (Zhou et al., 2018).	Excellent recycling efficiency (Oh et al., 2020). The use in composite processing appears to be far more promising (Yang et al., 2021).	Pre-commercial early adoption (in transport market) Early stage of commercialisation in other sectors (Sloan, 2020)	Transformation and transition
Depolymerisable polymers and chemical recycling	High-temperature energy requirements needed (Jiang et al., 2020). Additional transport and storage are required for centralised treatment (Huang et al., 2022) High investment required in technology.	Coloured, multilayer, and mixed-material plastic waste can be processed (Zeller et al., 2021). New plastics and chemicals produced can be used for a range of sensitive and demanding applications.	Commercial-scale (Kolb, 2021)	Transition

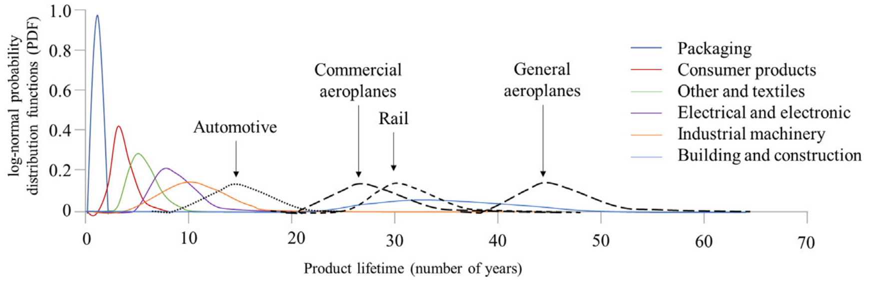

Fig. 3. Illustration of Typical Product Lifetimes in Transport.
Adapted from (Geyer et al., 2017).

is likely that wider system level enablers such as policy drivers alongside available skills and knowledge may determine implementation (Corvellec et al., 2021). Furthermore, we cannot rule out the development of new, unknown disruptive technology entrants.

Given the long lifetimes associated with mass transportation such as automotive, aeroplane and rail travel, there is a danger of technology lock-in over decades which can create medium to high term risks to the CE (Grafström and Aasma, 2021). For example, Fig. 3 shows the average age of a car at scrappage in the automotive sector in 2015 reached nearly 40 years (Society of Motor Manufacturers and Traders, 2021), the estimated lifetime of a train is 30 years (Stripple and Uppenberg, 2010), the average life cycle of an aircraft, from purchase to retirement, is between 20 and 36 years, but a life cycle of 40 to 50 years is common for general aviation (AerSale, 2019). Although several design strategies can be beneficial, such as dematerialization and design for recycling, a true CE strategy should address how we deal with existing embedded material stocks as well as radical new designs that disrupt the present system. Poorly established secondary materials markets are currently stifling businesses from implementing products and components designed for circularity (Johansson et al., 2020). Some technologies may require complete system transformation resulting in significant change, whereas others may be a transition from one to another over a period of time. Table 1 highlights how each coating are applicable to transformation or transition based on insights gathered from the data (academic literature, industry reports, patent searches) alongside conversation with industry stakeholders.

As well as long product lifetimes, there are also the development timescales of new products to consider. Given the safety issues for new aircraft introduction, it is understandably a lengthy qualification process for new materials before they can be integrated. Railway stock, also designed for lengthy lifetimes can be similarly difficult to uptake innovative technology. Integration into high volume new model automotive may be operating on a six-to-seven-year cycle for launch. There may be opportunity here to learn from faster moving sectors such as packaging and consumable electronics and it is important this is considered in any innovation discussion. There are already layers of complexity around product development and in-service lifetime to consider, which may lock-in materials and delay implementation of CE initiatives.

Despite the apparent similarities in materials and processes in the transport sector, a complex ecosystem of multiple actors, inputs and operations is developing at several distinct levels and timescales. We must also consider that any action may be blind to other actors and may take actions at odds with the process of implementing an innovation. We are just now beginning to recognise the value of systems thinking in understanding resource recovery systems and driving profound transformative change (Iacovidou et al., 2021). For example, new initiatives that gather like-minded businesses and researchers under a single flag to strive to improve the situation for everyone by implementing circular practises (Böhm et al., 2014). New high-profile efforts from around the world are fostering cultures by reusing waste as a raw material for someone else in the system. Collaboration, sharing knowledge and innovation are all essential for addressing current societal challenges (Öberg and Alexander, 2019; Carlile, 2004). This is demonstrated by recent announcements of cross-sector partnerships between businesses to manufacture lithium-ion batteries, a vital component in electric vehicles as well as energy storage devices (Jiang and Lu, 2018).

Alongside the areas highlighted above, there is a rising interest in investigating the link between a CE and data (Pagoropoulos et al., 2017). Data flows between the product, the user (including the customer, client, and operator), and the combination of activities that occur between the designer, the manufacturer, and the supply chain may be mapped against circular strategies to find new models of material usage and value generation (Charnley et al., 2019). A better understanding of how data obtained from digital technologies is still needed to realise the potential of a CE.

6. Conclusions

This research challenges us to consider the issue of adopting CE measures in the transport sector in a new light, highlighting the complications, assumptions and benefits of a circular transition. For this case, difficulties in establishing a CE are less technological in character. Below we summarise the enabling factors that can catalyse industrial growth of a new material, technology, or process for this case.

Policy and regulation play a key role in supporting or hindering the transition to a CE. Introducing an aligned multi-level governance framework will help to disrupt deeply established, unsustainable production and consumption patterns. Policy measures to date seem to solely encourage circulation of materials rather than to hinder legacy issues of a linear economy. Chemical recycling is seen as a solution to meeting the legal recycling requirements stipulated by waste legislation. However, most of these technologies are at early stages either with niche applications or pre-commercial early adoption. There is still a cost and performance gap that policy and regulation could help to close.

We need to think about how to overcome material ‘lock-in’ and circulation processes that keep materials in the economy that should be phased out from a design standpoint. Some of these coatings may require additional expense to adopt since they do not meet the parameters of typical processing procedures. Furthermore, the infrastructure necessary for material recycling and recovery may be too expensive for investment at present. However, for all options, we must also consider whether the environmental impacts attached to create a more complex surface structure, outweigh the benefits of creating it. Additional investment in education and skills is needed to ensure managers embrace opportunities from the CE and staff develop higher-level expertise needed (particularly around data-driven manufacturing). This should also encourage the sector to move away from current linear thinking.

Our research has several limitations. Since our study relied on carefully chosen examples, we accept that generalisation is limited. This is a Eurocentric view of technology adoption and manufacturers in other markets continue to use non-water borne coatings. We must also keep in mind that water-borne coatings perform effectively in some climates but not in others. Additional data, analysed through theory-based coding alongside researcher triangulation would improve the quality of analysis. Further research is also needed to examine and explore the disruption of dominate design thinking to find balance between disposing of current problems whilst investing in more radical transformation opportunities.

Declaration of competing interest

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

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