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Improving the understanding of circular economy potential at territorial level using systems thinking

Andrea Marcello Bassi[a,c,*], Marco Bianchi[b], Marco Guzzetti[a], Georg Pallaske[a], Carlos Tapia[b,d]

[a] Knowledge Srl, Via San Giovanni Battista 2, Olgiate Olona, Varese 21057, Italy
[b] TECNALIA, Basque Research and Technology Alliance (BRTA), Astondo Bidea, Edificio700, E-48160 Derio, Bizkaia, Spain
[c] Stellenbosch University Private Bag X1, Matieland, 7602, Stellenbosch, South Africa
[d] Nordregio, International Research Centre for Regional Development and Planning. Box 1658, SE-111 86 Stockholm, Sweden

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ABSTRACT

The definition of Circular Economy (CE) has evolved over time. It includes intervention options for reducing consumption, improving the efficiency of production, introducing recycling and reuse for materials management, including new business models geared at waste prevention. With the use of Systems Thinking and the creation of Causal Loop Diagrams (CLDs) we explore how CE strategies are related to territorial dynamics and how the outcomes of such strategies can support sustainable development. We first reviewed the literature, to identify the main drivers of change (i.e. feedback loops) triggered by CE interventions. We then applied the same systemic approach to six case studies across Europe in synergy with ESPON CIRCTER project. This allowed us to review, validate and improve the general systemic approach and further explore the role that specific territorial characteristics can play in the identification, selection and effective implementation of CE interventions. We find that some of the feedback loops emerged from the case studies are not found in the literature. On the one hand, new balancing loops have emerged, representing localized challenges to the implementation of CE strategies. On the other hand, new dynamics related to behavioural change have also emerged, which lead to self-reinforcing mechanisms in the case studies analysed, creating a stronger will for the implementation of CE interventions. The main result of our research is comprehensive CLD that can be used to assess and compare different CE strategies, fully considering the complexity of the CE and its various outcomes across social, economic and environmental indicators.

1. Introduction: circular economy, a systemic opportunity

The concept of Circular Economy (CE) – while not entirely new (see e.g. (Stahel and Reday, 1976)) – is increasingly gaining importance on the agendas of policymakers as main *operational tool* to address sustainability issues. (Winans et al., 2017; Korhonen et al., 2018). With this research we aim first to determine whether there are available tools that support a comprehensive assessment of CE strategies; second, to propose an overarching framework, based on qualitative modeling, to advance the general understanding of CE transition and its territorial implications.

The CE was defined by UNEP as "*an economy that reduces the consumption of resources and the generation of waste, and reuses and recycles waste throughout the production, distribution and consumption processes*" (UNEP, 2011). Emphasis is here put on waste generation, and the potential reuse and recycling of waste. Developed and industrialized countries, such as Japan, were among the first to employ the CE as economic development strategy, mainly within the industrial sector, with the aim of reducing imports through the minimization of waste generation in the production process (UNEP, 2011).

The definition was then expanded by several organizations, including the Ellen MacArthur Foundation which states: "*Looking beyond the current take-make-waste extractive industrial model,*

* Corresponding author.
E-mail addresses: andrea.bassi@ke-srl.com (A.M. Bassi), marco.bianchi@tecnalia.com (M. Bianchi), marco.guzzetti@ke-srl.com (M. Guzzetti), georg.pallaske@ke-srl.com (G. Pallaske), carlos.tapia@nordregio.org (C. Tapia).

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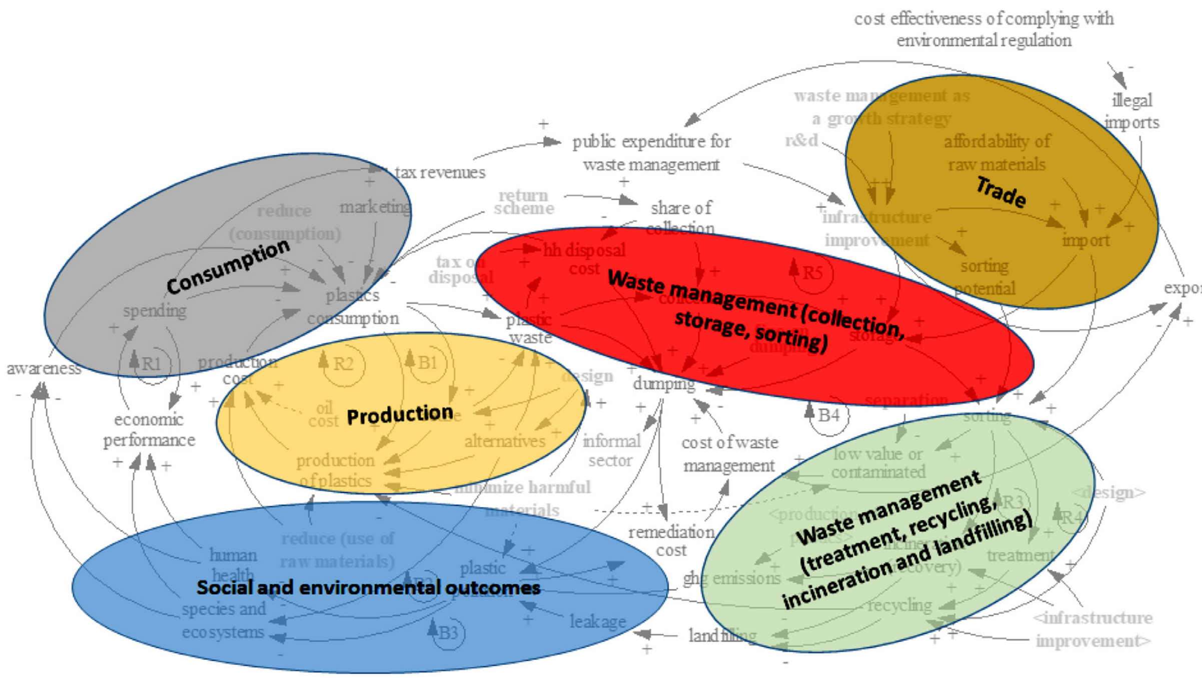

Fig. 1. Systemic Approach adopted by the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal. Presented at the first meeting of the Basel Convention Plastic Waste Partnership working group in Seychelles on March 2–5, 2020. Authors' elaboration.

a circular economy aims to redefine growth, focusing on positive society-wide benefits. It entails gradually decoupling economic activity from the consumption of finite resources, and designing waste out of the system. Underpinned by a transition to renewable energy sources, the circular model builds economic, natural, and social capital" (Ellen MacArthur Foundation, 2020). This broader definition points to the need to transform production processes and generate positive society-wide benefits. In this case the CE is seen as a new approach to development, where consumption, production and materials management are analyzed in a systemic way. As a result, the environmental impacts of waste, the social repercussions and the economic outcomes become the pillars of the analysis driving potential CE investments.

Given the breadth of the CE definition, a broad range of indicators is required to assess the performance of any CE investment or policy. Fig. 1 presents an overview of CE domain areas considered in the work of the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal, these are: (i) consumption, (ii) production and (iii) materials management, as well as (iv) social and environmental outcomes and (v) trade. *Consumption* refers to human behavior (e.g. affluence, culture, personal preferences for purchasing various types of products and services) and, together with *population* and *economic growth*, determines the total volume of products and materials utilized in the economy. *Production* considers the several production processes, from early stage product design to the efficiency of operations, for a variety of industries. Certain *environmental impacts* will arise from specific consumption and production patterns, including impacts on air emissions (from energy use) and water quality (from chemicals use), as well as resulting impacts on human health. Finally, *socioeconomic outcomes* need to be considered. These might relate to the economic cost of environmental and health impacts (e.g. increased level of pollution translating into higher health costs), but also to increased level of welfare (e.g. increased job offers, lower prices of goods etc.)

A key aspect of the CE definition is the underlying action-oriented approach, a characteristic that is also shared by the concept of Green Economy (GE). In fact, these concepts are not end-goals by themselves; instead both are strategies to more effectively reach previously-defined aspirational goals, being these international development goals like the SDGs, as in the case of the GE (UNEP, 2011), or national and regional transitional ambitions, like in the case of the CE. These strategies target a variety of environmental and socioeconomic domains, as well as sectors and economic actors. Hence the use of a systemic approach is often employed in order to better understand the complex causal relationships existing between domains.

The very broad scope of CE requires knowledge integration across (a) sectors (e.g. agriculture, industrial production, materials management), (b) societal and economic stakeholders (e.g. firms, consumers, institutions), and (c) multi-level governance (e.g. national and local initiatives should be based on a coordinated scheme, as the potential for the CE is underpinned to the specific territorial context). Similarly, the assessment of CE interventions further requires the integration of (d) all three dimensions of development (society, economy and the environment) and (e) the estimation of outcomes over time (for the short, medium and longer terms).

Given that there is uncertainty about the outcomes generated by investments in a CE, simulation models are often used to create a shared understanding and assess risks and opportunities related to the CE (Lieder et al., 2017; Winning et al., 2017; Moreno et al., 2019). Nevertheless, these models are not always designed to explicitly analyze the CE (or the CE in its entirety). This leads to the creation of partial assessments that do not fully capture the benefits of the CE. Rather they focus on specific aspects such as the potential for material recovery (OECD, 2013; EPRS, 2017); the economic growth and job creation potential (EC, 2018a); or the emission reduction (Rizos et al., 2017);

At this stage, there is not a comprehensive set of indicators on how circular economy performance should be measured across different geographies and territorial contexts. The European Commission (EC) has recently published a proposal for a Monitoring Framework for a circular economy (EC, 2018b). However, this supranational scheme does not live up to regional and local policy makers, as they face very different contexts compared to the national framework (Bianchi et al., 2020). As a result, several CE monitoring frameworks are emerging rather as a result of government efforts in developing CE strategies at sub-national levels. The lack of an integrated monitoring scheme, along with the complex nature of CE concept, has strongly limited the identification of the territorial dynamics linked to circular economic transformations. More specifically, the analysis of how local factors may condition the different strategies towards closed-loop systems, including the adoption of circular innovations by companies, public institutions and citizens is still under researched (Hobson, 2019; Korhonen et al., 2018; Marin and De Meulder, 2018). Although there are some examples of more comprehensive analyses assessing the impacts of CE implementations (see for instance Scarpellini et al. for case study of Spain (2019)), these are, in general, very *case-specific*. In other words, the multifaceted local contexts along with the availability of data in each setting prevented, up to date, the definition of an holistic framework that allows one to assess and compare different CE strategies.

We propose the use of a qualitative approach based on Systems Thinking (ST) to create system maps (Causal Loop Diagrams, CLDs) that fully explore the complexity of CE as well as of the systems in which it is applied. This approach goes beyond the identification of indicators. The goal is to identify the main drivers of change that are triggered by CE strategies, so that policy outcomes (both intended and unintended) can be identified to inform decision making processes.

The paper is organized as follows: Section 2 will present a broad overview of the main modeling approaches generally employed to analyze similar socioeconomic transitions. In Section 3, we (i) present and outline the main properties and advantages of the ST and CLDs approaches and (ii) describe the modeling process carried out during the study. Section 5 discusses main findings, while Section 6 provides some concluding remarks along with some suggestions for future research.

2. Review of modeling approaches

Ex-ante conceptualizations and simulations have been widely used to evaluate the macroeconomic impacts of circular economy transitions. Two main modeling approaches are used: partial or general equilibrium (McCarthy et al., 2018). The former is primarily sectoral and produces scenarios that do not consider price responses, and hence do not capture macroeconomic feedback loops; the latter considers full-economy impacts, and is generally carried out at macroeconomic level, assessing demand and supply dynamics via changes in prices. The following sections review the main methods and models for the assessment of different aspects of the CE, including (i) partial or general equilibrium approach, (ii) systems engineering models and (iii) life cycle assessments. . We also explain why we find the models currently available not fit for purpose. In other words, these models only capture certain facets of the CE, and miss most of the social, governance and environmental outcomes of action and inaction.

The CE aims at introducing new technologies and business models, triggering new behavioral choices, with the potential to stimulate new industries while potentially impacting negatively on others. As a result, macroeconomic impacts of CE investments can be expected. For this reason, macroeconomic models are commonly used to forecast the impact of CE interventions on GDP, consumption, investment and several other macroeconomic indicators. The OECD has conducted an extensive review of 24 models employed for CE assessments. The report concludes that the macroeconomic performance in most cases is forecasted to improve, and that important synergies emerge across development goals (e.g. economic growth, job creation and emission reduction) (McCarthy et al., 2018). This study covers Computable General Equilibrium (CGE) and macro-econometric models, with and without input-output material flows, for a single region or multi-region models. In macroeconomic models, consumption is the result of prices and volume. Consumption is a critical area of intervention for the CE since it affects production and materials management. Generally, consumption can be addressed as an aggregate monetary measure representing the materials that are spent in an economy or as a material flow that consider products that are consumed in an economy. The former is addressed with macroeconomic models, e.g. CGE or macroeconometric models (Schulze, 2016; Distelkamp and Meyer, 2019). The latter is captured by material flow, input-output models (Li, 2012; Nakamura and Kondo, 2018). In both cases input-output tables are used, to determine the inputs into the economy (and for a specific economic sector or actors) and the resulting outputs. Both types of model, on the other hand, miss information about (i) products, which are the primary subject of policy intervention, and measure only sectoral performance via material flow. These models do not include (ii) social and governance indicators, being driven by economic theory and the clearing of markets via prices. Environmental impacts (iii) are not considered in the determination of demand nor supply. Finally, (iv) customization at the territorial level (beyond national or regional data) is generally not possible to a large extent. Missing these four important elements makes so that only a few of the key dynamics underlying the CE are captured by these models.

Industrial production is generally assessed with systems engineering models (Yudken and Bassi, 2012). This is where each step of the production process is modeled, considering production inputs (including material extraction), required infrastructure, process and its efficiency, and resulting output. A large portion of the waste generated by economic processing occurs in the production step. The economic performance of the investment is the primary factor considered in decision making, and the technologies available for a given production process could be used in various geographies. As a result, the interventions in improving production can be identified and quantified more easily and streamlined more effectively than in the case of consumption (Yudken and Bassi, 2012). These models allow for the estimation of material flows throughout the production process and hence for the recycling and reuse of materials, and impacts on the cost of production. It results that impacts on the environment are captured, including energy use and air emissions, or water use and water pollution. On the other hand, these models have limited boundaries that do not capture consumption from citizens (e.g. product consumption and use, or generation of municipal solid waste), nor social and governance dynamics.

End-of-life (EOL) material management comprises various steps: collection, storage, sorting, incineration or treatment and recycling. As in the case of production, each of these steps requires the assessment of material inputs, required infrastructure, process and its efficiency, and resulting output. Systems engineering models are used in this area also (Cimren et al., 2010). EOL materials management is crucial for a CE. If interventions are not implemented at the source (e.g. within each industry and household, e.g. such as composting), the second-best option to avoid environmental, social and economic side effects, is to centralize waste collection, sorting, storage, incineration or treatment. Further, the recycling and reuse of materials requires scale to be economically viable. Only the use of a dedicated model for materials management can determine the extent to which a critical mass of waste can be collected, recycled and delivered to the market in a cost-effective way (Cimren et al., 2010). On the other hand, material flow models miss important social and environmental outcomes, as well as the macroeconomic consequences, both positive and negative, of different materials management strategies. This makes so that, up to recent times, and similarly to the experience of the energy sector that only recently has started incorporating the cost of carbon (e.g. as an air pollution cost or tax), models have been used to identify least cost options for the management and disposal of waste with a systems engineering approach (Martinez-Sanchez et al., 2017).

The lack of data and modeled estimates about the social, economic and environmental outcomes of materials management, at the urban, industrial and societal level is one of the main reasons for the mismanagement of waste, from excessive generation to landfilling or dumping, and the resulting emergence of environmental and human health impacts (Aguilar-Hernandez et al., 2018). It is therefore crucial to estimate such impacts, both physical and monetary, so at to shed light on the "externalities" generated by unsustainable economic processing, including waste treatment, and work towards their internalization (e.g. via the Polluter Pays Principle or the Extended Producer Responsibility). The use of biophysical models, coupled with economic analysis, allows to estimate the societal contribution of waste management investments, in addition to the standard economic return on investment for investors. By including societal costs in the analysis, many projects that may seem economically unviable when using a traditional approach can be unlocked. Environmental impacts can be measured by several approaches depending on scope and goal of the analysis. As an example, Life Cycle Assessment (LCA) is a standardized methodology widely used to estimate environmental impact associated with products and/or technologies along their whole life cycle (Costa et al., 2019). Similarly, economic-wide approaches such environmentally extended input-output table (EEIO) measure the environmental impacts linked with eventual changes in the underlying economy (Aguilar-Hernandez et al., 2018).

The microeconomic impacts of CE interventions are measured against the profitability of a company or industry, or impacts on the balance sheet. In this respect, material management in general and waste management in particular can affect both costs and revenues of companies. The former is a result of material and energy use and their cost, as well as the waste management fees charged by local and national governments. The latter is more and more influenced by the image and branding of the company in relation to sustainability (e.g. certification of the production process, such as ISO14001), a growing factor considered by consumers in their decision-making. Life Cycle Costing metrics (Hunkeler et al., 2008) and Techno-Economic Assessment (Lauer, 2008) are widely used methods to assess the possible microeconomic impacts of interventions. Models in this area are developed that consider each step -and related cost- of the production processes. The result of the analysis is the forecast of a company's profitability when various investments for materials management are considered. Examples include work carried out by GGGI in Cambodia for a Green Industry assessment (GGGI, 2018), and by the US National Commission for Energy Policy (now Bipartisan Policy Center) on energy intensive and trade exposed industries (Yudken and Bassi, 2012). These models, on the other hand, miss the social and governance dimension of materials management, by focusing on the private sector (microeconomic) dimension only.

Our review of the literature concludes that there are several methods and models that can be used to analyze the outcomes of CE strategies. On the other hand, no single model is capable of capturing the many facets of the CE, considering different economic actors, sectors and geographies. It results that existing models can provide a partial assessment of the CE at best. This is not a fault of any given model, it is primarily a result of the breadth of areas impacted and comprehensive nature of the CE.

Integration of knowledge for the CE is required and can be done in different ways, by connecting different models or by creating new integrated models. This implies that integration may also be partial (e.g. linking energy use to emissions and health impacts) rather than complete (e.g. linking consumption to production, to materials management, environmental and socioeconomic impacts, with a microeconomic and macroeconomic approach). System Dynamics approaches have not been used widely within the context of the CE. Still, there are interesting exceptions, like the study of Chaudhary and Vrat (2020), where SD was used to evaluate policy decisions to support gold recovery from phones in India. A few other studies from China used System Dynamics for material flow analysis (Gao et al., 2020; Xu et al., 2009).

3. Methods

ST is the methodology proposed to organize and conceptualize the different components of the CE (Aggesund, 2018). The following sections present the methodology used, and how ST contributed to the creation of an improved understanding of the CE potential at territorial level.

First, acknowledging that there is a lack of comprehensive models that can capture the different facets of the CE, we propose to work on the conceptualization of the CE, identifying all key structural drivers of change that should be considered for policy analysis. This work makes use of qualitative models, and builds on the review of existing models. It then extends current knowledge by identifying how different parts of the system, or models, can be integrated with one another for a more comprehensive assessment of the CE outcomes.

Second, we propose ST being the science of making reliable inferences about behavior by developing an understanding of underlying structure of a system. It allows us to better understand and forecast the outcomes of our decisions, across sectors, economic actors, over time and in space (Probst and Bassi, 2014). The core focus of ST the underlying functioning of the system analyzed. It supports the identification of key variables of such system across the social, economic and environmental dimension, as well as how these are interconnected with one another This makes ST well suited to assess the CE and its many outcomes across domains. In fact, originating from Systems Theory, ST is transdisciplinary (ESPON, 2019). The tools that ST makes available are feedback loops, delays and non-linearity. First, the variables of a system, being interconnected with one another, often for circular relations, or feedback loops. These can be either reinforcing (R) or balancing (B) (Forrester, 1961). The former trigger change in the system, the latter seek equilibrium (e.g. representing limits to growth). Delays allow to capture the time lag between action and outcomes, and contribute to the analysis of the temporal dominance of feedback loops in a system. For instance, a reinforcing loop may have been dominating in the past (e.g. driving consumption for a specific product higher), but this can be replaced by a balancing loop in the medium and longer term (e.g. when the market is saturated, the number of adopters reaches a plateau and then equilibrium). Non-linearity emerges from the combination of feedback loops and delays, giving rise to oscillatory behavior or, in the policy domain, to cases in which small interventions lead to large impacts while other large interventions lead to small or no impact. These three tools offered by ST allow to investigate the system, understand its key functioning mechanisms, and then identify entry points for intervention options that are effective. By focusing on the drivers of change in the system, practically any system, ST can be applied to several topics and types of systems.

Third, we find ST to be suited for conceptualizing the CE because it is designed to simplify complexity. Regarding complexity, ST allows to clearly distinguish between complicated and complex systems. The latter are characterized by the presence of several simultaneous circular relations, or feedback loops (Probst and Bassi, 2014). The combination of feedback loops and delays gives rise to non-linear behavior. Further, non-linearity leads to the shift of dominance in the system, giving rise to emergent behavior (Sterman, 2000). As a result, a CLD includes both dynamics that were dominant in the past, as well as those that may become dominant in the future. It results that, while not being able to capture "raptures" in the system, the emergence of new behavior can be analyzed within identified structures.

Fourth, we propose ST and specifically the process of creating CLDs, for their support in the creation of a shared understanding of the main drivers of change of the system. We have carried out an analysis of six case studies where CLDs were co-created live during interviews carried out with researchers and local stakeholders, based on data collected via literature review and direct contributions from the participants of the group model building session. The use of a tool that allows to graphically present causal relations across the key variables of the system proved to be very effective, especially for capturing social and governance dynamics that otherwise would be difficult to explain, comprehend and quantify.

3.1. Causal loop diagrams

We propose to use CLDs, a graphical and qualitative tool developed in the field of ST, which is a map of the system analysed, or, better, a way to explore and represent the interconnections between the key indicators in the analysed sector or system (Probst and Bassi, 2014).As indicated by John Sterman, "*A causal diagram consists of variables connected by arrows denoting the causal influences among the variables. The important feedback loops are also identified in the diagram. Variables are related by causal links, shown by arrows. Link polarities describe the structure of the system. They do not describe the behavior of the variables. That is, they describe what would happen if there were a change. They do not describe what actually happens. Rather, it tells you what would happen if the variable were to change.*" (Sterman, 2000).

CLDs include several elements, namely variables, arrows and polarity. The arrows represent called causal links, and their polarity (presented with *a* + or – sign next to the arrowhead) can be either positive (representing a direct relationship) or negative (representing an inverse relationship). As indicated above, circular causal relations between variables form feedback loops that can be either reinforcing or balancing (Forrester, 1961).

CLDs support the analysis of causality, from problem to its root causes, or from policy interventions to their systemic impacts (Probst and Bassi, 2014). CLDs can be in fact be used to create storylines corresponding to the implementation of policy interventions, by highlighting direct, indirect and induced policy outcomes across social, economic and environmental indicators.

CLDs are proposed for several reasons: first, they allow to combine the knowledge and views of all participants in the modeling process; second, they allow to clearly identify the boundaries of the analysis (e.g. what is relevant for the CE strategy developed at local level); third, they support the creation of knowledge about the dynamics underlying the sector or system analysed.

3.2. Modeling process implemented

Several CLD have been created to identify the key drivers of change impacts by the CE at territorial level. As part of the research presented in this paper one general CLD was created in two versions, and six CLDs were created to analyze case studies. The first version of the general CLD was created based on a review of the literature. The second and final version of the CLD integrates the findings of the research carried out for the six case studies, and add dynamics and depth to the first version.

The work started with the creation of a general CLD. This task was informed by the review of literature and the collection and analysis of data. As an example, the CLD includes all nine circular strategies presented in the circular economy Policy Report authored by Potting et al. (2017), as well as the policy assessment framework presented in Potting et al. (2018). Also, the CLD was inspired by the conceptualizations proposed by the (Ellen MacArthur Foundation, 2015), and a number of academic studies, including Kalmykova et al. (2018) and Vis et al. (2016)

It is crucial that a CLD is also built on solid and verifiable information. It was therefore not sufficient to work only with literature, also considering the gaps identified earlier in our literature review. As a result, validation was carried out using data and by investigating six case studies. This was crucial to better capture the territorial characteristics of CE strategies. Data on material flow at sub-national level and in-depth literature review on the case studies was carried out as part of the ESPON CIRCTER project (ESPON, 2019). The variables and causal relations included in the CLD have been confirmed and validated using available literature and (qualitative and quantitative) data collected via surveys and direct interaction with local researchers and stakeholders, for each of the six case studies. The case studies are presented in Table 1. The case studies cover urban, peri-urban and rural areas, several CE strategies and a variety of critical territorial factors upon which these strategies are built upon. All polarities of each CLD were validated against existing data or testimony from local researchers and stakeholders, with a co-creation process for the CLD. This implies that, given the early nature of some of the strategies analyzed, some of the polarities of arrows were determined based on expectations rather than on observations and data. On the other hand, this provided sufficient information on the rationale for designing a specific CE strategy in a specific location, and also allowed us to identify what feedback loops were considered to be relevant at local level when developing the CE strategy.

Once the CLDs for the six case studies were completed, the main feedback loops of each CLD were compared with the ones identified in the first version of the general CLD. The case studies have directly contributed to the validation of local dynamics, and the interpretation of the strength of selected feedback loops (e.g. the main driver for change in Maribor was the well-being of its citizens, while economic performance and competiveness were the primary motives for the creation of a circular economy strategy in central Germany and Basque Country). This information was then used to improve and finalize the general CLD that was enriched with feedback loops that initially were not identified and added to the diagram (see Table 3).

At the end of the process, the general CLD was based both on literature and on evidence collected from six case studies. Building on the existing body of work in the CE field, the general CLD includes elements of (1) production and (2) consumption. It shows how interventions on (1) the production side can reduce costs and increase economic competitiveness, while improving resilience and lowering environmental impacts. It also shows how better economic performance leads to more consumption and hence production, possibly offsetting the gains made initially. As a result, the CLD also includes interventions on (2) consumption, which complement those analyzed on the production side. Here it includes repair, refurbishing, remanufacturing or reduced consumption (refuse), which lead to reduction in resource use and environmental impacts. On the other hand, reduced production may lead to lower employment, which is compensated by the increase in jobs in repair and recycling among other options. In summary, the CLD was built to integrate knowledge across disciplines and domains.

Table 1
Overview of the case studies. Source: (ESPON, 2019).

Case study	Start	Approach & priorities	Quantitative targets	Outstanding measures
Scotland - circular economy strategy “Making Things Last”	2010	-Food and drink, remanufacture, construction, energy infrastructure;	-Cut food waste by a third until 2025	-Charter for Household Recycling
		-Design	-Scotland becomes worldwide leader in the sift to a circular economy	-Second-hand superstore
		-Waste prevention (households and industry)		-‘Recycling on the go’ to change lifestyles
		-New skills, and new thinking culture		-Circular Economy Investment Fund: circular design projects and services, in collaboration between businesses and academia
		-Longer lifetime for products		-Upskilling: Strategic agenda -Scottish Carbon Metric
				-The Scottish Institute for Remanufacture
Maribor - The WCYCLE strategy	2014	-Collaboration among public utility companies in the processing and re-use of material, energy and water waste resources	-Increase the recycling rate by 30%	-Wcycle Institute to promote collaboration among public utilities
			-Increase the share of reusable waste (from 14% to 44%)	-New high-tech waste management plant with the capacity to sort ant treat 200 Kilotons per year
			-Create new markets for secondary raw materials	
Brussels Regional Plan for a Circular Economy 2016–2020	2013	-Logistics, waste, construction, food and retail		-Business park
		-Economic opportunities of Circular Economy		-Link academic research in circular economy-work by public and private actors
		-Place-based economy		-Networking platforms
		-Create new jobs		-Monitoring scheme
Basque Country circular economy initiatives	2013	-Key metals and plastics, composites and rubber -A strong industry orientation	-Decrease raw material consumption by 6%	-Green public/private procurement
		-Eco-design, remanufacturing and advanced repair, servitisation and new business models	-Save 2000 Mio. euro	-Standardisation
				-Grants (eco-design, demonstration, industry 4.0. to drive a circular economy)
				-Financial support to equipment and infrastructure
				-Fiscal deductions
				-Circular economy monitoring framework
Sicily - Industrial symbiosis	2011	-Agri-food and construction		-Online platform to launch industrial symbiosis: to analyze material and waste flow and identify potential matches for waste reuse
		-Unlock the potential of industrial symbiosis in Sicily		-Guiding documents to implement the matches
				-Network of local stakeholders and companies - trust
Central Germany - The Bioeconomy Cluster	2012	-To build a bioeconomy leading market		-Foster joint innovation opportunities, share knowledge and support companies and research projects

4. Results

The following sections present the general CLD, as well as the main results of the work carried out to analyze the six case studies. A full description of the CLD, variable by variable and for each causal relation, is available in the supplementary materials of the paper.

4.1. Conceptualizing the circular economy based on a systemic perspective

The objective of the CE is to stimulate investments so as to transition from the current linear economic production setup to a closed-loop and more sustainable system (Ellen MacArthur Foundation, 2020).

As presented in Fig. 2, the CLD includes several variables, such as “production” and “material efficiency”. There represent, respectively, an indicator and an intervention. Interventions are presented in different colors, so as to support the identification of actions implemented by different economic actors: government (green), private sector (brown) and citizens (pink).

The CLD shows the interconnections between variables, as well as the outcomes of intervention options, based on the causal relations represented in the diagram. As an example, when production increases, material consumption also increases (EEA, 2016), all else equal (and hence a “+” sign is added to the arrow linking these two variables); conversely, when resource efficiency improves, material consumption declines (AMEC Environment and Infrastructure and Bio Intelligence Service, 2014), possibly even in absolute (in addition to relative) terms.

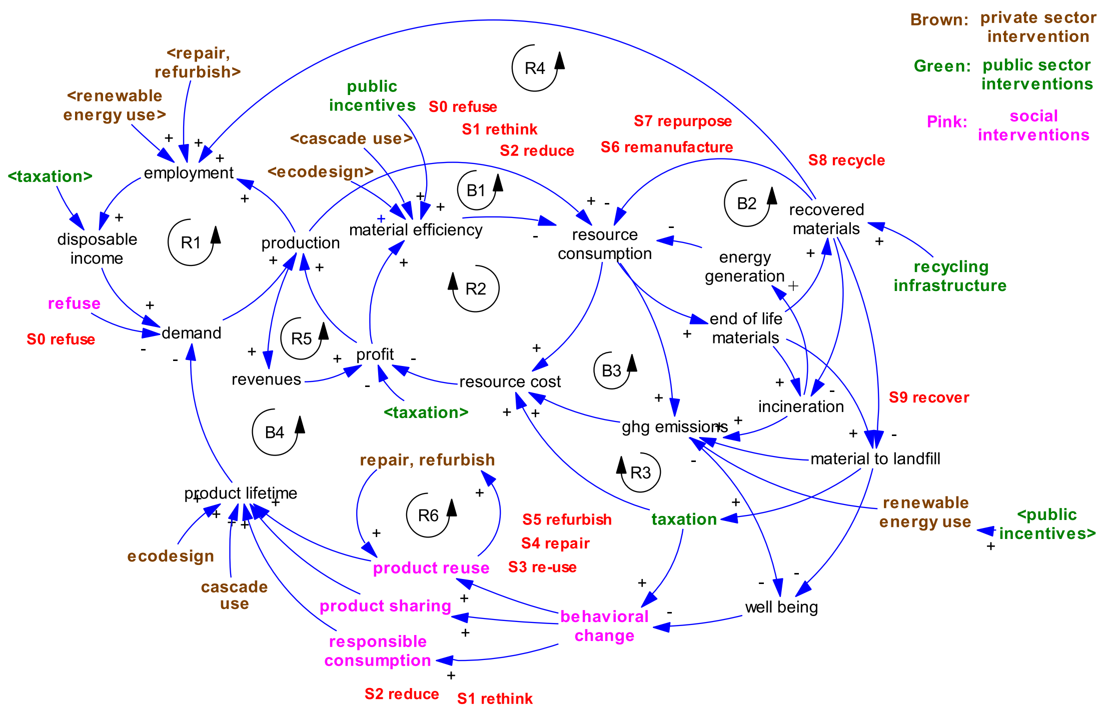

Fig. 2. Detailed integrated CLD. A causal link from variable A to variable B is positive if a change in A produces a change in B in the same direction; a causal link from variable A to variable B is negative if a change in A produces a change in B in the opposite direction. Example: the more demand, the more production (plus sign); the more production costs, the less profits (minus sign). Feedback loops, represented in the diagram with R or B sign surrounded by a circular arrow, can be classified as positive or negative. Positive (or reinforcing) feedback loops amplify change and are typically identified by a 'R' notation, while negative (or balancing) counter and reduce change are identified by a 'B' notation. Example: the more demand, the more production, the more employment, the more disposable income and the more demand (reinforcing loop); the more resource consumption, the more waste generation, the more recycling and the less resource consumption (balancing loop).

Extending the analysis beyond specific causal relations, feedback loops can be found in the CLD. A reinforcing loop is represented at the center of the diagram: when production increases, employment also increases; higher employment makes the area more attractive, and hence population increases (e.g. due to immigration); with higher population and employment, income and consumption increase in the region, leading to higher demand for products and hence higher production as well. It is important to note that the strength of feedback loops may change over time, and also based on local circumstances. It is therefore essential to validate CLDs in specific contexts (as presented later for six case studies) in addition that against theories and aggregate data.

When considering the full CLD, the following dynamics emerge: (a) the historical growth of disposable income has led to higher demand and production (OpenStax, 2014). This trend leads to two main consequences: (b) growing employment over time, resulting in the creation of disposable income and demand (reinforcing loop -R1-) and (c) higher resource consumption as a result of growing production (EC, 2015). This further leads to three main outcomes (d) higher generation of waste, (e) growing air emissions and (f) an overall increase of production costs (e.g. due to pollution control requirements, possible depletion of material production inputs in local supply chains) (OECD, 2013). These last three outcomes represent balancing feedback loops (B1, B3) that contrast reinforcing loop R1. Practically, the past economic growth has led to the emergence of side effects. Specifically, with reference to (d) waste has accumulated in landfills or was incinerated (Potting et al., 2018), leading to higher (e) emissions and human health impacts (OECD, 2013); and (f) the growing costs for environmental and health impacts, in addition to the higher costs for the sourcing of material inputs negatively affects profits, partially offsetting the gains created by growing demand (R1) (EMF, 2012; Greenovate! Europe, 2012).

The CLD shows that solutions to these side effects can be found when introducing circular economy. First, investments in recycling infrastructure are expected to reduce the flow of waste to landfills and incineration, curbing virgin resource consumption, lowering the cost of production, and reducing air emissions and pollution (B2) (OECD, 2013). Second, recycling supports employment creation and local growth resulting from the creation of local supply chains (R4 and R5) (EC, 2017). While this is positive, as indicated earlier, it will lead to income creation and higher demand and production and hence resource use. As a result, the effectiveness of recycling may be challenged by its positive economic impacts (ESPON, 2019).

Two main dynamics emerge from the analysis of the literature, and how this is presented in the CLD: (i) lower material use and landfilling, as a result of waste recycling and reuse, and (ii) higher material use due to the economic growth, as a result of the employment creation and cost reductions resulting from waste recycling and reuse (Potting et al., 2017). Given these two opposed outcomes, the final reduction in material use and ultimately waste landfilling may be smaller than expected due to the balancing effect played by the reinforcing loop (ii) described above. This emerging dynamic is known as 'rebound effect', which stems from the classic Jevon's Paradox (Polimeni and Polimeni, 2006). It is explored frequently in the energy sector in the context of energy efficiency investments (Grubb, 1990), and results from the simultaneous presence of reinforcing and balancing loops in the system analyzed.

In order to mitigate the strength and impact of the rebound effects, a combination of policy interventions should be explored. The diagram shows that when recycling is coupled with interventions that aim at improving material efficiency (e.g. public incentives or eco-design and cascade use), represented by B1, R2 and R5, more lasting outcomes can be expected

(Ellen MacArthur Foundation, 2015). In the same vein, emissions could be reduced by introducing incentives for investments in renewable energy (DEFRA, 2011).

When considering the full CLD, and the complete definition of the CE, which includes demand, production and materials management, different combinations of interventions emerge as viable options to have lasting impacts. When demand-side interventions are implemented in synergy with supply-side policies and investments, a new balancing loop is introduced and gains strength over time (B4). Specifically, taxation, product repair, refurbishment and remanufacturing all contribute to reducing waste and the demand for virgin materials. If behavioral change emerges due to the availability of -and appreciation for- for product reuse, product sharing and responsible consumption, a shift in dominance will emerge in material flows from reinforcing to balancing (EEA, 2017; Boston Consulting Group, 2016). The underlying cause is longer product and materials lifetime, both of which can also be done by design, with eco-design and cascade use. When product lifetime increases the same number of products are found in the economy (i.e. same number of adopters), but production and discard, and hence material use decline.

The CLD, via the identification of feedback loops, shows that only the simultaneous implementation of demand- and supply-side interventions will lead to a complete shift in the dynamics of the system (Ellen MacArthur Foundation, 2020). In this scenario waste landfilling and emissions would decline, as would health impacts, leading to lower taxation and improved well-being (ESPON, 2019).

In summary, the following key messages emerge from the analysis, as presented in Fig. 2:

- Currently we observe material flows that are, for the most part, mono-directional. Demand determines, production, which leads to materials use and waste creation in the manufacturing process. Product discard leads to waste creation as well, ever increasing the need for materials management (especially end-of life activities).
- If materials end up in landfills we require higher taxation to cover growing costs, and face negative impacts on well-being
- Material recycling and reusing reduces resource consumption, resulting in lower costs, possibly freeing up resources for investment and the expansion of production, leading to higher demand and resource consumption. Practically, it closes the cycle and it is (erroneously) thought to allow for “infinite” production and consumption, driving the economic system beyond the coping capacity of global ecosystems. This is because it weakens the balancing loop (B1) and, as a result, it strengthens the reinforcing loop (R1).
- Full circularity is realized when the loop dominance of current demand and production is reversed. If consumption is curbed, through systemic change, e.g. via recycling and reuse, refurbishing and repurposing, materials consumption can be curbed. Strategies for system change involve both (1) industries and (2) citizens (ESPON, 2019). Maintenance and repair, refurbishing, repurposing and remanufacturing offer economic opportunities, as well as rethinking, refusing, re-using. A positive economic return can be the trigger for the shift in loop dominance described above, and this can be achieved when making full use of the three dimensions of circularity: (i) demand, (ii) production and (iii) resource management.

4.2. Adapting the circular economy concept to the local context: a review of six case studies

The CLD presented earlier was created to summarize available knowledge on the CE. It is based on the review of existing literature and data. We then took a next step to validate the CLD, creating a customized CLD was created for each of the six case studies analyzed: Maribor, Central Germany, Scotland, Brussels, Basque Country and Sicily. This also helped testing the extent to which the CLD could account for the policy assessment framework presented in Potting et al. (2018) for each case study, a way to assess how complete the diagram is, as well as how comprehensive these six CE strategies are .Fig. 3 presents the CLDs for Maribor and Basque Country and Table 1 provides an overview of the CE strategies implemented by each case study. Below the main entry points for intervention, and the key drivers of change that emerged from the analysis carried out with the CLDs are presented. A full description of each case study is provided in the CIRCTER project report, including policy rationale and goals, statistics and measured outcomes of CE strategies to date (ESPON, 2019).

- The strategy of Maribor combines efforts on the supply side (e.g. sorting and recycling) with interventions that reduce the generation of waste for long-term sustainability (Wycycle, 2014). The project, which started in 2014, encourages collaboration among public utility companies in the processing and re-use of waste and energy resources. The main goal is to increase the recycling rate by 30% by 2023 and to expand the share of reusable waste from the current 14% to 44% by the same year (ESPON, 2019). Markets for secondary raw materials are also expected to increase, producing new economic benefits.
- Initiated in 2012, the CE strategy in Central Germany is crafted around the strengths of the region and aims at increasing competitiveness by reducing production costs (BioEconomy Cluster, 2012). An important synergy, supported by strong political will, is found in the improvement of citizens' well-being. Key strategic areas of intervention include the expansion of recycling infrastructure, the banning of single-use plastic waste, the introduction of training and awareness raising activities and introduce new balancing loops that curb known side effects of conventional production processes (by reducing material use and waste generation, and hence health impacts) and create new opportunities from waste recycling.
- The strategy of Scotland, which started in 2010, seeks to find a balance between managing demand and production, as well as waste flows (Goverment, S., 2010). It highlights that by reducing consumption (through recycling and reuse also of the construction materials of wind turbines and oil and gas platforms) there will be cost reductions for waste management, as well as new economic opportunities. Quantitative targets include cutting food waste by a third until 2025 as well as making Scotland a worldwide leader in the shift to a circular economy.
- The CE strategy for Brussels (2016–2020) aims at creating virtuous cycles by using a multipartite cooperation for strategy design and implementation and will adopt an evidence based approach to better involve citizens and update and improve the strategy on an ongoing basis (BRPCE, 2016). As a consequence, the city is encouraging a place-based economy through actions on circularity demand and offer, and the creation of positive framework conditions like the creation of circular jobs. Intervention options include the introduction of a “good food strategy” to stimulate behavioral change, the creation of capacity for local organization to better address the future needs of materials management, and improved coordination with citizens as well as surrounding municipalities and the region.
- The Basque Country strategy adopted in 2013 a systemic approach to increase competitiveness and do so sustainably, by preventing the emergence of side effects while aiming at reducing waste management costs (ihobe, 2013). It is expected that the implementation of the circular economy in the Basque country will decrease raw material consumption by 6% by 2030,

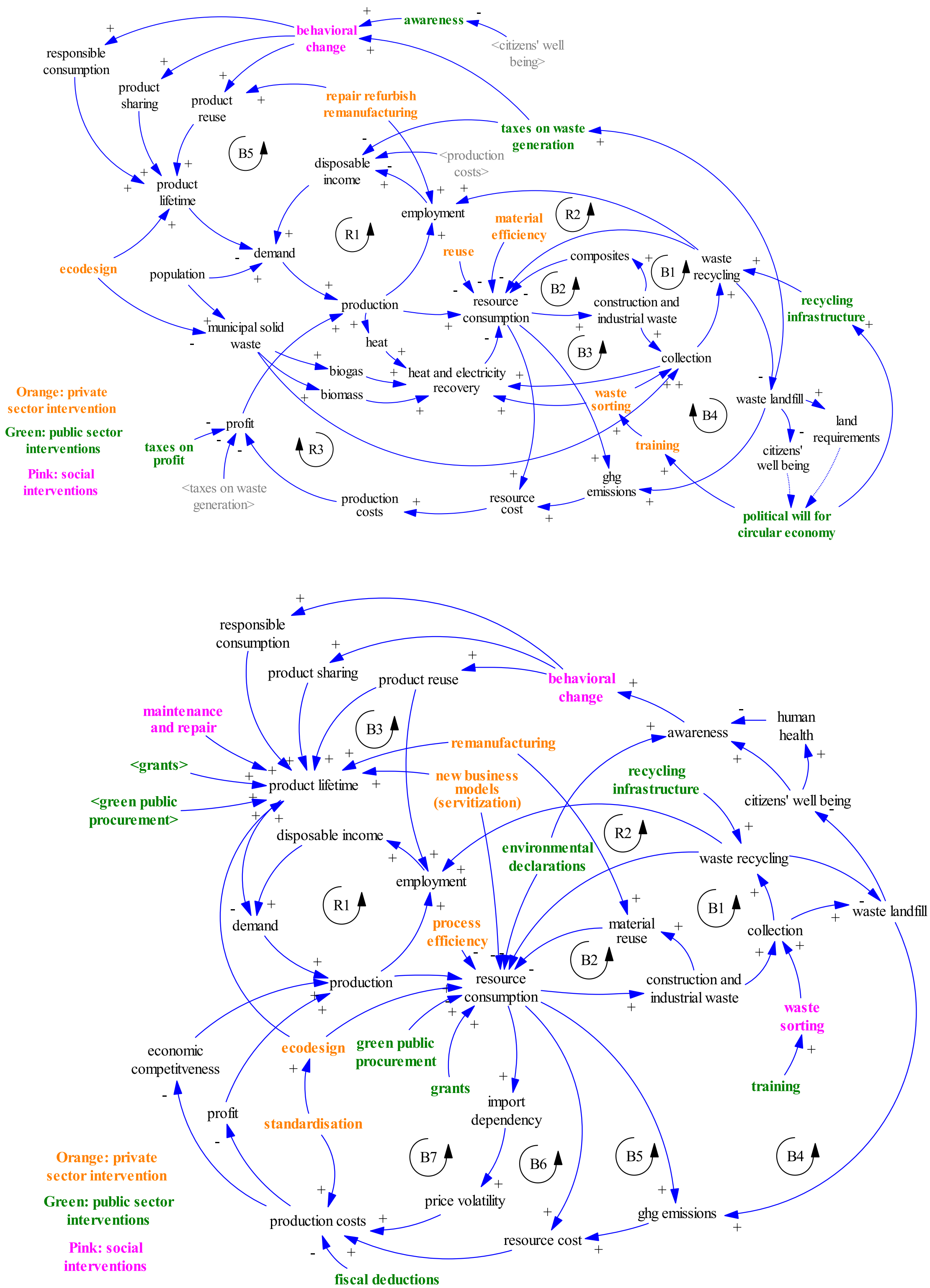

Fig. 3. CLDs developed for Maribor (top) and Basque country (bottom), two examples of the CLDs created for the six case studies.

saving 2000 million euro. The metal and transport industries would be the main beneficiaries, accounting for 49% of total saving. Basque companies are also expected to increase green product sales by 46% by 2025.

- The CE strategy for Sicily focuses on identifying partnerships for turning waste into resources, or valuable production inputs via Industrial Symbiosis (ENEA, 2014). Practically, in 2011 it provides a platform for companies to identify partners in the recycling and reuse of materials, to reduce costs for both the seller (waste management costs) and the buyer (purchase of production inputs), and enhance economic productivity. Around 700 matches were identified between the participating enterprises, while the platform is still being used.

Table 2
Overview of the circular economy strategies found in the six case studies. Source: (ESPON, 2019).

	General	Maribor	Central Germany	Scotland	Brussels	Basque Country	Sicily
S0: Refuse	**x**	x		x	x	x	
S1: Rethink	**x**	x		x		x	
S2: Reduce	**x**	x	x		x	x	
S3: Re-use	**x**	x	x	x		x	
S4: Repair	**x**	x		x		x	
S5: Refurbish	**x**	x		x		x	
S6: Remanufacture	**x**	x		x		x	
S7: Repurpose	**x**	x	x	x		x	
S8: Recycle	**x**	x	x	x		x	x
S9: Recover (energy)	**x**	x	x	x		x	x

As indicated above and presented in Table 2, while certain strategies take a holistic approach (e.g. Maribor, Scotland and Basque Country) and cover consumption, production and materials management; others are more focused on one of these strategies. For instance, the case of Central Germany emphasizes production, Brussels prioritizes behavioral change and the case of Sicily focuses on end-of-life materials for industrial symbiosis.

Table 3 shows instead the feedback loops that have been identified in each of the case studies. In all cases a combination of reinforcing (R) feedback loops, which amplify change, and balancing (B) loops, which counter change, was found. No CE strategy is mono-directional and therefore expects both elements of success and policy resistance. This was useful to characterize the circular economy strategies of the case studies, and to discuss in more depth with researchers and local stakeholders about the motivations for the creation of their specific CE strategy, as well as expectations for the future (e.g. which feedback loops are likely to emerge as dominant in the next 5 to 10 years, and in the longer term). We find that the CE strategy of Maribor and Central Germany are conceived for addressing known challenges such as health and industrial competitiveness (both characterized by balancing loops); in the case of Brussels and Scotland instead the CE strategies aim to create new opportunities, triggering new reinforcing loops.

All these strategies (S1-S9) are also included in the general CLD, being based on the work by Potting et al. (2018), which provides a valid policy assessment framework. On the other hand, we found that the underlying drivers of change that are triggered by these nine strategies change in the various case studies. In other words, the general CLD and those developed for the six cases studies all cover the same CE strategies (some more some less as shown in Table 2), but the changes triggered by these strategies change considerably from case to case. Further some of the feedback loops identified for the case studies were missing in the first version for the CLD. All the main feedback loops identified through the creation of CLDs are presented in Table 3.

Specifically, we found that the literature reviewed, both concerning models, frameworks and policy assessments, missed two main dynamics:

- Balancing factors: we found various new balancing factors in the case studies, representing challenges to implementation or emergent side effects. The literature instead, tend to focus on the virtuous dynamics triggered by the CE. An example is the feedback loop existing between the cost managing waste and municipal solid waste generation. Both in the case of Maribor and Germany it was found that if, in the case of success of the CE strategy, the cost of waste management would decline, families are expected to generate more waste.
- Social and governance dynamics: the case studies have highlighted very clearly the importance of social and governance dynamics both in determining policy interventions and in driving the uptake of CE practices. The CE strategy of Brussels and Maribor is entirely driven by social concerns and promoted by citizens. Political buy is has emerged as a result of public pressure. Most models and assessments focus instead on economic competitiveness and performance (e.g. the case of Central Germany and Basque country).

We used the first version of the general CLD to assess and compare the CLDs created for the case studies. Once the new feedback loops were identified, their inclusion in the general CLD was evaluated. Many feedback oops were included, or the general CLD was refined to better capture the dynamics that emerged from the case studies. On the other hand, not all feedback loops were included in the general CLD. Specifically, the ones that are triggered by multi-stakeholder involvement are represented through an event (e.g. instead of indicating the fact that stakeholder groups formed to support policy intervention, the CLD shows that due to the increase in pollution and the emergence of health impacts, behavioural change emerged, also supported by policy intervention). This is to clearly distinguish between endogenous and exogenous dynamics, and to make so that the diagram can be used to carry out "what if" qualitative scenario analysis, and possibly serve as a blueprint for the creation of quantitative models in the future.

5. Discussion

The systems analysis performed with the case studies shows that each CE strategy developed at local level leverages the specific territorial context. Maribor, in an urban setting, focuses on waste management and human well-being; Central Germany leverages the knowledge and innovation potential of the region to create new business opportunities in a circular bioeconomy; Scotland emphasizes material reuse for key local industries to reduce overall system costs; Brussels makes use of its strong local governance to directly involve citizens in a continuous and stakeholder-led planning process; the Basque country is one of the main industrial hotspots in Spain and, as a result, its CE strategy focuses on improving economic competitiveness; finally in Sicily, networks of companies are formed to create trust and initiate new business opportunities by turning waste into resources (industrial symbiosis) for the most relevant economic sectors of the island.

This finding highlights the importance of including territorial drivers of change, or localized feedback loops in the assessment of the CE strategies. Existing methods and models instead tend to focus on one or another area of the CE, as indicated in Section 2 (McCarthy et al., 2018).

The main outcome of the research performed is constituted by the general CLD. This has a dual purpose: (a) it supports the understanding of the existing literature and (b) it provides a holistic framework to compare and assess the local and territorial CE strategies across different local contexts. Hence, our CLD might set a basis to critically analyze various CE strategies in an objective way.

Table 3
Main feedback loops emerged from the assessment of the six case studies, and inclusion of such feedback loops in the general diagram. Source: (ESPON, 2019).

B/R	Feedback loops	General (final)	General (initial)	Maribor	Germany	Scotland	Brussels	Basque Country	Sicily
B	Production leads to (i) resource use and emissions, (ii) higher costs, (iii) reduced profits	x	x	x	x			x	x
B	Resource consumption leads to (i) waste generation and (ii) waste recycling	x	x	x	x	x		x	x
B	Resource consumption leads to (i) landfill, (ii) more taxation and lower income and (iii) reduced demand and production	x		x					
B	Resource consumption leads to (i) landfill, (ii) more taxation and (iii) behavioral change, reducing (iv) demand and production	x		x					
B	The cost of non-renewable resources leads to (i) higher willingness to pay for bioproducts, (ii) reduced waste generation and (iii) reduced costs				x				x
B	Environmental degradation (emissions and landfill) lead to (i) awareness raising and political will			x	x			x	
B	Product reuse leads to (i) lower demand and resource use, (ii) lower health impacts and awareness, (iii) reduced behavioral change	x	x	x				x	x
R	Demand leads to (i) production, (ii) employment, (iii) income	x	x	x	x	x		x	
R	Efficiency leads to (i) less consumption, costs and (ii) higher profits	x	x	x	x			x	x
R	Recycling leads to (i) less landfill and taxes, (ii) more income and demand, (iii) production and resource use	x	x	x				x	x
R	Recycling leads to (i) more employment, (ii) more income and demand, (iii) production and resource use	x	x	x	x	x	x	x	
R	Production leads to (i) revenues and (ii) profits	x	x						
R	Product reuse leads to (i) more repair, refurbish and remanufacturing	x	x	x		x	x		
R	Product reuse leads to (i) product appreciation and (when quality is ensured) and (ii) behavioral change	x				x			
R	Circular economy transition efficiency leads to (i) education and behavioral change and (ii) well-being and political will	x					x		
R	Multi stakeholder involvement leads to (i) higher circular economy efficiency and (ii) political will						x		x

The CLD itself highlights that all CE strategies impact, and are impacted by, both forces that trigger change (reinforcing loops) and forces that seek equilibrium (or oppose change, balancing loops). This is constant that is found in all case studies, and primarily pertains social and governance dynamics. This should place such dynamics very high in the agenda of decision makers, despite the fact that data are often missing to measure them.

Practically, the CLD bridges a gap between the comprehensive conceptual frameworks for the CE (e.g. (UNEP, 2011; Ellen MacArthur Foundation, 2020), the policy framework that comprises 9 strategies developed by Potting et al. (2018) and mathematical models that forecast and quantify CE policy outcomes (McCarthy et al., 2018).

Further, the analysis of the six case studies and the integration of relevant feedback loops in the CLD allows to link the CE diagram developed to the territorial factors that enable the effective implementation of CE interventions at regional and local levels. These factors were described and organized in a systematic review (see Tapia et al., 2020; ESPON, 2019). Specifically, we identified the following drivers of change connected to each of the territorial factors of relevance:

- **Agglomeration** factors are those that require a certain critical mass to operate (e.g. for industries to justify investments, or for citizens to trigger behavioural change). Agglomeration affects three key feedback loops: material recovery (B2), resource consumption and material efficiency (R2), and repair, refurbish and reuse (R6). Agglomeration is an important force that can enables a CE transition with different entry points, either consumption, production or materials management.

- **Land-based resources** influence material use (R2) and recovery (B2) as well as the potential for using renewable energy, supporting investments in production and materials management.
- **Accessibility** affects the resource use (R2) and recovery (B2), and (B4) related to citizen behavior. It enables the CE transition across consumption, production and materials management.
- **Knowledge** affects all feedback loops of the CLD, wither via technology adoption (e.g. material consumption (R2) and recovery (B2), waste management (R3)) or awareness (e.g. behavioural change for citizen (B4) and businesses (R4)).
- **Technology**, as indicated above can impact both production and product design, affecting the demand for products and employment creation (R1), material efficiency and consumption (R2), material recovery and resource consumption (B2), and behavioural change (B4).
- **Governance** and institutional systems are critical for the effective conceptualization, design and implementation of CE strategies at local level. Virtuous examples of governance include disincentivizing unsustainable practices, or stimulating sustainable ones (R2). Good governance also includes clear guidance on regulations and policy frameworks, which has emerged as a critical factor in many case studies (e.g. Sicily).
- **Territorial milieu**: a strategic and shared vision of a region is a major driver for achieving ambitious CE transformations (Preston, 2012). The territorial milieu enables material efficiency (R2) and recovery (B2) (e.g. in relation to industrial ecology and special economic zones, but also through behavioural change, leading by example), as well as a strong and shared regulatory environment (R3), creating a trust relationship and a favourable business environment.

We conclude by indicating the role that ST and CLDs play in integrating knowledge and providing a harmonized approach that allows to connect various thematic areas for policy analysis. This is exemplified by the focus on structural drivers of change, across sectors and economic actors, and dimensions of development, all of which are included in the general CLD.

Limitations of the research carried out include first the qualitative nature of the work performed which, while providing a valid framework for the assessment of CE strategies, does not allow to determine the dominance of feedback loops, nor the strength of the impact of CE strategies on specific indicators. As a result, it represents an intermediary step rather than a tool for a complete and comprehensive assessment of policy impacts, which can be carried out with quantitative models. Second, the CLDs are based on a limited number of case studies, six in the case of this research. Expanding the analysis to additional case studies may reveal the existence of new relevant feedback loops. Third, there is limited evidence of the impact of existing CE strategies, and therefore the validation of the CLDs was performed based on existing data and expectations (both positive and negative) of local researchers and stakeholder.

Potential next steps for this work, to address the first limitation mentioned above, include the quantification of the CLDs, using local data and quantitative models, e.g. based on System Dynamics to fully capture the complexity of the local systems analyzed. This assessment would allow to determine which of the dynamics identified in this study is relevant and dominant in the system, and hence to prioritize CE interventions for effective implementation, based on a systemic and integrated cost benefit analysis. This is the missing step to provide local policymakers with tools that can actively be used to inform decision making for CE strategies. Additional research could be carried out to address the following two limitations, to collect more data (e.g. through primary research) on the many emerging CE strategies and their impacts in Europe, e.g. in relation to the implementation of the EU Green Deal, and beyond.

6. Conclusions

The CE is a broad concept that touches upon social, economic and environmental dynamics. The use of ST and the creation of CLDs have allowed us to identify several feedback loops that can determine the success or failure of CE strategies in different geographies. Through the review of literature and the assessment of six case studies, we have identified what feedback loops might be crucial to leverage CE transitions based on given territorial characteristics.

Specifically, we find that:

- The local drivers and mechanisms for CE are strongly context specific. Several overarching factors, intrinsically connected to territories, were identified across the case studies. These are likely to influence the leverage mechanisms and drivers towards circular systems. Therefore, the preliminary recognition of such factors is key for the definition of place-based successful strategies.
- The general CLD model offers a tool to compare a specific CE situation to a more general perspective. This not only provides a comprehensive framework for a critical reflection on implemented local CE strategies, but it also offers insights on the potential adaptations and actions that might be considered to enhance CE.

Concerning the key drivers of the CE identified and included in the second and final version of the general CLD, our analysis highlights that both reinforcing and balancing loops should be considered when designing or assessing a CE strategy, including those that depict social and governance dynamics. Reinforcing loops trigger change in the system, while balancing loop seek equilibrium, and hence oppose change.

Among key reinforcing loops we identified both desirable and undesirable dynamics. Concerning the latter, economic growth leads to higher demand, employment and income, and hence to the generation of waste. Any cost reduction resulting from CE interventions that increases disposable income is therefore likely to create a rebound effect. Concerning the former, product reuse leads to a higher appreciation of products, job creation for repair and refurbishing, stimulating self-sustained growth in product and materials management. It results that reinforcing loop can stimulate desirable or undesirable change, leading to the strengthening of virtuous or vicious cycles.

The balancing loops identified also result in more or less desirable outcomes. Concerning the latter, resource consumption leads to waste generation, higher waste management costs and taxation, in addition to environmental and health impacts. All these outcomes reduce economic performance, either by resulting in higher costs, taxation, or reduced labor productivity, and reduce consumption. Regarding the former, the growth of environmental pollution leads to increased awareness and behavioral change; on the other hand, the reduction of pollution via recycling and reuse reduces the sense of urgency and awareness. It results that balancing loops create “lock in” effects, where the system shows policy resistance.

The identification of reinforcing and balancing loops allows to anticipate the outcomes of CE interventions. This allows to inform the creation of CE strategies, where interventions are designed to create new opportunities and, at the same time, counter emerging side effects.

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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