Towards a systemic view on rebound effects

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Towards a systemic view on rebound effects: Modelling the feedback loops of rebound mechanisms

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ABSTRACT

Rebound Effects (RE) are systemic responses that are relentlessly hindering the achievement of sustainability actions' intended effects. Despite the wide recognition of RE, the limited understanding of the underlying causal structures sustaining their occurrence hampers the ability to anticipate, prevent, and tackle them. To explore how feedback thinking can explain the occurrence of RE, this paper describes the structure of 26 rebound mechanisms based on qualitative system dynamics (SD) modelling using causal loop diagrams (CLD). Apart from a comprehensive catalogue of mechanisms, the elicitation of two generic rebound mechanisms reveals that RE are either the result of (1) reinforcing loops acting against quick fixes to control local resource consumption or (2) balancing reactions in the opposite direction of attempts to control local resource consumption leading to escalation behaviour. Four contributions highlight how this research supports a systemic view on RE, the natural evolutionary step required to understand and manage its occurrence.

1. Introduction

Never before has there been a greater urgency and engagement for sustainable solutions (Hauschild et al., 2020). However, rebound effects (RE) often emerge from the implementation of sustainability-driven solutions (Binswanger, 2001; Brockway et al., 2021; van den Bergh, 2011). RE are systemic responses that offset the initial intentions of sustainability-oriented actions (Hertwich, 2005; Lange et al., 2021), hindering the achievement of the full potential of sustainable solutions. RE can offset over 50% of the expected outcomes of well-intended actions (Brockway et al., 2021).

The study of RE started with the Jevons' Paradox (Alcott, 2005; Sorrell, 2009), which describes the general increase in coal consumption triggered by enhanced energy efficiency in the use of coal (Jevons, 1865). After a long period of little discussion, significant effort has been put into theorising RE as both a microeconomic (Khazzoom, 1980) and a macroeconomic (Brookes, 1990) phenomenon. After acknowledging its multilevel nature (Saunders, 1992), increasing empirical evidence for RE emerged (Binswanger, 2001; Greening et al., 2000).

The typology proposed by Greening et al. (2000) organised RE into direct, indirect, macroeconomic, and transformational effects. More recently, that initial typology evolved into more comprehensive categorisations of the mechanisms leading to RE (Brockway et al., 2021; Colmenares et al., 2020; Lange et al., 2021; Metic and Pigosso, 2022) and the distinction between rebound effect (i.e., the "quantitative size of a (measurable) impact") and rebound mechanisms (i.e., the "qualitative relation, e.g., a cause and effect chain" that determine the effect) (Lange et al., 2021, p. 1).

Currently, comprehensive analyses of empirical studies show ample evidence of RE through different estimation methods, such as structural models of economic growth, econometric studies, computable general equilibrium models, and integrated assessment models (Brockway et al., 2021; Colmenares et al., 2020). Nevertheless, the studies measuring the magnitude of RE are still diverse in definitions, boundaries, terminologies, methodologies, and data sources (Font-Vivanco et al., 2016; Freire-González, 2017; Sorrell et al., 2009), resulting in up to 84% variation in estimated RE magnitudes (Makov and Vivanco, 2018; Sorrell, 2009; Sorrell et al., 2009; Sorrell and Dimitropoulos, 2008).

Furthermore, scholars have often taken a deterministic approach to investigating RE (Giampietro and Mayumi, 2018), focusing more on calculating discrete percentages of RE magnitude (Colmenares et al., 2020) instead of focusing on how they unfold over time (Turner, 2013).

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Traditional assessment tools focus on single-unit impacts (Font-Vivanco et al., 2016; Laurenti et al., 2016) or historical correlation (Brockway et al., 2021), falling short in providing helpful information for managing them (Giampietro and Mayumi, 2018) from an ecological economics perspective.

RE studies have typically overlooked the feedback-driven causal processes underlying the broader complex systemic responses to sustainability interventions (de Gooyert et al., 2016; Guzzo, Walrave and Pigosso, 2023; Turner, 2013). RE studies still lag in addressing the causality between the sustainability-oriented action, the RE occurrence and the multiple mechanisms at play (Castro et al., 2022; Giampietro and Mayumi, 2018; Madlener and Turner, 2016). Although the interest in developing rigorous and relevant generic mechanisms constitutes a continuous pursuit in the RE research field, the codification of the system structures and behavioural mechanisms through which RE emerge still requires further clarification (Brockway et al., 2021; Madlener and Turner, 2016; Ruzzenenti et al., 2019; Sonnberger and Gross, 2018). Overall, "a clear-cut definition specifying causal relations is needed to guide empirical studies and ensure comparability" (Sonnberger and Gross, 2018, p. 15). The limitations imposed by the tools at hand and oversimplifications harm the capacity to truly understand RE. In response, this research explores how feedback thinking can help explain rebound mechanisms by mapping the causal structures sustaining the occurrence of rebound effects.

This research addresses the limitations of linear thinking and adopts feedback thinking to explore the RE field. Linear thinking interprets reality as a series of discrete events, often resulting in "side effects" (Sterman, 2000, 2001). Feedback thinking, however, enables accounting for the dynamic aspects of decision-making by acknowledging that today's problems are partly the reaction of yesterday's actions (Sterman, 2001, 2002). In this sense, RE are "side effects" of well-intended sustainability actions. System dynamics (SD) is employed as an approach to expand the mental models and incorporate feedback thinking to address "side effects" (Senge, 1990; Sterman, 2000). SD has been applied for long in ecological economics as a framework for problem-based learning (Farley et al., 2005) and to investigate sustainability transitions (Guzzo et al., 2022; Walrave and Raven, 2016).

Qualitative and quantitative SD modelling have been used to investigate RE emerging from sustainability-oriented action in a specific system of interest (Cavicchi, 2016; Dace et al., 2014; Fazeli and Davidsdottir, 2017; Hilty et al., 2006; Stepp et al., 2009). In some cases, RE was investigated as a type of unintended consequence (Laurenti et al., 2016) or leading to policy resistance in sustainability transitions (de Gooyert et al., 2016). RE has also been the primary phenomenon of interest in a few studies (Achachlouei and Hilty, 2016; Freeman, 2018; Freeman et al., 2016). Qualitative SD modelling helped indicate the specific structures leading to RE, such as decreased cost of driving leading to additional driving (Stepp et al., 2009), additional recycling minimising costs and leading to increased demand for materials (Dace et al., 2014), or the build-up of social norms reinforcing the amount of transportation (Freeman et al., 2016). Commonly, researchers analyse qualitative SD models to identify leverage points towards better sustainability outcomes (Cavicchi, 2016; de Gooyert et al., 2016; Laurenti et al., 2016; Stepp et al., 2009), which is a well-known strength of using causal loop diagrams (CLDs) (Lane, 2008; Meadows, 1999).

Nevertheless, the resolution and the understanding of the structures leading to RE occurrence vary considerably among the studies. For instance, some studies only refer to them as RE without naming the specific type (Dace et al., 2014; de Gooyert et al., 2016; Fazeli and Davidsdottir, 2017; Stepp et al., 2009), while others name the mechanisms accordingly to the identified structures (Achachlouei and Hilty, 2016; Freeman et al., 2016). In some cases, the granularity in the textual descriptions for rebound mechanisms explanations differs from the models presented (Dace et al., 2014; de Gooyert et al., 2016; Freeman, 2018). Furthermore, the studies show a lack of agreement on the structures and their respective names – for example, additional consumption through decreased prices has been referred to as direct economic RE (Achachlouei and Hilty, 2016), consumption RE (Laurenti et al., 2016), or simply RE (Fazeli and Davidsdottir, 2017; Stepp et al., 2009).

In the quantitative SD realm, the complimentary use of simulation enabled making informed assertions about the magnitudes and the thresholds for RE occurrence by analysing the behaviour of specific variables that could explain their occurrence under different scenarios (Dace et al., 2014; Hilty et al., 2006) or by activating and deactivating particular structures that lead to RE occurrence (Freeman et al., 2016). These studies reinforce that a sound understanding of the causal structures for the rebound mechanisms is critical to building models that enable the examination of the rebound thesis, guide the reasoning for RE occurrence, and provide valuable recommendations for allowing the minimisation and/or prevention of potential RE.

There is, therefore, an opportunity to build upon those experiences and develop a more comprehensive set of structures consistent with the state-of-the-art understanding of the mechanisms leading to RE (Brockway et al., 2021; Colmenares et al., 2020; Lange et al., 2021; Metic and Pigosso, 2022). This opportunity comes from the already demonstrated capabilities of CLD to help capture the mechanisms' structures, guide the development and sense-making of quantitative investigations, and identify leverage points. It is associated with expanding the understanding of the rebound phenomenon, specifically the mechanisms that cause RE. To help reach a more effective and efficient identification and quantitative modelling of RE in the future, this research focuses on developing a comprehensive set of structures modelled in CLD, following a qualitative SD approach based upon state-of-the-art rebound mechanisms. The modelled mechanisms are compared with system archetypes, i.e., structures that help make visible the "side-effects" of actions (Wolstenholme, 2003), as using the archetypes could facilitate RE identification (Achachlouei and Hilty, 2016).

The paper is structured as follows. Section 2 details the research methodology consisting of a two-phase iterative procedure. Section 3 presents the 26 modelled rebound mechanisms using CLD, consolidated into a catalogue. A thorough catalogue analysis clarifies the fundamental characteristics of the rebound mechanisms, exposing insights to understanding them. Finally, two generic structures are derived, uncovering the fundamental structures of rebound mechanisms. Section 4 consolidates four research contributions to RE. Finally, section 5 contains the final considerations and possibilities for additional research towards expanding a systemic view on the field.

2. Research methodology

Fig. 1 depicts the research structure employed to respond to three research questions (RQ) that guided the identification of how feedback thinking can help explain the structures leading to the occurrence of RE:

- RQ1: How to model rebound mechanisms into causal loop diagrams (CLDs)?
- RQ2: What generic structures can represent and explain the mechanisms leading to RE?
- RQ3: How can feedback thinking help to understand and address RE?

2.1. Phase 1: Modelling rebound mechanisms

A literature review was employed to identify review studies of rebound mechanisms. As a result, four studies that comprehensively described the mechanisms leading to RE were selected. Three of the selected references come from the energy economics (Brockway et al., 2021; Colmenares et al., 2020; Lange et al., 2021) domain and one from circular economy (Metic and Pigosso, 2022). The excerpts analysed in the original papers and the number of mechanisms described alongside the categorisation used by the authors can be found in Table A1.

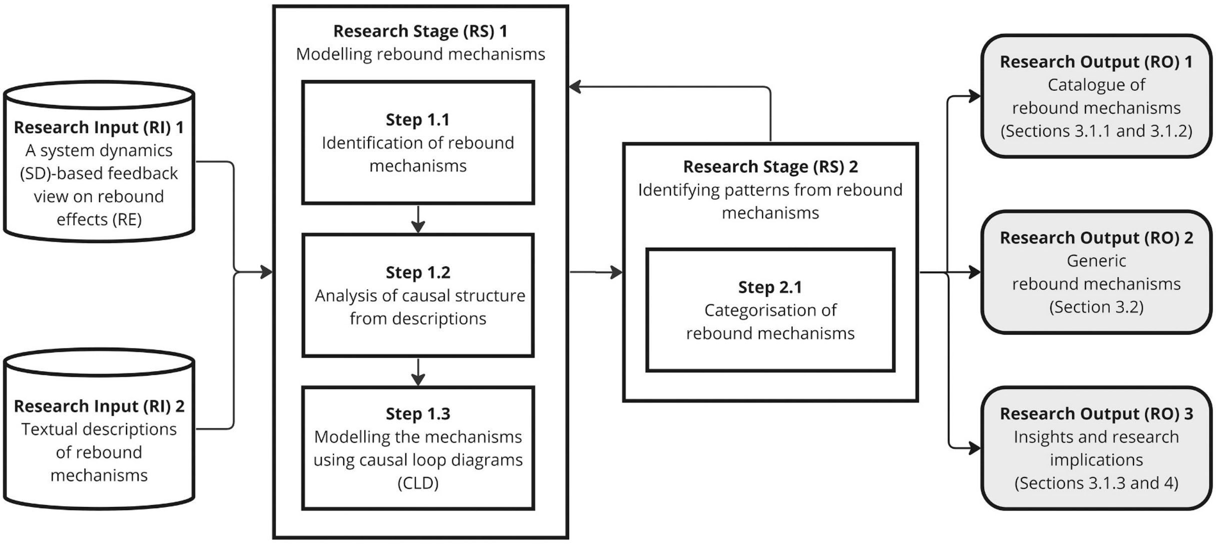

Fig. 1. Research structure including inputs, stages, steps, and outputs.

Research Stage (RS) 1 started by identifying and comparing rebound mechanisms with similar names or textual descriptions (**step 1.1**). Clustering similar mechanisms was done because sometimes inconsistent names or descriptions were encountered (e.g., the Indirect output mechanism, as described in Colmenares et al. (2020), holds a similar textual description to the re-investing mechanism in Metic and Pigosso (2022)). Table 1 makes explicit the connection between the modelled mechanisms included in the catalogue and how the authors of the four studies refer to them in the four studies.

Step 1.2 consisted of the analysis of the causal structure from the mechanisms' textual descriptions using deductive content analysis (Elo and Kyngäs, 2008; Hsieh and Shannon, 2005) and following rebound mechanisms fundamental features that enable mapping CLD structures (Barlas, 2002; Grösser and Schaffernicht, 2012; Lane, 2008):

- Intention: Element that determines the goal of the action, e.g., enhancing resource use through efficiency, effectiveness or sufficiency action.
- Trigger: Element that causes/mediates the feedback structure of the rebound mechanism, determining its existence.
- Driver: Element that influences/moderates the feedback structure of the rebound mechanisms, determining its strength.
- Causal relationship: Evidence of the cause-effect relationship between system elements (i.e., intentions, triggers, and drivers).
- Causal relationship polarity: Evidence of the directions of change between the influencing and influenced elements holding a causal relationship.

For example, the analysis of the textual description of the income effect provided by Metic and Pigosso (2022) is:

"Efficiency improvements <intention> may <causal relationship> reduce <polarity> the total cost of ownership of a product/service <trigger>, which in turn results <causal relationship> in an increased <polarity> disposable income <trigger> and ultimately <causal relationship> in more <polarity> consumption of that product/service <trigger>."

Based on the analyses, **step 1.3** consisted of modelling the mechanisms using CLD following feedback thinking (Sterman, 2000, 2001), which enabled positioning RE as a "side effect" of goal-oriented action. In line with the SD-based feedback view on RE, the following operational definition was employed to determine a rebound mechanism: *A cause-and-effect feedback structure composed of endogenous and exogenous elements (*i.e., *triggers and drivers, respectively) that explains the occurrence of a RE originating from a sustainability action.* When necessary, implicit elements, relationships and time delays were represented explicitly in the models to avoid ambiguity (Sterman, 2000) by triangulating the different descriptions for similar portions of the mechanisms. A variable was included when deemed to increase the explanatory potential of the mechanism and critical for further operationalisation. Time delays were used to represent lengthier reactions to change concerning the time scope adopted for modelling. In case the described mechanisms did not meet the operational definition, they were not included in the catalogue, and the reasons were made explicit (see Table A2).

Feedback loops, i.e., successions of cause-effect relations that start and end in the same system element and whose interplay can lead to specific patterns of behaviour (Barlas, 2002), were identified. The interplay of the feedback loops helped explain the rebound mechanisms. In general, these feedback loops could easily fall outside the sight of decision-makers. Therefore, we followed Wolstenholme (2003, 2004), who suggests making explicit those boundaries as they are critical element of system dynamics. We chose to use letters and thinner lines to communicate the decision-sphere of those making the sustainability action while numbering the feedback structures and using thicker lines to communicate balancing and feedback loops that relate to system reaction activating the rebound mechanism.

2.2. Phase 2: Identifying patterns from rebound mechanisms

In **phase 2**, the modelled rebound mechanisms (**step 2.1**) were categorised based on the eight criteria described in Table 2. The categorisation involved the analysis of each modelled mechanism against the available options for all the criteria. Some criteria allowed a single option (e.g., sustainability action, market, archetype), while others allowed multiple options (e.g., multiple actors, triggers, drivers, and associations of structures).

The iterative modelling and categorising mechanisms enabled reaching an equivalent level of specification between structures and high harmonisation through a few research strategies adopted: (i.) departing from the SD-based conceptual framework for rebound mechanisms with an operational definition for rebound mechanisms, (ii.) relying on descriptions for the mechanisms with a similar level of detail when modelling, (iii.) keeping the structures as simple as possible and including cause-and-effect structures or variables only when leading to additional explanatory potential of the mechanism, (iv.) using similar

Table 1
Rebound mechanisms as in the considered references.

ID	Modelled mechanism	Mechanisms described in reference papers			
		Colmenares et al. (2020)	Brockway et al. (2021)	Lange et al. (2021)	Metic and Pigosso (2022)
1 A	Income	• Direct - Income (+)	• Direct - Income effect (consumers)	• Micro - Income	• Direct - Price • Direct - Income
1B	Consumption time	• Time savings - Time			• Direct - Time (Consumer)
1C	Motivational consumption			• Micro - Preference Change	• Direct - Motivational • Economy-wide - Consumption efficiency
1D	*Re*-spending	• Indirect - Income (+)	• Indirect - Income effect (consumers)		• Indirect - Re-spending
1E	Re-spending with limited income	• Compensating cross elasticities - Fixed income (−)			
2 A	Output	• Direct - Output (+)	• Direct - Output effect (producers)	• Micro - Firm output	• Direct - Output
2B	Production time				• Direct - Time (Producer)
2C	Re-investment	• Indirect - Output (+)	• Macroeconomic - Growth effect		• Indirect - Re-investing
2D	Cost-dependent output		• Indirect - Output effect (producers)	• Meso - Prices of intermediate goods and services	• Economy-wide - Cross-factor
3 A	Substitution	• Direct - Substitution (+) • Indirect - Substitution (−)	• Direct - Substitution effect (consumer) • Indirect - Substitution effect (consumer)	• Micro - Substitution of products	• Indirect - Substitution (Consumer)
3B	Motivational substitution	• Indirect - Behavioural (+)			• Indirect - Motivational
3C	Factor substitution	• Direct - Factor substitution (+) • Indirect - Factor Substitution (−)	• Direct - Substitution effect (producer) • Indirect - Substitution effect (producer)	• Micro - Substitution of production factors	• Indirect - Substitution (Producer)
3D	Composition substitution	• Interactive - Composition (+)	• Macroeconomic - Composition effect	• Macro - Production-composition	• Economy-wide - Composition
3E	Sectoral allocation	• Macroeconomic - Growth: Sectoral allocation		• Macro - Investment-composition	
4 A	Demand adjustment initiated by sufficiency				• Direct - Sufficiency (Consumer)
4B	Demand adjustment initiated by efficiency	• Interactive - Market price (+)	• Macroeconomic - Energy market effect	• Meso - Prices of final goods and services	• Economy-wide - Resource market
4C	Demand adjustment with investment adjustment	• Interactive - Disinvestment (−)	• Macroeconomic - Disinvestment effect		
4D	Re-design	• Complementary - Re-design (+)		• Micro - Product re-design	
4E	Supply adjustment				• Sufficiency - Producer
4F	Producer-induced demand adjustment			• Meso - Price of a single energy carrier	
4G	Sector-induced demand adjustment			• Macro - Overall energy price	
5 A	Economies of scale	• Interactive - Economies of scale (+)	• Macroeconomic - Scale effect	• Meso - Economies of scale	
5B	Market price	• Macroeconomic - Price			• Economy-wide - Market price
5C	Labour income	• Interactive - Rising Labor income (+)	• Macroeconomic - Labour supply effect	• Macro - Wages	
5D	Labour income with limited labour supply	• Macroeconomic - Labour supply (−)			
5E	New economic activity	• Macroeconomic - Growth: Fiscal multiplier		• Macro - Multiplier	• Economy-wide - Frontier

Table 2
Criteria used to perform the categorisation of the rebound mechanisms.

Criterion	Definition	Options	Application
Sustainability action	Intervention that initiated the rebound mechanism in the descriptions.	• Efficiency; • Effectiveness; • Sufficiency.	Single choice
Scope of effect	Scope of effects considering enhanced demand for goods (products and services) and processes.	• Direct (Same good or process) • Indirect (Other good or process); • Economy-wide (General increase in economic activity)	Single choice
Actors	Identification of who is acting in the mechanism.	• Consumer/household; • Firm; • Sector/supply chain; • Regional/national economy.	Multiple choice
Level	Level of aggregation at which the mechanism takes place, based upon the types of actors involved.	• Micro (One type of actor) • Meso (Interaction of more than one type of actor, including the sector/supply chain) • Macro (Occurring at the regional/national economy)	Single choice
Triggers	Identification of the factors mediating the rebound mechanism (within causal chains)	• Economic / financial • Consumer choices	Multiple choice
Drivers	Identification of the factors moderating the rebound mechanism structure (exogenous factors influencing causal chains)	• Company choices • Socio-cultural influences • Physical constraints • Goods attributes	Multiple choice
Archetypes	Identification of system archetypes (i.e., fundamental causal structures that can provide meaningful insights about counterintuitive behaviour from well-intended actions) that describe the mechanism.	Following (Braun, 2002; Senge, 1990; Wolstenholme, 2003)	Single choice
Association of structures	Identification of adaptation or combination of structures to describe the mechanisms.	The catalogue of structures	Multiple choice

visual structures that preserve the archetypes, and (v.) modelling and categorising the mechanism departing from a similar set of triggers and drivers. The two phases occurred iteratively and contributed to the three research outputs described in the results and discussion sections.

3. Results

The results read as follows. Section 3.1 presents the comprehensive catalogue of modelled rebound mechanisms (RO 1). It starts by describing the dynamics of sustainability action (Section 3.1.1), and providing a description of four selected mechanisms (Section 3.1.2), being followed by the cross-analysis of the 26 modelled mechanisms (Section 3.1.3), and by the description of the insights from the modelling and analysis process (RO3 in Section 3.1.4). Finally, section 3.2 contains the generic rebound mechanisms representing the most basic feedback structures stimulating RE occurrence (RO 2).

3.1. Towards a catalogue of rebound mechanisms

3.1.1. The dynamics of sustainability action aiming at enhanced resource consumption

Understanding the dynamics of rebound mechanisms includes two critical factors: (1) articulating the use of CLD for describing the endogenous causal understanding of a system; and (2) describing the dynamics of sustainability action to make explicit the expected outcomes of actions aiming at enhanced resource consumption.

A CLD articulates the endogenous causal understanding of a system by representing the causal relationships (arrows) between system elements, the direction of change between the influencing and influenced elements (polarity represented by the '+' and '-'signs), and the existence of feedback loops (i.e., successions of cause-effect relations that start and end in the same system element, and which interplay can lead to specific patterns of behaviour) (Barlas, 2002; Lane, 2008). While reinforcing or positive feedback loops compound an initial change in the system, leading to exponential growth or collapse, a balancing or negative loop counteracts change, leading to goal-seeking behaviour (Barlas, 2002). Additionally, time delay marks (represented by two lines crossing the causal relationship) indicate the time delay which may separate causes and effects in time and space, thereby influencing the system behaviour (Barlas, 2002). The CLD enables the depiction of a given system's structure and the assessment of potential system behaviours over time (Grösser and Schaffernicht, 2012; Lane, 2008).

Fig. 2 represents the dynamic of sustainability action. In general, consumers and decision-makers in companies and public institutions will engage in sustainability actions to enhance the sustainability of a local system they can act on. More specifically, decision-makers will engage in actions that aim to improve the material and energy resource consumption of that system (e.g., to produce it, use it, discard it), considering the limitations of what is possible to improve in terms of efficiency, effectiveness, and sufficiency while keeping it attainable to their socio-economic context (*Ba*). For instance, decision-makers in companies will most likely engage into sustainability action that fall within their technical and operational capabilities and that make sense from a business perspective. Decision-makers knowledge on what is possible and attainable to improve will partially determine their gap to intended sustainability.

These actions are responses for releasing the societal pressures for sustainability, contributing to enhanced general resource consumption (*Bb*). The effects of the sustainability action depend on the planetary processes of accumulation (material delays) and the societal perceptions towards the state of Earth (information delays). When societal pressure builds up, it materialises through citizen and consumer activism, policies and regulations, customers' requirements, and investment rules. These pressures exacerbate the gap to intended sustainability, pushing decision-makers to find new ways to enhance the sustainability of the local system at reach by improving the resource consumption in those systems (incl. both material and energy).

Meanwhile, the resource consumption of other systems also contributes to general resource consumption. Therefore, even though a local system may be very sustainable there will still be pressures to do more if all the others are not sustainable. Therefore, decision-makers will be consistently engaging into sustainability action aiming at improving local resource consumption (*Ba*) until those actions are enough to release the societal pressures (*Bb*) but being consistently defeated by

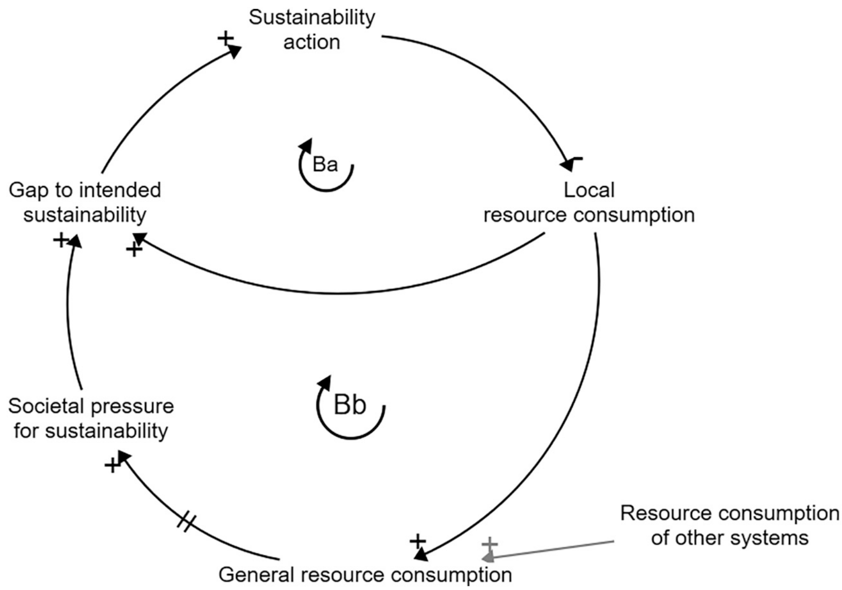

Fig. 2. A generic causal loop diagram (CLD) of the dynamics of sustainability action aiming at enhanced resource consumption. (Ba) reads as decision-makers engaging into sustainability action aiming at improving local resource consumption. (Bb) reads as enhanced local resource consumption contributes to general resource consumption and releases societal pressures.

what they may regard as the high level of resource consumption by other systems.

3.1.2. Description of rebound mechanisms available in the catalogue

The resource consumption of other systems might not tell the whole story as rebound mechanisms are feedback structures activated by triggers and influenced by drivers that arise from the implementation of a sustainability intervention in the local system, offsetting potential sustainability gains (e.g., controlling *general resource consumption*), and keeping the need for action to release the *societal pressures for sustainability* are sustained. Out of the 26 mechanisms available in the catalogue, four CLD models exemplify the mechanisms: income (ID 1 A), consumption time (ID 1 B), substitution (ID 3 A) and demand adjustment initiated by sufficiency (ID 4 A).

In the **income mechanism** (Fig. 3), an *efficiency action* leads to enhanced *efficiency of product/service A,* decreasing the *costs of consuming product/service A*. The decreased consumption costs lead to an additional *budget available for the consumption* of more units of the same product/

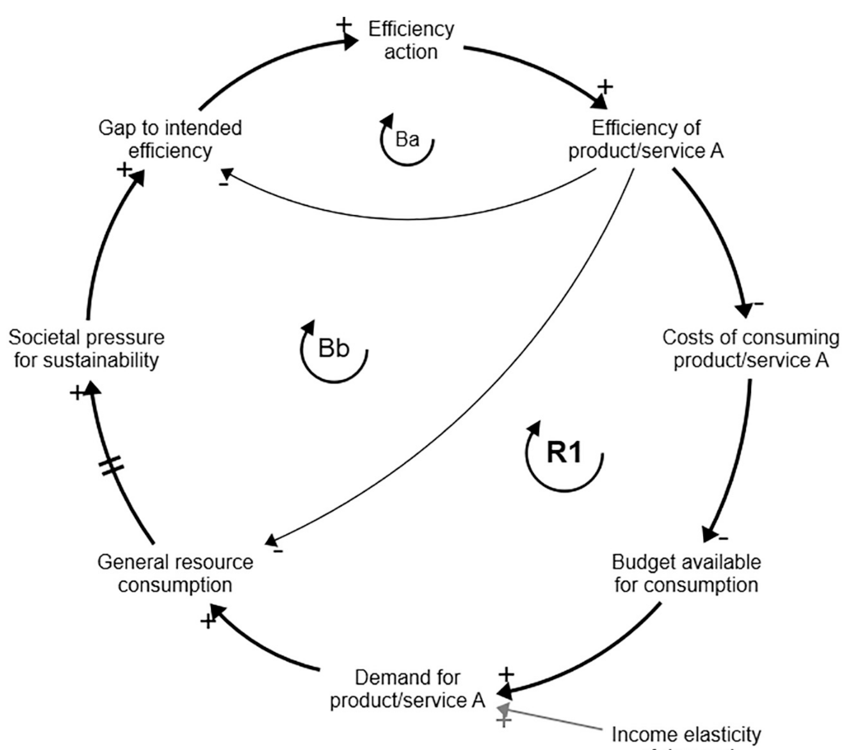

Fig. 3. A causal loop diagram (CLD) of the Income mechanism. (R1) reads as released budget from decreased costs of consumption leading to additional consumption.

service, adding to the *demand for product/service A* and, ultimately, to *general resource consumption* – eventually closing the reinforcing loop (*R1*) and playing against the intended balancing effects of the initial action (Ba and Bb). The income effect has been widely discussed in transportation, where additional car ownership and driving have been identified due to increased fuel efficiency (Mayo and Mathis, 1988; Pui and Othman, 2017; Stepp et al., 2009; Wheaton, 1982). An important driver for the income mechanism is the *income elasticity of demand* for that product, which defines the degree to which additional *budget available for consumption* will lead to more *demand for product/service A*.

Leverage points are places in a system where small changes in their structure can considerably influence system behaviour (Abson et al., 2017; Meadows, 1999). For example, one fundamental leverage point in systems is to reduce the strength of undesirable positive reinforcing feedback loops (Meadows, 1999). In that sense, the CLD makes explicit a few variables to control and reduce the effect of the income mechanism. For instance, the relationships between the increased *efficiency of product/service A*, the decreased *costs of consuming product/service A*, and the additional *demand for product/service A* due to the increased *budget available for consumption* can hint at leverage points to prevent the RE from occurring. For example, is it possible to combine complementary sustainability strategies so that the decreased costs from higher efficiency flow into additional services, contributing to lowering general resource consumption? Can the company influence customers to use the released budget due to efficiency for better vehicle maintenance instead of longer rides?

The **consumption time mechanism** (Fig. 4) is similar to the income mechanism (Fig. 3). Still, it happens in cases in which an *efficiency action* leads to decreasing *time for consuming product/service A* and releasing the *time available for the consumption* of more units of the same product/service, adding to the *demand for product/service A* and, ultimately, to *general resource consumption.* For example, a more efficient mode of transportation might release time for mobility and cause people to move longer by moving further away from work. This effect has been examined in studies considering high-speed transport technologies (Buhl and Acosta, 2016), connected and automated vehicles (Taiebat et al., 2019), and ride-sharing (Yin et al., 2018), which is an effectiveness action. Although no driver was apparent in the textual descriptions, it may be fair to speculate *that the time elasticity of demand emerging from time available for consumption* will drive additional *demand for product/service A*. Analogous to the income mechanism, the leverage points in preventing the consumption time mechanism revolve around influencing the use of the time available for additional consumption. How to instigate reflection from the consumer perspective to avoid using the released time for resource-intensive action?

The **substitution mechanism** (Fig. 5) represents the consumption of different products and services due to the enhanced efficiency of a given product or service. In that case, the *demand for product/service A* and *product/service B* relies upon the *relative price between product/service A and B*. Decreased *costs of consuming product/service A* emerging from the increased *efficiency of product/service A* will influence the *relative price between them*, adding to *demand for product/service A* and *general resource consumption* – eventually closing the reinforcing loop (*R1*) and playing against the intended effects of the action. Concurrently, the change in relative prices might drive the *demand for product/service B* down, leading to decreased *general resource consumption* (*B1*). The total effect when considering R1 and B1 in the substitution mechanism depends on the *substitutability between product/service A and B and* the relative *efficiency of product/service A and B.* Suppose the action leads to substituting away from a more efficient product/service (e.g., from walking to work to using a shared electric car as mentioned in Metic and Pigosso (2022)). In that case, the total effect in *general resource consumption* is even more detrimental. Thus, *B1* would make the RE magnitude to be worse.

In this case, a clear leverage point is influencing consumers towards the beneficial change and away from the detrimental ones, enabling secondary benefits from this mechanism. For example, in addition to providing electric mobility, Lynk & Co – a shared mobility provider – fosters more liveable cities with less car space to sustain walking in the long run.

Finally, in the **demand adjustment mechanism** (Fig. 6), an individual's *sufficiency action* that leads to decreased *demand for product/service A* will lead to an *excess of supply* vs. *demand of product/service A* if the *supply of product/service A* (driver) is not adjusted accordingly. The excess of supply might unfold into pressuring companies to diminish the

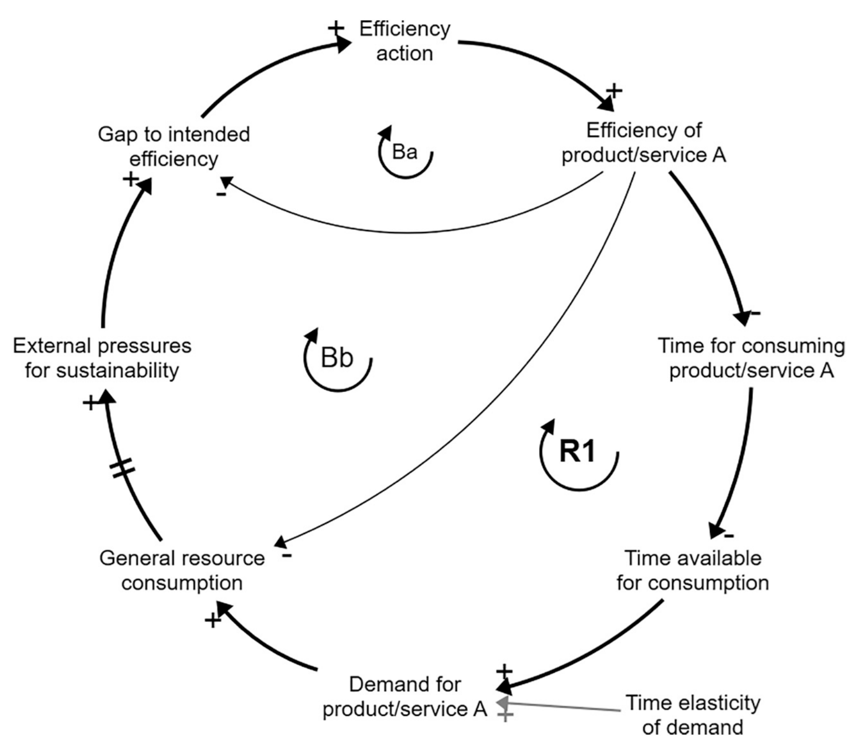

Fig. 4. *A causal loop diagram (CLD) of the consumption time mechanism.* (R1) reads as released time leading to additional consumption.

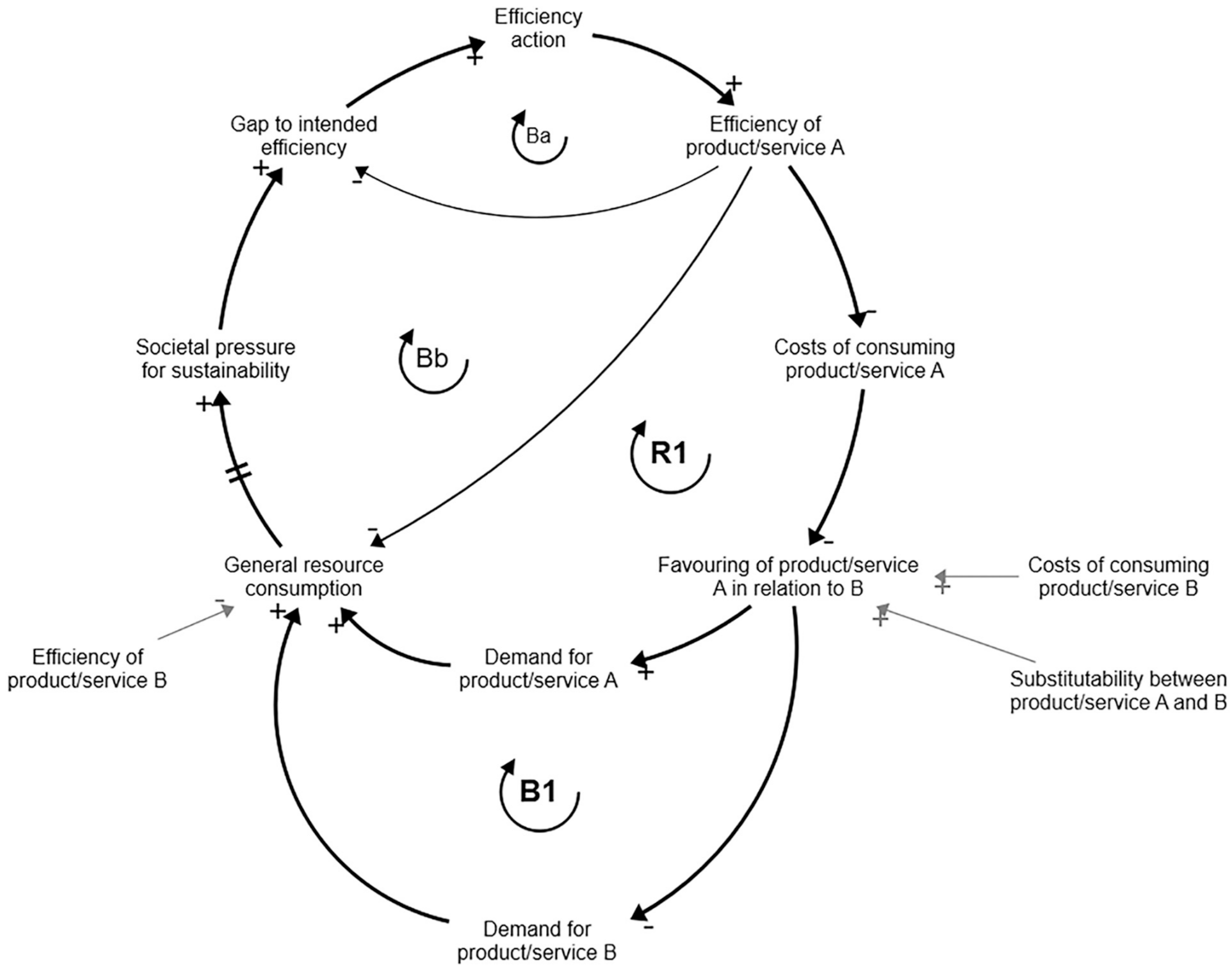

Fig. 5. A causal loop diagram (CLD) of the substitution mechanism. (R1) reads as decreased relative costs favouring substitution from product/service B to A (additional demand for A). (B1) reads as decreased relative costs favouring substitution from product/service B to A (decreased demand for B).

price for product/service A, which will activate *others' demand for product/service A,* compensating for additional *general resource consumption* (B1). Figge et al. (2014) suggest that in perfect competition, a fall in demand for a product like clothing will likely be partly or fully compensated by increased demand by other consumers.

In this case, a critical leverage point is controlling the reactions to excess supply by raising other actors' awareness towards more sufficient lifestyles and taking the sufficiency action themselves. In that sense, actors aware of the implications of resource consumption might try to influence several consumers so that they do not react to potential decreased prices to excess supply. This strategy aligns with Patagonia's 'Don't buy this jacket' advertisement, suggesting customers reflect before they purchase their jacket. This strategy could influence customers not to be caught by lower prices and buy things they do not need even if tempted by other providers' actions.

3.1.3. *Overview of the catalogue of rebound mechanisms*

Table 3 organises all 26 modelled rebound mechanisms following the criteria presented in Table 2. There are five classes of mechanisms determined by the structures they are associated with (represented by the number in the rebound mechanism ID): 1. Variations of the income mechanism, 2. Variations of the output mechanisms, 3. Variations of the substitution mechanism, 4. Variations of the demand adjustment mechanism, and 5. Combinations of the income and output mechanisms with delays indicating longer-term reactions. Mechanisms are ordered within each class following the markets considered in the mechanisms, the actors involved, and the types of triggers/drivers stimulating the occurrence of RE. All the 26 rebound mechanism structures modelled in CLD are available in the complementary dataset (Guzzo, Walrave, Videira et al., 2023). The four mechanisms described in section 3.1.1 showcase the catalogue by representing different archetypes, classes of triggers and drivers, and actors taking part in the mechanisms.

Table 3 shows that, in general, efficiency actions are dominant in describing how the rebound mechanisms initiate (24 mechanisms in total) – indicating the gaps in studies investigating effectiveness and sufficiency-driven RE. Some mechanisms consider only the reactions to the same good or process, i.e., direct (13), while others affect different goods or processes, i.e., indirect (10). Most mechanisms involve firms' (15) actions, while half involve consumers (13). The primary triggers and drivers are economic (22 and 15, respectively), including consumption costs, budget available for consumption, cost of production and profits. A few mechanisms are triggered by consumer choices (3). Meanwhile, goods' attributes (e.g., substitutability and efficiency of the alternative system) and company choices (e.g., the choice to re-invest or raise wages) are recurrent drivers (11 each).

The analysis of the association between structures showed that all the mechanisms adapt or combine at least one of the following mechanisms: the income (ID 1 A), output (ID 2 A), substitution (ID 3 A), and demand adjustment initiated by sufficiency (ID 4 A); respectively 10, 10, 5, and 7 structures. The analysis of the archetypes showed that most of the mechanisms represent variations of the "fixes that fail" archetype (19), including all the variations of the income, output, and substitution mechanisms. Seven rebound mechanisms represent the "escalation" archetype, including all the variations of the demand adjustment

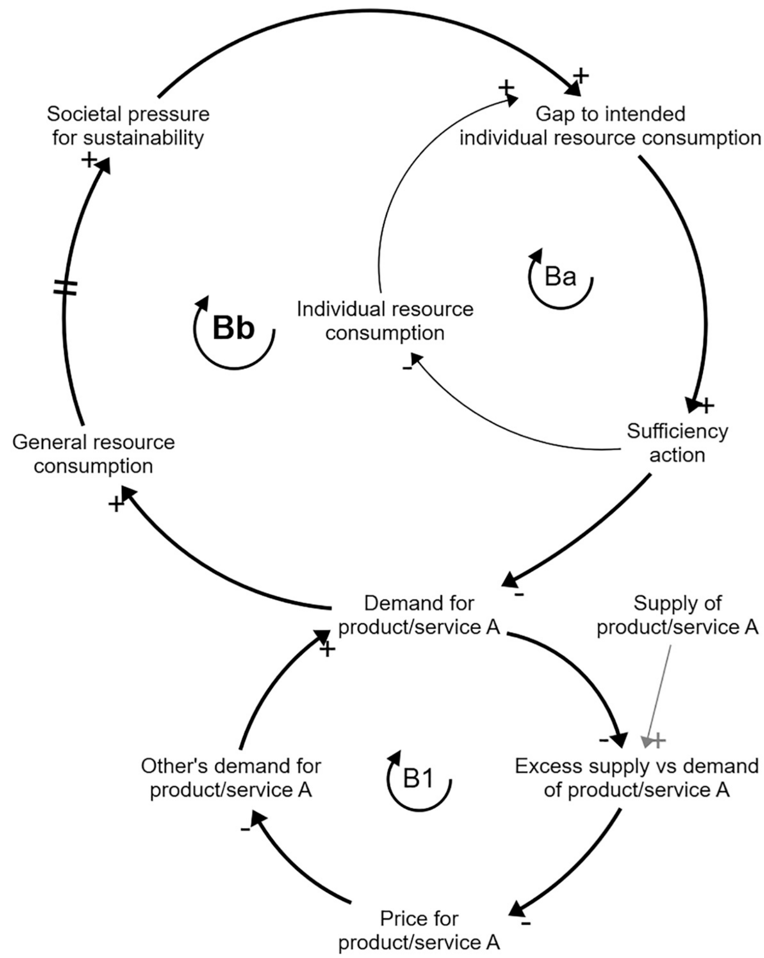

Fig. 6. A causal loop diagram (CLD) of the demand adjustment mechanism initiated by sufficiency. (B1) reads as upwards demand adjustments from decreased demand.

mechanism. Efficiency interventions initiate all the "fixes that fail" structures, while the only two mechanisms initiated by sufficiency interventions unfold into "escalation". Nevertheless, efficiency intervention also initiated an escalation rebound mechanism (i.e., the re-design mechanism). Therefore, there is not a direct connection between the action and the type of rebound mechanism. The two archetypical structures are further explored in section 3.2.

3.1.4. *Insights from the cross-analysis of modelled rebound mechanisms*

Cross-analysing the catalogue leads to five insights regarding rebound mechanisms' structure, behaviour, and nature. First, different mechanisms hold similar structures but differ into the actor involved and the triggers activating them. For example, the income (ID 1 A) and output (ID 2 A) mechanisms hold similar structures but consider different actors. The first focuses on consumers' actions and consider economic triggers and drivers – they are triggered by the released budget for consumption from decreased consumption costs, driven by the elasticity of demand for that product/service. The second focuses on the producers' actions and also consider economic triggers and drivers – they are triggered by increased profits from reduced production costs, driven by the consumers' demand for products or services. In turn, the income mechanism (ID 1 A) and the consumption time mechanism (ID 1 B) hold similar structures, consider the consumers as the main actors, but the type of triggers activating them differ. The first is triggered by decreased costs (economic), and the second by the decreased time needed to consume (physical constraint). Similar structures with different triggers can indicate interrelations between the rebound mechanisms and potential synergies and compromises in deriving interventions to manage them.

Insight (1): A thorough consideration of the actors, triggers and drivers taking place in the system can help identify a diversity of rebound mechanisms.

Rebound mechanisms associate by combining simpler ones, making specific decision-making structures explicit, or employing different triggers. For instance, the re-spending mechanism (ID 1 D) adapts the income mechanism (ID 1 A), where the released budget drives the consumption of different products/services instead of the same. The combination of the income and re-spending mechanisms could happen indefinitely, as many options exist for re-spending the released budget. Meanwhile, the substitution mechanism (ID 3 A) considers that consumers might use the released budget to fulfil different needs. The three mechanisms might co-occur as consumers can choose different options while holding limited financial resources.

It is, therefore, critical to clarify what determines the specific dynamics of supply and demand responses to identify which RE might unfold in particular cases. One decision-making spectrum relates to what causes additional consumption in the same market or considering alternatives. The conditions for additional consumption of the same product/service (income mechanism – ID 1 A), a different product/service (re-spending mechanism – ID 1 D) or substituting to others (substitution mechanism – ID 3 A) will determine the mechanism at play. Furthermore, the share of the released budget to consume a given product/service will limit the other options, so the effect of one mechanism limits the effect of the others.

Another decision-making spectrum relates to the interplay of triggers. For instance, the income (ID 1 A), consumption time (ID 1 B), and

Table 3
Analysis of the rebound mechanisms following the categorisation criteria presented in Table 2.

Rebound mechanism		Sustainability-action			Scope of effect			Actor				Level			Trigger						Driver						Archetype		Association of structures			
ID	Mechanism name	Effi.	Effe.	Suf.	Dir.	Ind.	*E*-w	Con.	Firm	Sec.	Eco.	Mi.	Me.	Ma.	E	Con. C	Com. C	SI	PC	GA	E	Con. C	Con. D	SI	PC	GA	FFT	Esc.	In.	Ou.	Su.	De.
1 A	Income	●			●			●				●			●						●						●		●			
1 B	Consumption time	●			●			●				●							●						●		●		●			
1 C	Motivational consumption	●			●			●				●				●						●					●		●			
1 D	*Re*-spending	●				●		●				●			●						●					●	●		●			
1 E	Re-spending with limited income	●				●		●				●			●						●					●	●		●			
2 A	Output	●			●				●			●			●								●				●			●		
2 B	Production time	●			●				●			●							●								●			●		
2 C	Re-investment	●				●			●			●			●						●		●			●	●			●		
2 D	Cost-dependent output	●				●			●	●			●		●								●			●	●			●		
3 A	Substitution	●				●		●				●			●						●					●	●				●	
3 B	Motivational substitution	●				●		●				●				●						●				●	●				●	
3 C	Factor substitution	●				●			●			●			●						●					●	●				●	
3 D	Composition substitution	●				●				●			●		●						●					●	●				●	
3 E	Sectoral allocation	●				●				●			●		●						●		●			●	●				●	
4 A	Demand adjustment intiated by sufficiency			●	●			●	●				●		●						●							●				●
4 B	Demand adjustment initiated by efficiency	●			●			●	●				●		●						●							●				●
4 C	Demand adjustment with investment adjustment	●			●			●	●				●		●								●					●		●		●
4 D	Re-design	●			●				●			●			●					●						●		●				●
4 E	Supply adjustment			●	●			●	●	●			●		●						●		●					●				●
4 F	Producer-induced demand adjustment	●			●				●	●			●		●						●							●				●
4 G	Sector-induced demand adjustment	●			●					●			●		●						●							●				●
5 A	Economies of scale	●			●			●	●				●		●						●		●				●		●	●		
5 B	Market price	●				●		●	●				●		●						●		●			●	●		●	●		
5 C	Labour income	●					●		●		●			●	●								●				●		●	●		
5 D	Labour income with limited labour supply	●					●		●		●			●	●	●						●	●				●		●	●		
5 E	New economic activity	●					●			●	●			●	●								●				●		●	●		
	Total	24	0	2	13	10	3	13	15	7	3	12	11	3	22	3	0	0	2	1	15	3	11	0	1	11	19	7	10	10	5	7

The following meanings define the columns: Efficiency (Effi.), Sufficiency (Suf.), Effectiveness (Effe.), Direct (Dir.), Indirect (Dir.), Economy-wide (E-w), Consumer (Con.), Sector (Sec.), Economy (Eco.), Economic (E), Consumer choices (Con. C), Company choices (Com. C), Socio-cultural influences (SI), Physical constraints (PC), Goods attributes (GA), Fixes that fail (FFT), Escalation (Esc.), Income (In.), Output (Ou.), Demand (De.), Substitution (Su.).

motivational consumption (ID 1 C) mechanisms involve consumer responses considering different classes of triggers. The triggers indicate some of the limited resources people consider when consuming and the criteria for decision-making. Therefore, understanding how economic factors, physical constraints, and individual decision-making play together is critical to determining RE's occurrence and magnitude. It may be the case that different triggers' behaviour will activate different rebound mechanisms through time.

Insight (2): Operationalising the mechanisms requires making explicit the decision-making structures through which actors consider alternative consumption and production options and the accumulation and depletion of limited resources that determine those decisions.

Structural analysis of the rebound mechanisms' structures enabled assessing the conditions for RE occurrence and the identified triggers and drivers hinted at potential leverage points. In some cases, positive and negative feedback loops coexist in rebound mechanisms, as in the substitution mechanism (ID 3 A). While the reinforcing loop R1 (representing the substitution effect towards product/service A) adds to general resource consumption by default, the balancing loop B1 (representing the portion that moves away from product/service B) might or might not lead to additional general resource consumption depending on the identified drivers (*substitutability* and the *ration between efficiencies*). Thus, there might be scenarios where moving away from product/service B is desired, while in other cases not. Identifying thresholds for the different scenarios will be critical to understanding the RE occurrence conditions and identifying the leverage points to act. For instance, if moving away from product/service B is desired, additional interventions could accelerate that change.

Insight (3): Structural analysis of mechanisms helps identify the potential leverage points to weaken the rebound mechanisms' detrimental effects, potentially strengthening the beneficial ones.

Some rebound mechanisms tend to present structures with limited causal traceability. This lower granularity or resolution is noticeable in using delays (which indicate hidden processes) or more abstract variables. For instance, the new economic activity mechanism (ID 5 E) shows that *companies' profits* can lead to *new economic activity through several means*, considering *decisions to raise wages and re-invest*. Apart from the delayed processes and the more abstract variables, it also leaves somewhat implicit how new economic activity will unfold, which should be further explored in practice if the intention is to address the reasons for this kind of RE.

Insight (4): Although CLDs enable representing rebound mechanisms, a few structures might not be transparent enough to depict them thoroughly. In that case, further describing the specific structures can enhance understanding towards enhancing explanatory potential and identifying leverage points.

Some mechanisms do not share the structure of other rebound mechanisms. For instance, the symbiotic mechanism (Metic and Pigosso, 2022) describes that the more resources flow to favour a given strategy, the more it is bound to succeed to the detriment of another. For instance, investing in recycling might make remanufacturing less appealing in the long run. Although lock-ins are critical higher-order consequences of design and innovation, they fall outside the operational definition adopted for a rebound mechanism in this research. Also, imperfect substitution (Metic and Pigosso, 2022) shows that some strategies might still require primary resources when the substitutability of primary for secondary resources is imperfect. For instance, when adopting recycled material as input, you might still need virgin resources to meet the product's functional requirements. Although detrimental to resource consumption, no feedback structure is associated with the description of the mechanism. This phenomenon might be closely related to induced effects, and it should be considered within the intended consequences by a fair technical analysis of the solution. Also, the innovation (Lange et al., 2021) or induced innovation (Colmenares et al., 2020) mechanisms are secondary effects of the sustainability-oriented action cascading to different products, processes, and sectors. For instance, the proof of the technological and market success of a new fuel in aviation might spill over to other industries, such as the automotive. Nevertheless, it is not a reaction from the initial efficiency action but entails a new sustainability-oriented action made possible by changes caused by the initial one. In that case, it seems to make sense to investigate eventual RE separately. Therefore, these mechanisms were disregarded alongside others – see Table A2 for all the rebound mechanisms disregarded with references and reasons.

Insight (5): Some mechanisms might emerge as features of the economic system, design and innovation, or other higher-order consequences of sustainability actions. While they hinder the achievement of enhanced resource consumption and global sustainability, they are conceptually different from the definitions for rebound mechanisms adopted. They were, therefore, not included in the catalogue.

3.2. Identifying generic rebound mechanisms

The collection of rebound mechanisms shows that well-intended sustainability interventions in a local system will activate chains of economic, behavioural and other triggers and drivers that will counteract the controlling of general resource consumption, undermining global sustainability. The rebound mechanisms modelled take the form of feedback loops that eventually act against the deeper intentions of the action and feedback as extra pressure for action. Two generic rebound mechanisms, consisting of adaptations of the "fixes that fail" and "escalation" SD archetypes (Braun, 2002; Senge, 1990; Wolstenholme, 2003) to the RE domain, are derived from the catalogue. Fundamentally, all rebound mechanisms resemble these two archetypes and expose the system reactions on resource consumption or production that are detrimental to the intentions of sustainability action.

First, actions that decrease resource consumption in a local system (e.g., product, service, or process) can activate triggers that result in additional supply or demand for those systems (or other alternative systems), adding to general resource consumption (Fig. 7). This type of rebound mechanism forms reinforcing feedback loops that offset the potential benefits of sustainability action. They resemble a "fixes that fail" structure – the sustainability action is a quick fix that enhances resource consumption in the local system but triggers the rebound mechanism, which may cause general resource consumption to return closer to its previous level or worsen it (Braun, 2002). Since the local resource consumption and the reaction caused by the rebound mechanism will contribute to increasing general resource consumption, the RE magnitude depends on the difference between both effects. Suppose the effect emerging from the rebound mechanism, or mechanisms concomitantly activated, is higher than the effect of the local resource consumption into general resource consumption. A RE magnitude higher than 100% may be expected, leading to backfire.

Second, when people's or companies' actions decrease the supply or demand for a given system, this might result in others' reactions that may compensate for the effort, leading to RE (Fig. 8). This type of rebound mechanism forms two balancing feedback loops that control local resource consumption in the opposite direction of the initial intentions of diminishing them, indicating an escalation structure. Escalation-like structures occur when two or more actors feel pressured or threatened by the action of the other, and the action of one will lead to a reaction of the other in the opposite direction, further increasing the threat (Braun, 2002). In this case, the RE magnitude will depend on the difference between the effect of the sustainability action in controlling demand or supply and the effect of the system reactions on demand or supply. If the reactions are more intense than the action, the RE magnitude will be higher than 100%, leading to backfire.

By conveying the structures underlying the known rebound mechanisms, the generic rebound mechanisms can significantly help decrease the burden of minding the whole catalogue when examining a system. Therefore, if an examiner can systematically search for feedback loops that play against the outcomes of sustainability action in ways similar to

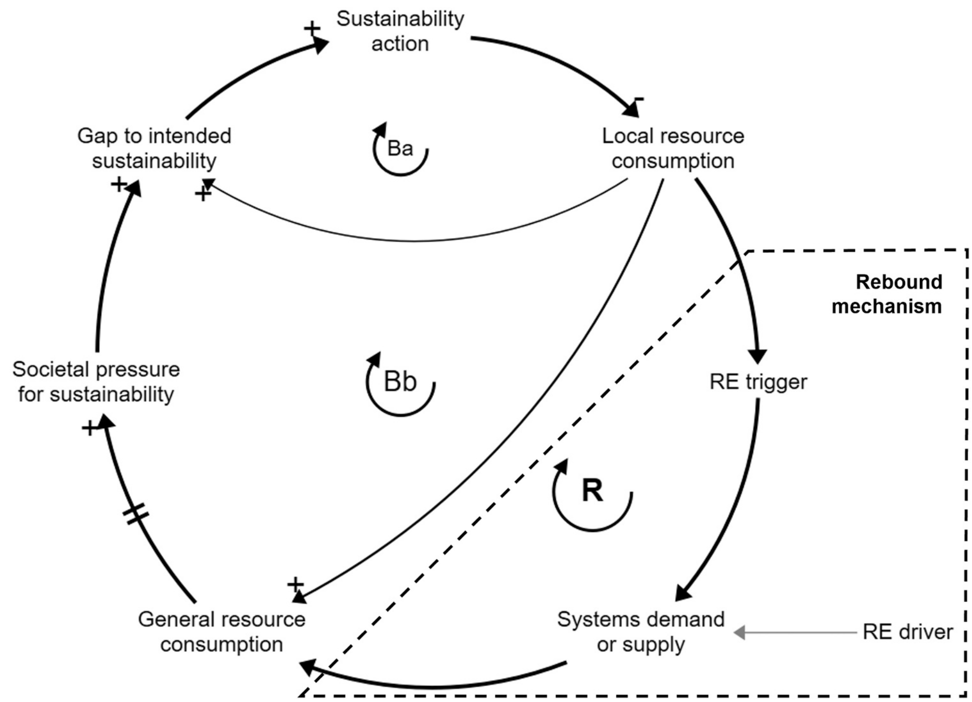

Fig. 7. A causal framework for rebound mechanisms that reinforces general resource consumption through additional demand or supply for systems. The polarity links in the generic rebound mechanism are not indicated, as different polarity conditions can lead to a reinforcing loop in the mechanisms.

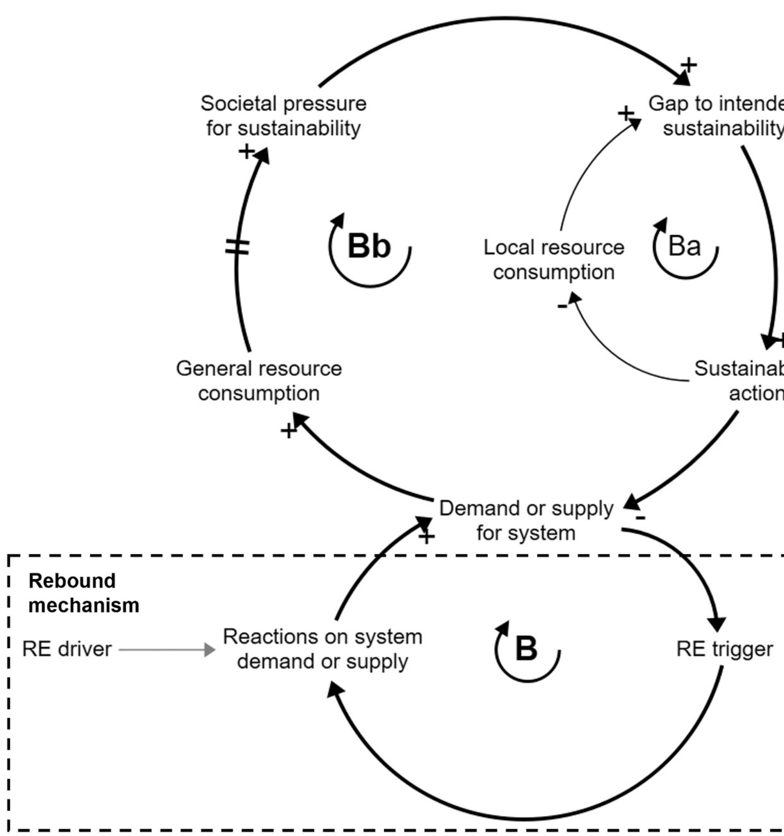

Fig. 8. A causal framework for rebound mechanisms that balances the efforts to control supply or demand for systems. The polarity links in the generic rebound mechanism are not indicated, as different polarity conditions can lead to a balancing loop in the mechanisms.

the "fixes that fail" and "escalation" structures, they might encounter the rebound mechanism at play. Additionally, the archetypes hold known behaviour over time associated with each structure. So, outcomes of sustainability-oriented actions that systematically fail as resource consumption returns closer to its previous level or worsens might also indicate the effects of rebound mechanisms. Therefore, in addition to empowering examiners to find the causes for RE, the generic mechanisms indicate that understanding systems' over-time behaviour is needed to address the rebound phenomenon.

4. Discussion: Research contributions for the RE field

The discussion builds upon the catalogue of rebound mechanisms and the generic mechanisms developed to suggest four research contributions to the RE field. The **first implication** of this research is showcasing the **ability to systematically map rebound mechanisms through feedback-driven structures**. The CLD structures make explicit the causal relationship between the sustainability action and the change in resource consumption, enhancing its causal traceability by enabling the isolation of the rebound mechanism from other potential changes in the system that might lead to additional use of resources (Azevedo, 2014; Gillingham et al., 2016; Madlener and Turner, 2016). Such capability can guide empirical studies and ensure comparability among them (Sonnberger and Gross, 2018) by sustaining ceteris paribus assumptions in RE investigations, which is critical to enabling fair mechanism-effect comparisons (Azevedo, 2014; Giampietro and Mayumi, 2018). Also, the consistent use of CLD with similar structures to represent rebound mechanisms helps in providing a consistent and transparent boundary of analysis (Azevedo, 2014; Madlener and Turner, 2016) in addressing simultaneity and endogeneity concerns (Gillingham et al., 2016; Madlener and Turner, 2016), and ultimately decreasing the uncertainty in the magnitudes of and reasons for the effects (Azevedo, 2014).

Additionally, the description of the causal structures unveiled the duality between the local effects of action and the reaction to general system sustainability, making explicit the detrimental effects of a near-sighted focus on the visible outputs of actions. The attention to rebound mechanisms as higher-order effects emerging from the system's reactions is essential to help avoid overly optimistic projections of the outcomes of sustainability action (Colmenares et al., 2020; van den Bergh, 2011), which is in the very basis of "encountering" RE afterwards. It also reinforces the role of qualitative models to identify the direct and indirect effects of initiatives and avoid self-defeating actions (Stepp et al., 2009). The attention to the feedback-driven mechanisms enables a broad, systemic view of the effects of sustainability-oriented action, which is critical to allowing the intended effects of sustainability transitions (van den Bergh, 2011).

The structures presented in this research are not specific to a given sector or geography but comprehensive towards the RE field. Also, the mechanisms are not deterministic, so it is not in every situation that increased efficiency will decrease costs or release time for consumption. Therefore, it is crucial to identify each case's relevant mechanisms and remember that they can occur concomitantly. So, if the intention is to investigate specific problems, such as the environmental sustainability of ICT adoption in Europe (Hilty et al., 2006) or the effects of eco-design policies in solid waste management in Latvia (Dace et al., 2014), it is necessary to adapt those structures to the specific cases. Complimentary descriptions of the mechanisms available in the original papers and more fundamental literature can help in the adaptation process.

The mechanisms and generic structures are expected to help model conceptualisation and reach rapid prototypes that enable productive discussions about RE occurrence (Lane, 2008). The set of mechanisms and generic structures should support the identification of a plausible set of mechanisms that should be investigate in the formal model. Furthermore, the identification of rebound mechanisms can support the elaboration of behaviour over time charts (Braun, 2002; Kim, 2000) that articulate the expected behaviour of critical variables that should be considered when investigating RE. Early identification of mechanisms and their potential influence over time in the system dynamics can be useful because, in some cases, RE was only identified due to a mismatch in expected behaviour and the calculated behaviour from a specific change (Dace et al., 2014).

The modelled mechanisms can also help reach more agile and robust simulation models capable of investigating RE. Coupling qualitative SD with simulation can enhance the insight capacity into the potential system behaviours (Lane, 2008) and enable more profound and rigorous analyses of the system dynamics (Wolstenholme, 1998). A sound understanding of the dynamic hypothesis for RE occurrence will be critical to identifying the physical and informational structures that determine behaviour over time in reaching the simulation models. Therefore, the mechanisms could sustain the development of simulation models that enable tracking back the causal reasons for RE after calculating the thresholds for occurrence and the magnitudes.

The **second contribution** of this research is to **help tackle well-known sources of uncertainty in RE investigations**, such as multiple causal relationships, feedback, and delays (Guzzo, Walrave and Pigosso, 2023). First, the transparent causal chain of triggers influenced by drivers in the modelled mechanisms helps identify the interplay of those multiple elements into reaching RE. Thus, the catalogue of mechanisms responds to the limitation in RE investigations of simplistic causal assumptions in complex systems sustaining RE occurrence (Guzzo, Walrave and Pigosso, 2023).

The feedback structures representing the mechanisms help appreciate multiple elements concomitantly playing a role in a system, which have often been treated in isolation or ignored in previous studies as they are challenging to identify, often overlap and mutually influence one another (Sonnberger and Gross, 2018). In addition, the CLD representation of the mechanisms helps clarify causal linkages and address potential confounding factors, whose limited understanding is strongly connected to incorrect conclusions about the existence and magnitude of RE (Greening et al., 2000; Sorrell and Dimitropoulos, 2008). In that direction, the systematic analysis of the generic structures identified through formal modelling and simulation could provide insight into the tendency of given mechanisms towards backfiring. Finally, the mechanisms can help endogenise the interplay among variables from different domains, such as energy efficiency, economic productivity, and population consumption (Binswanger, 2001; Sonnberger and Gross, 2018; Sorrell et al., 2009).

Regarding the nature of feedback loops, the mapped rebound mechanisms provide evidence that feedback loops are not inherently good or bad. By definition, balancing or reinforcing loops will not play against or in favour of the expected outcomes of sustainability-oriented action, as theoretically, reinforcing loops acting against an intervention could act in its favour as well (Barlas, 2002). Also, balancing loops lead systems towards an equilibrium point, but this equilibrium point might be in a different direction than the desirable state (Barlas, 2002), as in the case of the escalation-type mechanisms. This insight can contribute to explaining that RE might not only offset but also reinforce the intended resource savings (Sorrell et al., 2020) – which has been referred to as co-benefits and positive spillovers (Hertwich, 2005), conservation, super conservations, amplifying effects, leverage effects, and rebound forward (Font-Vivanco et al., 2016). Thus, identifying the positive and negative effects of mechanisms into RE magnitude requires careful analysis of the system structure and simulation.

Finally, delays between actions and reactions and the multiple feedback mechanisms can help explain time lags and changes of magnitude among rapid response direct RE, slower response indirect REs and the long-term equilibrium of the economy and resource use of economy-wide RE (Brockway et al., 2021; Castro et al., 2022; Trincado et al., 2021). The structures make it explicit that behaviour might take time to reach a steady state, clarifying that the moment for assessing a RE influences its magnitude. However, these dynamics are hard to study using, for instance, regression-type analyses: depending on the moment of measurement, completely different, even opposing, effects might be found. Thus, relying on a static measure of RE magnitude implicitly holds the assumption of steady-state systems, which is not always true. Therefore, the feedback view can be a starting point for enabling more reliable analyses.

The **third contribution** of the research is the **possibility of identifying ways to prevent or mitigate RE by analysing the structure of the mechanisms** sustaining them in search of leverage points. Few of the status quo studies offer actionable recommendations to reduce RE (Reimers et al., 2021), as analyses based on the relation between the output and input of a system will fall short in providing useful information for managing them (Giampietro and Mayumi, 2018). In response, structural analyses of rebound mechanisms enabled making initial claims on leverage points. Fundamental leverage points in rebound mechanisms reduce the strength of undesirable feedback loops or reinforcing the strength of desirable ones (Meadows, 1999). The use of leverage points based on the analysis of the interplay of the triggers and drivers sustaining rebound mechanisms is a strategic way to constrain the variables that lead to REs, such as time, money, scarce results, production factors, and space, as suggested by van den Bergh (2011). Therefore, the fundamental structures of rebound mechanisms can work as the missing analytical framework that can support decision-makers in identifying mechanisms, preventing their occurrence (Lange et al., 2021; Madlener and Turner, 2016) and managing their dynamic behaviour. In that sense, the identification of generic rebound mechanisms connected to the system archetypes opens up the opportunity for investigating the application of generalisable solution archetypes for mitigating RE (Wolstenholme, 2003).

Several leverage points will aim to control additional demand or supply further while sustaining providers' revenues and profits and fulfilling customers' needs. This task is not easy because the prevailing business paradigm builds upon improved efficiency, decreased costs, and additional sales. Nevertheless, the released budget occurring in many of the rebound mechanisms also opens opportunities for proposing additional services that can enhance the use of resources, such as providing better maintenance for cars, strategies widely debated in the product-service systems literature (Guzzo et al., 2019; Tukker, 2015). The leverage points are also an invitation for a more significant paradigm shift, where companies strive for sufficiency by helping consumers identify what is too much and bring the satiation point closer to companies' and individuals' fair shares of resource consumption, which is a vivid debate in the sufficiency transitions (Jungell-Michelsson and Heikkurinen, 2022; Niessen and Bocken, 2021) and the absolute sustainability domains (Hauschild et al., 2020; Li et al., 2021). Nevertheless, it is vital to remember that two rebound mechanisms were linked to sufficiency, which can also lead to RE.

Some of the leverage points identified still lead to essential trade-offs. For instance, some of the cost-related leverage points can have a detrimental effect on innovation adoption, which is vital to lowering general resource consumption in the first place. In that sense, it has been argued that sustainability action must encourage adoption and discourage RE simultaneously (Exadaktylos and van den Bergh, 2021) so that RE does not become an excuse for inaction (Gillingham et al., 2013). Additionaly, there is an essential line of argument towards considering the benefits of rebound mechanisms (Gillingham et al., 2016; Madlener and Turner, 2016), which can be a fair argument because some mechanisms might release additional financial resources to income-restricted families, in particular in developing countries.

Thus, decision-makers should be empowered to identify and balance the environmental impacts emerging from RE with the welfare portion of it (Gillingham et al., 2016; Madlener and Turner, 2016). In that direction, feedback thinking can help to identify strategic leverage points that can weaken the effects of triggers, drivers, and feedback loops sustaining the rebound mechanisms while addressing the tension with innovation adoption and welfare goals. Additionally, the identified leverage points must be further integrated into the design process, as designers still need to translate them into design features that will change the products, services, and business models to materialise the expected change in behaviour. This discussion is emerging within the systems and design thinking literatures (Pohl et al., 2020).

The **fourth contribution** is **providing a common language between the different areas investigating RE**, which is a critical gap in research (Font-Vivanco et al., 2016; Font-Vivanco and van der Voet, 2014). The definition for RE adopted in this research considers the behavioural and system reactions that offset the intentions of sustainability-oriented actions (Hertwich, 2005; Lange et al., 2021). It was operationalised considering the causal relationships between actions and reactions focused on material and energy resource consumption, in line with prevailing discussions in the RE literature (Brockway et al., 2021; Colmenares et al., 2020; Lange et al., 2021; Metic and Pigosso, 2022). This work contributes with an integrative perspective to investigating RE by setting causality as central and adding a new layer to lenses inherited from energy economics, ecological economics, and industrial ecology.

The functioning of the identified triggers and drivers transcend knowledge areas or theories by including soft and hard elements, from economic to social influence factors determining actors' behaviour. For instance, a more efficient car might lead to RE due to releasing the budget for consumption (where money is a limiting factor), time for consumption (where time is a limiting factor), or moral licensing (where sustainable behaviour is a societal expectation). Therefore, grasping the interplay of economic, physical, and behavioural triggers is critical as RE often occurs due to multiple factors. The coherent and transdisciplinary frame to represent rebound mechanisms in this research can complement the dominant neoclassical economic perspective in the field (Azevedo, 2014), challenge the idea of humans as entirely rational decision-makers (Sonnberger and Gross, 2018), and finally bridge the perspective of economists, engineers and social scientists in better understanding the mechanisms through which RE occur (Madlener and Turner, 2016).

Additionally, the systemic view adopted in this research helps separate rebound mechanisms from other sources of failure, such as technical faults in the implementation or misleading assumptions about individual behaviour (Friedrichsmeier and Matthies, 2015). Conversely, identifying dissimilar structures helped differentiate RE from other unintended consequences, such as technological lock-ins (de Gooyert et al., 2016), as in the case of the symbiotic effect. Such an effort responds to the progressive broadening and blurring of the RE concept, which can "jeopardise the analytic coherence of the term" (Font-Vivanco et al., 2016, p. 61). A coherent frame to represent and explain rebound mechanisms is relevant because if the phenomena do not share the mechanisms, they will not share the understanding or resolution of it (Friedrichsmeier and Matthies, 2015). Also, knowing the limits between RE and other kinds of "side effects", unintended consequences and paradoxes enables shared learning from different but related phenomena. Undoubtedly, more permissive definitions for RE could lead to including other mechanisms in the catalogue. Still, it is critical to deliberate if an action taken for economic, financial, or time-efficiency reasons that lead to higher-level reactions in environmental sustainability are RE or features of the prevailing economic growth paradigm.

5. Final remarks

This research aimed to explore the use of feedback thinking to explain rebound mechanisms available in the literature by mapping the structures sustaining the occurrence of RE using CLD. The comprehensive catalogue of rebound mechanisms makes explicit that similar structures sustain RE occurrence, sometimes combining basic structures, which evidences the interaction among different RE. In general, the collection of rebound mechanisms shows that well-intended sustainability interventions in a local system will activate chains of economic, behavioural, and other triggers and drivers that will counteract the controlling of general resource consumption. Finally, four research contributions consolidate how this research sustains a more systemic understanding of the RE phenomena, the natural evolutionary step required to understand and manage their occurrence.

Several research and application opportunities unfold from this research. One string of future research is related to further developing the catalogue of mechanisms. At least three paths exist in this direction. First, the known structures – including the generic rebound mechanisms – can serve as a basis for developing new mechanisms by systematically identifying potential combinations of structures and how the different sets of triggers and drivers can stimulate RE occurrence. Second, there is a need to include other socio-cultural and behavioural mechanisms – such as moral licensing, which is already extensively discussed in the literature (Reimers et al., 2021; Sonnberger and Gross, 2018; Sorrell et al., 2020). Finally, investigating RE emerging from interventions addressing the utility of systems (i.e., effectiveness interventions) could contribute to new mechanisms, such as sharing systems leading to less careful behaviour from users and shorter product lifetimes (Acquier et al., 2017).

Therefore, the catalogue presented in this research is not complete but a critical stepping stone. The methdo to reach the mechanisms enables replicability and is fundamental to further developing the catalogue. The use of content analysis sustained by the definition of the rebound mechanism and its elements (i.e., action's intention, trigger, driver, causal relationship, and polarity), the good practices of SD modelling, and the guidelines for comparing structures are some of the features that make the process reproducible. Also, the two generic mechanisms can support identifying additional rebound mechanisms and potential leverage points.

Meanwhile, parsimony is necessary for developing the catalogue of mechanisms as mechanism-based knowledge requires adding disciplinary lenses while ensuring compatibility (Hedström and Ylikoski, 2010). In that sense, too many mechanisms may make it less actionable and insightful for research and case-specific recommendations. In that direction, the categorisation of mechanisms will contribute by identifying their fundamental differences and showing blind spots.

Finally, testing the validity of mechanisms is essential in resolving any potential bias in the modelling process. The validation of the structures, identification of leverage points and exploration of their potential in mitigating leverage points can occur through quantitative analytical methods (Kampmann and Oliva, 2020), such as Loops that Matter (Schoenberg et al., 2020). Also, formal modelling of mechanisms in known cases in different domains, such as energy, food, and mobility, through simulation models can be used to examine structure-behaviour consistency with "fixes that fail" and "escalation" system archetypes. Comparison to existing empirical cases can shed light on potential reasons for the notorious discrepancy of RE magnitude identified in the literature.

However, armed with causal lenses and a broad set of mechanisms, each system will be particular to its conditions. Therefore, the second research string is related to further investigating the use of the catalogue and the generic mechanisms in identifying RE in practice. Thus, an important follow-up research question is to which extent can the structures sustain the identification of RE in ex-ante investigations? Is it enough to stick to qualitative SD for making hypotheses of RE occurrence? In which circumstances the operationalisation of the mechanisms into stock and flow structures for simulations becomes critical? In addition to SD, researchers employing other modelling paradigms should benefit from using causal representations to sustain their studies as they can help make explicit assumptions about the system's functioning.

This study presents a few limitations. First, the catalogue of mechanisms is based on four review studies, whereas the RE literature is vast and follows multiple lenses. Therefore, the modelled structures may not represent all the known mechanisms and, clearly, the ones yet to be discovered. Second, turning textual description into CLDs involved choosing specific variables as modelling means suppressing detail and making approximations to enhance explanatory relevance. The modellers selected the variables and relationships in a way that could better represent the rebound mechanisms following a casual perspective, which does not rule out other forms to represent them. Also, the iterative process of creating the catalogue and obtaining the generic mechanisms added conformity to the structures obtained. On one side, it might enhance the applicability of the mechanisms in practice due to the similarity of structures. On the other hand, this can also lead to bias towards a set of dominant structures that define the mechanisms. Finally, there was no demonstration of a problem-specific rebound mechanism or clarity on the instantiation process into a case, which will make tangible how the catalogue and generic structures can unfold into examining and tackling RE in practice.

Overall, this research moves the RE field towards a systemic view on RE by incorporating feedback thinking to understand and manage their occurrence. Making sense of the structures that sustain RE occurrence provides the means to advance in modelling and analysing RE, complementing other approaches. The causal structures enable formal analyses of RE that can describe, explain, and ultimately help identify leverage points to manage them. A causal understanding of RE is a step further to reaching the full potential of sustainability-oriented actions.

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.

Data availability

The data that support the findings of this study are openly available in DTU Data at https://doi.org/10.11583/DTU.24591201.

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Appendix

Table A1
References employed in the modelling.

Reference	Title	Domain	Rebound mechanisms categorisation used	Excerpts analysed in the original paper	Method for mechanisms identification
Colmenares et al. (2020)	The rebound effect representation in climate and energy models	Energy economics	• Consumer-caused micro-economic RE • Producer-caused micro-economic RE • Producer and consumer interaction-caused macro-economic RE	Tables 1 and 2 – 24 mechanisms described	Analysis of fundamental RE studies
Brockway et al. (2021)	Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications	Energy economics	• Direct and indirect (partial equilibrium models), and • Macroeconomic (general equilibrium). • Economy-wide RE as the net result of the above.	Appendix B – 14 mechanisms described	Analysis of fundamental RE studies
Lange et al. (2021)	The Jevons paradox unravelled: A multilevel typology of rebound effects and mechanisms	Energy economics	• Micro level • Meso level • Macro level • Global level	Tables 3, 4, and 5 – 16 mechanisms described	Analysis of existing typologies
Metic and Pigosso (2022)	Research avenues for uncovering the rebound effects of the Circular Economy: a systematic literature review	Circular Economy	• Direct, indirect, and economy-side. • Level (micro, *meso*, and macro), • Actor (consumer and producer) • Sustainability dimension (economic, environmental, and social)	Tables 1, 2, and 3 – 25 mechanisms described	Systematic literature review

Table A2
Rebound mechanisms disregarded with references and reasons.

Rebound mechanism – as categorised and named in the reference	Reference	Reasoning
Direct - Symbiotic	Metic and Pigosso (2022)	Describes the effects of a technological lock-in into resource consumption. Lock-ins are another class of higher-order consequences of design and innovation.
Indirect - Imperfect substitution	Metic and Pigosso (2022)	It is a feature of design and innovation. There is no feedback structure associated to the description. It should be considered within the intended consequences by a fair technical (in case of material quality) or market analysis (in case of attractiveness) of the solution.
Indirect - Consumption accumulation	Metic and Pigosso (2022)	There is no feedback structure associated to the description. It is a feature of decision-making that determines the substitutability between two products/services and partially explain the substitution type of rebound mechanisms driven by consumers.
Consumer - Indirect - Embodied energy (+)	Colmenares et al. (2020)	There is no feedback structure associated to the description. It can be easily mapped when grasping the intended consequences. It should be considered by an adequate use of life cycle thinking and setting up an adequate functional unit.
Producer - Indirect - Embodied energy (+)	Colmenares et al. (2020)	Not enough causal explanation to derive a mechanism. The means through which the increased demand for energy emerges is not described.
Economy-wide - New market	Metic and Pigosso (2022)	There is no feedback structure associated to the description. It is a feature of design and innovation as some products or services require associated infrastructure to exist. It should be considered within the intended consequences. An adequate functional unit would resolve.
Economy-wide - Structural change	Metic and Pigosso (2022)	Not enough causal explanation to derive a mechanism. The means through which “shift of production patterns” occur are unclear as to their contribution to “higher resource consumption”.
Economy-wide - International	Metic and Pigosso (2022)	Not enough causal explanation to derive a mechanism. The reasons for the “more efficient technology” not being accompanied by “the incentives to improve resource production” is not clear. The connection of increasing affluence and consumption in the example is a feature of the economic system.
Macroeconomic - Growth: Induced innovation	Colmenares et al. (2020)	It is not a reaction from the initial efficiency action but requires a new action to occur. It seems to make sense to investigate the RE separately in that case.
Macro - Innovation	Lange et al. (2021)	It is not a reaction from the initial efficiency action but requires a new action to occur. It seems to make sense to investigate the RE separately in that case.

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