Social Science & Medicine 367 (2025) 117706

Contents lists available at ScienceDirect

Social Science & Medicine

journal homepage: www.elsevier.com/locate/socscimed

Converging perspectives on the processes exacerbating adolescent obesity: An integrative systems approach

Anaely Aguiar [a,*], Jefferson K. Rajah [a], Kaitlin Conway-Moore [b], Natalie Savona [b], Cécile Knai [b], Ioana Vlad [c], Oddrun Samdal [d], Harry Rutter [e], Nanna Lien [f], Birgit Kopainsky [a]

[a] System Dynamics Group, Department of Geography, University of Bergen, Bergen, Norway
[b] Faculty of Public Health Policy, London School of Hygiene & Tropical Medicine, London, UK
[c] Policy and Public Affairs Department, World Cancer Research Fund International, London, UK
[d] Department of Health Promotion and Development, Faculty of Psychology, University of Bergen, Bergen, Norway
[e] Department of Social & Policy Sciences, University of Bath, Bath, UK
[f] Department of Nutrition, Institute of Basic Medical Sciences, University of Oslo, Oslo, Norway

ARTICLE INFO

Keywords:
Adolescents
Obesity
Systems mapping
Causal loop diagram
Feedback loop
Systems thinking
System dynamics

ABSTRACT

Adolescent obesity is a complex public health challenge with steadily increasing and variable prevalence among countries. This paper synthesises the driving feedback mechanisms of adolescent obesity studied in the CO-CREATE project, furthering our understanding of the complexity of this issue. Using systems thinking principles and causal loop diagramming, we integrated the following knowledge and perspectives derived from diverse sources into a causal loop diagram (CLD): a systems map generated by adolescents through participatory modelling workshops, a comprehensive literature review, and input from subject-matter experts during validation workshops. We used a structured and iterative approach to include drivers and to identify feedback loops exacerbating adolescent obesity. The CLD identified 27 key feedback loops across four themes: twelve related to the commercial food environment, six to the physical activity environment, four to mental wellbeing and five to social norms. These loops indicate not only diet and physical activity as drivers of obesity but also stress and other emotional and social pressures. Recognising the imperative need to integrate the perspectives and experiences of adolescents into our analysis, this work advocates for the synthesis of experiential insights with empirical research. The integrated CLD can be used as a visual tool that fosters collaboration among stakeholders and engenders a more comprehensive and inclusive system understanding that can provide holistic intervention considerations to tackle adolescent obesity. Additionally, the CLD lays a foundation for subsequent quantitative modelling works to further address this issue and develop context-based approaches to prevention and evaluation of adolescent obesity.

1. Introduction

Rising obesity prevalence is an urgent public health problem globally (European Union, 2014; NCD Risk Factor Collaboration, 2016). In the European region, the prevalence of overweight and obesity in children and adolescents aged 5–19 remains high (World Health Organization, 2022) and potentially increasing in some countries (Inchley et al., 2020). Among adolescents, obesity has several short- and long-term impacts on health and wellbeing (Park et al., 2012; Quek et al., 2017; World Health Organization, 2016) as overweight/obesity can often track into adulthood (Cruz et al., 2018; Singh et al., 2008). Arising from an interplay of factors such as genetics, biology, individual behaviours, social factors (e.g., weight-related stigma), and the physical environment, obesity is now seen as a complex public health issue (Huang et al., 2015; Swinburn et al., 2019). Compounding this complexity is the fact that the consequences of adolescent obesity extend beyond physical health effects such as

* Corresponding author.
E-mail addresses: anaely.aguiar@uib.no (A. Aguiar), jefferson.rajah@uib.no (J.K. Rajah), kaitlin.conway@lshtm.ac.uk (K. Conway-Moore), nataliesavona@cordisbright.co.uk (N. Savona), cecile.knai@lshtm.ac.uk (C. Knai), i.vlad@wcrf.org (I. Vlad), oddrun.samdal@uib.no (O. Samdal), hr526@bath.ac.uk (H. Rutter), nanna.lien@medisin.uio.no (N. Lien), birgit.kopainsky@uib.no (B. Kopainsky).

https://doi.org/10.1016/j.socscimed.2025.117706
Received 23 February 2024; Received in revised form 7 January 2025; Accepted 13 January 2025
Available online 22 January 2025

cardiovascular diseases and sleep pattern disturbances into psychological health aspects such as depression, anxiety and poor self-worth (Blanchard et al., 2023; Rankin et al., 2016; Shephard, 2018).

Investigating the drivers of adolescent obesity requires an understanding of its multifaceted features, including feedback loops (i.e., circular chains of causality), delays (e.g., the time needed for effects of reduced physical activity to contribute to obesity in adolescents), nonlinear relationships between variables (e.g., the relationship between stress levels and obesity, where moderate stress levels have a different impact on weight as compared to high stress levels); and dynamic behaviour (i.e., when multiple feedback loops interact with each other to give rise to complex behaviour over time). These features are inherent in the different drivers and their interconnections, both between individuals and across different populations (Atkinson et al., 2015). Systems science offers a complement to conventional approaches to understanding complex public health issues by providing a conceptual framework that focuses on the interrelationships among system components (Carey et al., 2015; Trochim et al., 2006). Most of these approaches apply systems thinking principles and include participatory systems mapping methods to effectively organise thinking and elucidate complex feedback structures so that action can be taken to address them (Barbrook-Johnson and Penn, 2022; Checkland and Poulter, 2006; Peters, 2014; Richardson and Andersen, 2010).

Within the participatory system dynamics field (Király and Miskolczi, 2019), scholars have engaged stakeholder groups to co-produce causal loop diagrams (CLDs) on the drivers of obesity prevalence (Allender et al., 2015; Cavill et al., 2020; McGlashan et al., 2018; Stankov et al., 2023). A seminal CLD of obesity was created in the United Kingdom and published in the quasi-government report Tackling obesities: future choices, commonly known as 'Foresight Report' (Butland et al., 2007). It depicted the 'obesity system' in a conceptual map, for the first time, effectively demonstrating its complexity by illustrating the interdependencies among multiple variables driving energy balance in individuals. Though the Foresight map has been criticised for being *too* complex, its illustration of multiple, interconnecting drivers of obesity was ground-breaking and remains influential in obesity research and policy to this day (Finegood et al., 2010; Savona et al., 2018). The Foresight map does not expressly address obesity in the adolescent age group, though others have mapped adolescent obesity drivers specifically (Calancie et al., 2022; Felmingham et al., 2023; Swierad et al., 2020; Waterlander et al., 2020). Other studies have built CLDs drawing from scientific literature (Crielaard et al., 2021; Sawyer et al., 2021; Waterlander et al., 2021) to illustrate major mechanisms driving adolescent obesity behaviours. Even though there have been studies that incorporate drivers (which, for the purpose of this paper, we define as individual factors or variables) and feedback mechanisms elicited from different stakeholder views into a single diagram (e.g., McGlashan et al., 2018; Pluchinotta et al., 2022), there is a paucity of studies that apply systems mapping to integrate different knowledge sources into a CLD on the major processes exacerbating adolescent obesity (as an exception, see Luna Pinzon et al., 2023). This gap calls for an integration of insights from diverse perspectives, including adolescents as key stakeholders, but also in diverse empirical contexts, to clearly depict the major feedback loops which are hypothesised to be driving high adolescent obesity prevalence. Such integration can help better understand why it is challenging to tackle this issue.

This research is part of the EU-funded project, CO-CREATE *(Confronting Obesity: Co-creating policy with youth)*, which aims to work directly with adolescents across Europe to develop policy solutions to childhood obesity (for more details, see Klepp et al., 2023). One of the work packages in this project employed participatory systems mapping with adolescents aged 16 to 18 in five European countries (Netherlands, Norway, Poland, Portugal and England) to elicit their perceptions of the primary drivers of obesity in their age group (Savona et al., 2021). This study aims to synthesise the complex interactions of drivers and feedback loops that cause and exacerbate adolescent obesity as identified in the CO-CREATE project using systems thinking principles and causal loop diagramming. To address this aim, we build on the consolidated diagram that resulted from the systems mapping workshops with adolescents within the project, where they were tasked with mapping the drivers of rising adolescent obesity (i.e., problem behaviour of interest) (Savona et al., 2021). More specifically, here, we support and add to the systems map of adolescents' views with an extensive literature review as well as consultation workshops with experts in the field. Such knowledge triangulation and integration processes allow us to present a more comprehensive and rigorous systems map depicted as an integrated CLD. In turn, our work contributes to enhancing our understanding of the underlying system structure driving adolescent obesity and its complex feedback interactions.

2. Methods

2.1. Causal loop diagrams

A CLD consists of variables connected by causal links, denoting the causal influence amongst them (Meadows et al., 2018). Each link between any two variables is assigned a polarity to indicate their interdependency: a positive polarity indicates that the variables change in the same direction (e.g., when A decreases, B decreases), and a negative polarity indicates that they change in the opposite direction (e.g., if A decreases, B increases, or vice versa). CLDs serve as visualisation tools that can map the intricacies of an issue, including multifaceted factors, causal connections (Cassidy et al., 2022), policy resistance, feedback, and adaptation (Baugh Littlejohns et al., 2021; Garrity, 2018). Importantly, such diagrams seek to capture the feedback processes embedded in the interconnections between variables (Burrell et al., 2021). A feedback loop consists of a series of variables and causal links that create a closed chain of causal influences. There are two fundamental feedback loops, namely: reinforcing loops, representing actions of growth and decline, and balancing loops, representing mechanisms that strive to control and stabilise (Coletta et al., 2021; Sterman, 2000). In this context, 'balancing' does not equate to imply a value judgment in the form of a positive influence, as it can also have a negative effect on a problematic issue, e.g., in the form of policy resistance (e.g., de Gooyert et al., 2016), just as 'reinforcing' does not equate to a negative influence, as reinforcing loops can act either as vicious or as virtuous cycles.

Causal loop diagramming is thus the process of constructing a CLD to represent the complex feedback structure of a given issue. This process entails the mapping of important variables, which are grounded in scientific and/or experiential knowledge (Forrester, 1992; Homer, 2014), that serve as both their cause and effect relationships and the resulting feedback loops. To that effect, our work is grounded in qualitative data (i.e., variables and causal links) from three knowledge bases. Experiential knowledge was captured through participatory workshops with young people (Savona et al., 2021). As for scientific knowledge, we examined existing literature studying system dynamics models on adolescent obesity (Aguiar et al., 2023a,b) and broader obesity research literature on the relationship between mental health, social media and adolescent obesity (Aguiar et al., 2023a,b; Blanchard et al., 2023; Nwosu et al., 2023; Sawyer et al., 2021; Waterlander et al., 2021). We focused on the feedback mechanisms explaining rising adolescent obesity as opposed to mechanisms that describe policy or intervention implementation processes. Moreover, we further sought input from subject-matter experts to discuss and improve the accuracy of our depicted relationships and the overall framework of the integrated CLD.

2.2. Process of the development of CLDs

We used a structured approach to integrate the findings from the systems mapping sessions with adolescents, literature review and expert validation workshops so as to identify the factors and mechanisms that drive overweight and obesity in adolescents. The overall process of data analyses and development of the CLDs was inspired by established approaches (Eker and Zimmermann, 2016; Kim and Andersen, 2012; Turner

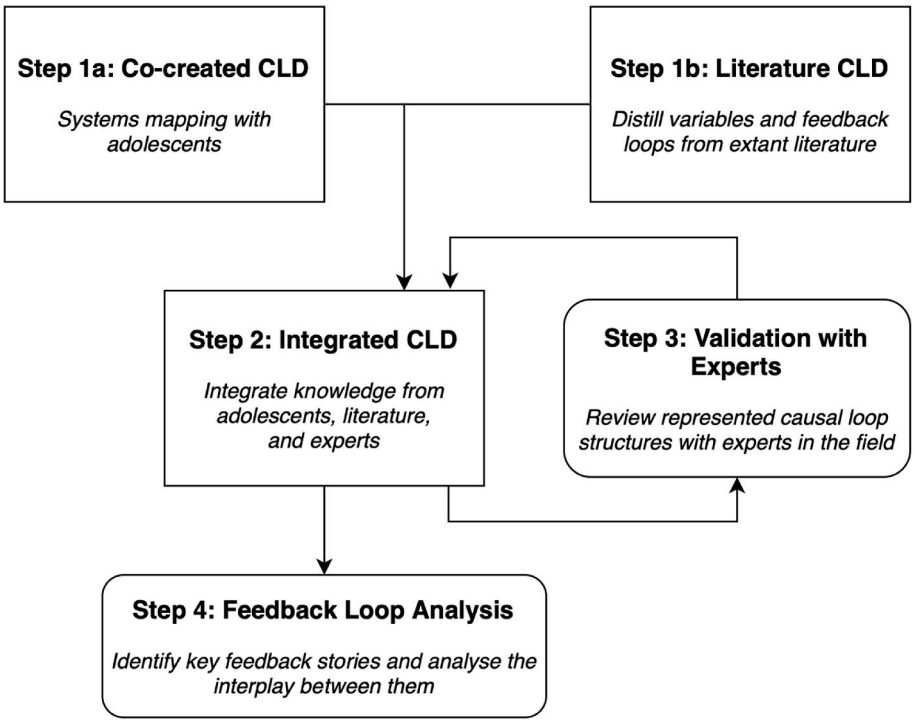

Fig. 1. The process of developing and analysing an integrated causal loop diagram on the drivers and feedback mechanisms of adolescent obesity in the CO-CREATE project.

et al., 2013). The various steps in this process are visually depicted in Fig. 1.

2.2.1. Step 1a: The Co-created CLD

As mentioned, the co-created diagram was generated from systems mapping workshops with 20 groups of adolescents (N = 257) from five European countries, where they were tasked to collaboratively map the drivers of adolescent obesity. Using a common protocol, recruited participants were aged between 16 and 18 from schools across diverse socio-economic background and geographic areas (for a detailed description of the CO-CREATE workshops and the findings, see Savona et al., 2021). Here, we briefly summarise the key insights that emerged from this prior work: Across the five countries, emotional and mental pressures, especially related to stress and body image, were recognised as a central driver of obesity, with the pervasive influence of social media and social media influencers also highlighted. However, each country exhibited unique factors: the Netherlands emphasized the negative role of online activity and unhealthy parental influence; Norway highlighted the limited mechanised transportation to school and equipment for physical activity; Poland omitted online activity, focusing instead on lack of sleep, fitness aspirations, and social connectivity; Portugal included the poor utilisation of parks and greenspaces to exercise; and in the UK map, physical inactivity was not seen to be a major factor driving excess weight gain, and home life and knowledge/-information factors were not mentioned at all. A consolidated systems map, which represents the adolescents' collective mental model of the drivers of obesity, was the end result of these workshops (see Fig. S1 in the supplementary material). This co-created CLD represents adolescents' perceptions of the major drivers of adolescent obesity, and the relationships among those drivers forming feedback loops.

2.2.2. Step 1b: Literature CLD

We conducted a systematic literature review of the factors and mechanisms driving overweight and obesity in adolescents, with a focus on the existing system dynamics simulation models (for details on the review protocol, see Aguiar et al., 2023a,b). For this study, we only extracted the feedback mechanisms related to the explanatory models as opposed to structures that represent policy or intervention implementation processes. We deemed this necessary to ensure that the model boundary is consistent with the systems mapping workshops that were geared towards explaining the drivers of adolescent obesity. We additionally conducted health-based systematic reviews on the relationship between mental health, social media and adolescent obesity (for details on the review protocol, see Blanchard et al., 2023; Nwosu et al., 2023). We then followed a purposive approach to extract the variables from the reviewed literature which were drawn from the consolidated systems map developed with adolescents. First, we categorised and analysed the most frequently mentioned variables in the studies we reviewed and grouped these according to the themes reflected in the adolescents' consolidated systems map in Savona et al. (2021). We then extracted the relationships between these variables from original text excerpts in each study and interpreted the causal connections as they were presented. The variable and causal link extraction was conducted by two systems analysts (A.A., B.K.), and any disagreements about the extracted variables and relationships were discussed until consensus was reached. Thereafter, we established the directional relationships between pairs of variables (i.e., link polarities) as outlined in the original texts. We then identified feedback loops among the interacting factors identified in the literature that contribute to the increase and persistence of adolescent overweight and obesity. To further support our research and fill knowledge gaps in the initial body of literature reviewed, we also consulted reference lists from these publications. The process described here was iterated to include additional variables and causal links that supported adolescents' views in their consolidated system map.

We first developed a complete literature CLD, rather than immediately incorporating the identified mechanisms into the adolescents' CLD as we were interested in identifying points of convergence and divergence in different stakeholder perspectives. We will elaborate on these in section 3.1.

2.2.3. Step 2: The Integrated CLD

We integrated the two CLDs by preserving distinctions and consolidating similarities. We catalogued the variables and connections shared across both CLDs and incorporated them into a unified CLD following a similar process as in Savona et al. (2021). This process involved consolidating similar variables across the two CLDs, accompanied by adjustments to make variable names more generalisable for the purpose of diagram synthesis. For example, the term 'stress' was turned into 'psychosocial stress' to differentiate the stress or pressure induced from the social environment (e.g., pressure from bullying) from the individual level stress involving hormones and biochemical processes. We then focused on capturing the feedback loops present in both CLDs. Once all the convergent areas were unified, we incorporated any additional loops that were present in at least one of the CLDs into the unified CLD. While important variables and links were included, we discarded the ones that were not part of a feedback loop since they were peripheral to the endogenous structure of the adolescent obesity system and thus, not within the scope of our study. For example, *knowledge about the risk of obesity* and *health literacy* were excluded from the integrated CLD as they were not part of feedback loops in the adolescents' map nor in the CLD from the literature. Further refinements were iteratively made to the integrated CLD based on input from experts.

2.2.4. Step 3: Validation with Experts

To build confidence in the variables and relationships represented in the integrated CLD, we conducted a series of validation workshops involving experts from various areas within obesity research, including population weight dynamics, physical activity, commercial food environment and mental health. For triangulation purposes and where existing knowledge was lacking, the expert judgement of the workshop participants helped support and expand on each hypothesised causal relationship in the integrated CLD. A total of four workshops, one per theme, were held with expert groups, consisting of obesity researchers and public health policy advisors, in 2021 using frameworks commonly used in model validation workshops (Andersen and Richardson, 1997; Hovmand et al., 2011, 2012). In particular, we adapted the 'Model Review' script from Scriptapedia (Hovmand et al., 2011). A thorough review of the CLD was carried out with six to seven domain-experts, in each workshop, to support and expand on existing relationships and to ensure that essential variables and relationships were neither overlooked nor omitted from the diagram. To this end, the questions posed to the experts were designed to elicit additional feedback, seek clarifications, and identify any missing or redundant elements in the system structure. During the reviewing process of the CLD, the experts assessed the underlying assumptions and structures, and suggested additional literature sources, which then informed subsequent iterations and refinements of the integrated CLD.

2.2.5. Step 4: Feedback Loop Analysis

After validating our integrated CLD, we delved deeper into its components by identifying and analysing the feedback narrative of the system at hand – the structure and interplay of the feedback loops that give rise to adolescent obesity (Turner and Goodman, 2023). First, we identified each feedback loop within the CLD, tracing the cause-and-effect relationships and their polarities within the loop. After isolating all major feedback loops, we determined the net polarity of the loop. This was done by discerning whether each loop was reinforcing, meaning it amplified the initial development, or balancing, indicating that it maintained equilibrium or pushed towards an implicit or explicit target state (where the target can be either desirable or undesirable).

When the major feedback loops were identified and their polarities established, we identified the feedback story for each loop. While the causal pathway of a feedback loop focuses on the polarities of the causal links between variables for tracing the effects of an initial change introduced to the loop, feedback stories explicitly relate the overall causal logic of the loop to the underlying real-world processes meant to be represented by the loop. Finally, we constructed the larger feedback narrative of the system by analysing the interplay among the major feedback loops shown in the integrated CLD. The feedback narrative structures the dynamics of the obesity problem in terms of how the major feedback loops interact with each other, offering a holistic understanding of how the system's structure drives adolescent obesity prevalence (Rajah and Kopainsky, 2025).

3. Results

3.1. Areas of convergence and divergence in the adolescents' systems map and the CLD based on scientific literature

Both the adolescents' systems map and the literature-based CLD captured drivers related to the food and physical activity environment, affecting diet and physical activity, respectively. For instance, both CLDs identified mechanisms driving unhealthy food consumption focusing on unhealthy food choices and lack of healthy choices, unhealthy food habituation and exposure to unhealthy food advertisement. Notably, the two CLDs distinguished between unhealthy and decreased healthy consumption processes, providing a nuanced understanding of dietary behaviours. Moreover, both CLDs highlighted common factors that reduce energy expenditure. These factors encompassed low levels of physical activity, screen time, as well as the limited availability of physical activity infrastructure and access to green spaces. The shared recognition of these elements in both adolescent perspectives and scientific literature underscores the robustness of these determinants in shaping the dynamics of energy intake and expenditure within the context of how they drive adolescent obesity. Also, the consistency of mechanisms identified by the adolescents and literature may have stemmed from their awareness of health-related studies, reflecting their health knowledge.

Although both literature and adolescents considered societal pressures, they diverged in terms of the level of detail in describing them. For instance, adolescents highlighted emotional/mental wellbeing and social media/gaming pressures in their map, shedding light on the importance of low self-esteem and harmful online activities. Conversely, the literature CLD provided additional feedback loops related to how the food industry invest more in marketing and R&D in the food type that generates more profits, in this case unhealthy food. Also, adolescents described factors related to the home life such as household income and time to prepare meals in the diagram they created, elucidating how parental finances can influence both the unaffordability of healthy food and physical activity inaccessibility, which play a pivotal role in adolescents eating and exercise habits (Savona et al., 2020). Yet, these factors were not part of feedback loops. In contrast, the literature-based CLD offered a more comprehensive view on peer and parental influence dynamics which shape adolescents' norms regarding poor nutrition and physical activity.

3.2. The integrated CLD

Adolescent obesity can be understood through an energy balance equation, where the interplay of energy intake and energy expenditure affects body weight, which is the central variable of the integrated CLD shown in Fig. 2 When there is an energy imbalance, with an excess of energy intake compared to expenditure, weight gain occurs, and vice versa. Nonetheless, various environmental factors play a role in altering the balance of energy intake and expenditure, leading to changes in body weight (Swinburn et al., 2011). Thus, the complex

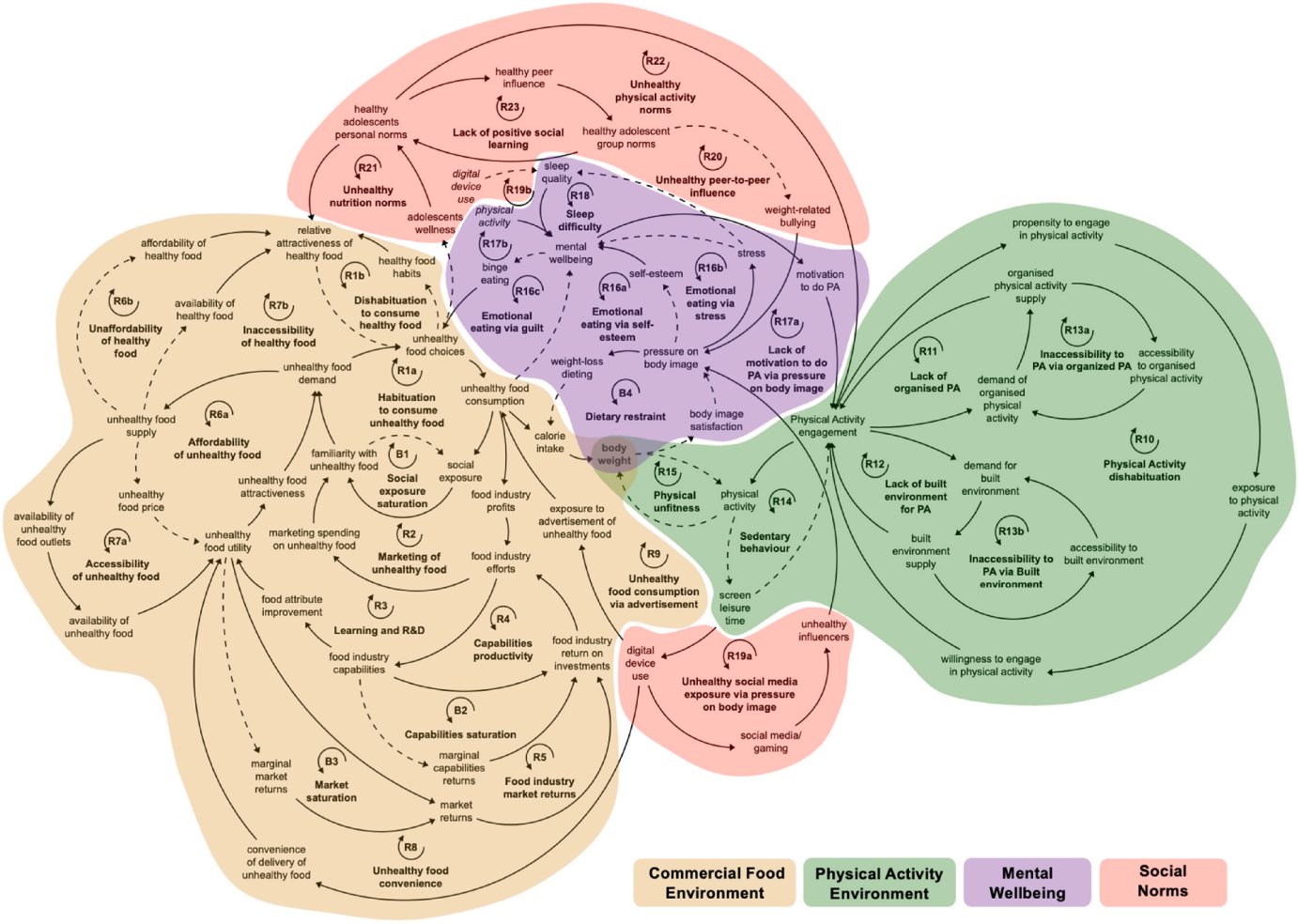

Fig. 2. Integrated CLD incorporating adolescents' views, literature, and expert input within the CO-CREATE project. The letter R with curved arrow: reinforcing loop; the letter B with curved arrow: balancing loop; italics: a copy of a variable (ghost); solid arrows: positive causal link; dotted arrows: negative causal link.

socio-environmental factors and interrelationships conducive to adolescent obesity, drawn from the integration process of the adolescents' systems map, reviewed literature, and expert consultations, are depicted in the integrated CLD. A total of 27 feedback loops (23 reinforcing and 4 balancing) are included in the integrated CLD. The feedback stories captured in these loops revolve around obesity drivers in four identified themes: *Commercial Food Environment, Physical Activity Environment, Mental Wellbeing,* and *Social Norms*. Each theme is described in detail in the next sections. In our analysis, we identified and described a total of 12 feedback stories associated with diet and eating behaviours, 6 tied to physical activity and sedentary behaviours, 4 interconnected with mental health, and 5 related to social norms. It is noteworthy that certain feedback stories traversed across themes, underscoring the complex web of factors at play in exacerbating adolescent obesity. The CLD developed by adolescents and the one built from the literature are shown in the supplementary material in Figs. S1 and S2, respectively.

3.2.1. Commercial food environment theme

In this theme (see Table 1 and Fig. 3), a critical variable is the *consumption of unhealthy food*. This variable is influenced by feedback mechanisms, such as becoming habituated to unhealthy food and exposure to advertisement of unhealthy food. The two main areas driving consumption of unhealthy food are *demand* (i.e., the consumer perspective) and *supply* (i.e., the food industry's perspective). In the demand side, the central processes are habituation to consume unhealthy food and dishabituation to consume healthy food captured by the loops R1a and R1b. Given an increase in *food demand*, a habituation mechanism is set in motion where adolescents get more or less used to eating a type of food (Blumenthal and Gold, 2010; Dockner and Feichtinger, 1993). The development of habituation is related to the type of food that is most familiar to consumers and upon which they place more value when choosing what to consume (Abrahamson and Rosenkopf, 1997; Alessie and Kapteyn, 1991; Seetharaman et al., 1999) until exposure saturation is reached (B1). This mechanism further reinforces the preferred type of food demand, in this case unhealthy food, which increases the financial performance of the food industry via higher *profits* from this type of food. This in turn leads to greater *efforts to market unhealthy food* (R2) as well as a higher capacity for *learning and research and development (R&D)* and *food attribute improvement* (R3) (i.e., food portfolios on nutritional and motivational quality. Motivational quality derives from three attributes: price, taste, and availability) among companies which produce this food (Schroeter et al., 2008).

The main variable in the supply side is *food industry capabilities*. The industry capabilities depend on productivity, total efforts, and the share of resources allocated to improving a particular food attribute (Struben et al., 2014). The food industry invests in *food capabilities* to obtain more *profits*. This is determined by the *industry's efforts* to generate more *return on investments*. These processes are captured by loops Capabilities productivity (R4) and Food industry market returns (R5). Both loops are constrained by saturation processes where the effect of diminishing returns from improvements in attributes and capabilities create a

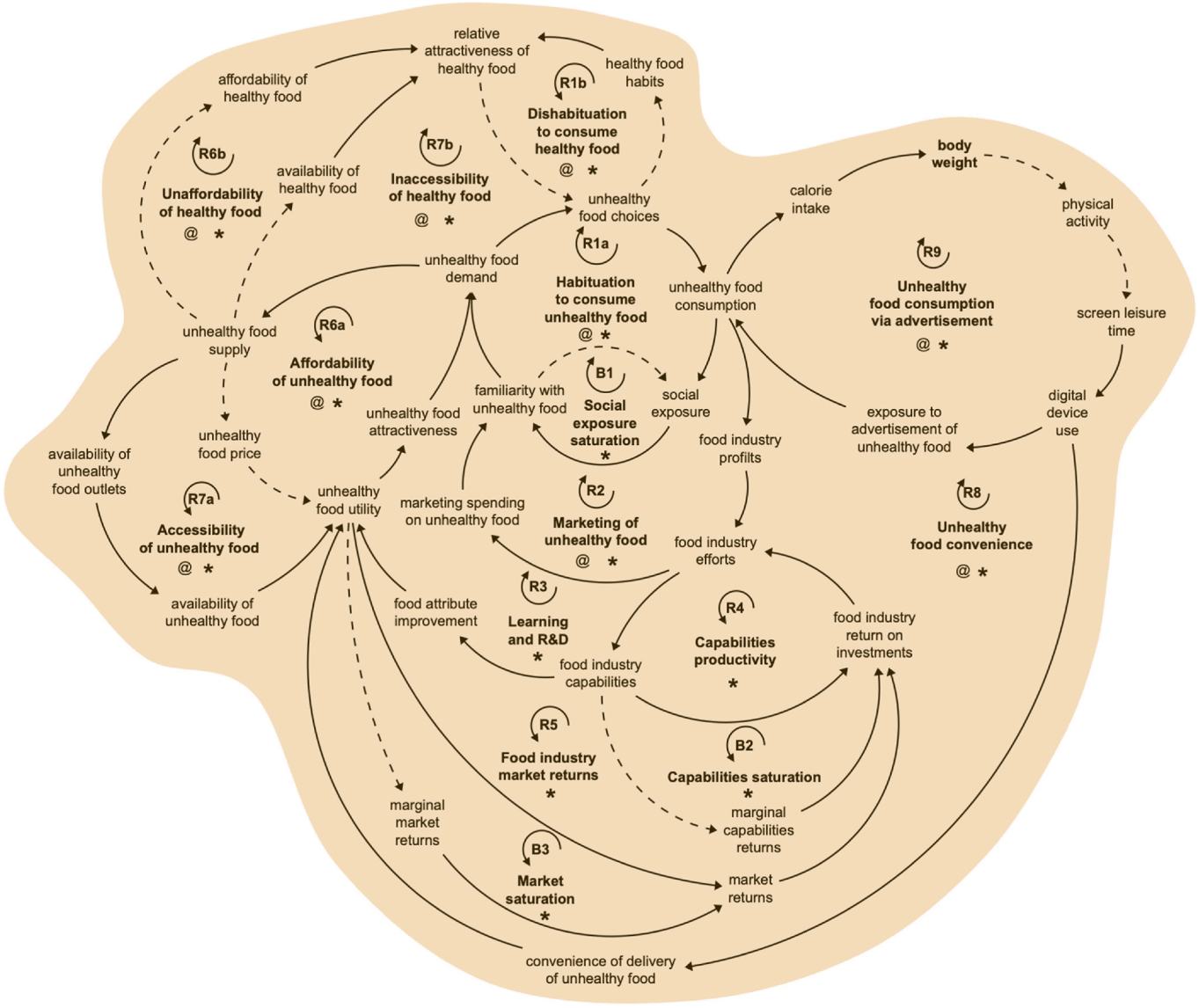

Fig. 3. Segment of the Commercial Food Environment theme in the integrated CLD in the CO-CREATE project. The letter R with curved arrow: reinforcing loop; the letter B with curved arrows: balancing loop; solid arrows: positive causal link; dotted arrows: negative causal link; @: feedback loop existing in the co-created system map with adolescents; *: feedback loop extracted from the literature; &: feedback loop co-developed with experts during validation workshops.

Table 1
Feedback loop names, labels, pathways, and stories within the commercial food environment theme of the integrated CLD in the CO-CREATE project.

Feedback Loop Name and Label	Feedback Loop Pathway	Feedback Story
Habituation to consume unhealthy food (R1a) and Dishabituation to consume healthy food (R1b)	*(R1a) unhealthy food demand → unhealthy food choices → unhealthy food consumption→ social exposure → familiarity with unhealthy food → unhealthy food demand* *(R1b) unhealthy food choices → healthy food habits → relative attractiveness to healthy food → unhealthy food choices*	The habituation to unhealthy food has a significant impact on unhealthy food demand, which in turn affects the consumption of unhealthy food and furthers habituation. Higher familiarity with unhealthy food increases social exposure consumers have to unhealthy food. Then, the higher the familiarity with unhealthy food, the higher the unhealthy food demand. In contrast, the process of dishabituation to consume healthy food occurs when higher unhealthy food choices lead to a lower attractiveness of healthy food allowing for more unhealthy food choices.
Social exposure saturation (B1)	*social exposure → familiarity with unhealthy food → social exposure*	The social exposure to unhealthy food does not grow indefinitely. There is a point at which consumers exposed to unhealthy food makes their exposure to it ineffective.
Marketing of unhealthy food (R2)	*unhealthy food choices → unhealthy food consumption → food industry profits → food industry efforts → marketing spending on unhealthy food → familiarity with unhealthy food → unhealthy food demand → unhealthy food choices*	The food industry increases its profits from sales by making direct investments in marketing campaigns aimed at promoting the type of food that is more successful and profitable, in this case unhealthy food, which leads to higher familiarity and demand for unhealthy food.
Learning and R&D (R3)	*unhealthy food consumption → food industry profits → food industry efforts → food industry capabilities→ food attribute improvement → unhealthy food utility → unhealthy food attractiveness → unhealthy food demand → unhealthy food choices → unhealthy food consumption*	The utility or value that consumers derive from consuming unhealthy food hinges on the quality of its attributes, which enhance as food companies acquire specific capabilities related to those attributes. Profits play a crucial role in fostering the development of these capabilities through research and development investment and in building food-related attributes to boost profitability. This makes unhealthy food more attractive and increases its consumption, which in turn increases industry profits.
Capabilities productivity (R4)	*industry efforts → food industry capabilities → food industry return on investments → industry efforts*	Food companies allocate and adjust their resources based on the budget available and how profitable the food type is. This means that the food industry invests more in the food type that is more successful or that yields more returns on investments.
Capabilities saturation (B2)	*industry efforts → food industry capabilities → marginal capabilities returns → food industry return on investments → industry efforts*	Once attributes and capabilities reach a certain level, their effect on unhealthy food utility and therefore its consumption declines even if investment in capabilities increases further.
Food industry market returns (R5)	*industry efforts → food industry capabilities → food attribute improvement → unhealthy food utility → market returns → food industry return on investments → industry efforts*	Companies track the market aiming to allocate more of their invested resources in the food type and attributes that deliver higher returns on investment. As food demand increases, driven by improvements in food attributes, then the returns on investment grow stronger.
Market saturation (B3)	*industry efforts → food industry capabilities → food attribute improvement → unhealthy food utility → marginal market returns → market returns → food industry return on investments → industry efforts*	As market returns of unhealthy food grow, its growth rate decreases over time leading to ever smaller increases in marginal market returns. In other words, the more mature the market is, the more costly it is to improve utility and the less likely it is that the consumers' willingness to pay matches the increased cost.
Affordability of Unhealthy Food (R6a) and Unaffordability of Healthy food (R6b)	*(R6a) unhealthy food supply → unhealthy food price → unhealthy food utility → unhealthy food attractiveness → unhealthy food demand → unhealthy food supply (R6b) unhealthy food supply → affordability of healthy food → relative attractiveness of healthy food → unhealthy food choices → unhealthy food consumption→ social exposure→ familiarity with unhealthy food → unhealthy food demand →unhealthy food supply*	The feedback processes related to affordability of the type of food revolve around price, and the relative attractiveness of that type of food to consumers. When unhealthy food price is lower than the price of healthy food, it makes it more attractive to consumers generating more value for consumers, boosting their habituation to unhealthy food, and ultimately, increasing unhealthy food demand and supply.
Accessibility of Unhealthy Food (R7a) and Inaccessibility of Healthy Food (R7b)	*(R7a) unhealthy food supply → availability of unhealthy food outlets → availability of unhealthy food → unhealthy food utility→ unhealthy food attractiveness → unhealthy food demand → unhealthy food supply* *(R7b) unhealthy food supply → availability of healthy food → relative attractiveness of healthy food → unhealthy food choices → unhealthy food consumption→ social exposure→ familiarity with unhealthy food → unhealthy food demand → unhealthy food supply*	Accessibility to both types of food is influenced by the availability of a specific type of food in the market. This depends on the food industry's efforts to place the most in-demand and profitable food types in food outlets. When unhealthy food is more easily accessible than healthy foods (e.g., placed in more reachable supermarket shelves; or resulting from entire food deserts), unhealthy food becomes more attractive to consumers leading to higher unhealthy food demand and supply.
Unhealthy food Consumption via Advertisement (R8)	*unhealthy food consumption → calorie intake → body weight → physical activity → screen leisure time→ digital device use → exposure to unhealthy food advertisement → unhealthy food consumption*	The unhealthy food consumption by advertisement loop deals with the exposure to unhealthy food by advertisements, particularly on digital devices, increased by the higher time spent in front of screens. This furthers reinforces sedentary behaviour related to screen leisure time which leads to higher unhealthy food consumption.
Unhealthy food Convenience (R9)	*unhealthy food consumption → calorie intake → body weight → physical activity → screen leisure time → digital device use → convenience of delivery of unhealthy food → unhealthy food utility → unhealthy food attractiveness → unhealthy food demand → unhealthy food choices → unhealthy food consumption*	Unhealthy food consumption contributes to calorie intake, which impacts body weight and physical activity levels. Screen leisure time and digital device use contribute to the convenience to access food delivery and to more attractiveness of unhealthy food, perpetuating the demand for these choices and ultimately increasing the consumption of unhealthy food.

balancing process (B2) and the growth of market returns is tempered by the limiting factor of market saturation (B3). The feedback loops associated with affordability (R6ab) and accessibility (R7ab) of a certain type of food also influence the food habituation mechanisms. If unhealthy foods dominate over healthy food through these feedback processes, they contribute to dishabituation and unaffordability of healthy food and the further increase of calorie intake and ultimately, a higher body weight. Moreover, excess weight gain leads to a *sedentary behaviour*, privileging *screen leisure time* over *physical activity*. Consequently, adolescents are more likely to be exposed to *unhealthy food advertisement* with increased *screen time*, reinforcing unhealthy food consumption habituation (Boyland et al., 2021) as well as the convenience to access food delivery of unhealthy food. These processes are captured in R8 and R9, in which less *physical activity* generates more *screen leisure time* where adolescents spend more time *using digital devices* which gives them a higher *exposure to advertisement of unhealthy food* and *convenience of delivery of unhealthy food.* In turn, these lead to further reinforcement of the habituation to consume unhealthy food (R1a).

3.2.2. Physical activity environment theme

The physical activity (PA) environment theme (see Table 2 and Fig. 4) captures the factors that exert influence over adolescents' physical activity level, ultimately reducing energy expenditure. The physical activity environment plays an important role in increasing physical activity engagement (Carver et al., 2023; Fathi et al., 2020; Saelens et al., 2018; Sallis et al., 2006). The main driving forces of obesity within the physical activity environment theme are reinforcing feedback loops that interact with the supply and demand aspects of the PA environment. These two mechanisms generate an effect on poor *physical activity engagement*, which also leads to a reduced *propensity to engage in PA* and *exposure to PA,* leading to lower *PA engagement* (R10).

Important components within this theme are the lack of organised PA (after school activities such as sports and PA programs) (R11), and lack of self-organised PA (R12). The latter is largely contingent on the reduced availability of a *built environment* that enables physical activity, which includes physical factors like green spaces, sidewalks, bike paths, and sports facilities and constitutes the supply aspect of the PA environment. On the demand side, factors such as the lower *willingness to participate in PA* and the inclination towards PA are influenced by the scarce supply of PA opportunities, originating from both the lack of school-based activities and the built environment (R13ab). Another key feedback loop deals *with sedentary behaviour* (R14). *Sedentary behaviours* including TV viewing, video game playing, and computer use (collectively referred to as 'screen time') reduce physical activity and increase body weight (Nagata et al., 2023). Whereas *physical unfitness* (R15) deals with people's inability to do physical activity when they have higher body weight (Giabbanelli et al., 2012).

3.2.3. Mental wellbeing theme

The mental wellbeing theme (see Table 3 and Fig. 5) plays a pivotal role in body weight changes capturing the main mental health and emotional processes that lead to behaviours driving obesity in adolescents. This theme was examined in depth in Aguiar et al. (2023a,b). Mental wellbeing affects both sides of the energy balance equation (Förster et al., 2023; Russell-Mayhew et al., 2012). The core dynamics in this theme are generated by four reinforcing loops and one balancing loop: emotional eating, lack of motivation to do PA, sleep difficulty and dietary restraint. In the energy intake side, the emotional eating loop is triggered by an increase in *body weight* through *unhealthy food consumption* reducing *self-esteem* and increasing *stress,* which in turn lowers *mental wellbeing* and promotes *binge eating (R16a)*. These feedback loops set out from a weight bias stemming from the disparity between the

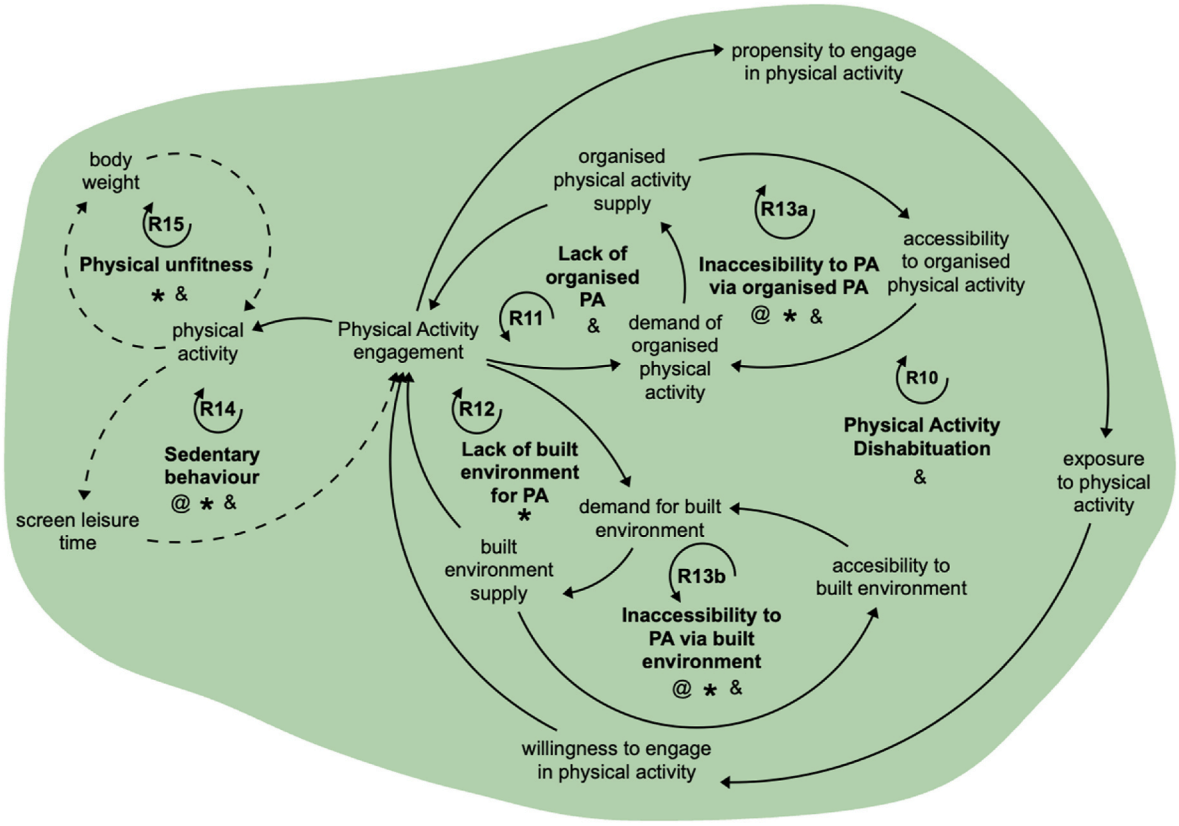

Fig. 4. Segment of the Physical Activity Environment theme in the integrated CLD in the CO-CREATE project. The letter R with curved arrow: reinforcing loop; the letter B with curved arrows: balancing loop; solid arrows: positive causal link; dotted arrows: negative causal link; @: feedback loop existing in the co-created system map with adolescents; *: feedback loop extracted from the literature; &: feedback loop co-developed with experts during validation workshops.

Table 2
Feedback loop names, labels, pathways, and stories within the physical activity environment theme of the integrated CLD in the CO-CREATE project.

Feedback Loop Name and Label	Feedback Loop Pathway	Feedback Story
Physical Activity dishabituation (R10)	*physical activity engagement → propensity to engage in PA → exposure to PA → willingness to engage in PA→ physical activity engagement*	This feedback loop involves the connection between an adolescent's willingness to participate in physical activity and their actual engagement in PA. When adolescents are not exposed to PA, it reduces their inclination or likelihood to participate in PA, which in turn reinforces their lower initial willingness to engage in it. This loop can be conceptualised as 'social habituation to PA'. It can be constrained by the availability of resources for organised PA and the existing physical environmental conditions which can turn into dishabituation to PA.
Lack of organised Physical Activity (R11)	*physical activity engagement→ demand of organised physical activity → organised physical activity supply → physical activity engagement*	This feedback loop involves the connection between an adolescent's willingness to participate in organised sports and after-school physical activity and their engagement in those activities. When adolescents are not exposed to organised PA, their likelihood to participate in PA decreases, which in turn influences their initial willingness to engage in it. This feedback loop can be constrained by the availability of school resources for PA.
Lack of built environment for Physical Activity (R12)	*physical activity engagement → demand for built environment → built environment supply → physical activity engagement*	This feedback loop describes the effect of scarce physical elements in the environment, including community infrastructure such as green spaces, gym facilities, sidewalks, bike paths, etc., on adolescents' willingness to participate in PA. When adolescents are not exposed to physical environment (i.e., infrastructure or equipment) to support PA, it decreases their likelihood to participate in PA, which in turn lowers their engagement in it.
Inaccessibility to PA via organized PA (R13a) and Inaccessibility to PA via Built Environment (R13b)	*(R13a) accessibility to organised physical activity → demand for organised physical activity → organised physical activity supply → accessibility to organised physical activity* *(R13b) accessibility to built environment → demand for built environment → built environment supply → accessibility to built environment*	These reinforcing feedback loops consist of the lack of supply of organised activities after school where adolescents can engage in physical activity and of infrastructure available in the community to exercise. These processes include aspects such as unaffordability to engage in after-school activities, not being able to reach the community infrastructure dedicated for PA, etc.
Sedentary behaviour (R14)	*physical activity → screen leisure time → physical activity engagement → physical activity*	Lower levels of physical activity could lead to an increased use of screens such as TV, video games, mobile phones, tablets, computers, etc., reinforcing lower levels of physical activity and further increasing body weight.
Physical unfitness (R15)	*physical activity → body weight → physical activity*	Lower levels of physical activity lead to an increase in body weight since energy expenditure declines, this leads to a lower ability to do physical activity.

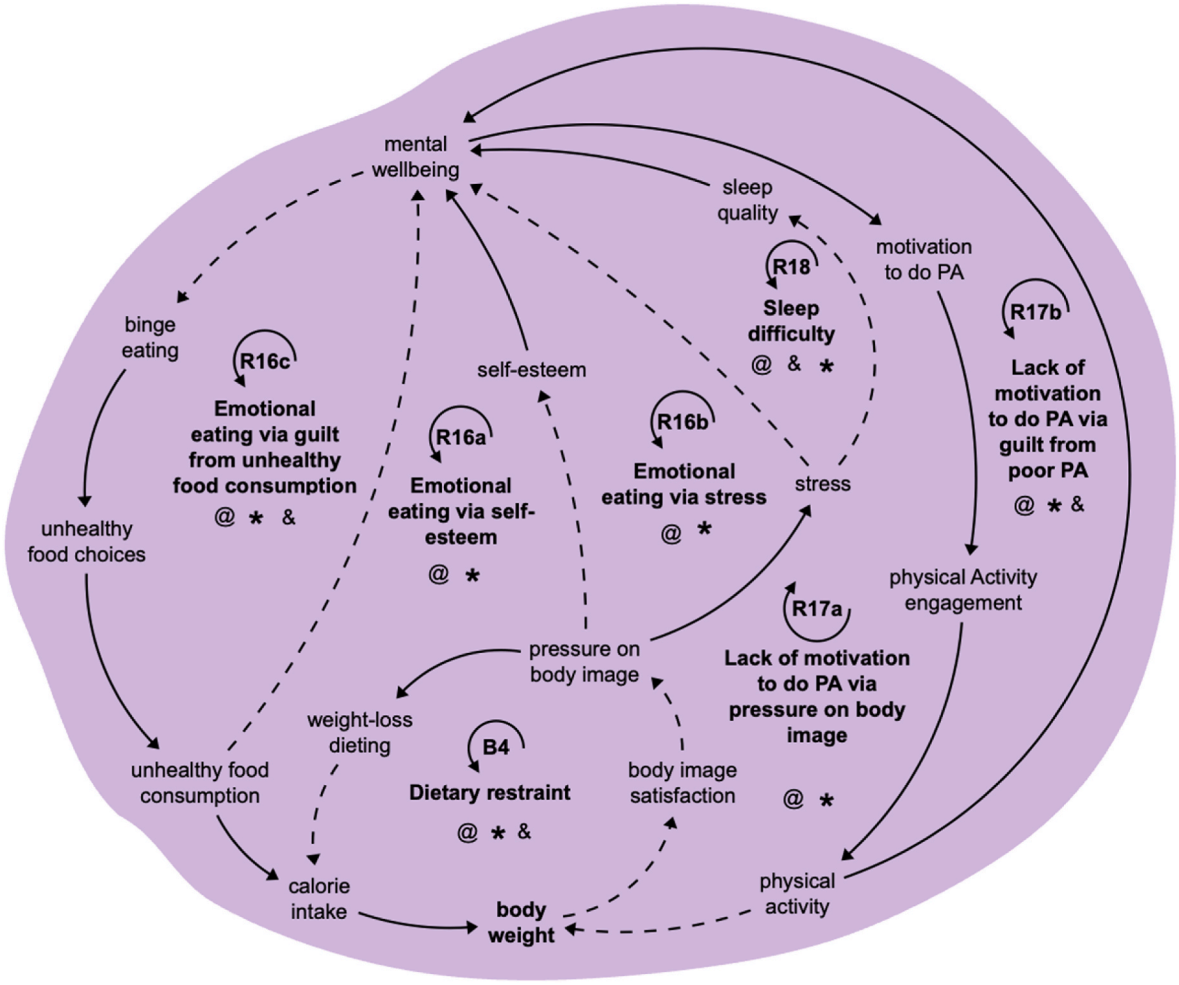

Fig. 5. Segment of the Mental Wellbeing theme in the integrated CLD in the CO-CREATE project. The letter R with curved arrow: reinforcing loop; the letter B with curved arrows: balancing loop; italics: a copy of a variable (ghost); solid arrows: positive causal link; dotted arrows: negative causal link; @: feedback loop existing in the co-created system map with adolescents; *: feedback loop extracted from the literature; &: feedback loop co-developed with experts during validation workshops.

Table 3
Feedback loop names, labels, pathways, and stories within the mental wellbeing theme of the integrated CLD in the CO-CREATE project.

Feedback Loop Name and Label	Feedback Loop Pathway	Feedback Story
Emotional eating via *Self-esteem (R16a), Emotional eating* via *stress (R16b) and Emotional eating* via *guilt (R16c)*	*(R16a) body weight → body image satisfaction → pressure on body image → self-esteem → mental wellbeing → binge eating → unhealthy food choices → unhealthy food consumption → calorie intake → body weight* *(R16b) body weight → body image satisfaction → pressure on body image → stress → mental wellbeing → binge eating → unhealthy food choices → unhealthy food consumption → calorie intake → body weight* *(R16c) unhealthy food consumption → mental wellbeing → binge eating → unhealthy food choices → unhealthy food consumption*	The pressure on body image contributes to an incremental increase in psychosocial stress and to lower self-esteem. Both psychosocial stress and lower self-esteem are associated with poor mental wellbeing in adolescents. Particularly, psychosocial stress is composed of several external factors (known as stressors) such as school pressure and weight-related bullying, as well as perceived pressure on body image. The combination of increased psychosocial stress and poor mental wellbeing produces emotional eating behaviours that add extra calories beyond what is needed to balance energy expenditure, leading to higher body weight, therefore, reinforcing higher psychosocial stress and poorer self-esteem. The feedback loop R16c deals with an immediate negative effect of unhealthy food consumption on mental wellbeing in which adolescents may feel guilty for consuming junk food leading to a deterioration of mental wellbeing and motivation to further binge eating unhealthy food.
Dietary restraint (B4)	*body weight → body image satisfaction → pressure on body image → weight-loss dieting → calorie intake → body weight*	The influence of celebrities and social media personalities can exacerbate pressures related to body image. This influence often results in diminished satisfaction with one's own body image and may encourage adolescents to adopt restrictive diets aimed at weight loss, resulting in reduced calorie intake and short-term weight loss.
Lack of motivation to do PA via pressure on body image (R17a) and Lack of motivation to do PA via guilt from poor PA (R17b)	*(R17a) body weight → body image satisfaction → pressure on body image → stress → mental wellbeing→ motivation to do PA → physical activity engagement → physical activity → body weight* *(R17b) physical activity → mental wellbeing → motivation to do PA → physical activity engagement → physical activity*	As in the Emotional eating loop, the weight bias generates pressure on body image. As pressure on body image increases, psychosocial stress increases as well, reducing the motivation to do PA. The lower the motivation to do PA, the lower the physical activity engagement and physical activity levels (PALs) are. Lower PAL implies that less energy will be expended, therefore, producing a positive energy balance and higher body weight. There is also a more immediate process that worsens mental wellbeing produced by guilt from doing poor PALs leading to a further reduced motivation to do PA and PA engagement, ultimately lowering physical activity.
Sleep difficulty (R18)	*body weight → body image satisfaction → pressure on body image → stress → sleep quality → mental wellbeing → binge eating → unhealthy food consumption → calorie intake → body weight*	As the perceived pressure on body image increases with higher body weight, psychosocial stress increases as well, which reduces sleep quality. The lower the quality of sleep, the lower mental wellbeing. Poor mental wellbeing leads to unhealthy eating behaviours, such as binge eating, increasing body weight which intensifies body image dissatisfaction and increases pressure on body image further.

present weight and the perceived ideal weight. This weight bias subsequently generates a sense of discontentment in relation to the adolescents' weight condition resulting in perceived *pressure on body image*, generating a sense of dissatisfaction in relation to the adolescent's weight status (R16ab and B4). This, in turn, contributes to a decline in *mental wellbeing* and ultimately leads to the development of obesity also due to the lack of motivation to do PA. Also, the combination of low *self-esteem* and *stress* leads to lower *mental wellbeing* and a Lack of motivation to do PA (R17ab), which in turn lowers *engagement in PA* and reduces *physical activity* and *energy expenditure*. There also may be an immediate negative impact of consuming unhealthy food on adolescents' mental wellbeing (R16c), where feelings of guilt from eating junk food can deteriorate mental health and potentially lead to further binge eating of unhealthy foods (Malmir et al., 2023). In addition, *stress* reduces the *quality of sleep* (R18) and further lowers *mental wellbeing*, which in turns leads to a lower *motivation to do PA* and further reduces *physical activity*. The Sleep difficulty feedback loop (R18) links individual factors such as *stress* and *screen use* to *sleep quality* (Guerrero et al., 2019) but also demonstrates how these factors are mutually reinforcing; for instance, increased *screen use* could exacerbate *stress*, leading to even more screen use in a continuous cycle (Santos et al., 2023). In the context of screen use, all feedback loops were perceived to be channelled through the *availability of technological devices*.

3.2.4. Social norms theme

This theme (see Table 4 and Fig. 6) deals with how adolescent social norms, related to dietary and physical activity behaviours, are shaped and reproduced. Social norm-related loops affect body weight through food consumption, physical activity, and mental wellbeing (Shoham et al., 2015). The feedback loop associated with *social media usage* and higher *exposure to unhealthy influence, poor mental wellbeing* and more *unhealthy food consumption* (R19ab) (Blanchard et al., 2023) was identified as an important feedback process as it is interconnected with both food consumption and physical activity behaviours. In addition, the Emotional eating loops (R16abc) and Unhealthy peer-to-peer influence loop (R20) reduce the *mental wellbeing* of adolescents with respect to negative *peer interactions*, *negative body image,* and *emotional instability* toward *food choices* and *physical activity* (Draper et al., 2015).

There are feedback loops associated with the role of *adolescent personal norms* in relation to both nutrition and physical activity. Here, personal norms refer to one's 'moral or personal obligation to perform a certain behaviour' (Zillich and Riesmeyer, 2021). *Unhealthy nutrition norms* (R21) are reproduced by the feedback between unhealthy food choices, reduced wellness experienced, and low *attractiveness of healthier options*. This in turn, reduces the relative appeal of *healthy choices*, and fosters Dishabituation to consume healthy food simultaneously (R1b). Similarly, in the area of physical activity, feedback loops are observed in

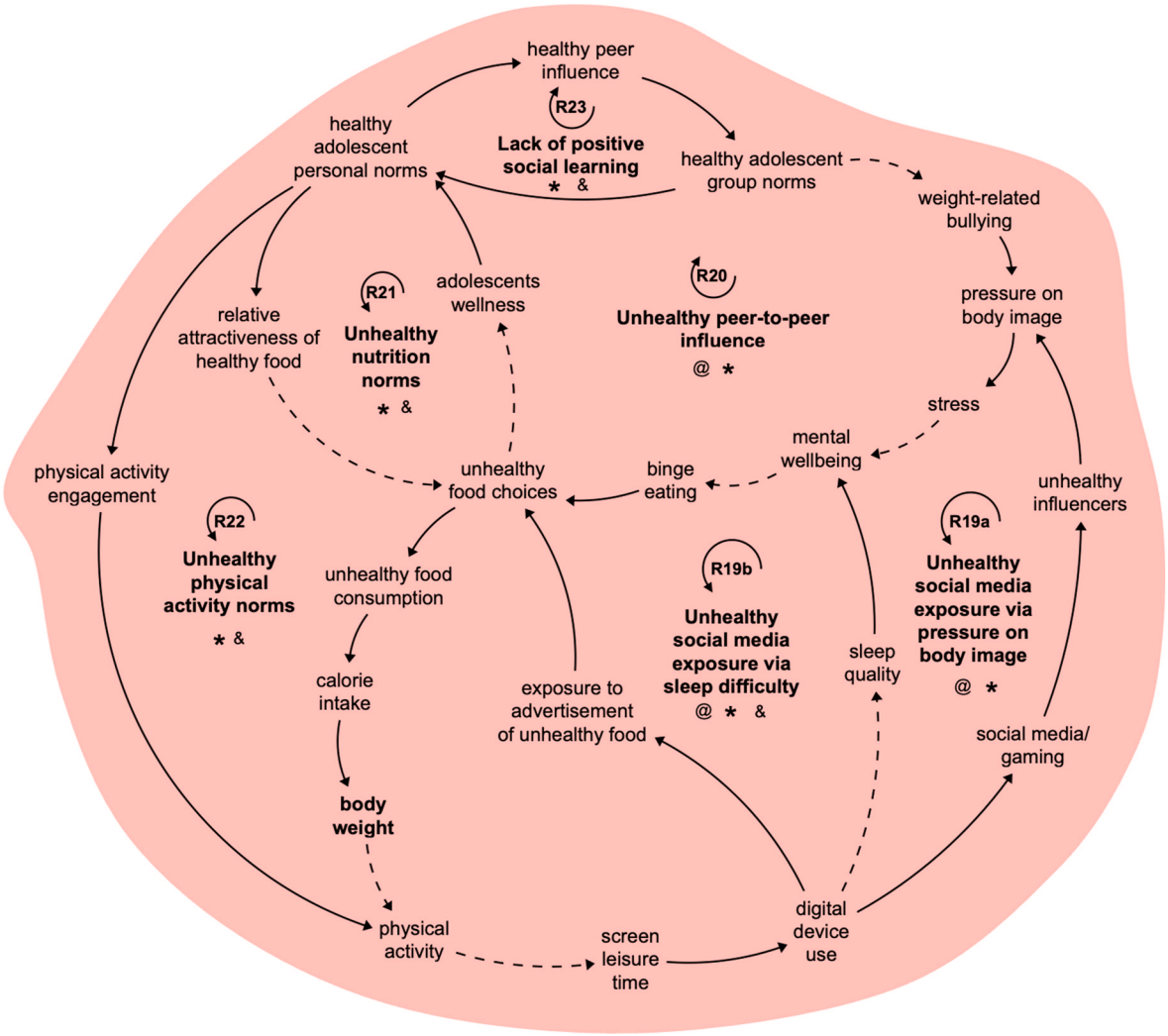

Fig. 6. Segment of the Social Norms theme in the integrated CLD *in the CO-CREATE project. The letter R with curved arrow: reinforcing loop; the letter B with curved arrows: balancing loop; solid arrows: positive causal link; dotted arrows: negative causal link;* @: feedback loop existing in the co-created system map with adolescents; *: feedback loop extracted from the literature; &: feedback loop co-developed with experts during validation workshops.

Table 4
Feedback loop names, labels, pathways, and stories within the social norms theme of the integrated CLD in the CO-CREATE project.

Feedback loop name and label	Feedback Loop Pathway	Feedback story
Unhealthy social media Exposure via pressure on body image (R19a) and Unhealthy social media exposure via sleep difficulty (R19b)	*(R19a) unhealthy food consumption → calorie intake → body weight → physical activity → screen leisure time→ digital device use → social media/gaming → unhealthy influencers → pressure on body image → stress → mental wellbeing → binge eating → unhealthy food choices → unhealthy food consumption* (R19b) *unhealthy food consumption → calorie intake → body weight → physical activity → screen leisure time → digital device use → sleep quality → mental wellbeing → binge eating unhealthy food choices → unhealthy food consumption*	These feedback loops describe how higher consumption of unhealthy food contributes to higher calorie intake. This increase in caloric intake leads to an increase in body weight. The higher the body weight, the lower the engagement in physical activity. Reduced physical activity levels prompt an increase in leisure time spent in front of screens. Increased screen leisure time links to a rise in digital device usage, fostering greater interaction with social media/gaming. Elevated social media usage exposes adolescents to more unhealthy influencers. The intensified exposure to unhealthy influencers increases the pressure on body image, this lowers mental wellbeing resulting in a loop of making more unhealthy food choices and increasing unhealthy food consumption. Also, a higher digital device use reduces sleep quality which lower mental wellbeing as well. This then increases binge eating and further unhealthy food consumption.
Unhealthy peer-to-peer influence (R20)	*unhealthy food choices → adolescents wellness → healthy adolescent personal norms → healthy peer influence → healthy adolescent group norms→ healthy peer influence → weight related bullying → pressure on body image → stress → mental wellbeing → binge eating → unhealthy food choices*	Unhealthy food choices among adolescents leads to a decline in their overall wellness. This diminished wellness, in turn, hinders the formation of healthy adolescent personal norms. Through peer-to-peer influence from social interactions, lower healthy adolescent personal norms contribute to the deterioration of group norms. This decline intensifies weight-related bullying, especially within school settings. More bullying leads to an increased pressure on adolescents' body image, exacerbating their stress levels and subsequently diminishing their mental wellbeing. The poorer the mental wellbeing, the more the tendency to engage in binge eating behaviours, culminating in a further increase in unhealthy food choices.
Unhealthy nutrition norms (R21)	*unhealthy food choices → adolescents wellness → healthy adolescent personal norms → relative attractiveness of healthy food → unhealthy food choices*	This feedback loop captures how reduced healthy food choices weaken healthy adolescent personal norms, thus decrease the attractiveness of healthy food, increasing, in turn, unhealthy food choices.
Unhealthy physical activity norms (R22)	*unhealthy food choices → adolescents wellness → healthy adolescent personal norms → physical activity engagement→ physical activity → screen leisure time→ digital device use → exposure to advertisement of unhealthy food → unhealthy food choices*	This loop represents the effect of decreased healthy adolescent personal norms resulting from unhealthy food choices on poorer physical activity engagement. A poorer physical activity engagement leads to a lower physical activity level which, in turn, increases the screen leisure time and digital devices usage. With higher usage of digital devices, there is more exposure to advertisements of unhealthy food, thus increasing unhealthy food choices.
Lack of positive social learning (R23)	*healthy adolescent personal norms → healthy peer influence → healthy adolescent group norm → healthy adolescent personal norms*	Weak healthy adolescent personal norms contribute to sustaining unhealthier group norms by way of lower healthy peer influence within the adolescent community that is more damaging. As healthier group norms decrease, they, in turn, shape the overall healthy adolescents personal norms. This reinforcing loop creates a detrimental social environment where negative habits and choices become the norm, preventing adolescents to contribute to and benefit from the promotion of wellbeing and healthy lifestyles.

regard to personal norms (Simpkins et al., 2013). An example of this is the interplay between weak personal norms surrounding walking and cycling, and the resultant impact on these very norms, forming loop R22. While personal norms are in part sustained through the reproduction of past behaviour and habituation, they are also shaped by the social environment through the process of social learning (Bandura, 1999). Adolescents' personal norms are shaped through the internalisation of group norms from peer-to-peer social interactions and identifications (Bamberg and Möser, 2007; Zillich and Riesmeyer, 2021). Importantly, social learning is a process of reciprocity where adolescents influence the group social norms and simultaneously internalise (i.e., influenced by) those norms (Bandura, 1999). In this case, the lack of positive social learning loop (R23) captures the weak circulation of healthy norms for adolescents to model after.

Unhealthy personal norms, therefore, can lead to several harmful consequences in the social environment. The lack of positive social learning process socialises adolescents towards unhealthy nutrition (R21) and physical activity (R22) practices, which could then become Dishabituated to consume healthy food (R1b). Unhealthy peer influence (R20), in this process, could further propagate to a weaker integration among greater groups (e.g., classrooms, neighbourhoods), thus increasing negative behaviours such as bullying (Lian et al., 2018). These interacting feedback loops thus contribute to a negative social norm around unhealthy eating and unhealthier lifestyles among adolescents (Roberts et al., 2019). If so, R19a can potentiate the vicious cycle of increasing *digital device use and social media/gaming* such that the *unhealthy influencers'* effect on mental wellbeing is increased (R16abc, R17ab, R18 and B4).

4. Discussion

4.1. Summary

As part of the CO-CREATE project, this study aimed to integrate three sources of information on the main drivers, causal links, and feedback processes exacerbating obesity among adolescents into a single CLD. By integrating a systems map developed by adolescents with a CLD based on scientific literature, we identified gaps and originalities, highlighting feedback mechanisms extending beyond dietary and physical activity factors and towards societal, psychosocial, and emotional pressures that generate obesity-related behaviours in adolescents. 27 main feedback loops resulted from our analysis describing the main feedback mechanisms increasing body weight and perpetuating high adolescent obesity prevalence, which were then supported and expanded through consultation with experts in the field of adolescent obesity. When identifying the loops, we particularly emphasised the feedback stories, i.e., the descriptions of real-world processes that feedback loops attempt to represent (Rajah et al., 2024).

4.2. Value of integrating perspectives

Integrating different perspectives in CLDs is essential for a more comprehensive and robust representation of key system structures or components underpinning complex health issues, in this case, adolescent obesity. The inclusion of adolescents' experiential knowledge in the CLD on factors that drive harmful diet and physical activity behaviours highlights the importance of considering the perspective of the affected population directly (Samdal et al., 2023).

Additionally, while literature reviews provide a foundation based on existing knowledge, expert input helps refine, support and expand on the relationships between variables, improving the overall accuracy of the CLD (Turner and Goodman, 2023). During our expert validation workshops, the experts did not disagree nor were they opposed to any of the adolescent-suggested variables and links. Instead, they identified missing variables, links, and feedback loops that the adolescents did not describe, and they supported these additions with relevant literature. For instance, experts provided helpful inputs related to definitions and linkages concerning the physical activity environment variables, and specifically the different processes involved in organised physical activity and the supply and demand of the built environment for adolescents' physical activity accessibility which were not shown in the adolescents' system map. This was an iterative process that helped further refine of the integrated CLD.

Lastly, by integrating different perspectives and knowledge sources, we can identify gaps and foster the emergence of novel insights (Pluchinotta et al., 2022; Schaffernicht and Groesser, 2014). Following the example of Luna Pinzon et al. (2023) who also integrated multiple perspectives on adolescent obesity in the Netherlands, we used a broader empirical basis across multiple European case studies and found that new feedback loops emerged from the integration and validation processes, including the feedback loops R13ab Inaccessibility to physical activity and R18 Sleep difficulty, which were formed during the integration process and had not been feedback loops in the two individual CLDs. Moreover, during the integration process, it was recognised that several critical factors and feedback structures, such as mental health and social pressures — particularly the adverse effects of social media use — are underrepresented in the current literature. These elements, identified as key drivers of obesity, warrant a more detailed investigation to inform the obesity research agenda. Future studies exploring these relationships may yield robust empirical evidence expanding beyond current expert knowledge.

4.3. Insights from feedback stories in the integrated CLD

Given the study's focus on mapping the drivers of adolescent obesity, we predominantly found reinforcing loops that formed of vicious cycles. These loops exacerbate, rather than mitigate, the prevalence of obesity and unhealthy behaviours among adolescents. Our findings, thus, have the potential to contribute to a more holistic understanding of how persistent vicious cycles can impact energy-balance related behaviours in adolescents, offering insights that can promote the use of systems approaches to enhance adolescents' wellbeing. Specifically, the feedback loops associated with the commercial food environment, which are fuelled by the persistent availability of low-priced foods high in fat, sugar or salt, propagate the consumption of these unhealthy foods. Another significant loop contributing to unhealthy adolescent behaviours is the sedentary behaviour loop, governed by factors such as higher leisure screen time and the advertising of unhealthy foods.

The integrated CLD brought attention to the complex dynamics within the commercial food environment, emphasising its significant centrality. Moreover, our results highlight the intricate interconnections and interdependencies among sleep quality, physical activity, and technology usage domains, shedding light onto potential points for system-level interventions. Additionally, the integrated CLD illustrates the significance of adolescents' vulnerabilities in the online environment, suggesting that addressing online activities and interactions could serve as a crucial entry point for interventions, influencing mental health, social norms, and overall choices related to diet and physical activity. Thus, the identified vicious cycles underscore the imperative for policies and interventions aimed at obesity prevention to redirect these cycles, transforming them from operating in detrimental ways to virtuous ones.

4.4. The integrated CLD as a knowledge repository

This paper emphasises the strength of an integrative approach and reveals that each source of knowledge depicted in the CLDs is an element of the mental models held by the stakeholders involved and what is available in the body of literature. Hence, the integrated CLD presented here serves as an initial knowledge repository that provides a more detailed overview of the feedback mechanisms boosting harmful energy-balance related behaviours as perceived by young people, with

additional support from recent research outputs and expert opinions. However, it should not be interpreted as exhaustive. Our integrated CLD emphasises reinforcing loops or vicious cycles that amplify the dynamics of unhealthy behaviours. This overrepresentation of reinforcing loops reflects a broader trend in group modelling sessions, where attention tends to concentrate on reinforcing feedback mechanisms, potentially overlooking balancing ones and other dynamics critical to understanding the complexity of obesity.

Balancing loops that act as constraints and limits often tend to be uncovered during simulation modelling, and when policy structures are introduced to alleviate the problem. Hence, the balancing loops included in our integrated CLD (B1, B2, B3 and B4) were mainly sourced from the systematic review of SD models. Given the boundaries of the existing models, most of these balancing loops that act as constraints on reinforcing loops are found in the Commercial Food Environment theme. In turn, this suggests that additional balancing loops are currently absent in the other themes of the integrated CLD. While the incorporation of such constraining and alleviating balancing loops lies beyond the current scope of this paper, this knowledge repository can be updated as the state-of-the-art improves in the future.

Nevertheless, the vicious cycles captured in this initial repository are still useful to understand the underlying structures responsible for the persistence of the problem and to consider the impact of these cycles when attempting to improve the larger system (Lane and Husemann, 2008). All loops shown in the CLD (reinforcing and balancing) currently operate to exacerbate obesity and thus provide an explanation for observed trends in adolescent obesity. Additionally, the CLD provides the scaffold for conceptualising dynamic hypotheses for simulation models. Specifically, for system dynamics modellers aiming to quantify the feedback structure underlying obesity prevalence, such a repository is useful for delineating the boundary of their model (Rajah et al., 2024). That is, such modellers could use this initial knowledge repository to ensure that their boundary selection includes the major feedback loops responsible for driving overweight and obesity. In doing so, they further contribute to knowledge creation that can be used to update this repository.

4.5. The integrated CLD as a tool to reflect critically on potential system interventions

Maps and models are commonly used to represent and simplify the complexity of a reality that is challenging to conceive of in its entirety (Harrison, 1995). A model is an abstraction of reality that embodies only the essential features of reality relevant to the investigation, omitting much of the detail (Dalcher, 2018). The CLD capturing different perspectives of adolescent obesity depicted in this paper is a non-simulatable, visual map that helps promote understanding of the complex issues at hand, encourage dialogue and engagement between stakeholders, and provide some level of decision support. A common misconception regarding the use of CLDs in public health is that they provide comprehensive roadmaps, delineating every possible intervention point within a system. However, their main strength lies instead in guiding us to verify the causal logic of policy alternatives and to ensure their internal consistency with the feedback structures embedded within.

Policymakers considering fiscal measures to address diet-related health could use tools such as CLDs to ensure they ask the right questions regarding policy interventions, shifting away from quick-fix solutions towards those informed by feedback dynamics. For instance, a CLD can help policymakers visualise how a proposed intervention, such as a sugar tax, falls within the broader feedback structure. Traditionally, policies like the sugar tax are viewed through a linear cause-and-effect lens, where the assumption is that increasing the price of sugary products will lead to reduced consumption and subsequently lower rates of obesity. However, this logic may be inadequate if feedback processes are considered. In this example, such a policy may fail to account for systemic factors like mental health mechanisms, especially in the adolescent population, which could weaken the intended effects of the policy. By using the CLD, policymakers can better understand which parts of the system a proposed intervention will influence and where it might fall short. If poor mental wellbeing feedback loops are stronger, for instance, individuals may continue to consume sugary products despite higher prices, as the price change does not impact the underlying issue driving consumption patterns. Therefore, CLDs offer a structured way to tailor policies to more effectively address the specific needs and challenges faced by adolescents.

Effective use of CLDs as tools to support this kind of anticipatory action is not without its challenges. It may well require a conceptual shift on the part of policymakers and others, from a traditional public health approach that tends to focus on specific interventions to a broader emphasis on the system as whole, and the interactions and interdependencies within it. Importantly, while CLDs can offer insights into a system's structure, mentally simulating potential trajectories of a system over time solely from its causal-loop representation is unreliable. A simulation model that quantifies the feedback structure is required to understand the relative and time-dependent strengths of the complex feedback interactions inherent in obesity and other public health problems, address harmful unintended consequences, and generate public health gains across multiple domains simultaneously. Therefore, this work can be taken forward, based on the feedback structure, to identify critical areas for further analysis with potential meaningful intervention points for policy intervention (Richardson, 2020; Richardson and Andersen, 2010) as it provides a robust foundation for subsequent quantification efforts of a simulation model of the drivers of adolescent obesity. Likewise, dealing with analytical problems to gain a deeper understanding of the dynamics requires simulation, and intervention points cannot be fully justified without a simulation model for hypothesis testing. In such quantitative assessment of the consequences of interventions, exogenous variables that were not included in this CLD as well as important absent balancing loops need to be accounted for in the structure and analysis of a simulation model. Only then can we further verify the effects and unintended consequences of potential policy alternatives.

4.6. Limitations of this study

We acknowledge that our work has some limitations, and that further analyses are desirable. Our integrated CLD provides a visual representation of the main feedback mechanisms that contribute to rising adolescent obesity, as obtained from the findings of the knowledge integration process across three sources. Therefore, the variables, links and feedback loops portrayed in the integrated CLD are exclusively based on these three sources: the participatory process with adolescents, the literature reviewed, and expert consultation workshops conducted within the CO-CREATE project. As discussed above, there may be additional variables and connections that could be further included in the CLD. Moreover, given that the final CLD is a result of both the content of the different knowledge sources and the authors' own interpretation, it is likely that variables, links, and feedback loops, may differ from other studies that have not been included in this diagram. The role of our interpretation was mainly to ensure the coherence of the method and to fill in gaps where the data sources did not fully converge. However, we took measures to mitigate the risk of bias or overinfluence from our own interpretation. First, we relied on multiple and diverse sources of information to ensure the relationships and variables represented in this work's CLD were well supported by published work. Any relationship, variable addition or removal and feedback loops suggested by our interpretation were triangulated with data from these sources to minimise the subjective influence. Second, the CLD was developed iteratively, as we presented versions of the CLD to experts and stakeholders for feedback which help refined the assumptions and interpretations in the diagram.

Throughout this study, we encountered considerable challenges when attempting to capture the complex interconnections driving adolescent obesity prevalence. One of the primary difficulties arose during the process of aggregating variables and merging factors on the basis of two distinct CLDs. This endeavour required careful consideration and posed the risk of potentially sacrificing crucial details that are integral to a comprehensive understanding of the issue being mapped. One example of 'lost' variables during the integration process is the exclusion of exogenous variables (i.e., those not affected causally by another variable, depicted by having only arrows outwards in a CLD, thus not part of feedback loop) as shown in the original CLDs. Lastly, further research may look into representing social disparities in obesity prevalence, such as those associated with race/ethnicity or economic status that could be incorporated in CLDs. However, these considerations are currently beyond this study's scope given that our stakeholders focused on general mechanisms driving adolescent obesity.

5. Concluding remarks

This work presents an integrated causal loop diagram that brings together the co-produced knowledge of adolescents with expert judgement and scientific literature. It shows the development of an initial knowledge repository focused on the feedback processes contributing to the exacerbation of adolescent obesity. CLDs provide a holistic, integrated view of a complex issue i.e., adolescent obesity, an approach often not sufficiently applied. By incorporating different viewpoints into CLDs, they can lead to more informed decision-making and a better systemic understanding of obesity as a complex and dynamic problem. Embracing the dynamic nature of systems and involving various perspectives ensures the creation of thorough and adaptable knowledge repositories, in the form CLDs, that can evolve with new information over time.

Funding

This project was funded under the EU Horizon 2020 project "Confronting Obesity: Co-creating policy with youth (Co-Create)" under grant agreement No 774210.

CRediT authorship contribution statement

Anaely Aguiar: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jefferson K. Rajah:** Writing – review & editing, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **Kaitlin Conway-Moore:** Writing – review & editing, Validation, Methodology, Investigation, Conceptualization. **Natalie Savona:** Writing – review & editing, Validation, Methodology, Investigation, Data curation, Conceptualization. **Cécile Knai:** Writing – review & editing, Validation, Project administration, Methodology, Funding acquisition, Conceptualization. **Ioana Vlad:** Writing – review & editing, Validation, Methodology, Conceptualization. **Oddrun Samdal:** Writing – review & editing, Validation, Project administration, Funding acquisition, Conceptualization. **Harry Rutter:** Writing – review & editing, Validation, Project administration, Funding acquisition, Conceptualization. **Nanna Lien:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Birgit Kopainsky:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.socscimed.2025.117706.

Data availability

Data will be made available on request.

References

Abrahamson, E., Rosenkopf, L., 1997. Social network effects on the extent of innovation diffusion: a computer simulation. Organ. Sci. 8 (3), 289–309.

Aguiar, A., Gebremariam, M.K., Romanenko, E., Önal, F., Kopainsky, B., Savona, N., Brown, A., Allender, S., Lien, N., 2023a. System dynamics simulation models on overweight and obesity in children and adolescents: a systematic review. Obes. Rev. 24 (S2), e13632. https://doi.org/10.1111/obr.13632.

Aguiar, A., Önal, F., Hendricks, G., Blanchard, L., Romanenko, E., Fismen, A., Nwosu, E., Herstad, S., Savona, N., Harbron, J., 2023b. Understanding the dynamics emerging from the interplay among poor mental wellbeing, energy balance-related behaviors, and obesity prevalence in adolescents: a simulation-based study. Obes. Rev. 24, e13628.

Alessie, R., Kapteyn, A., 1991. Habit formation, interdependent preferences and demographic effects in the almost ideal demand system. Econ. J. 101 (406), 404–419.

Allender, S., Owen, B., Kuhlberg, J., Lowe, J., Nagorcka-Smith, P., Whelan, J., Bell, C., 2015. A community based systems diagram of obesity causes. PLoS One 10 (7), e0129683. https://doi.org/10.1371/journal.pone.0129683.

Andersen, D.F., Richardson, G.P., 1997. Scripts for group model building. Syst. Dynam. Rev. 13 (2), 107–129. https://doi.org/10.1002/(SICI)1099-1727(199722)13:2<107::AID-SDR120>3.0.CO;2-7.

Atkinson, J.-A., Page, A., Wells, R., Milat, A., Wilson, A., 2015. A modelling tool for policy analysis to support the design of efficient and effective policy responses for complex public health problems. Implement. Sci. 10 (1), 26. https://doi.org/10.1186/s13012-015-0221-5.

Bamberg, S., Möser, G., 2007. Twenty years after Hines, Hungerford, and Tomera: a new meta-analysis of psycho-social determinants of pro-environmental behaviour. J. Environ. Psychol. 27 (1), 14–25.

Bandura, A., 1999. Social cognitive theory: an agentic perspective. Asian J. Soc. Psychol. 2 (1), 21–41.

Barbrook-Johnson, P., Penn, A.S., 2022. Systems Mapping: How to Build and Use Causal Models of Systems. Springer Nature.

Baugh Littlejohns, L., Hill, C., Neudorf, C., 2021. Diverse approaches to creating and using causal loop diagrams in public health research: Recommendations from a scoping review. Publ. Health Rev. 42, 1604352. https://doi.org/10.3389/phrs.2021.1604352.

Blanchard, L., Conway-Moore, K., Aguiar, A., Önal, F., Rutter, H., Helleve, A., Nwosu, E., Falcone, J., Savona, N., Boyland, E., 2023. Associations between social media, adolescent mental health, and diet: a systematic review. Obes. Rev. 24, e13631.

Blumenthal, D.M., Gold, M.S., 2010. Neurobiology of food addiction. Curr. Opin. Clin. Nutr. Metab. Care 13 (4), 359–365.

Boyland, E., Muc, M., Kelly, B., Halford, J.C., Vohra, J., Rosenberg, G., Christiansen, P., 2021. Indirect associations between commercial television exposure and child body mass index. J. Nutr. Educ. Behav. 53 (1), 20–27.

Burrell, M., White, A.M., Frerichs, L., Funchess, M., Cerulli, C., DiGiovanni, L., Lich, K.H., 2021. Depicting "the system": how structural racism and disenfranchisement in the United States can cause dynamics in community violence among males in urban Black communities. Soc. Sci. Med. 272, 113469.

Butland, B., Jebb, S., Kopelman, P., McPherson, K., Thomas, S., Mardell, J., Parry, V., 2007. Tackling Obesities: Future Choices-Project Report, vol. 10. Citeseer.

Calancie, L., Fullerton, K., Appel, J.M., Korn, A.R., Hennessy, E., Hovmand, P., Economos, C.D., 2022. Implementing group model building with the shape up under 5 community committee working to prevent early childhood obesity in somerville, Massachusetts. J. Publ. Health Manag. Pract. 28 (1), E43–E55. https://doi.org/10.1097/PHH.0000000000001213.

Carey, G., Malbon, E., Carey, N., Joyce, A., Crammond, B., Carey, A., 2015. Systems science and systems thinking for public health: a systematic review of the field. BMJ Open 5 (12), e009002. https://doi.org/10.1136/bmjopen-2015-009002.

Carver, A., Cerin, E., Akram, M., Sallis, J.F., Cain, K.L., Frank, L.D., Geremia, C.M., Conway, T.L., Glanz, K., Saelens, B.E., 2023. Associations of home and neighborhood environments with children's physical activity in the U.S.-based Neighborhood Impact on Kids (NIK) longitudinal cohort study. Int. J. Behav. Nutr. Phys. Activ. 20 (1), 9. https://doi.org/10.1186/s12966-023-01415-3.

Cassidy, R., Borghi, J., Semwanga, A.R., Binyaruka, P., Singh, N.S., Blanchet, K., 2022. How to do (or not to do)… using causal loop diagrams for health system research in low and middle-income settings. Health Pol. Plann. 37 (10), 1328–1336.

Cavill, N., Richardson, D., Faghy, M., Bussell, C., Rutter, H., 2020. Using system mapping to help plan and implement city-wide action to promote physical activity. Journal of Public Health Research 9 (3), 1759. https://doi.org/10.4081/jphr.2020.1759 jphr.2020.

Checkland, P., Poulter, J., 2006. Learning for action: a short definitive account of soft systems methodology, and its use practitioners. Teachers and Students. Wiley, p. 200.

Coletta, V.R., Pagano, A., Pluchinotta, I., Fratino, U., Scrieciu, A., Nanu, F., Giordano, R., 2021. Causal loop diagrams for supporting nature based solutions participatory design and performance assessment. J. Environ. Manag. 280, 111668. https://doi.org/10.1016/j.jenvman.2020.111668.
Crielaard, L., Nicolaou, M., Sawyer, A., Quax, R., Stronks, K., 2021. Understanding the impact of exposure to adverse socioeconomic conditions on chronic stress from a complexity science perspective. BMC Med. 19 (1), 1–20.
Cruz, F., Ramos, E., Lopes, C., Araújo, J., 2018. Tracking of food and nutrient intake from adolescence into early adulthood. Nutrition 55–56, 84–90. https://doi.org/10.1016/j.nut.2018.02.015.
Dalcher, D., 2018. The map is not the territory: musings on complexity, people and models. PM World Journal 7 (3).
Dockner, E.J., Feichtinger, G., 1993. Cyclical consumption patterns and rational addiction. Am. Econ. Rev. 83 (1), 256–263.
Draper, C., Grobler, L., Micklesfield, L., Norris, S., 2015. Impact of social norms and social support on diet, physical activity and sedentary behaviour of adolescents: a scoping review. Child Care Health Dev. 41 (5), 654–667.
Eker, S., Zimmermann, N., 2016. Using textual data in system dynamics model conceptualization. Systems 4 (3), 28. https://doi.org/10.3390/systems4030028.
European Union, 2014. EU action plan on childhood obesity 2014-2020. https://health.ec.europa.eu/system/files/2016-11/childhoodobesity_actionplan_2014_2020_en_0.pdf.
Fathi, S., Sajadzadeh, H., Mohammadi Sheshkal, F., Aram, F., Pinter, G., Felde, I., Mosavi, A., 2020. The role of urban morphology design on enhancing physical activity and public health. Int. J. Environ. Res. Publ. Health 17 (7), 2359.
Felmingham, T., Bolton, K.A., Fraser, P., Allender, S., Brown, A.D., 2023. Measuring shifts in mental models in the prevention of childhood obesity in rural Australia. Health Educ. Behav., 10901981231165339
Finegood, D.T., Merth, T.D.N., Rutter, H., 2010. Implications of the Foresight obesity system map for solutions to childhood obesity. Obesity 18 (S1), S13–S16. https://doi.org/10.1038/oby.2009.426.
Forrester, J.W., 1992. Policies, decisions and information sources for modeling. Eur. J. Oper. Res. 59 (1), 42–63. https://doi.org/10.1016/0377-2217(92)90006-U.
Förster, L.-J., Vogel, M., Stein, R., Hilbert, A., Breinker, J.L., Böttcher, M., Kiess, W., Poulain, T., 2023. Mental health in children and adolescents with overweight or obesity. BMC Publ. Health 23 (1), 135. https://doi.org/10.1186/s12889-023-15032-z.
Garrity, E.J., 2018. Using systems thinking to understand and enlarge mental models: helping the transition to a sustainable world. Systems 6 (2), 15.
Giabbanelli, P.J., Torsney-Weir, T., Mago, V.K., 2012. A fuzzy cognitive map of the psychosocial determinants of obesity. Appl. Soft Comput. 12 (12), 3711–3724. https://doi.org/10.1016/j.asoc.2012.02.006.
de Gooyert, V., Rouwette, E.A.J.A., van Kranenburg, H., Freeman, E., van Breen, H., 2016. Sustainability transition dynamics: towards overcoming policy resistance. Technol. Forecast. Soc. Change 111, 135–145. https://doi.org/10.1016/j.techfore.2016.06.019.
Guerrero, M.D., Barnes, J.D., Chaput, J.-P., Tremblay, M.S., 2019. Screen time and problem behaviors in children: exploring the mediating role of sleep duration. Int. J. Behav. Nutr. Phys. Activ. 16 (1), 1–10.
Harrison, E.F., 1995. The Managerial Decision-Making Process *(No Title)*.
Homer, J., 2014. Levels of evidence in system dynamics modeling. Syst. Dynam. Rev. 30 (1–2), 75–80.
Hovmand, P., Rouwette, E., Andersen, D., Richardson, G., Calhoun, A., Rux, K., Hower, T., 2011. Scriptapedia: A Handbook of Scripts for Developing Structured Group Model Building Sessions.
Hovmand, P.S., Andersen, D.F., Rouwette, E., Richardson, G.P., Rux, K., Calhoun, A., 2012. Group model-building 'scripts' as a collaborative planning tool. Syst. Res. Behav. Sci. 29 (2), 179–193.
Huang, T.T.-K., Cawley, J.H., Ashe, M., Costa, S.A., Frerichs, L.M., Zwicker, L., Rivera, J. A., Levy, D., Hammond, R.A., Lambert, E.V., Kumanyika, S.K., 2015. Mobilisation of public support for policy actions to prevent obesity. Lancet 385 (9985), 2422–2431. https://doi.org/10.1016/S0140-6736(14)61743-8.
Inchley, J., Currie, D., Budisavljevic, S., Torsheim, T., Jåstad, A., Cosma, A., Kelly, C., Arnarsson, Á., Samdal, O., 2020. Spotlight on adolescent health and well-being. Findings from the 2017/2018 health behaviour in school-aged children (HBSC) survey in Europe and Canada. Int. Rep. 1, 146.
Kim, H., Andersen, D.F., 2012. Building confidence in causal maps generated from purposive text data: mapping transcripts of the Federal Reserve. Syst. Dynam. Rev. 28 (4), 311–328.
Király, G., Miskolczi, P., 2019. Dynamics of participation: system dynamics and participation—an empirical review. Syst. Res. Behav. Sci. 36 (2), 199–210.
Klepp, K.-I., Helleve, A., Brinsden, H., Bröer, C., Budin-Ljøsne, I., Harbron, J., Knai, C., Lien, N., Luszczynska, A., Nesrallah, S., Oldridge-Turner, K., Rito, A., Samdal, O., Savona, N., Stensdal, M.K., Allender, S., Hoelscher, D.M., Rutter, H., 2023. Overweight and obesity prevention for and with adolescents: the "Confronting obesity: Co-creating policy with youth" (CO-CREATE) project. Obes. Rev. 24 (S1), e13540. https://doi.org/10.1111/obr.13540.
Lane, D.C., Husemann, E., 2008. Steering without Circe: attending to reinforcing loops in social systems. Syst. Dynam. Rev. 24 (1), 37–61. https://doi.org/10.1002/sdr.396.
Lian, Q., Su, Q., Li, R., Elgar, F.J., Liu, Z., Zheng, D., 2018. The association between chronic bullying victimization with weight status and body self-image: a cross-national study in 39 countries. PeerJ 6, e4330.
Luna Pinzon, A., Stronks, K., Emke, H., Van Den Eynde, E., Altenburg, T., Dijkstra, S.C., Renders, C.M., Hermans, R., Busch, V., Chinapaw, M.J.M., Kremers, S.P.J., Waterlander, W., 2023. Understanding the system dynamics of obesity-related behaviours in 10- to 14-year-old adolescents in Amsterdam from a multi-actor perspective. Front. Public Health 11. https://doi.org/10.3389/fpubh.2023.1128316.
Malmir, H., Mahdavi, F.S., Ejtahed, H.-S., Kazemian, E., Chaharrahi, A., Mohammadian Khonsari, N., Mahdavi-Gorabi, A., Qorbani, M., 2023. Junk food consumption and psychological distress in children and adolescents: a systematic review and meta-analysis. Nutr. Neurosci. 26 (9), 807–827. https://doi.org/10.1080/1028415X.2022.2094856.
McGlashan, J., Hayward, J., Brown, A., Owen, B., Millar, L., Johnstone, M., Creighton, D., Allender, S., 2018. Comparing complex perspectives on obesity drivers: action-driven communities and evidence-oriented experts. Obesity Science & Practice 4 (6), 575–581. https://doi.org/10.1002/osp4.306.
Meadows, D.H., Meadows, D.L., Randers, J., Behrens, W.W., 2018. The limits to growth. In: Green Planet Blues. Routledge, pp. 25–29.
Nagata, J.M., Smith, N., Alsamman, S., Lee, C.M., Dooley, E.E., Kiss, O., Ganson, K.T., Wing, D., Baker, F.C., Gabriel, K.P., 2023. Association of physical activity and screen time with body mass index among US adolescents. JAMA Netw. Open 6 (2), e2255466. https://doi.org/10.1001/jamanetworkopen.2022.55466.
NCD Risk Factor Collaboration, 2016. Trends in adult body-mass index in 200 countries from 1975 to 2014: a pooled analysis of 1698 population-based measurement studies with 19· 2 million participants. Lancet 387 (10026), 1377–1396.
Nwosu, E., Makwambeni, P., Herstad, S.H., Etsebeth, H., Hendricks, G., Aguiar, A., Alaba, O., Blanchard, L., Fismen, A., Lien, N., 2023. Longitudinal relationship between adolescents' mental health, energy balance-related behavior, and anthropometric changes. Obes. Rev. 24, e13629.
Park, M.H., Falconer, C., Viner, R.M., Kinra, S., 2012. The impact of childhood obesity on morbidity and mortality in adulthood: a systematic review. Obes. Rev. 13 (11), 985–1000. https://doi.org/10.1111/j.1467-789X.2012.01015.x.
Peters, D.H., 2014. The application of systems thinking in health: why use systems thinking? Health Res. Pol. Syst. 12 (1), 51. https://doi.org/10.1186/1478-4505-12-51.
Pluchinotta, I., Salvia, G., Zimmermann, N., 2022. The importance of eliciting stakeholders' system boundary perceptions for problem structuring and decision-making. Eur. J. Oper. Res. 302 (1), 280–293. https://doi.org/10.1016/j.ejor.2021.12.029.
Quek, Y.-H., Tam, W.W.S., Zhang, M.W.B., Ho, R.C.M., 2017. Exploring the association between childhood and adolescent obesity and depression: a meta-analysis. Obes. Rev. 18 (7), 742–754. https://doi.org/10.1111/obr.12535.
Rajah, J.K., Atkins, A.E.P., Tang, C., Bax, K., Wilkerson, B., Fernald, A.G., Langarudi, S.P., 2024. Understanding hydrologic, human, and climate system feedback loops: results of a participatory modeling workshop. Water 16 (3). https://doi.org/10.3390/w16030396. Article 3.
Rajah, J.K., Kopainsky, B., 2025. A systemtic method to integrate co-produced causal loop diagrams based on feedback stories. Syst. Dynam. Rev. 41 (1), e1794.
Rankin, J., Matthews, L., Cobley, S., Han, A., Sanders, R., Wiltshire, H.D., Baker, J.S., 2016. Psychological consequences of childhood obesity: psychiatric comorbidity and prevention. Adolesc. Health Med. Therapeut. 125–146.
Richardson, G.P., 2020. Core of system dynamics. System Dynamics: Theory and Applications 11–20.
Richardson, G.P., Andersen, D.F., 2010. Systems thinking, mapping, and modeling in group decision and negotiation. Handbook of Group Decision and Negotiation 313–324.
Roberts, N., Li, V., Atkinson, J., Heffernan, M., McDonnell, G., Prodan, A., Freebairn, L., Lloyd, B., Nieuwenhuizen, S., Mitchell, J., Lung, T., Wiggers, J., 2019. Can the target set for reducing childhood overweight and obesity Be Met? A system dynamics modelling study in new South Wales, Australia. Syst. Res. Behav. Sci. 36 (1), 36–52. https://doi.org/10.1002/sres.2555.
Russell-Mayhew, S., McVey, G., Bardick, A., Ireland, A., 2012. Mental health, wellness, and childhood overweight/obesity. Journal of Obesity 2012, e281801. https://doi.org/10.1155/2012/281801.
Saelens, B.E., Glanz, K., Frank, L.D., Couch, S.C., Zhou, C., Colburn, T., Sallis, J.F., 2018. Two-Year changes in child weight status, diet, and activity by neighborhood nutrition and physical activity environment. Obesity 26 (8), 1338–1346.
Sallis, J.F., Cervero, R.B., Ascher, W., Henderson, K.A., Kraft, M.K., Kerr, J., 2006. An ecological approach to creating active living communities. Annu. Rev. Publ. Health 27, 297–322.
Samdal, O., Budin-Ljøsne, I., Haug, E., Helland, T., Kjostarova-Unkovska, L., Bouillon, C., Bröer, C., Corell, M., Cosma, A., Currie, D., 2023. Encouraging greater empowerment for adolescents in consent procedures in social science research and policy projects. Obes. Rev. 24, e13636.
Santos, R.M.S., Mendes, C.G., Sen Bressani, G.Y., de Alcantara Ventura, S., de Almeida Nogueira, Y.J., de Miranda, D.M., Romano-Silva, M.A., 2023. The associations between screen time and mental health in adolescents: a systematic review. BMC Psychology 11 (1), 127. https://doi.org/10.1186/s40359-023-01166-7.
Savona, N., Aguiar, A., Knai, C., Macauley, T., 2020. Country and master maps Deliverable 4.6. London School of Hygiene and Tropical Medicine. https://www.fhi.no/globalassets/dokumenterfiler/studier/co-create/4_co-create-deliverable-4.6-final.pdf.
Savona, N., Macauley, T., Aguiar, A., Banik, A., Boberska, M., Brock, J., Brown, A., Hayward, J., Holbæk, H., Rito, A.I., Mendes, S., Vaaheim, F., van Houten, M., Veltkamp, G., Allender, S., Rutter, H., Knai, C., 2021. Identifying the views of adolescents in five European countries on the drivers of obesity using group model building. Eur. J. Publ. Health 31 (2), 391–396. https://doi.org/10.1093/eurpub/ckaa251.
Savona, N., Rutter, H., Cummins, S., 2018. Tackling obesities: 10 years on. J. Epidemiol. Community Health 72 (2). https://doi.org/10.1136/jech-2017-210121, 93–93.

Sawyer, A.D., van Lenthe, F., Kamphuis, C.B., Terragni, L., Roos, G., Poelman, M.P., Nicolaou, M., Waterlander, W., Djojosoeparto, S.K., Scheidmeir, M., 2021. Dynamics of the complex food environment underlying dietary intake in low-income groups: a systems map of associations extracted from a systematic umbrella literature review. Int. J. Behav. Nutr. Phys. Activ. 18, 1–21.

Schaffernicht, M.F., Groesser, S.N., 2014. The SEXTANT software: a tool for automating the comparative analysis of mental models of dynamic systems. Eur. J. Oper. Res. 238 (2), 566–578.

Schroeter, C., Lusk, J., Tyner, W., 2008. Determining the impact of food price and income changes on body weight. J. Health Econ. 27 (1), 45–68.

Seetharaman, P., Ainslie, A., Chintagunta, P.K., 1999. Investigating household state dependence effects across categories. J. Market. Res. 36 (4), 488–500.

Shephard, R.J., 2018. Does it matter if I am overweight? 2. Some psycho-social consequences. The Health & Fitness Journal of Canada 11 (3), 22–66.

Shoham, D.A., Hammond, R., Rahmandad, H., Wang, Y., Hovmand, P., 2015. Modeling social norms and social influence in obesity. Current Epidemiology Reports 2 (1), 71–79. https://doi.org/10.1007/s40471-014-0032-2.

Simpkins, S.D., Schaefer, D.R., Price, C.D., Vest, A.E., 2013. Adolescent friendships, BMI, and physical activity: untangling selection and influence through longitudinal social network analysis. J. Res. Adolesc. 23 (3), 537–549. https://doi.org/10.1111/j.1532-7795.2012.00836.x.

Singh, A.S., Mulder, C., Twisk, J.W., Van Mechelen, W., Chinapaw, M.J., 2008. Tracking of childhood overweight into adulthood: a systematic review of the literature. Obes. Rev. 9 (5), 474–488.

Stankov, I., Henson, R.M., Headen, I., Purtle, J., Langellier, B.A., 2023. Use of qualitative systems mapping and causal loop diagrams to understand food environments, diet and obesity: a scoping review protocol. BMJ Open 13 (3), e066875.

Sterman, J., 2000. Business Dynamics: Systems Thinking and Modelling for a Complex World. McGraw-Hill Education.

Struben, J., Chan, D., Dube, L., 2014. Policy insights from the nutritional food market transformation model: the case of obesity prevention. Ann. N. Y. Acad. Sci. 1331, 57–75.

Swierad, E., Huang, T.T.-K., Ballard, E., Flórez, K., Li, S., 2020. Developing a socioculturally nuanced systems model of childhood obesity in Manhattan's Chinese American community via group model building. Journal of Obesity 2020, e4819143. https://doi.org/10.1155/2020/4819143.

Swinburn, B.A., Kraak, V.I., Allender, S., Atkins, V.J., Baker, P.I., Bogard, J.R., Brinsden, H., Calvillo, A., Schutter, O.D., Devarajan, R., Ezzati, M., Friel, S., Goenka, S., Hammond, R.A., Hastings, G., Hawkes, C., Herrero, M., Hovmand, P.S., Howden, M., et al., 2019. The global syndemic of obesity, Undernutrition, and Climate change: the Lancet Commission report. Lancet 393 (10173), 791–846. https://doi.org/10.1016/S0140-6736(18)32822-8.

Swinburn, B.A., Sacks, G., Hall, K.D., McPherson, K., Finegood, D.T., Moodie, M.L., Gortmaker, S.L., 2011. The global obesity pandemic: shaped by global drivers and local environments. Lancet (London, England) 378 (9793), 804–814. https://doi.org/10.1016/S0140-6736(11)60813-1.

Trochim, W.M., Cabrera, D.A., Milstein, B., Gallagher, R.S., Leischow, S.J., 2006. Practical challenges of systems thinking and modeling in public health. Am. J. Publ. Health 96 (3), 538–546. https://doi.org/10.2105/AJPH.2005.066001.

Turner, B.L., Goodman, M., 2023. Capturing the science behind the craft: a reporting framework to improve quality and confidence in nonsimulated models. Syst. Dynam. Rev. 40 (4), e1752.

Turner, B.L., Kim, H., Andersen, D.F., 2013. Improving coding procedures for purposive text data: Researchable questions for qualitative system dynamics modeling. Syst. Dynam. Rev. 29 (4), 253–263.

Waterlander, W.E., Luna Pinzon, A., Verhoeff, A., den Hertog, K., Altenburg, T., Dijkstra, C., Halberstadt, J., Hermans, R., Renders, C., Seidell, J., Singh, A., Anselma, M., Busch, V., Emke, H., van den Eynde, E., van Houtum, L., Nusselder, W. J., Overman, M., van de Vlasakker, S., et al., 2020. A system dynamics and participatory action research approach to promote healthy living and a healthy weight among 10–14-year-old adolescents in Amsterdam: the LIKE Programme. Int. J. Environ. Res. Publ. Health 17 (14). https://doi.org/10.3390/ijerph17144928. Article 14.

Waterlander, W.E., Singh, A., Altenburg, T., Dijkstra, C., Luna Pinzon, A., Anselma, M., Busch, V., van Houtum, L., Emke, H., Overman, M.L., Chinapaw, M.J.M., Stronks, K., 2021. Understanding obesity-related behaviors in youth from a systems dynamics perspective: the use of causal loop diagrams. Obes. Rev. 22 (7), e13185. https://doi.org/10.1111/obr.13185.

World Health Organization, 2016. Consideration of the Evidence on Childhood Obesity for the Commission on Ending Childhood Obesity: Report of the Ad Hoc Working Group on Science and Evidence for Ending Childhood Obesity. Geneva, Switzerland.

World Health Organization, 2022. WHO European Regional Obesity Report 2022. World Health Organization, Regional Office for Europe.

Zillich, A.F., Riesmeyer, C., 2021. Be yourself: the relative importance of personal and social norms for adolescents' self-presentation on Instagram. Social Media+ Society 7 (3), 20563051211033810.