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REVIEW

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System dynamics simulation models on overweight and obesity in children and adolescents: A systematic review

Anaely Aguiar[1] | Mekdes K. Gebremariam[2] | Eduard Romanenko[2] | Furkan Önal[1] | Birgit Kopainsky[1] | Natalie Savona[3] | Andrew Brown[4] | Steven Allender[4] | Nanna Lien[2]

[1]System Dynamics Group, University of Bergen, Bergen, Norway

[2]Department of Nutrition, University of Oslo, Oslo, Norway

[3]Faculty of Public Health and Policy, London School of Hygiene and Tropical Medicine, London, UK

[4]Global Centre for Preventive Health and Nutrition, Deakin University, Geelong, Victoria, Australia

Correspondence
Nanna Lien, Department of Nutrition, University of Oslo, PO Box 1046 Blindern, 0316 Oslo. Norway.
Email: nanna.lien@medisin.uio.no

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Summary

It has increasingly been recognized that developing successful obesity prevention policies and interventions requires understanding of the complex mechanisms driving the obesity pandemic and that models could be useful tools for simulating policies. This paper reviews system dynamics simulation models of mechanisms driving childhood overweight and obesity and/or testing of preventive interventions. A systematic literature search was conducted in six databases from inception to January 2023 using terms related to overweight/obesity, children, and system dynamics. Study descriptives, mechanisms, and where to intervene (the leverage points), as well as quality assessments of the simulation models were extracted by two researchers into a predetermined template and narratively synthesized. Seventeen papers describing 15 models were included. Models describing the mechanisms ranged from only intrapersonal factors to models cutting across multiple levels of the ecological model, but mechanisms across levels were lacking. The majority of interventions tested in the simulation models were changes to existing model parameters with less emphasis on models that alter system structure. In conclusion, existing models included mechanisms driving youth obesity at multiple levels of the ecological model. This is useful for developing an integrated simulation model combining mechanisms at multiple levels and allowing for testing fundamental system changes.

KEYWORDS
obesity prevention, simulation models, system dynamics, youth

1 | INTRODUCTION

Current high levels and rising obesity prevalence is an urgent public health problem, in both adults and children globally.[1–3] Obesity has several short- and long-term impacts on the health and well-being of children[4,5] and childhood obesity often tracks into adulthood.[6] Furthermore, there are clear social inequalities with higher prevalence of overweight and obesity among children of lower socio-economic status.[7] Multiple biological, psychosocial, cultural, environmental, and economic drivers of behavior underlie positive energy balance leading to overweight and consequently obesity.[8–12] These drivers operate at multiple levels with a variety of

Abbreviations: BMI, body mass index; MeSH, Medical Subject Headings; OW/OB, overweight and obesity; PA, physical activity; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses; SD, system dynamics; SES, socio-economic status; SSB, sugar-sweetened beverage; US, United States.

mechanisms that interact with one another which is often illustrated, but less often operationalized, as ecological models in public health.[13–15] In light of the problem itself and the complexity of its drivers, there have been multiple efforts to combat overweight and obesity (OW/OB) in children ranging from clinical interventions to public policies[16,17] but efforts have yielded few effective and scalable solutions for either.[18]

The failure of most countries to reverse and prevent the obesity epidemic using behavior focused interventions evaluated with traditional study designs[19,20] suggests that obesity is a fundamentally complex public health problem requiring intervention efforts to engage with the complexity of obesity causes and effects.[21] Thus, recent attempts to halt and reverse the obesity prevalence trends among children have examined the benefit from approaches that enable understanding complexity, including system science.[22,23] A complex systems approach allows the consideration of nonlinear relationships between variables, accumulations, feedback loops, and emergence effects which linear approaches typically have to disregard.[24,25]

Across different branches of systems science a common method is the development of computer models that simulate the system outcomes arising from the complex interactions among the system's variables.[26] One method, system dynamics (SD) modeling, is an aggregate-level modeling type, historically applied for national level policy evaluation.[27] SD is a computer-based approach for scenario and policy analysis in complex dynamic systems[28,29]; it centers on the idea that feedback structures and interactions among variables within a system are responsible for the system behavior over time.[30] SD uses quantitative computer models to uncover and understand endogenous sources of complex system behavior; that is, it seeks to find explanations for system behaviors by understanding the internal structure (i.e., variables and their causal interactions) of a system rather than focusing on factors external (exogenous) to the system.[31] By using formal simulation, SD enforces theoretical precision, makes assumptions transparent, promotes data analysis and hypothesis testing, identifies potential leverage points and allows for scenario and policy analysis,[32] which is particularly useful for quantitative estimates of the outcomes of policies related to overweight and obesity prevention.[33,34] In the policy testing the leverage points are particularly important as they have been defined as "places within a complex system where a small shift in one thing can produce big changes in everything."[35]

This review was conducted in order to synthesize evidence regarding existing systems dynamic simulation models related to childhood obesity, and to draw lessons from these models that could inform future studies in general and the CO-CREATE project in particular.[36] Within the CO-CREATE project the results of the review were combined with the qualitative input from youth[37] to develop SD models to simulate the effects of policy ideas for obesity prevention developed by youth.[38]

This study reviews existing SD simulation models which have modeled environmental factors and mechanisms driving childhood OW/OB and to investigate if, and in what context, SD modeling is being used to inform policy and/or decision-making processes related to preventing OW/OB in children and adolescents.

2 | METHODS

This systematic review was conducted and reported in accordance with the recommendations of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).[39] The protocol was registered on PROSPERO (registration number: CRD42019125424) priori to conducting the review.

2.1 | Search, selection of articles and extraction of data

Using a combination of text and Medical Subject Headings (MeSH terms), the following databases were searched by AA; MEDLINE, EMBASE, PsyINFO, CINAHL, Scopus and Web of Science. The search algorithm was structured using the following main search terms: (obesity OR overweight OR adiposity) AND (children OR adolescents) AND (system dynamics OR systems modeling). The search was conducted during February–April 2019 for the whole life of each database, followed by three search updates until April 2021, February 2022, and January 2023. The search was restricted to studies published in the English language. The search terms and strategy were adapted to match the specific structure of each database searched. In addition, reference lists of the identified articles were screened. The detailed search strategy is reported in the Supporting information Table S1.

Titles and abstracts were imported into the reference management program ENDNOTE 9 and screened against the inclusion and exclusion criteria by one reviewer (AA) with expertise in system dynamics. Eligible studies for inclusion were those that applied the system dynamics simulation method to model overweight and/or obesity determinants or any obesity-related behaviors (i.e., diet and physical activity) of children or adolescents as models for understanding etiology or for testing policies/interventions. Studies investigating adults only or not reporting on children or adolescents separately, as well as interventions focusing on treating children and adolescents with overweight and obesity, were excluded. No restrictions on target group characteristics such as gender, baseline weight status, or country were applied. Full texts were assessed when the abstract was found insufficient to make conclusions about inclusion.

Standardized data extraction forms were developed covering the following: (i) study overview (author(s), year, and country, study aim, target population groups, setting, model outcome [diet behavior and physical activity]), (ii) model description (model focus, model type, conceptual model, key model variables, feedback loops, and leverage points), (iii) study design (scenarios or interventions modeled, simulation time, empirical data used, calibration, and validation tests conducted), and (iv) findings (results and conclusions, leverage points). The data was extracted by two reviewers (AA and MG) independently, and any discrepancies between the reviewers were resolved by discussion with a third reviewer.

2.2 | Synthesis of results

A narrative approach to synthesis was chosen to address our research aims.[40] To describe the main model structures of factors and mechanisms driving OW/OB, NL in collaboration with AA, MG, and BK sorted the models by their main factors at the levels of the ecological model by McLeroy et al.[14]—intrapersonal, interpersonal, organizational, community, and public policy—unless the model themselves referred to the Bronfenbrenner[13] type of levels as micro, meso, exo, and macro.

Interventions aimed at preventing OW/OB were analyzed using a simplified Intervention Level Framework.[41] That framework is based on the levels of intervention for complex problems described by Meadows[35] and oriented to public health by Bolton et al.[42] For characterizing the leverage points or specific interventions tested in the different models, we assessed how the interventions were represented in the models. Interventions at the lowest level (lowest in terms of effectiveness according to Meadows[35]) are represented as parameter changes that result in changing the strength of a relationship in the model. Interventions at a medium level change the structure of the simulation model by adding/removing variables and/or connections between variables. Such structural changes modify the feedback structure of the model. Finally, interventions at the highest level change the goals in the modeled decision rules. Leverage points assessment was performed by one reviewer (BK) and independently checked by a second reviewer (FO). Disagreements were resolved by consensus between these two reviewers.

2.3 | Model validity assessment

SD simulation models are validated through structural and behavioral tests to assess their robustness and limitations.[24,43] A model validation checklist similar to the one presented by Jalali et al.[44] was created specifically for this review (Table S2), to assess the models of the included studies based on principles developed by system dynamics practitioners.[24,43,45] Studies were given a quality score based on how many of the six criteria in the validation checklist were met. The six criteria for model validity and transparency resulted in a maximum model validity score of 18. Model validity was assessed by one reviewer (AA) and independently checked by a second reviewer (BK). Disagreements were resolved by consensus between these two reviewers.

3 | RESULTS

There were 1988 records identified from the searches of which 625 articles remained after eliminating duplicates. The initial screening of titles and abstracts resulted in 89 articles for full text review. The full text review resulted in 74 records being excluded. Two additional articles were found through reference list checking of the 15 remaining articles (Figure 1), resulting in 17 articles with 15 models included. The three search updates did not contribute any articles after full text reviews.

3.1 | Characteristics of the included studies

All 17 included studies were published in the last decade and eight were set in the United States (US). Seven studies included children, adolescents and adults, separating them into age cohorts where each age group transferred to the next cohort over time[46–52]; seven articles examined children and adolescent populations.[47,53–58] Three studies investigated adolescents only.[59–61] Five studies only modeled etiology of childhood obesity[48,50,60–62] and five studies only tested interventions to prevent childhood obesity,[52,55–58] while seven studies did both[46,47,49,51,53,54,60] (Table 1).

3.2 | Main model structures of factors and mechanisms driving OW/OB

Starting from the intrapersonal understanding of the factors driving OW/OB Rahmandad[50] and Hall et al.[62] simulated bodyweight development as energy balance and growth in all ages and childhood, respectively. These simulation models do not further specify individual dietary behaviors or physical activity. Meisel et al.[48,49] simulate transfer rates between BMI categories by age group in an urban Colombian population. The first version of the simulation model includes processed food and sugary drinks, leisure time PA, transport PA, and screen time,[48] whereas the second version of the simulation model omits the behaviors, but addresses differences by socio-economic status (SES).[49] Dietary behavioral factors contributing to obesity have been represented through the contribution of portion size and meal frequency on weight and obesity of British children,[53,54] and soda consumption on adolescent population level OW/OB in Nebraska.[61] Frerichs' simulation model addresses social transmissions of OW/OB between adults and child and child to child without explicitly including dietary or physical activity (PA) behaviors.[46]

Four etiological simulation models cut across multiple levels of the ecological model. Lan et al.[59] simulate the influence of intrapersonal level factors (perceptions of health and self-body image) and interpersonal factors (diet associated parenting behaviors and peer ridiculing due to body shape) and organizational factors (school nutrition education) on amounts of PA and high-caloric diet intake with population level OW/OB as the outcome. SES of the parents is included in the simulation model. Carrete's simulation model addresses how factors at the micro, meso, exo, and macro levels of the ecological model can explain population level OW/OB of urban Mexican children, but does not specify any dietary or PA behaviors.[60] The simulation model by Roberts et al.[47] includes physical food (access, price, and marketing) and PA environment, interpersonal factors (parenting, weight-related bullying, and social norms), and intrapersonal factors (mental health and screen time) as influences on healthy food choice and physical activity leading to healthy weight and to OW/OB on the population level. The simulation model by Struben et al.[51] primarily represents the macro level factors of food supply and governmental policy in relation to food demand and food attributes (price, taste, availability, and nutritional quality) in regards to energy balance leading to change in body mass index (BMI) disaggregated by age and gender.

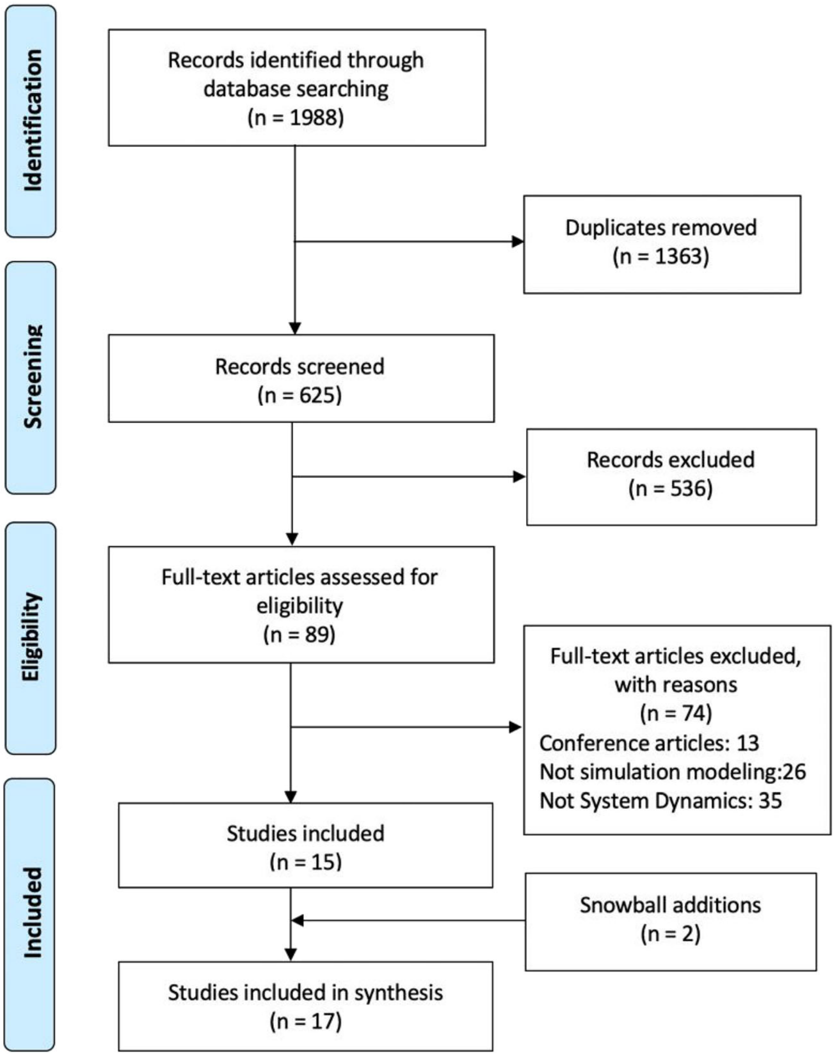

FIGURE 1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram of identification and selection of studies for the systematic review on of system dynamics simulation models of childhood overweight/obesity.

Table 1 furthermore shows that there is a large variety in key model variables (stocks and types of variables) included in the simulation models depending on the aim and main outcomes of the simulation models. However, only six of the studies specified any of the feedback loops underpinning their simulation model.[46,51,53,54,56,59]

3.3 | Intervention testing and leverage points for OW/OB prevention

At the intrapersonal behavioral level, the simulation model on portion size and meal frequency was used to test whether the British target set for childhood OW/OB by 2020 could be reached.[53,54] They concluded that it could only be reached by 2026, but did not specify the interventions which could change the portion size and meal frequency. The simulation model on social transmission of OW/OB analyzed the effect on social transmissions of all combinations ($n = 15$) of prevention and treatment interventions targeting adults or children.[46] They found that combinations of prevention and treatment generally had greater impact than either alone, and that intervention combinations that focus more on adults may result in greater reductions in childhood obesity than those that target children only if adult interventions have higher residual impact on children. However, the preventive and treatment interventions were not further specified.

Safan et al.[57] simulated the effect of peer influence and different types of nutrition education in school on the proportion of healthy eaters, taking the problem of recidivism into account. They found that positive peer influence and food association learning can significantly modify the culture of eaters and thus promote healthier eating behaviors among children. Powell et al.[56] simulated the effect of 15 interventions on obesity prevalence rates in the state of Georgia, USA. These interventions were mainly on increasing physical activity in the school and after-school program setting and safety of active transport to and from school but also some on providing healthy foods in these settings, reimbursement for nutrition counseling for children with OW/OB and even increased prevalence of breastfeeding. Mandating daily physical education at school and integrating moderate to vigorous physical activity into elementary school classrooms had the largest projected impact on the prevalence of childhood obesity with reduction to 12 and 10%, respectively. Meisel et al.[49] used their

TABLE 1 Description of the included studies for the systematic review on of system dynamics simulation models of childhood overweight/obesity.

Reference, year and country	Study aims	Target population groups	Model outcome	Model type	Key model variables (stocks/ parameters/equations)
54 Abidin et al. 2014 UK	To simulate the effects of changes in eating behavior of British children (2–15 years) on weight and obesity; and identify how long will it take to remove obesity as a public health concern by 2020, using system dynamics optimization.	British child population by gender and three age bands (2–4 years, 5–10 years, and 11–15 years)	Average weight (AW), average body mass index (ABMI), and the prevalence of obesity (POB)	Etiology Intervention testing	Key stocks: Average of fat portion size from outside meal, average weight, average height, and prevalence of obesity. Key elements: .- Fractional rate of portion size outside home .- Fractional rate of number of meals consumed .- Food intake and food expenditure. .- Physical measurement. .- BMI impact
53 Abidin et al. 2014 UK	To compare and determine the effective strategy for obesity prevention by improving the consumption of portion size and meal frequency.	Child population aged between 2 to 15 years old.	Body weight and BMI.	Etiology Intervention testing	Key stocks: Prevalence of obesity, Average weight, average height. Key elements: .- Average number of meals consumed from outside per day .- Energy intake from outside per day .- Average energy expenditure
60 Carrete et al. 2017 Mexico	To contribute to the understanding of how elements of the socioecological system shape individual behaviors by analyzing overweight and obesity from a sociological perspective that takes into account the influence of relevant social factors regarding the development of healthy behavior patterns of urban Mexican children.	Elementary school students from 9 to 12 years old	Overweight and obesity prevalence	Etiology intervention testing	Key stocks: Macro level influenced by: .- National policies .- Culture Exo level influenced by: .- Local policies .- Availability of recreational activities. .- Availability of junk food. Meso level influenced by the following: .- School intervention .- Social influence Micro level influenced by: .- Family habits and economy .- Friends influence
46 Frerichs et al. 2013 USA	(1) to assess the sensitivity of childhood overweight and obesity prevalence to peer and adult social transmission rates, and (2) to test the effect of combinations of prevention and treatment interventions on the prevalence of childhood overweight and obesity.	Children and adults by age groups in the United States	Overweight and obesity prevalence (BMI and percentile guidelines) among children	Etiology Intervention testing	Key stocks: Health status related to weight (i.e., normal weight, overweight, and obese adults and similarly normal weight, overweight, and obese children). Key elements: .- Likelihood of adult to adult social transmission of overweight and obesity

(Continues)

TABLE 1 (Continued)

Reference, year and country	Study aims	Target population groups	Model outcome	Model type	Key model variables (stocks/parameters/equations)
					.- Likelihood of child to child social transmission of overweight and obesity .- Likelihood of adult to child social transmission of overweight and obesity .- Prevention intervention impact on adult and child overweight and obesity .- Treatment intervention impact on adult and child overweight and obesity
62 Hall et al 2013 USA	Developed a model of childhood energy balance and bodyweight dynamics that accounts for healthy growth and development of obesity and makes quantitative predictions about weight management interventions.	Children and adolescents (5–18 years)	Bodyweight dynamics and obesity development	Etiology	Key elements: .- Energy intake and expenditure .- Fat-free mass .- Body fat mass .- Excess of body weight .- Excess of energy intake
52 Kuo et al. 2016 USA	To address the range and health impacts of obesity prevention strategies in local communities in Los Angeles County (LAC) for three program focus areas.	Adults and youth by sex and age group (18–29, 30–64, >65)	Obesity prevalence	Intervention testing	Key stocks: Youth population, non-CVD adult population, post-CVD adult population. Non obese youth, obese youth, non-obese non-CVD adults, obese non CVD adults, non-obese post CVD adults, obese post CVD adults.
59 Lan et al. 2015 (no place specified)	To investigate the factors affecting elementary school students' BMI values.	Elementary school students	BMI values	Etiology	Key stocks: Students' concept of health, Obesity levels and nutrition education. Key elements: .- Educational attainment and socioeconomic status of parents .- Amounts of students' physical activity .- Students' high- calorie diets .- Effectiveness of the implementation of school nutrition education.
61 Liew, 2018 USA	To project the prevalence of soda consumption and obesity given the declining trends in soda consumption and permission to	Students between 15 to 19 years old	Change in soda consumption and obesity in adolescents	Etiology	Key stocks: Soda consumers, schools permitting the sales of soda pop or fruit drinks and number of adolescents with obesity.

TABLE 1 (Continued)

Reference, year and country	Study aims	Target population groups	Model outcome	Model type	Key model variables (stocks/ parameters/equations)
	purchase soda pop or fruit drinks, as well as the expected percentages increase in people between ages 15 to 19 and students in grades 9–12 with obesity.				Key elements: .- Percentage decline in regular consumers .- Percentage decline in schools that permit soda sales .- Percentage increase in the number of people between ages 15 to 19 .- Adolescent population growth
55 Liu et al. 2016 USA	To inform policymakers' understanding of how allocating revenue collected by SSB taxation across sustainable implementation strategies might maximize benefits of such taxation for childhood obesity prevention.	2–19 age kids (boys) & adolescent population	Total weight reduced due to reduced SSB consumption	Intervention testing	Key stocks: Revenue from Excise tax, Budget for building healthy environment, realized demand, Budget allocated for building park, Net added park land areas, Budget allocated for subsidizing kids and adolescent, realized energy intake from SSB in boy group, Cumulative reduced energy intake with SSB reduction for boys, Energy expenditure due to increased physical activity for boys. Key elements: .- Changes in perceived demand. .- Increment in price due to tax. .- Annual per capita SSB consumption. .- Money allocated for interventions.
48 Meisel et al. 2016 Colombia	To capture the transitions of the population by BMI categories within the Colombian urban population.	Colombia population by age groups, gender and BMI categories (not overweight, overweight and obese)	Prevalence of obesity, Transference rates between BMI categories by age group	Etiology	Not overweight, overweight, and obese. Not overweight, overweight and obese who met LTPA, PFSD, ST, and TPA
49 Meisel et al. 2018 Colombia	To investigate the nutritional stage dynamics within the urban population of Colombia using a System Dynamics model. A model was proposed and can be used: (1) to estimate the transference rates (TRs) between BMI categories by age and SES, (2) to identify the population subgroups toward which intervention efforts should be targeted, and (3) to monitor the potential effect of public health	Colombian urban population by age groups (0–59 years), BMI categories (not overweight, overweight, and obese) and Socio-Economic Status (SES)	Prevalence of obesity, Transference rates between BMI categories by age group	Etiology Intervention testing	Key stocks: weight status categories by age and socioeconomic status (SES) Key elements: .- Prevalence rates by age, body mass index (BMI) and socioeconomic status (SES). .- Mortality rates by age group .-Population size by age group .- Births fraction by BMI category and SES .- Fertility rates

(Continues)

TABLE 1 (Continued)

Reference, year and country	Study aims	Target population groups	Model outcome	Model type	Key model variables (stocks/ parameters/equations)
	policy interventions aimed at preventing overweight and obesity across age and SES categories.				
56 Powell et al. 2017 USA	Simulated the potential impact of a given policy intervention or combination of policy interventions on the prevalence of obesity in childhood in Georgia through 2034.	Georgia children and adolescents (up to 18 years)	Obesity prevalence (specifically, BMI for age percentiles)	Intervention testing	Not specified
50 Rahmandad 2014 USA	Replicates key trends in human growth including (A) Changes in energy requirements from birth to old ages. (B) Short and long-term dynamics of body weight and composition. (C) Stunted growth with chronic malnutrition and potential for catch up growth	Population sub-groups: Gender, age (infants, children, and adults) and race.	Growth, body weight (BMI) and composition	Etiology	Keys stocks: Body weight partitioned in Fat Mass (FM), Fat Free Mass (FFM) and Height (H). Key elements: Energy Intake, Total Energy expenditure. Resting energy expenditure
47 Roberts et al. 2018 Australia	The aim of the study is to support the Australian Government and stakeholders responsible to achieve a target to reduce the population prevalence of childhood overweight and obesity by 5% over 10 years. A system dynamics model was developed to address the question of what combination of high-level strategies is likely to be needed to meeting the target.	Children between 0 and 17 years of age	The proportion of overweight and obese children aged 5 to 16 living in NSW from 2016 to 2025, overall and stratified by age	Etiology intervention testing	Key stocks: Overweight/obesity percentage by age, energy balance (intake and expenditure). Key elements: .- Impact of healthy food index on replacement energy consumption .- Base activity factor .- Impact of excess energy on transfer rates .- LT weight loss .- Impact of program delivery on engagement .- Parental influence .- Impact of active transport on activity .- Impact of healthy lifestyle on activity .- Impact of OW/OB on activity .- Impact of accessibility on activity .- Impact of walkability on activity .- Impact of technology on workforce productivity .- Effectiveness of TV advertising .- Reduction in sedentary behavior .- Consumption of SSB percentage

TABLE 1 (Continued)

Reference, year and country	Study aims	Target population groups	Model outcome	Model type	Key model variables (stocks/parameters/equations)
57 Safan et al. 2018 USA	To evaluate the role of socialization and school environments on the diet dynamics in children's schools settings.	Different population groups including children.	Population cohorts divided by "Moderately" healthy eaters, "Less" healthy eaters and "Healthy" eaters	Intervention testing	Key stocks: Moderately, Less and Healthy individuals. Key elements: .- Peer influence rate .- Recidivism rate .- Efficacy of nutrition education program .- Susceptibility to shift from M to L and from M to L. .- Per capita entry/removal rate .- Efficacy of food association program
58 Shahid & Bertazzon 2015 Canada	Used local spatial analysis to assess the relationship of childhood obesity and overweight with their risk factors at the neighborhood level, and simulation modeling to simulate localized interventions, particularly neighborhood walkability, aimed at reducing childhood obesity and to estimate their potential impact over time.	Children (4.5–6 years old)	Number of obese, overweight, and healthy weight children in per 1,000 children	intervention testing	Key stocks: healthy-weight, overweight and obese children. Key elements: .- Proximity to fast food outlets .- Proximity to parks .- Walkability (Walkscore) .- Neighborhood pathway length .- Median income .- Immigrants .- Education
51 Struben et al. 2014 Canada	To analyze how supply, demand, and governmental policy endogenously evolve and collectively influence population health and shape the nutritional quality of consumed food portfolios.	Canadian population, calibrated to nationally-representative data (Segmented by age and gender)	BMI	Etiology Intervention testing	Key stocks: propensity to consider a category, energy stored, population, attribute-related capabilities, serving size. Key elements: food demand, food supply, population health (BMI, caloric intake and market share) and government policy; Disaggregation of age and gender, firm type, food attributes (price, taste, availability, and nutritional quality).

TABLE 1 (Continued)

Reference, year and country	Feedback loops	Simulations, scenarios and/or intervention (s) modeled	Simulation time	Empirical data used	Validation tests conducted	Leverage points
54 Abidin et al. 2014 UK	Three reinforcing loops RL1, RL1, and RL1 (food consumption loop) and	Reversion values of Average Weight, BMI reduction and POB measurement	1970–2030	Health survey for England (HSE) and other published	Structure tests and behavior reproduction	Modifying parameters

(Continues)

TABLE 1 (Continued)

Reference, year and country	Feedback loops	Simulations, scenarios and/or intervention (s) modeled	Simulation time	Empirical data used	Validation tests conducted	Leverage points
	one balancing loop BL (energy balance loop)	using an optimization process: • Phase 1 (1970–2012): represents the past and present situations that lead to obesity. • Phase 2: refers to the capability of the ICOD model to reverse the future of AW, ABMI, and POB trends through change in fat portion size of outside meal and total number of meals		sources from a literature review		
53 Abidin et al. 2014 UK	Three reinforcing loops RL1, RL1, and RL1 and one balancing loop (energy balance loop)	Compared simulation runs: Base run: without policy change Strategy 1: the effect of reducing portion size for an outside meal parameter (50% reduction), on Average weight and Average BMI. Strategy 2: the effect of reducing the frequency of meals parameter (50% reduction), on Average weight and Average BMI.	1970–2030	Health survey for England (HSE) and other published sources	Parameter and structure verification. Behavior reproduction	Modifying parameters
60 Carrete et al. 2017 Mexico	Not specified	The effects that the major elements of each subsystem of the socioecological framework, have on childhood overweight Scenarios included the following: 1. Reliance on macro- and exo-policies (governmental policies) 2. full commitment from the families	2000–2050	Interviews with students and parameters from existing literature	Not stated by the authors	Modifying parameters

TABLE 1 (Continued)

Reference, year and country	Feedback loops	Simulations, scenarios and/or intervention (s) modeled	Simulation time	Empirical data used	Validation tests conducted	Leverage points
		3. alignment of both scenarios where governmental policies increases commitment from the families				
46 Frerichs et al. 2013 USA	There are two reinforcing loops seen in both the adult and child populations: (1) a loop between the increase in overweight and obesity that leads to a rise in the likelihood of social transmission and (2) a loop from the increase in overweight and obesity that leads to a decrease in normal weight population, which leads to a subsequent increase in the likelihood of maintained social transmission.	The impact of varying model parameters of social transmission and weight loss behavior rates to test the effect of combinations of behavioral and treatment interventions. The model includes an explicit intervention impact parameter (apart from adult-to-child and child-to-child social transmission) to capture the potential to actively engage targeted individuals to model and encourage healthy behaviors among the other age group at varying degrees.	10 years	NHANES (2009–2010) and US surveillance system data and research literature	Behavior reproduction, sensitivity analysis	Modifying parameters
62 Hall et al 2013 USA	Not specified	Sex-specific growth was modeled as the combination of increasing energy intake with time and an age dependent function representing the net effect of various complex physiological processes that stimulate accretion of fat-free mass while obeying both energy balance and macronutrient balance.	20 years	Data from existing literature	Behavior reproduction mathematical validation	Modifying parameters
52 Kuo et al. 2016 USA	Not specified	Implemented strategies for three focus areas: physical	50 years	NHANES (1988–1994 to 1999 to 2004)	Behavior reproduction and sensitivity analysis	

(Continues)

TABLE 1 (Continued)

Reference, year and country	Feedback loops	Simulations, scenarios and/or intervention (s) modeled	Simulation time	Empirical data used	Validation tests conducted	Leverage points
		activity-promotion, health marketing, and creation of healthy food environments.				Model not transparent enough to characterize interventions
59 Lan et al. 2015 (no place specified)	.- R1: Diet-associated parenting behaviors and students' BMI values. .- R2: Students' perception of self-body image and BMI values. .- R3: Effectiveness of the implementation of school nutrition education and students' concepts of health. .- R4: Students' experience of being ridiculed due to their body shapes and high calorie diets.	Influence of students' concepts of health on obesity, the influence of the educational attainment and socioeconomic status of parents on the amount of physical activity of student; the influence of the implementation of school nutrition education on students' high calorie diets	48 months	Not specified	Behavior reproduction	Modifying parameters and structures
61 Liew, 2018 USA	Not specified	Soda consumption, school permission to sell soft drinks percentage of obesity increase in students in grades 9–12	20 years	Youth Risk Behavior Surveillance System (YRBSS) and Census data 2015.	Not stated by the authors	Modifying parameters
55 Liu et al. 2016 USA	Not specified	The model captures the implementation of three interventions: (a) levying an excise tax on SSBs; (b) allotting SSB tax revenue to construct safer outdoor activity spaces; and (c) allocating SSB tax revenue to subsidize an underserved population composed primarily of children and adolescents with vegetables and fruits (VF) at school.	20 years	Data from existing literature	Integration error, behavior reproduction and sensitivity analysis	Modifying parameters
	Not specified	(1) The TR from overweight to not	2005–2030	National Survey ENDS, Profamilia (2005, 2010)	Not stated by the authors	Modifying parameters

TABLE 1 (Continued)

Reference, year and country	Feedback loops	Simulations, scenarios and/or intervention (s) modeled	Simulation time	Empirical data used	Validation tests conducted	Leverage points
48 Meisel et al. 2016 Colombia		overweight is increased from 2011 to 2030; (2) The TR from obese to overweight is increased from 2011 to 2030; and (3) the TRs from obese to overweight and from overweight to not Overweight, are changed to a value. of 0.01 from 2011 to 2030.				
49 Meisel et al. 2018 Colombia	Not specified	Testing scenarios where policy actions regarding to the new public health law fully implemented through PA promotion and healthy nutritional initiatives. 1.- Increasing transition rate obese to overweight and from overweight to not overweight category for population age 5 to 14 years. 2.- Increasing transition rate obese to overweight and from overweight to not overweight category for population age 15 to 24 years.	2005–2030	National Survey ENDS (2005–2010), Colombian National Department of Statistics (DANE) and World Data Bank.	Integration error, parameter assessment, extreme conditions, behavior reproduction and sensitivity analysis	Modifying parameters
56 Powell et al. 2017 USA	feedback loops (demonstrate how outputs from one policy (e.g., improved behavior due to classroom physical activity) may influence or feed back into the classroom physical activity policy level)	1.- No policy change. 2.- Individual and combination of 15 interventions Interventions on physical education ($n = 3$), in class activities ($n = 1$), recess activity ($n = 3$), After-school programs -Provide after-school programs for all children -Require existing after-school programs to include	20 years	Population data from US Census Bureau, BMI data for children in Georgia from K-12	Not stated by the authors	Modifying parameters and structures

(Continues)

TABLE 1 (Continued)

Reference, year and country	Feedback loops	Simulations, scenarios and/or intervention (s) modeled	Simulation time	Empirical data used	Validation tests conducted	Leverage points
		a physical activity component -Provide after-school programs for all who want to participate and require all programs to have a physical activity component -Require existing preschool programs to provide quality physical activity and nutrition components -Increase proportion of students who can safely walk or bike to school - Require all food served in school cafeteria lines to meet the USDA School Nutrition Guidelines -Provide Medicaid reimbursement for medical nutrition therapy counseling for overweight and obese children -Increase the prevalence of "any breastfeeding at 6 months" to 60.6%, a Healthy People 2020 objective				
50 Rahmandad 2014 USA	Not specified	the model replicates key trends in human growth including (A) Changes in energy requirements from birth to old ages. (B) Short and long-term dynamics of body weight and composition. (C) Stunted growth with chronic malnutrition and potential for catch up growth	0–12 Months (Infant) 0–20 Years (Child) 17–80 Years (Adult)	Centers for Disease Control and Prevention (CDC) and NHANES (1999–2008)	Extreme conditions, parameter assessment, integration error, and behavior reproduction	Modifying parameters

TABLE 1 (Continued)

Reference, year and country	Feedback loops	Simulations, scenarios and/or intervention (s) modeled	Simulation time	Empirical data used	Validation tests conducted	Leverage points
47 Roberts et al. 2018 Australia	not specified	Interventions modeled: 1. Increased healthy food choices in Government settings (2) Settings-based, state-wide primary prevention programs	2010–2030	Australian Bureau of Statistics, NSW Health administrative datasets (HealthStats NSW) and NSW Department of Planning and Environment population projections	Sensitivity analysis and behavior reproduction	Modifying parameters
57 Safan et al. 2018 USA	Not specified	Evaluation of four models in order to evaluate different combinations of changes in social interactions and school environments in response to the implementation of different school nutrition education programs and policies targeting different levels of the socio ecological framework.	Not stated	Data from existing literature	Not stated by the authors	Modifying structure and parameters
58 Shahid & Bertazzon 2015 Canada	Not specified	Simulations: Scenario: "base" (no intervention); Scenario: "Walkscore10" (10 point increase); and Scenario: "Walkscore20" (20 point increase)	2009–2015	Primary Health Activity Network Timely Information Management (PHANTIM), 2005 to 2008 Statistics Canada Census (2006)	Not stated by the authors	Modifying parameters
51 Struben et al. 2014 Canada	Major feedback loops diagram (Figure 2) .- Social Exposure R1 .- Learning and R&D R2a .- Industry marketing R2b .- Market Return R3a .- Capability productivity R3b .- Saturation B3a B3b	1. Projections based on 2010 cal consumption. 2. Industry initiatives. 3. Governmental initiatives. 4. Collective initiatives for market and government stimuli of nutritious food product innovation.	2010–2050	Data from existing literature	Behavior reproduction, sensitivity analyses	Modifying parameters

simulation model which took SES into account to simulate the effect of a law that stipulates that schools should have a healthy food program and promote PA. This decreased the OW/OB prevalence compared with the model-generated prevalence without this intervention. Shahid & Bertazzon[58] simulated the effect on weight status distribution of walkability interventions in neighborhoods in Calgary. The simulated intervention yielded a modest but measurable reduction in the number of obese children over a short time period, but also revealed other potential risk factors once the walkability was improved.

Struben et al.[51] simulated a whole range of policies (single and combinations) such as industry self-regulation and health- and nutrition-sensitive governmental policy and also explored policies on innovation. Results showed how single-pronged initiatives, whether designed and deployed under governmental or private sector leadership, are ineffective, failure-prone, and costly. Liu et al.[55] simulated how allocating revenue collected by sugar-sweetened beverage (SSB) taxation across sustainable implementation strategies might maximize benefits of such taxation for childhood obesity prevention. Kuo et al.[52] used the PRISM simulation model[63] to analyze intervention strategies for three focus areas: PA-promotion, health marketing, and creation of healthy food environments within Los Angeles County, USA. The intervention strategies were aimed at reducing the number of youth with obesity, youth below levels of recommended PA, and youth with excess junk food consumption. The joint effect of sustained strategies until 2040 was found to reduce the numbers of adolescents in these three outcome categories. Carrete et al.[60] simulated three scenarios; policies at the macro and exo levels of the ecological model taking into consideration policy resistance due to lack of involvement, and interventions engaging families at the micro level, as well as a combination of these. The first two scenarios gave an increase in number of children with OW/OB, but the latter was less severe. The final scenario assuming synergies between the two first ones, gave a significant decrease in OW/OB over 25 years. Roberts et al.[47] simulated nine different interventions that primarily changed environmental factors such as availability of healthy foods in governmental settings, price of food, advertisements for food and settings based primary prevention programs, but also intrapersonal factors through social marketing campaigns and targeted interventions toward the pre- and post-natal phase and through clinical services in New South Wales, Australia. These interventions were simulated in four scenarios; business as usual, enhanced business as usual (higher reach and adoption), enhanced business as usual with built environment and finally adding also advertisement restrictions and food price policies so all policies were included. Only the final scenario was able to reach the target of 5% reduction in childhood OW/OB by the end of 2025/early 2026.

Simulation models used diverse time horizons ranging from 48 months to 50 years (Table 1). Most of the included studies used empirical data from governmental sources to build and/or validate their simulation models. The majority of the models (70%) were parameterized so that the error of the models' behavior with respect to the reference mode was minimized.[64]

Analysis of the leverage points revealed that apart from the simulation model by Kuo et al.,[52] which was not transparent enough to characterize the interventions, the remaining 16 all accommodated leverage points at the lowest level of parameter change. Lan et al.,[59] Safan et al.,[57] and Powel et al.[56] in addition included leverage points at the medium level of structural changes by representing the introduction of school nutrition education or mandating school physical education and integrating physical activity in classrooms.

3.4 | Model validity assessment in the studies

The average assessment score of the 17 simulation models in our review (Table 2) was 12, and only four (23%) satisfied 90% or more of the maximum score (≥16).

Eight studies had an explicit description of model structure, model output, conceptual boundary, temporal boundary, level of aggregation, sources of parameter values, initial values, decisions involving calculations, exogenous variables considered, data sources, and overall rationale.[46,47,50–52,55,57,62] Ten model structures were causal-descriptive, built as to how the real system operates, and explained how the behavior is generated or changed.[46–52,55,57,58,62] Four studies provided a thorough description and explanation of the model validation procedure they carried out to build confidence in the model including tests performed, explanations of each test and graphical representation of tests.[47,49,55,62] The most common validation tests performed by the authors were structure test, parameter test, extreme conditions test, sensitivity analysis, and behavior reproduction.

Seven studies fully documented their models, providing a detailed description of the computational operations the model is designed to perform allowing an independent party to implement and simulate the model[47,49–52,55,62] (e.g., equations and algorithmic rules, all model parameters, units, and initial values are fully reported, data sources, and code). Five (29%) of 17 models did not document their model.

Regarding model visualization, eight studies included comprehensive model representations such as causal loop diagrams and stock and flow diagrams which were shown to facilitate model reproducibility.[46–48,51–53,55,58]

4 | DISCUSSION

This review describes the structures and mechanisms of existing SD simulation models on childhood OW/OB and the interventions/policies tested with these models. We found that a large variety of drivers of obesity from the intrapersonal to the public policy level of the ecological model were included in the etiological models of structures and mechanisms, and that this was taken advantage of in the simulation models by testing a large variety of policies and interventions particularly at the public policy level or cutting across levels. Calls for applications of SD to public health generally and obesity prevention in particular are numerous.[26,65,66] However, the modeling process can be expensive and time consuming, particularly when involving stakeholders or trying to enact policy change.[67] The review highlighted areas for improvement in taking full advantage of the SD perspective in obesity prevention. Many of the

TABLE 2 Model validity assessment scores of system dynamics simulation models of childhood overweight/obesity.

Criteria Included articles	Description of model assumptions	Explanation of how the model structure is consistent with relevant descriptive knowledge of the system	Description of the process used to test and build confidence in the model	Explanation of how model results can be reproduced	Model documentation	Model visualization	Total score
54 Abidin et al., 2014a	2	2	2	1	1	3	**11**
53 Abidin et al., 2014b	1	2	2	1	0	2	**8**
60 Carrete et al., 2017	1	2	0	1	0	2	**6**
46 Frerichs et al., 2013	3	3	1	2	2	3	**14**
47 Roberts et al., 2018	3	3	3	3	3	3	**18**
59 Lan et al., 2014	1	1	0	0	0	2	**4**
61 Liew, 2018	2	1	0	0	0	1	**4**
49 Meisel et al., 2018	2	3	3	3	3	0	**14**
48 Meisel et al., 2016	2	3	0	2	2	3	**12**
55 Liu et al., 2016	3	3	3	3	3	3	**18**
56 Powell et al., 2017	1	2	0	0	0	0	**3**
50 Rahmandad, 2014	3	3	2	3	3	0	**14**
57 Safan et al., 2018	3	3	0	3	2	1	**12**
58 Shahid and Bertazzon, 2015	2	2	1	2	1	3	**11**
51 Struben et al., 2014	3	3	2	3	3	3	**17**
62 Hall et al., 2013	3	3	3	3	3	0	**15**
52 Kuo et al., 2016	3	3	1	3	3	3	**16**

simulation models did not document key feedback loops driving the system's behavior and only tested leverage points at the lowest level of changing parameters, and thus, the full potential of examining interactions between multiple levels of the ecological model is still underutilized. Moreover, the quality assessment revealed that less than 25% of the reviewed studies documented the models in sufficient detail to satisfy all model validity and transparency criteria. Given the costs involved in SD simulation modeling, it is crucial to consider how to take full advantage of the SD perspective of feedback driving behavior and clearly document insights generated from modeling.

Our review draws together potential generic structures of childhood obesity from SD simulation models to support further research to build models of childhood obesity to support prevention. Generic structures are parts of models that apply to multiple problems and settings, allowing models to be built more quickly off the basis of findings from previous models.[68] For qualitative SD models of obesity, Brennan et al.[69] identified common structures across models from 49 different communities, such as those related to health behaviors, food, and PA environments, but also social determinants and community capacity. At the core of most models was a structure to simulate the effect of energy balance on the OW/OB rates, but the focus of the models differed and our review thus contributes different structures which could be used to compile a comprehensive simulation model. The model by Roberts et al.[47] was the most comprehensive, clearly drawing on the epidemiological and behavioral understanding of drivers of obesity, but without becoming overly complicated like the FORESIGHT model.[8] It is also the simulation model most aligned with the qualitative model of Brennan et al.[69] but lacks their structures on social determinants and local capacity. Socio-demographic factors such as sex/gender, SES or race/ethnicity were only included in four of the simulation models,[49–51,59] which is in contrast with the importance placed on understanding and preventing social inequalities in public health.[2,3]

Twelve of the 17 studies tested interventions or policies which could reduce OW/OB among youth, and there were more simulation models targeting higher levels of the ecological model than just the intrapersonal or interpersonal level indicating exploitation of the advantage of SD modeling in addressing the gap of traditional public health interventions and their evaluations.[19,20] Struben et al.[51] and Liu et al.[55] take full advantage of the SD approach to explore macro level policies on regulation of the food supply chain and the potential of combing taxation on SSB with development of PA promoting environments. Kuo et al.[52] simulate a range of policies which have been implemented across different levels within a county and support the recommendations of implementing a comprehensive suite of policies in order to curb the obesity epidemic.[2,3] This is also supported by the need for combining all types of interventions to reach the OW/OB target in New South Wales by 2025 in the simulations by Roberts et al.[47] Finally, an important learning from the Carrete et al.[60] study is the need to align macro level policies with interventions that engage the parents at the micro level in order to harvest the potential synergies of such polices and overcome potential policy resistance in the population. Taken together, these five studies demonstrate the strengths of SD-modeling as a complimentary strategy to randomized controlled trials in exploring the potential effects of policies at the macro level or suites of policies across levels. However, there were very few simulation models addressing differences by gender[51] or SES.[49] Furthermore, the diverse policies explored need to be combined and implemented as comprehensive policy packages which requires capacity building in systems thinking also at the community level.[70]

This review showed clearly that current reporting of SD models is inadequate, specifically reporting did not meet validity and transparency criteria nor did the reviewed studies report basic SD conventions like feedback structures or assess leverage points. New guidelines for reporting of system studies have been proposed[71] that set minimum information across domains of development, implementation, and evaluation. Making such checklists an aspect of journal review, similar to those that exist for other study designs (e.g., Schulz et al.[72]) will advance quality, replicability, and comparability between studies.

While this review focused on SD models for childhood obesity in particular, other reviews considering obesity offer further evidence of the need to make fuller use of the SD perspective and to document models. The review on obesity models by Xue et al.[73] drew a similar conclusion to our review in that models were not documented well enough to allow for replication. Their review did not document feedback structures in the models, and while they summarized the conclusions of the articles, they did not consider these conclusions through the lens of leverage points as our review has. The review on obesity by Morshed et al.[74] put an emphasis on the feedback perspective in their description of SD models, and found similarly that relatively few papers document the feedback structures driving model behavior. Morshed et al.,[74] similar to our review, found that relatively few studies take full advantage of the opportunity to use SD to carefully examine causal effects that cut across multiple levels of the ecological model. Our review builds on previous reviews by summarizing which feedback loops are documented in the childhood obesity literature, which levels of the ecological model the studies cover, and which leverage points were addressed in the models.

4.1 | Strengths and limitations

To our knowledge, this is the first systematic review focusing on SD-based simulation studies on the relationships of determinants of and interventions addressing childhood obesity. This review used a systematic search across multiple databases and a review protocol with clear inclusion and exclusion criteria. The lack of new studies in the updated searches indicates the relevance of the review in order to build the knowledge foundation for future models. Assessment of the existing models against a framework of levels of intervention operationalized the use of intervention level frameworks for application to model-based studies in public health. As quality assessment guidelines for SD models are scarce, the authors developed a compiled checklist of validity assessment based on model documentation and testing principles developed by SD researchers and practitioners.[24,43,45] This checklist facilitated a structured process for assessing the quality and transparency of the models in the included studies.

The results of this review should nevertheless be assessed with some caution. In particular, we only included studies written in English and gray literature was not included. The screening and selection process was performed by only one person (AA). Additionally, it was difficult to give a validity score to the models because of the heterogeneity of these studies (i.e., model purpose, intervention type, level of aggregation, and the extent to which they uncovered feedback loops) and a considerable level of quality discrepancy was observed on model documentation and validation. In this regard, we advise a higher expectation regarding model validation and documentation practices for the SD models published in the public health domain.[75] This would enable researchers to replicate and adapt the models and enable future researchers to assess the confidence and usefulness of the models and suggest improvements or refinements.

4.2 | Implications and future research

While SD modeling appears to be used with increasing frequency in obesity prevention efforts, questions remain on how to make the best use of models and how to translate modeling processes into action or policy change.[67] Following qualitative conceptualization, projects may go multiple directions to identify leverage points or next steps. While there are standard recommendations for moving from qualitative modeling to a quantitative simulation model,[24] other approaches have emerged in response to the perceived complexity and cost of SD modeling. Some examples include using network analysis to understand collaborative relationships between actors,[76] tracking action over time,[77] or using simulation modeling as a learning tool to assist stakeholders in designing action.[70] While each of these approaches have their own unique strengths and weaknesses, they do not take full advantage of what simulation modeling has to offer.

This review draws attention to another option, drawing together possible generic structures that could assist in the modeling process and enhance understanding of leverage points to prevent childhood obesity. Future research could review qualitative models of obesity in the literature to identify common structures for simulation. Further research is also needed to understand how to best apply results from other modeling studies to new projects and how this can best facilitate action.

5 | CONCLUSION

The studies reviewed provide simulation-based tools to help identify potential major drivers of obesity, test different policies and interventions, determine resources needed for obesity prevention, and provide decision tools for policymakers. However, there is a need for better quality in documentation of the models, and further research on how to best combine generic structure from different models as well as taking full advantage of SD modeling for examining the interactions of drivers across multiple levels of the ecological model.

AUTHOR CONTRIBUTIONS

Anaely Aguiar, Birgit Kopainsky, Nanna Lien, and Mekdes K. Gebremariam conceptualized and designed the review. Anaely Aguiar developed the search strategy, conducted the search, and wrote up of the initial draft of the manuscript. Anaely Aguiar screened and selected the data, and Anaely Aguiar and Mekdes K. Gebremariam extracted the data. Anaely Aguiar, Furkan Önal, and Birgit Kopainsky conducted the model validity assessment. Anaely Aguiar, Mekdes K. Gebremariam, Eduard Romanenko, Furkan Önal, Birgit Kopainsky, and Nanna Lien analyzed and discussed the data. Anaely Aguiar, Mekdes K. Gebremariam, Birgit Kopainsky, Natalie Savona, Steven Allender, and Nanna Lien revised and edited the manuscript throughout its development. Nanna Lien, Steven Allender, and Andrew Brown contributed significantly to drafting the revised and final manuscript. All authors read and approved the final manuscript.

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CONFLICT OF INTEREST STATEMENT

No conflict of interest statement.

DATA AVAILABILITY STATEMENT

All data generated during the process of this systematic review are included as supporting information in this article.

ORCID

Anaely Aguiar https://orcid.org/0000-0002-2440-4785
Eduard Romanenko https://orcid.org/0000-0002-0776-1780
Natalie Savona https://orcid.org/0000-0002-3006-3681
Steven Allender https://orcid.org/0000-0002-4842-3294
Nanna Lien https://orcid.org/0000-0003-1486-4769

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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