

Modeling of Urban Food Systems
to Improve Food Security of Vulnerable Populations using System
Dynamics and Geospatial Information Systems

Reiner Braun

A Thesis

In the Department

Of

Building, Civil and Environmental Engineering

Presented in Partial Fulfillment of the Requirements

For the Degree of

Doctor of Philosophy (Building Engineering)

at Concordia University

Montréal, Québec, Canada

April 2026

© Reiner Braun, 2026

CONCORDIA UNIVERSITY
SCHOOL OF GRADUATE STUDIES

This is to certify that the thesis prepared

By: **Reiner Braun**

Entitled: **Modeling of Urban Food Systems to Improve Food Security of Vulnerable Populations using System Dynamics and Geospatial Information Systems**

and submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY (Building Engineering)

complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the final examining committee:

_____	Chair
Dr. Carol Fung	
_____	External Examiner
Dr. Molly D. Anderson	
_____	Arms-Length Examiner
Dr. Shannon Lloyd	
_____	Examiner
Dr. Fuzan Nasiri	
_____	Examiner
Dr. Mazdak Nik-Bakht	
_____	Thesis Supervisor
Dr. Ursula Eicker	
_____	Thesis Co-Supervisor
Dr. Dieter Hertweck	

Approved by _____

Dr. C. An, Graduate Program Director

04-01-2026 _____

Dr. Mourad Debbabi, Dean of Gina Cody School of Engineering and Computer Science

Abstract

Modeling of Urban Food Systems to Improve Food Security of Vulnerable Populations using System Dynamics and Geospatial Information Systems

Reiner Braun, Ph.D.

Concordia University, 2026

Urban food insecurity persists despite the growing availability of food in cities, disproportionately affecting vulnerable populations with limited access to healthy, plant-based diets. This thesis presents a Decision Support System (DSS) and a Spatial System Dynamics (SSD) model designed to evaluate food insecurity in urban food systems and to support spatially differentiated policy interventions.

The research integrates geospatial analysis with system dynamics simulation to investigate (i) the role of urban food production in shaping food insecurity, (ii) the spatial distribution of food availability and accessibility, and (iii) the dynamic impacts of policy measures targeting food security. The Design Science Research Methodology (DSRM) structures the development of innovative IT artifacts for urban and regional decision-makers.

The resulting artifacts comprise a high-level Causal Loop Diagram capturing reinforcing and balancing mechanisms of food insecurity, stock-and-flow subsystems modeling accessibility, household finances, and household circumstances, and a microservices-based DSS that couples system dynamics with GIS through a shared database. Documented data workflows ensure transparency and reproducibility.

The model is applied to the urban agglomeration of Montréal. Baseline results estimate household food insecurity (HFI) at 12.8%, closely aligning with published values for Québec. Scenario and extreme-condition analyses establish plausible bounds for the system and reveal pronounced spatial heterogeneity across boroughs. Results demonstrate that uniform policy interventions yield non-uniform effects, with some areas experiencing substantial improvements while others show limited or adverse responses. The thesis underscores the analytical and decision-making value of integrating system dynamics with spatial data for urban food policy assessment.

Acknowledgments

I would like to express my sincere gratitude to my supervisor, **Prof. Dr. Ursula Eicker**, for her invaluable guidance, expertise, and continuous support throughout the course of this doctoral research. Her insightful feedback, encouragement, and academic leadership were essential to the development and completion of this thesis.

I am equally grateful to my co-supervisor, **Prof. Dr. Dieter Hertweck**, for his constructive advice, thoughtful perspectives, and support, which significantly enriched this work.

I would also like to thank the members of my doctoral committee **Prof. Dr. Fuzhan Nasiri**, **Prof. Dr. Mazdak Nik-Bakht** and **Prof. Dr. Shannon Lloyd** for their careful review of my research and for their valuable comments and suggestions, which helped strengthen both the theoretical and practical contributions of this thesis.

I would like to express my sincere appreciation to **Dr. Anant Jani**, whose insights and guidance were instrumental in shaping my understanding of the importance of the topic of food security for vulnerable populations. His perspective and encouragement played a key role in motivating the focus of this research.

My sincere appreciation goes to my external examiner, **Prof. Dr. Molly Anderson**, for her time, expertise, and insightful evaluation of this work.

I gratefully acknowledge the **Canada Excellence Research Chair (CERC) in Smart, Sustainable and Resilient Communities and Cities** at **Concordia University** for providing an intellectually stimulating research environment, institutional support, and opportunities for interdisciplinary collaboration. I am thankful to all members of the CERC team for their collegiality, discussions, and shared commitment to impactful research.

Finally, I would like to thank my sister, **Brigitte Braun**, for her unwavering encouragement, understanding, and support throughout this academic journey. Her insightful feedback and thoughtful discussions during the modeling process provided valuable perspectives that helped improve this research.

Dedication

This thesis is dedicated to my parents and my sister, for their unconditional love, constant encouragement, and belief in me throughout this journey.

Table of Contents

List of Figures.....	ix
List of Tables	xi
List Abbreviations.....	xiii
Chapter 1. Introduction.....	14
1.1 Problem statement: Land use, urbanization, and efficiency in food production.....	18
1.2 Research questions, objectives, and outputs	21
1.3 Approach	22
1.4 Motivation and Applications	26
1.5 Thesis Structure.....	26
Chapter 2. Literature Review	28
2.1 Search strategy and record selection	28
2.2 Literature analyzed related to the objectives.....	29
2.2.1 Literature addressing decision support systems.....	29
2.2.2 Literature addressing technologies for urban food production	33
2.2.3 Literature addressing food demand and local food supply chains	41
2.2.4 Literature addressing spatial system dynamics	43
Chapter 3. Methodology	45
3.1 Methodological approach and research design.....	45
3.2 System dynamics as modeling method.....	48
3.3 High-level conceptual model.....	52
3.3.1 Public transport – balancing loop (B1)	54
3.3.2 Income and food budget – Balancing loop (B2)	56
3.3.3 Household food insecurity – Balancing loop (B3).....	58
3.3.4 Urban food production – Reinforcing loop (R1).....	60
3.3.5 Supermarkets and healthy food stores – Reinforcing loop (R2)	62
3.4 Converting the conceptual model into a simulation model (Stock and Flow Model).....	64
3.4.1 Subsystem geographical accessibility	64
3.4.2 Subsystem household finances	69
3.4.3 Subsystem household circumstances	71
Chapter 4. Decision Support System Framework.....	74
4.1 Theoretical and methodological foundations	75
4.1.1 Design Science Research Methodology (DSRM).....	75
4.1.2 Coupling strategies: Advantages and disadvantages.....	77
4.1.3 Standards and interoperability	80

4.2	System architecture and technical design.....	86
4.2.1	Principles of microservices	89
4.2.2	Infrastructure.....	90
4.3	Component Interactions.....	92
4.3.1	Data ingestion and preparation	93
4.3.2	Integration of simulation models workflow.....	94
4.4	Pipeline for creating XMILE models.....	94
4.5	Advantages and challenges	97
4.5.1	Advantages	97
4.5.2	Challenges.....	98
Chapter 5.	Primary and Secondary Data	99
5.1	Data Flow Diagram for data integration into DSS	100
5.2	Detailed Description of Key Datasets.....	103
5.2.1	Food Establishments	103
5.2.2	Follow-up on requests for food aid at 211	108
5.2.3	Statistics Canada 2021 Census.....	115
5.2.4	Mapping of food aid request data to the census data	117
5.2.5	Mapping of food establishment data with building data	120
5.3	Summary and Integration.....	124
Chapter 6.	Spatial System Dynamics Simulations	125
6.1	Initial Simulations to Understand the Model Behavior	125
6.2	Model Behavior under Extreme Conditions	130
6.2.1	Minimizing household food insecurity in the local area	130
6.2.2	Maximizing household food insecurity in the local area	133
6.3	Simulation of Borough Food Insecurity	136
6.3.1	Baseline simulation for the borough-specific household food insecurity	136
6.3.2	Food deserts, food swamps and mixed conditions: Selected boroughs for a more detailed analysis.	138
6.3.3	Sensitivity analysis for the three selected boroughs	143
6.4	Summary and Discussion of the Spatial System Dynamics (SSD) model.....	147
Chapter 7.	Conclusions.....	149
7.1	Main Contributions	149
7.1.1	Identified gaps in existing systems and how they are addressed	149
7.1.2	Key results obtained in the Montréal case study.....	151
7.1.3	Contribution to the knowledge base	151
7.1.4	Artifact contributions (DSRM).....	151
7.2	Limitations	152
7.2.1	Limitations in the System Dynamics Model.....	152
7.2.2	Limitations in the developed DSS	152
7.2.3	Limitations in data availability and data processing	153

7.3	Future Work	153
CONTRIBUTION OF AUTHORS		155
Chapter 8.	References	156
Appendix A.	Artifact inventory.....	170
Appendix B.	Query words, word clouds and network graphs	173
Appendix C.	System dynamics model documentation	213
Appendix D.	Data set, description, and source	232
Appendix E.	Mapping Tables of 211 Montréal Food Aid Request to the Census 2021	237
Appendix F.	Review of Urban Agriculture Projects.....	241
Appendix G.	Glossary	244

List of Figures

Figure 1	Prevalence of Household Food Insecurity by Province, 2021. Source: [19]	18
Figure 2	Global land use for food production [20].....	19
Figure 3	Information System Research Framework [23]	23
Figure 4	Flowchart to develop the artifacts, including the five key elements.....	24
Figure 5	Flow chart of record screening and selection criteria	29
Figure 6	Interior view of a vertical farm (VF), a container farm (CF), and a greenhouse (GH).	34
Figure 7	Basic concept of spatio-temporal simulation	44
Figure 8	The six steps to develop a system dynamics model adapted from [22]	48
Figure 9	Overview of system driving food intake in low-income groups [112]	50
Figure 10	High-level Causal Loop Diagram (CLD) of the developed Spatial Food Systems Model	53
Figure 11	Balancing loop (B1) focusing on public transport and food accessibility	55
Figure 12	Balancing loop (B2) focusing on income and food budget.....	57
Figure 13	Balancing loop (B3) focusing on household food insecurity.....	59
Figure 14	Reinforcing loop (R1) focusing on urban food production options.....	61
Figure 15	Reinforcing loop (R2) focusing on urban food production options.....	63
Figure 16	Subsystem geographical access, including the stock and flows in the system	65
Figure 17	Details on the Stock and Flow structure for the number of supermarkets and healthy food stores.	66
Figure 18	Details on the Stock and Flow structure for the number of fast food outlet and restaurants	67
Figure 19	Dynamics around public transport infrastructure and its impact on local food accessibility	68
Figure 20	Stock and flow highlighting the dynamics of urban food production.....	69
Figure 21	Subsystem household finances.....	70
Figure 22	Subsystem household circumstances	72
Figure 23	Illustration of the different coupling strategies: Loose coupling, Moderate coupling, Tight coupling, and Embedded (own illustration).	79
Figure 24	Main structure of an XMILE model.....	81
Figure 25	View of a model block in an XMILE file	82
Figure 26	View of the pgAdmin GUI and a query on the fast-food outlets of Ville-Marie (NUM=20)	83
Figure 27	Concept of the Decision Support System (DSS), model as a business process diagram with the software Visual Paradigm	87
Figure 28	Deployment diagram for the different components to be able to run an SSD simulation.....	90
Figure 29	Illustration of the data integration and preparation workflow	93
Figure 30	Illustration of the SD model integration into the SSD Simulation Core.....	94

Figure 31	Pipeline for Creating XMILE Models for Integration into the SSD Framework	95
Figure 32	Data flow diagram for the data sets used in the DSS to run SSD simulations.....	101
Figure 33	Open food establishments in each borough	104
Figure 34	Food establishments activity in Montréal for the years 2016 – 2023	106
Figure 35	Cumulative food establishments activity in Montréal for the years 2016 - 2023 ..	107
Figure 36	Food aid requests by borough	110
Figure 37	Frequency of food aid requests vs. household situation	111
Figure 38	Frequency of food aid requests vs. housing situation	111
Figure 39	Frequency of food aid requests vs. education level	112
Figure 40	Frequency of food aid requests vs. source of household income	113
Figure 41	Median age and number of food aid requests by borough (Follow-up food aid request data).....	114
Figure 42	Spatial distribution of food aid requests across Montréal, calls per total number of households.....	115
Figure 43	Data flow diagram for the mapping of food establishments, with building information and categories of food establishments used for the system dynamics simulation .	120
Figure 44	Before geocoding (left) and after geocoding (right)	121
Figure 45	Initial simulation results for the island of Montréal (food accessibility, availability, and household food insecurity) NUM=0 is the complete island.....	129
Figure 46	Simulated food accessibility, availability, and household food insecurity for the island of Montréal, NUM=0. For opening hours of supermarkets and daily stores = 1, and new build rate fast food outlet = -0.215.	131
Figure 47	Simulated household food insecurity for Montréal if physical access to food is at maximum.	131
Figure 48	Simulated food accessibility, availability, and household food insecurity for the island of Montréal, NUM=0. For opening hours of supermarkets and daily stores = 1, and new build rate fast food outlet = -0.215 and new build rate urban farms CG = 0.1.	132
Figure 49	Simulated household food insecurity for Montréal if physical access to food and availability are at maximum.....	132
Figure 50	Simulated household food insecurity for Montréal if physical access to food and availability are at maximum, and shelter costs are reduced.....	133
Figure 51	Simulated food accessibility, availability, and household food insecurity for the island of Montréal, NUM=0. For opening hours of supermarkets and daily stores = 0, and new build rate fast food outlet = 0.215, new build rate urban farms CG = 0.0 and reduction in shelter costs = -0.01.	135
Figure 52	Borough-specific household food insecurity at t=0 and t=120 (after 10 years).....	137
Figure 53	Simulated food availability for the three selected boroughs.....	142
Figure 54	Simulated food accessibility for the three selected boroughs	142
Figure 55	Simulated household food insecurity for the three selected boroughs.....	143

Figure 56	Sensitivity analysis for HFI, Beaconsfield (NUM = 7)	144
Figure 57	Sensitivity analysis for HFI, Ville-Marie (NUM = 20)	145
Figure 58	Sensitivity analysis for HFI, Montréal-Nord (NUM = 16)	146
Figure 59	Subsystem household circumstances	217

List of Tables

Table 1	Concept matrix for the literature review addressing the main objective (M=methods, T=topic, L=level of work).....	32
Table 2	Illustration of the different urban farming (UF) systems	33
Table 3	Method of cultivation CEA system, group size and operational status (2025): All cases vs. North America.....	38
Table 4	Method of cultivation CEA system, size in m ² : All cases vs. North America.....	38
Table 5	Method of cultivation CEA system vs. facility type: All cases vs. North America.	39
Table 6	Method of cultivation CEA system vs. growing system: All cases vs. North America	39
Table 7	Indicative energy intensity of urban food-production technologies (kWh per kg of product)	40
Table 8	Indicative yield potential of urban food-production technologies (kg per m ² per year)	40
Table 9	Indicative production cost ranges of urban food-production technologies (CAD/kg)	41
Table 10	Reference and focus topic of the publications examined for the secondary-objective 2 (first category).....	42
Table 11	Mapping of research questions to methods, data sources, and outputs.....	46
Table 12	The seven guidelines of the DSRM and the way of applying the guidelines for the SSD – DSS	76
Table 13	Details on the Follow-up on requests for food aid at 211	109
Table 14	Overview of the thematic categories and attributes retained from the Statistics Canada data	116
Table 15	Segment from the mapping table of food establishments to categories of the system dynamics model	123
Table 16	Parameters derived from data and used for the initial run of the SSD simulation.	126
Table 17	Parameters based on assumptions and used for the initial run of the SSD simulation	127
Table 18	Parameters derived from data and used for the initial run of the SSD simulation, and are constants for the Montréal Island	128
Table 19	Comparison of the main characteristics for the boroughs with the highest and lowest household food insecurity (HFI)	138

Table 20	Parameter with the strongest influence on HFI at months 1, 36, 72, and 120 for each selected borough.....	146
Table 21	Mapping of identified gaps, contribution and thesis outputs	150

List Abbreviations

API	Application Programming Interface
BPTK-Py	Business Prototyping Toolkit for Python
CLD	Causal Loop Diagram
CEA	Controlled Environment Agriculture
CF	Container Farm
CityGML	City Geography Markup Language
DSRM	Design Science Research Methodology
DSS	Decision Support System
FAO	Food and Agriculture Organization
FEW	Food-Energy-Water
GH	Greenhouse
GIS	Geospatial Information System
GUI	Graphical User Interface
HFI	Household food insecurity
HVAC	Heating, Ventilation, and Air Conditioning
IS	Information System
LED	Light-emitting diodes
OGC	Open Geospatial Consortium
PF	Plant Factory
PP	Participatory Processes
PV	Photovoltaic
UA	Urban Agriculture
UF	Urban Farming
URF	Urban Rooftop Farming
SD	System Dynamics
SFSM	Spatial Food Systems Model
SSD	Spatial System Dynamics
VF	Vertical Framing

Chapter 1. Introduction

Food is fundamental to human well-being; it maintains health, enables daily life, and shapes social stability. Since food expenditure accounts for a large portion of household budgets in many countries, sudden price increases can quickly lead to hardship and also undermine the legitimacy of the government and political stability. Ensuring that people can reliably obtain safe and nutritious food has therefore become a central policy challenge. Recent shocks, such as the COVID-19 pandemic [1, 2], the Russian invasion of Ukraine [3], and renewed violence around Israel and Gaza [4], have highlighted how quickly international food trade can be disrupted. When transport routes, input markets, or export flows falter, prices for key commodities such as wheat and sunflower oil can rise sharply, with immediate consequences for household budgets and the affordability of healthier, more sustainable diets. The Arab Spring protests, which began in late 2010, are frequently cited as an illustrative case where elevated food prices contributed to broader social and political unrest [5–7]. Against this backdrop, the term food security is widely used, yet it is defined in different ways across research, policy guidance, and non-governmental reporting.

An early, influential formulation was offered by the World Bank in 1986:

“Access by all people at all times to enough food for an active and healthy life.” [8]

A more detailed and widely cited definition was later articulated by the Food and Agriculture Organization (FAO) of the United Nations, notably in the “Rome Declaration on World Food Security and World Food Summit Plan of Action” (1996) [9] and in “The State of Food Insecurity in the World 2001.” [10].

In these documents, food security is defined as:

“when all people, at all times, have physical and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life.”

The FAO formulation has been adopted beyond UN reporting and is echoed in European Union policy discussions. In its 2023 report “Analysis of main drivers on food security”, the European Commission uses the same definition and emphasizes that achieving food security requires food systems that simultaneously support environmental integrity, social well-being, and economic viability [11].

In 2019, the Government of Canada launched “The Food Policy for Canada”, with the following vision for the future of food in Canada:

“All people in Canada are able to access a sufficient amount of safe, nutritious, and culturally diverse food. Canada’s food system is resilient and innovative, sustains our environment and supports our economy.” [12]

The above definitions show that access to food and a nutritionally balanced diet are central to Canada's food policy.

However, in academic discourse, it is not so straightforward to pinpoint a precise and uniform definition of food security. In 1993, Sithm compiled a comprehensive overview of the various ways in which food security is defined, resulting in a collection of 194 different definitions [13]. The concept of food security has evolved from a relatively narrow understanding of overall food supply to a multidimensional framework that encompasses the social, economic, political, and environmental conditions under which people gain access to food. Earlier views focused largely on national food availability and caloric intake, reflecting a policy emphasis on production, stocks, and supply security. The definition adopted at the 1996 World Food Summit was structured around the four frequently cited dimensions of availability, access, utilization, and stability, thereby acknowledging that hunger and malnutrition can persist even where overall food supply is sufficient.

However, recent scholarly work and policy debates have argued that the conventional four-pillar model remains incomplete, as it tends to underestimate the role of structural inequality, political power, and ecological limits in the emergence of food insecurity [14]. In response to this criticism, the High-Level Panel on Food Security and Nutrition proposed in 2020 adding agency and sustainability as two additional dimensions [15]. Agency refers to the ability of individuals and communities to participate in and influence decisions regarding food systems, while sustainability emphasizes the long-term ecological, social, and economic viability of food provision. This expanded perspective redefines food security not only as a matter of ensuring adequate food intake, but also as a matter of democratic participation, social justice, and the resilience of food systems over time.

This broader conceptualization is particularly important in the context of current crises. As recent debates show, food insecurity is shaped not only by supply shortages and price shocks but also by conflict, climate change, urban inequality, corporate concentration, and communities' unequal capacities to respond to shocks.

Importantly, understanding how people, social movements, businesses and public institutions communicate differently is also central to transforming food systems, because these differences reveal where power in the food system is located and how it is exercised. The report *Shaping Food Security Narratives* argues that food security narratives are never neutral: they shape which problems are recognized, which solutions appear legitimate, which actors are treated as credible, and ultimately, which policies receive funding and institutional support [16]. In this sense, narratives function as political instruments. Dominant narratives, especially productivist ones, are backed by international organizations, national governments and transnational corporations, and therefore tend to reproduce existing concentrations of corporate power. By contrast, grassroots and

locally embedded narratives are often rooted in lived experience, but are undervalued at national level because of persistent power imbalances and the devaluation of experiential knowledge. The report, therefore, suggests that examining who speaks, to whom, in what language, and with what institutional backing is indispensable for understanding how power circulates through food systems and why some voices are amplified while others remain marginal.

This argument is reinforced by Molly D. Anderson's work, which shows that struggles over food are also struggles over democracy, participation and control [17]. In her discussion of food democracy, Anderson argues that concentrated corporate power has increasingly shaped both food markets and food governance, and that democratic alternatives require the genuine inclusion of underrepresented groups in decision-making as well as public institutions that respect and respond to deliberation.

Food security should therefore not be understood simply as a technical policy goal, but as a contested and evolving field that links access to food with issues of resilience, governance, justice, and sustainability. Such a perspective is particularly relevant to this work, as it helps to situate food insecurity within the broader dynamics of the food system, rather than reducing it solely to a supply problem.

Due to urbanization and changing agri-food systems, two new types of food environments have emerged, food deserts and food swamps.

“Food deserts are geographic areas where residents’ access to diverse, fresh or nutritious foods is limited or even non-existent, due to the absence or low density of “food entry points” within a practical travelling distance. Food swamps are areas where there is an overabundance of foods of high energy density and minimal nutritional value. They offer few options for affordable, nutritious foods.” [18]

For both food deserts and food swamps, the built environment, like the density of food-selling points (supermarkets, restaurants, or fast-food outlets), food production areas, and public transportation, is a key factor. A study conducted by Valerie Tarasuk, Tim Li, and Andrée-Anne Fafard St-Germain presents an in-depth analysis of food insecurity across Canadian provinces based on data from the 2021 Canadian Income Survey [19]. The study defines household food insecurity as inadequate or uncertain access to food due to financial constraints. In 2021, 15.9% of households, representing about 5.8 million Canadians, including 1.4 million children, experienced some level of food insecurity, with prevalence ranging from 13.1% in Quebec to 20.3% in Alberta (see Figure 1). The report identifies income and housing conditions as key predictors: low-income households, renters, and homeowners with mortgages showed significantly higher vulnerability. Households dependent on social assistance (63%), COVID-19 benefits (42%), or employment insurance (39%) were most affected, while those relying on public pensions were comparatively protected. Food insecurity also has a strong racial dimension: over 30% of indigenous households outside reservations, and a higher proportion of racially discriminated groups were affected by food insecurity when compared with white households. Single-parent families, especially those led by women, and individuals living alone are among the most vulnerable demographics. Despite extensive monitoring since 2005, the report concludes that food insecurity in Canada has not improved, indicating the persistence of deep-seated structural inequalities. The authors criticize the government’s continued funding of charitable food programs, arguing these do not address root causes. Instead, they advocate for evidence-based policy interventions that strengthen income security, such as reforming social assistance, improving minimum wages, indexing benefits to inflation, and expanding income supports akin to Canada’s public pension system. Without such measures, the report warns that inflation and stagnant wages will further intensify food insecurity across the country.

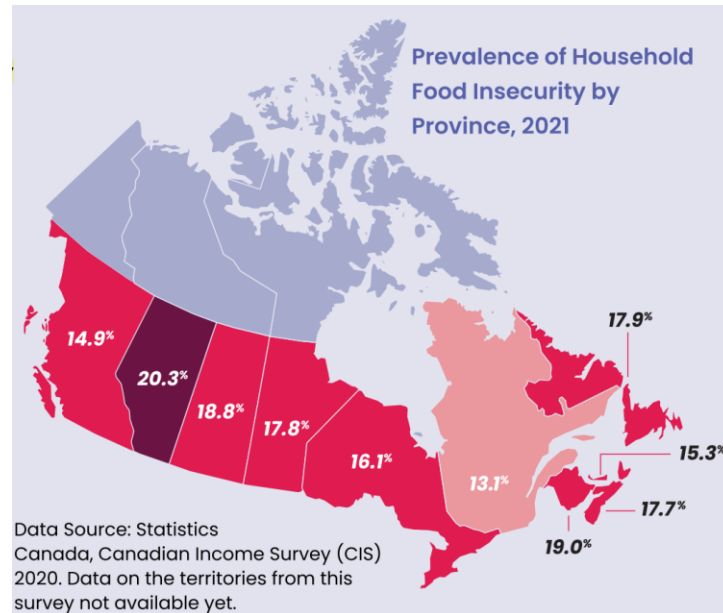


Figure 1 Prevalence of Household Food Insecurity by Province, 2021. Source: [19]

In this thesis, the urban agglomeration of Montréal will be used as a case study to show the functionalities of the developed Decision Support System (DSS) in understanding the main drivers and conditions that impact food security in dense urban spaces. The focus of this thesis is to model Montréal's urban food system in order to assess Household Food Insecurity (HFI). The methodology employed will encompass spatial analysis and the simulation of dynamic interactions among relevant drivers, with the objective of addressing the research questions posed. The thesis is expected to make a scientific contribution in two areas: (1) it contributes to a better understanding of the design of urban food systems to reduce food insecurity for vulnerable people, and (2) it makes a contribution to a better understanding of the elements of what a decision support system needs, from the perspective of an Information System (IS) and user functionalities.

1.1 Problem statement: Land use, urbanization, and efficiency in food production

To understand the extent and importance of food production on resource consumption, such as land area, it is important to look at the land area currently used for food production. Figure 1 shows the global land use for food production in the year 2013. The world has a total area of about 510 million square kilometers, of which about 29% is land area and the rest is ocean. The habitable zone, where human life takes place, occupies about 71% of the land area. Agriculture occupies about 46% of the global habitable land, which is about 48 million square kilometers. Urban and built-up land, which includes settlements and infrastructure, accounts for about 1.5 million square kilometers, or about 1% of the total land area.

Global land use for food production

Our World
in Data

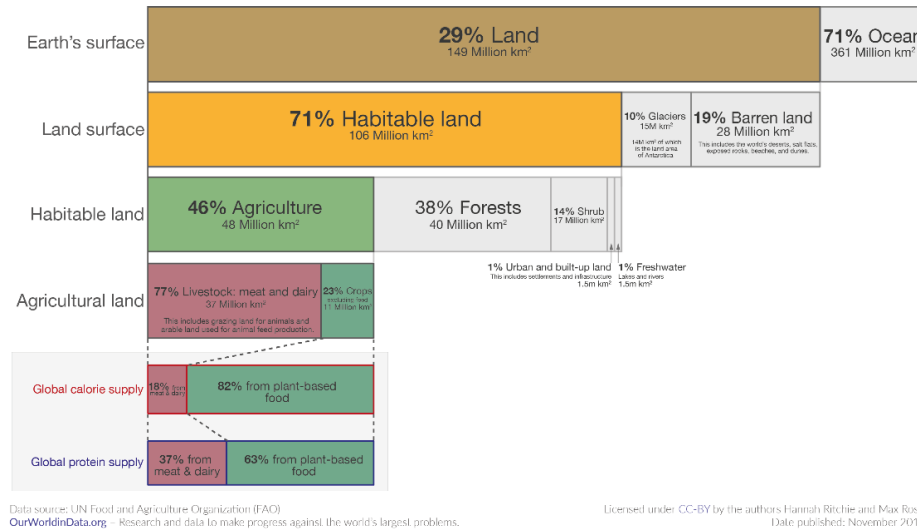


Figure 2 Global land use for food production [20]

Considering the land area used for agriculture, the high share of about 77% for meat and dairy products is remarkable. Although livestock occupy the largest share of land, meat and dairy products contribute only 18% of the world's calories and 37% of the protein supply. Plant-based foods provide the remaining share of calories and protein in the global human diet by only occupying 23% of the agricultural land. This raises the question, to what extent can existing urban areas contribute to food security when it accounts for only about 1% of the habitable area? Especially in view of the growing population, it can be assumed that the consumption of land and resources for food production will increase significantly, and thus, the conversion of land, such as forests, into agricultural land will continue.

A simple examination of the land area allows two preliminary conclusions to be drawn:

1. if the area under cultivation cannot be increased in urban and peri-urban areas, the productivity per area must be increased,
2. the use of land for growing crop products is much more efficient than growing animal feed

In fact, studies show that vertical farming systems produce higher yields per area compared to conventional outdoor farming [21]. The potential of urban farming systems is particularly high in the production of plant-based foods. For example, vegetables such as tomatoes, lettuce, peppers,

or fruit such as strawberries and blueberries can be grown in vertical farms, and public areas such as parks or community gardens are suitable for growing nuts and fruits.

In addition to the limitations of land use, challenges are also encountered in the modeling of complex systems. System Dynamics (SD) is a methodological framework that has been utilized for a period of five decades in numerous domains, including physics, climate research, and financial market modeling. Despite the long-standing utilization of SD as a methodological tool, its potential remains largely untapped, particularly in light of the rapid advancements in computing capabilities and the increasing accessibility to data, which are facilitating the exploration of entirely novel applications.

In his book *Business Dynamics: Systems Thinking and Modeling for a Complex World* (2000), John D. Sterman [22] highlights several challenges for the future which SD could help to unravel.

The challenges relevant to this thesis are outlined hereafter.

System dynamics modeling, grounded in the theory of nonlinear dynamics, has advanced considerably, yet core theoretical challenges remain unresolved. Questions such as

"When and how do systems self-organize to produce coherent patterns in both time and space? To what extent are dynamic and complex systems self-similar across different temporal and spatial scales? What determines these scaling relationships?"

On the technological front, increasing computational power is transforming the way simulations are conducted and how users interact with models. Sterman points to innovations such as

"Automated mapping of parameter space. Hitting the run button will generate a high-resolution map of model behavior over a user-specified range of parameters and initial conditions ..."

Technological developments are changing the modeling process, enabling faster and more detailed exploration of system behaviors. At the same time, efforts to make models more interoperable and data-driven are essential. As noted,

"Linking models with one another and with a wide range of databases is another important area of technological development. At present, finding, checking, and updating data is difficult, expensive, and time-consuming. Incompatibilities abound. Future simulation software will seamlessly integrate data from a variety of sources, automatically update the model by querying the data servers over public or private networks. Integrating dynamic models with enterprise management software will enable managers to go beyond spreadsheets. The key challenge is using technology to learn more effectively about the

dynamics of our models, to develop tools to aid understanding of complex systems. There are dangers, however. Modelers must resist the temptation to use greater computer power to build bigger and bigger models in the vain belief that the more detailed and comprehensive the model the better it must be. While computer power grows exponentially, our ability to absorb information remains the same. Larger and larger models may only result in less and less understanding, fewer insights and less implementation success."

Together, these theoretical and technological issues form a central part of the problem statement in system dynamics modeling, highlighting the need for both deeper conceptual clarity and smarter, not just larger, use of computational tools.

This thesis seeks to demonstrate the interconnection between temporal and spatial relationships, the automation of parameterization in models when adjusting the location of investigation while using a consistent system model for simulation, the capacity of users to define parameters for the establishment of initial conditions, and the integration of system models with databases to facilitate automated model updates.

1.2 Research questions, objectives, and outputs

The overarching research objective of this thesis is to develop a Decision Support System (DSS) that assists decision-makers in understanding the interrelationships in complex systems and leveraging this knowledge to make more informed decisions regarding the design and implementation of measures to achieve defined goals on how to design and implement urban food systems to increase food security of vulnerable populations. The thesis describes and examines factors that influence urban food systems, collects relevant data, and develops a computational model that is general enough to be applied across regions and cities and specific enough to answer concrete local questions for the urban agglomeration of Montréal.

The following research questions (RQ), associated objectives, and expected outputs are the core of the thesis:

RQ1: *What urban food production technologies are available, and what key technical requirements and constraints determine their practical feasibility in cities?*

Objective: *To identify and evaluate different technologies that can be used for urban food production. Greenhouses, vertical farms, container farms, and community gardens will be considered to assess their potential use under different conditions, such as location, climate, built environment, and land area that can be allocated to growing food.*

Output: *A typology and evidence-based feasibility assessment of urban farming systems.*

RQ2: *How does the urban food environment impact the availability and accessibility of healthy food?*

Objective: *Analyze the food demand and local food supply chains (from production sales locations like supermarkets or farmers markets) as a function of the socio-economic situation at the district level using the Montréal case study.*

Output: *Baseline assessment of availability and accessibility based on spatial indicators derived from Montréal datasets (food outlets, socio-economic vulnerability, food aid requests).*

RQ3: *How can a system model be developed to describe the interdependencies of urban food production and policy changes to increase food security for vulnerable people?*

Objective: *Development of a Spatial System Dynamics (SSD) model that combines geospatial information and stock flow modeling.*

Output: *A SSD model and the calculation of scenarios that provide insights into the most important factors for urban food systems that can be presented to planners and decision-makers.*

1.3 Approach

In the thesis, the Design Science Research Methodology (DSRM) as described by Hevner *et al.* [23] is followed to develop the DSS. Design science in Information Systems (IS) research is a problem-solving approach.

The IS framework is composed of three primary components: The “Environment, IS Research, and the Knowledge Base”.

The Environment defines the phenomenon of interest and outlines the problem space. The Knowledge Base provides the existing scientific foundations (e.g., theories, frameworks, models) and methodological guidance that inform the artifact’s design and evaluation, while the resulting insights and artifacts contribute back to extend that knowledge. The IS Research is divided into two sub-sections. The development and building of theories and artifacts, and a rigorous process of justification and evaluation by evaluating the developed IS through case studies, simulations or other methods to show the capability of the system. The objective of the Develop/Build and Justify/Evaluate process is to construct artifacts that are aligned with the identified business requirements.

IT artifacts may vary from software, formal logic, and rigorous mathematics to informal natural language descriptions. The IT artifacts enable scientists to understand the problem addressed by the artifact and the feasibility of their solution approach. Figure 3 shows the conceptual framework for understanding, executing, and evaluating IS research that combines behavioral science and design science.

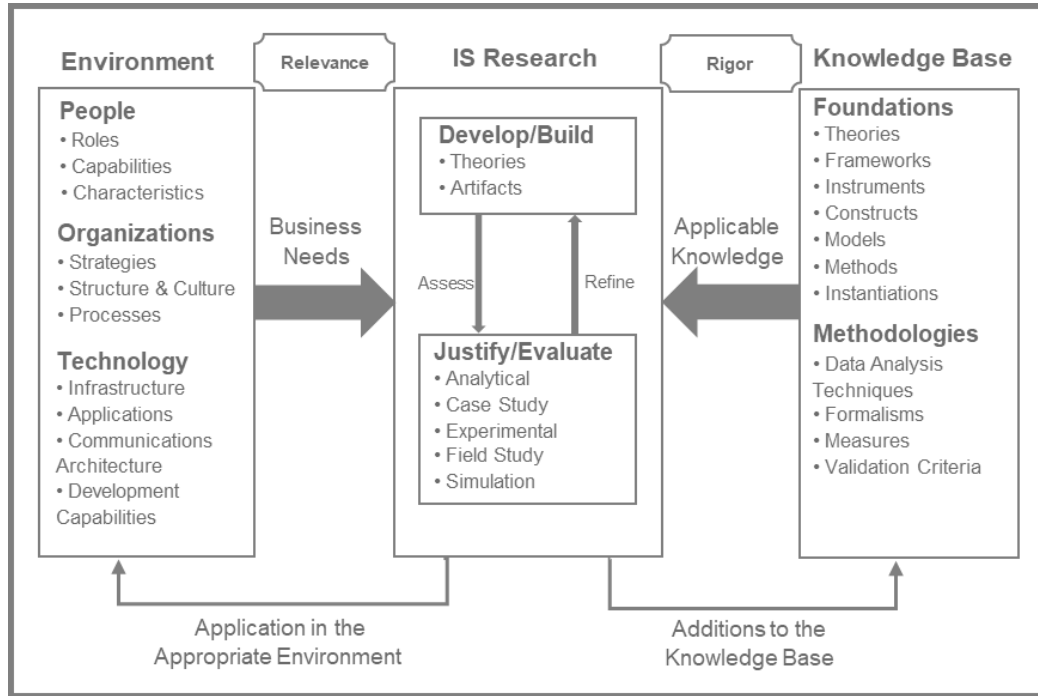


Figure 3 Information System Research Framework [23]

For Hevner *et al.* [23]

“Behavioral science addresses research through the development and justification of theories that explain or predict phenomena related to the identified business need.”

and

“Design science addresses research through the building and evaluation of artifacts designed to meet the identified business need.”

In the context of this thesis, the business need is a DSS that assists decision-makers in making better decisions on how to design and implement urban food systems. The design science part involves applying existing knowledge, such as system dynamics and state-of-the-art frameworks in software development, as well as collecting and analyzing data from literature and data portals, to create the artifacts.

The IS research in this thesis contributes in this way to improve the knowledge base (e.g., an improved system dynamic model, new methods for data analysis, and a framework for a DSS for spatial system dynamics simulations).

Figure 4 shows the framework for developing the artifacts. For a structured approach, the process is divided into five sections: Technology Assessment (Chapter 2 – setting the foundations based on existing literature and creation of an overview on Urban Farming (UF) systems), SD Modeling (Chapter 3 – Methodology, build a theory and an executable model), Decision Support System Framework (Chapter 4 – Build the code and deployment pipeline), Primary & Secondary Data (Chapter 5 – Collect and analyse relevant data), and Spatial System Dynamics Simulations (Chapter 6 – Development and testing of the SD model in Vensim before deploying it into the DSS framework). Together, these components form the spatial system dynamics DSS for urban food security.

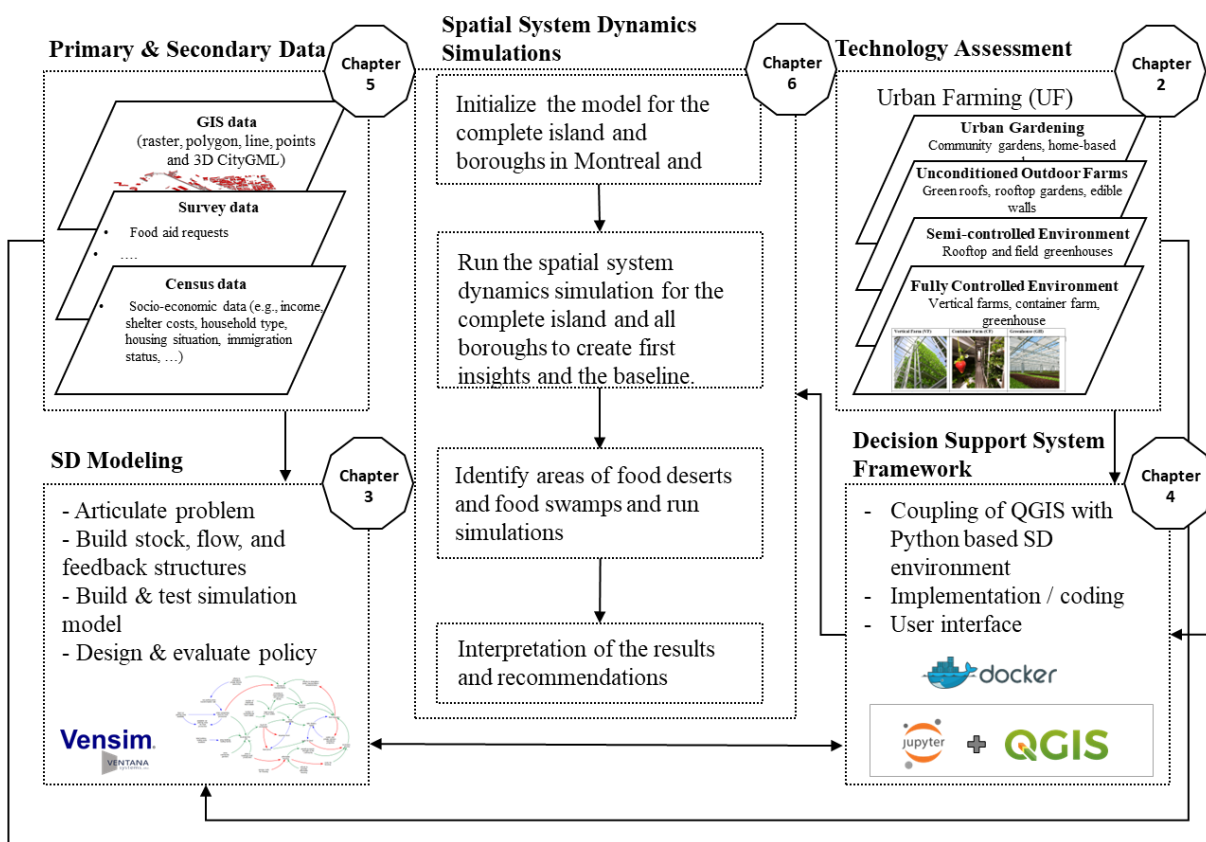


Figure 4 Flowchart to develop the artifacts, including the five key elements.

The purpose of the DSS is to provide a framework through which strategies and measures can be developed. It is used to test the impact of various spatial and economic factors (e.g. public transport, retail development, urban food production, or cost of living adjustments) on access to healthy food in different neighbourhoods and areas.

Hevner *et al.* [23] provides the following definitions for IT artifacts:

“IT artifacts are broadly defined as constructs (vocabulary and symbols), models (abstractions and representations), methods (algorithms and practices), and instantiations (implemented and prototype systems).”

The complete artifact inventory can be found in Appendix A. In the following, a summary of the artifacts is presented:

At the conceptual core are the constructs and models (five artifacts). These include the high-level causal loop diagram and the subsystem stock-and-flow structures that ground the theory linked to the model, together with structural constructs such as mapping tables that formalize how external data are interpreted in the model. Their purpose is to capture and communicate the system’s feedback logic and state changes in a form that is analyzable, extensible, and reusable for other researchers.

The design principle of moderate coupling is core for the DSS and describes how spatial data and system dynamics interact through a shared database. The purpose of this principle is architectural; it balances performance with flexibility so that modeling, data management, and visualization can evolve independently without breaking interoperability. It is the methodological hinge between SD and GIS within the DSS.

Translating the design choices of the DSS into a working platform required a substantial body of instantiations and software (13 artifacts). This category covers the DSS itself as a microservices-based system, the spatial system dynamics simulation core, the Python based SD model compiled from a XMILE file, the REST API microservice, the PostGIS data store, model library and deployment infrastructure.

Complementing the software are specifications and standards (six artifacts). These include the XMILE model representation, the REST API specification, the data-flow diagram and its Visual Paradigm XML, and accompanying documentation. Their purpose is to guarantee transparency, versionability, and tool-agnostic interoperability so that models, data pipelines, and services can be inspected, exchanged, and re-implemented by others.

Further, methods and workflows artifacts (seven artifacts) that operationalize data preparation and modeling are developed. ETL (Extract, Transform, and Load) pipelines to move data from sources (e.g., data portals) into the DSS database, the integration workflow of Vensim models into Python code (Vensim→XMILE→BPTK-Py compiler→Python code), mapping and reverse-geocoding procedures, and population-weighted aggregation queries. Their purpose is procedural rigor, turning heterogeneous inputs into harmonized, well-documented, and testable datasets and parameters that faithfully initialize and evaluate the simulations.

Finally, the corpus of data assets (eight artifacts) comprises one primary field-compiled dataset and multiple secondary sources (Open Data Montréal, 211 food-aid records, CERC buildings, OSM layers, and Statistics Canada census boundaries and profiles), plus standardized exports used to load the DSS. Their purpose is empirical coverage, to provide the spatial, socio-economic, and sectoral information necessary for calibration, contextual analysis, and stakeholder-relevant interpretation of model outputs.

Taken together, these artifacts show a coherent chain from theory and design principles to an operational, standards-compliant software instantiation and a documented, reproducible data and method foundation.

1.4 Motivation and Applications

Over the past 15 years, I have been working in the field of building simulations and conducting modeling of renewable energy systems. The focus was primarily on designs and processes that could be used to technically improve buildings and systems. As part of an international research project on the food-energy-water (FEW) nexus, I worked with experts from different disciplines. I was fascinated to see to what extent the fields food, energy and water influence each other and how limited we are today in taking a holistic view to improve the system. From my point of view, the challenges lie partly in the collection of data, the definition of common goals, the combination of simulation models, and the integration of non-technical parameters such as policy or societal changes and the needs/preferences of stakeholders into computational models.

There is often a lack of evidence-based figures for decision-making about how an urban system might look in a particular context and how to navigate the trade-off considerations in designing and building them. Creating evidence-based figures and developing appropriate methods and models motivated me to do this work.

1.5 Thesis Structure

The thesis is organized into seven chapters. **Chapter 2** provides a comprehensive review of the existing literature on decision support systems, technologies for urban food production, demand and local food supply chains, and spatial system dynamics. It discusses the current state of the art in research and addresses open gaps in the various fields of research. **Chapter 3** is devoted to the presentation of the developed system dynamics model for urban food systems with a focus on food security for vulnerable people. The model is initially described as a high-level causal loop diagram, which is used to understand the main balancing and reinforcing mechanisms in the system. The causal loop diagram is then transferred into a stock and flow model, which can be integrated into the simulation environment. **Chapter 4** focuses on the decision support system framework,

presenting the key concepts behind the software architecture and how the different components, the so-called micro services, interact with each other. **Chapter 5** presents the primary and secondary data sources utilized in this thesis. It underscores the challenges associated with working with data from disparate sources, such as open data portals and OpenStreetMap. Additionally, it offers insights into the integration of data necessary to comprehend an urban food system. **Chapter 6** employs the comprehensive framework to assess Montréal's urban food system. A baseline is developed to represent the current state of Montréal's food systems with regard to food security for vulnerable people. Based on this scenario, potential policy interventions are presented, and their impact on food accessibility, availability, and household food insecurity is projected for the next ten years.

The final **Chapter 7** of the thesis is devoted to the conclusion and directions for further research.

Additional sources that support the work: To facilitate reproducibility and allow readers to run the model developed in this thesis, the key implementation resources are made available. An executable version of the model can be found on GitHub: <https://github.com/reiner-os4os/ssd-dss>. The repository includes a parameterized configuration for Ville-Marie and for the entire Island of Montréal, which serves as a reference implementation to illustrate the system's dynamics. Beyond the core model, the supplementary code and the linked datasets support independent installation and operation of the complete decision support system. Detailed documentation is provided for each dataset and its preprocessing, enabling the approach to be applied and recalibrated for other cities.

Chapter 2. Literature Review

In the following section, the relevant literature to achieve the objectives of the thesis is analyzed, and the research of the thesis is placed in the context of the current state of the art. The analysis of existing literature is used to identify further research needs and places previous results in the context of the proposed methodology.

2.1 Search strategy and record selection

To get an overview of the current state of research, an extensive literature review was carried out using the Web of Science (WoS) and Scopus (SC) databases. The goal was to obtain a comprehensive literature review of the research area, consisting of journal articles, books, and conference papers from a range of sources, and to identify research gaps. The database search was performed in March 2023, using specific query words for the different objectives. Table A 2 in Appendix B shows the query words used for the search and the results of the bibliometric search for each objective. There were no restrictions on publication date, and only English-language publications were selected. The flow chart for the screening of the documents and the selection criteria is shown in Figure 5. The number of publications in the individual steps refers to the entire literature examined.

For a further selection of the publications and to understand the connection of the topics, word clouds, and network graphs were generated based on text analysis of the abstracts. A network graph allows for the visualization of correlations between individual publications and to identify clusters of topics that are relevant for further analysis. In the next step, each publication was subjected to full-text analysis and evaluated according to the following criteria: focus topic, level of work (e.g., urban, peri-urban, metropolitan, or building), modeling method, capabilities, and method limitations. Each publication was then assigned a central topic. As a last step, connections with a weighting factor of the edges greater than 0.03 were made visible in the network graph. The word clouds and network graphs generated are presented in Appendix B.

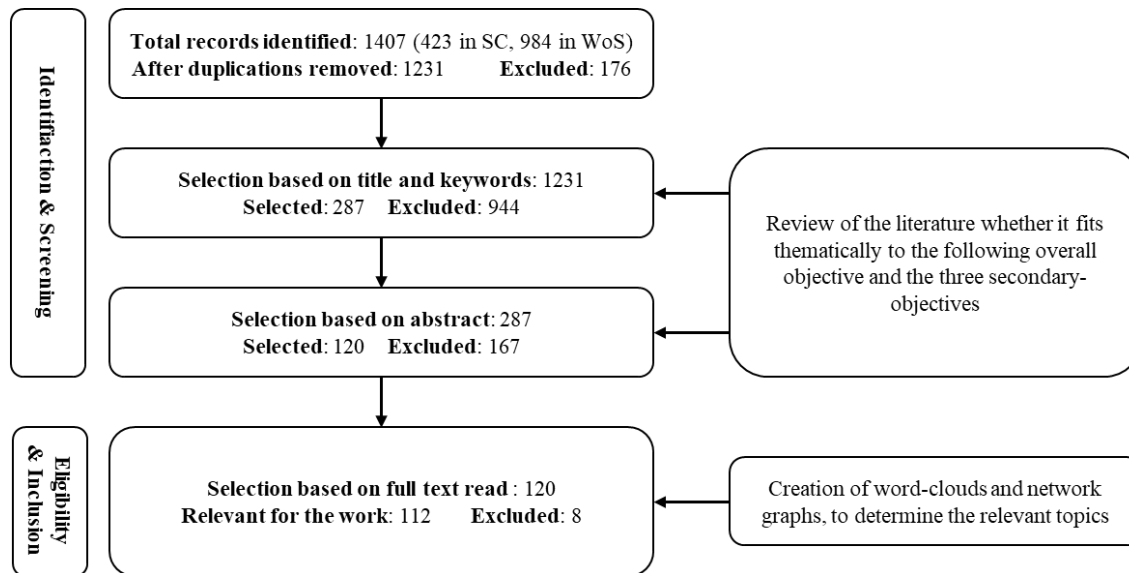


Figure 5 Flow chart of record screening and selection criteria

2.2 Literature analyzed related to the objectives

2.2.1 Literature addressing decision support systems

Main objective: *Develop a decision support system (DSS) that assists urban and regional decision-makers in making better decisions on how to implement urban food production systems to increase the food security of vulnerable populations.*

In total, 24 publications were identified for full-text analysis relevant to the main objective of this thesis. The following can be concluded from the literature reviewed:

A DSS would need different components and should (i) offer the possibility to work on the tasks in a participative way with the stakeholders, (ii) provide the capabilities to evaluate technical systems and their implementation potential, and (iii) give insights into the current and future use of urban spaces.

DSS and participatory processes (PP): Francisco *et al.* [24] used system dynamics (SD) as a method to develop a policy tool to create community-supported agriculture strategies in the field of the food-energy-water (FEW) nexus. Rich *et al.* [25] combined SD models with participatory approaches to identify spatial influences in urban settings. The main focus was on the food supply chain in urban and peri-urban areas. Urban food security in metropolitan areas was the focus of Dijkshoorn-Dekker *et al.* [26]. By involving stakeholders in informal governance processes, social innovation, and the co-production of knowledge in food system transitions, GIS was used as a tool of interaction with the involved participants. Dynamic GIS was used by Arciniegas *et al.* [27] as a

tool to work on food systems during workshops. The GIS tool includes an interactive layered digital map that stores and communicates the map layers to enable stakeholders to propose changes in spatial patterns. It provides real-time feedback on the impacts of the changes via dynamic charts. The literature shows that SD or GIS, or even a combination of both, are used to interact with participants. In particular, the direct feedback of inputs and their effects on the system is essential when a tool is used in a participation process.

DSS and technical systems: The focus of DSS and technical systems is predominantly on the scale of buildings. In general, it can be concluded that a combination of the building structure and farm system is assessed in the literature. Li *et al.* [28] presented a holistic decision support framework for urban farming systems that considered the energy and material consumption for vegetable production, the economic and environmental performance and demonstrated the use of the framework for a case study of a vertical farm in Singapore. The applied dynamic model can simulate the heating, ventilation, and air conditioning (HVAC) system of an urban farming system, including optimization of the system. The modeling of the building geometry, including the estimation of the energy yield, as well as the study of the load demand and the integration of photovoltaic (PV) solar systems for vertical farming, was the focus of Teo and Go [29]. Rooftop farming was the focus of Contractor *et al.* [30], where a method was presented that can be used to evaluate buildings with regard to their potential for roof-top agriculture.

DSS and the use of urban spaces: The third cluster deals with urban areas and their usage for urban agriculture. Thiesen *et al.* [31] examined urban agriculture in terms of its ecosystem services and developed indicators to evaluate alternative agro-ecosystems. Decision-makers can use the tool to compare different urban agriculture sites, e.g., urban farms or food gardens in residential areas and public spaces, and evaluate their ecosystem services. A decision support tool for inventorying the spatial characteristics of vacant and underutilized land for urban food production is presented by [32, 33]. Users can perform a series of “what-if” scenarios and sensitivity analyses to better articulate potential trade-offs.

The other publications focus on DSS of open lands for agricultural production [34], or by inventorying vacant and underutilised land and testing scenario trade-offs Ghodsvalli *et al.* [35] land and resource use [36], environmental performance [37] and Life Cycle Assessment [38], bioenergy crops [39], food environments [40], land management and soil conservation [41], tools for Nature-Based solutions [42] and IoT and plant care [43].

Food access and distribution are operationalised through rapid GIS screening of service coverage versus potential need by Bacon and Baker [44]. Governance and implementation pathways are addressed through municipal policy and planning assessments by Robert and Mullinix [45] and the integration of stakeholder preferences into peri-urban farming and planning choices by Marques-Perez and Segura [46].

Table A 3 in Appendix B provides a more detailed overview of the publications studied for the main objective.

The concept matrix in Table 1 synthesizes the findings from the full-text analysis by mapping each included publication against a consistent set of analytical themes. Specifically, the matrix shows (i) which methods (M) are applied (system dynamics, GIS/spatial modelling, simulation), (ii) which topic (T) areas are covered (e.g. vertical/rooftop farming, vacant land, policy/governance), and (iii) the level of work (L) (regional/national, city/metropolitan, building/parcel). An “X” indicates that a paper explicitly contributes to the respective theme, enabling rapid comparison across the literature and highlighting where evidence clusters or where gaps remain for the DSS development aligned with the thesis objective. Importantly, Table 1 makes an integration gap visible: only a small subset of studies combines system dynamics with GIS/spatial modelling, and none couples this combination with a simulation component to deliver spatially explicit dynamic simulations at the city/borough scale. Conversely, city-scale GIS-based simulation studies and city-scale system dynamics studies occur largely as separate strands, indicating an opportunity for DSS development that links dynamic feedback modelling with spatial decision layers at an urban scale.

Note: The two review papers, Surls *et al.* [47] and Mino *et al.* [42], are excluded from the concept matrix, which focuses on primary studies.

Table 1 Concept matrix for the literature review addressing the main objective (M=methods, T=topic, L=level of work)

Reference	(M) System dynamic	(M) GIS / spatial modelling	(M) Simu- lation	(T) FEW nexus	(T) Vertical farming	(T) Rooftop farming	(T) Vacant land	(T) Policy / governance	(L) Regional / national	(L) City / metro- politan	(L) Parcel / building
Francisco <i>et al.</i> [24]	X		X	X				X		X	
Rich <i>et al.</i> [25]	X	X						X			
Dijkshoorn-Dekker <i>et al.</i> [26]		X								X	
Arciniegas <i>et al.</i> [27]		X	X							X	
Li <i>et al.</i> [28]			X								X
Teo and Go [29]			X		X						X
Contractor <i>et al.</i> [30]						X		X			
Thiesen <i>et al.</i> [31]											X
Kirnbauer and Baetz [33]							X	X			
Kirnbauer and Baetz [32]			X				X	X			
Ghodsvli <i>et al.</i> [35]		X	X	X						X	
Erickson <i>et al.</i> [34]		X					X	X	X	X	
Aladin <i>et al.</i> [43]			X								
Terribile <i>et al.</i> [41]		X						X		X	
Downs <i>et al.</i> [40]											
Bacon and Baker [44]		X								X	
Robert and Mullinix [45]								X		X	
Marques-Perez and Segura [46]								X	X		
Vega-Azamar <i>et al.</i> [36]	X	X							X	X	
Dias <i>et al.</i> [37]								X	X	X	
Laurentiis <i>et al.</i> [38]										X	
Verstegen <i>et al.</i> [39]		X	X				X		X		

2.2.2 Literature addressing technologies for urban food production

Objective: To identify and evaluate different technologies that can be used for urban food production. Greenhouses, vertical farms, container farms, and community gardens will be considered to assess their potential use under different conditions, such as location, climate, built environment, and land area that can be allocated to growing food.

In total, 28 publications were identified as relevant in the full-text analysis. The analysis examined the publications for the following criteria: (1) focus topic of the publication, (2) technologies used and the technical requirements of the system, (3) food products/cultures that can be produced, and (4) identified challenges of the technologies.

Each publication was assigned a central topic (e.g., vertical farming (VR), urban rooftop farming, or greenhouse (GH)). Table 2 shows the categories of urban farming (UF) systems, which can be classified into urban agriculture (UA) and urban gardening. UA represents the professional cultivation methods and urban gardening represents, more community-based and unprofessional approaches. The UA methods can be subdivided into fully controlled environmental plant factories, typically soil-less systems, semi-controlled and unconditioned outdoor farms, which are typically soil-based systems.

Table 2 Illustration of the different urban farming (UF) systems

Urban Farming (UF)	Method	Facility type
Urban Agriculture (UA) (professional methods)	Fully Controlled Environment - Plant factories (PF) Soil-less cultivation systems	Vertical Farms (VF) - Indoor farming - Rooftop vertical farm - Multi-story building vertical farm/warehouse Container Farm (CF)
	Semi-controlled Environment Soil-less or soil-based cultivation systems	Greenhouse (GH) - Rooftop greenhouses - Field/open land greenhouses
	Unconditioned Outdoor Farms Soil-based cultivation systems	- Green roofs - Rooftop gardens - Edible walls - Open land farms
Urban gardening (unprofessional methods)	Urban gardening	- Home-based gardening - Community-based and other shared gardening - Guerrilla gardens - Home gardening methods in buildings (corridor, rooftop, and facade)

In professional systems, plant growth is monitored, and the environment is controlled to ensure optimal growing conditions. Technologies, such as light-emitting diodes, provide supplementary light to the plants [48–50], solar panels provide heat, photovoltaics provide electricity [51] and HVAC systems regulate the air temperature and humidity of the indoor environment [52].

Vertical farms (VF) and container farms (CF) are so-called plant factories (PF) where plant production takes place in a closed, fully controlled environment, such as an artificially illuminated and highly insulated structure [53]. In a vertical farm (VF), vegetables, fruits, and grains can be grown in vertically stacked layers. Here, the conditions on the different floors are controlled so that different types of crops can be produced [54]. A CF consists of one or more containers of the same design. A CF is smaller than a classic vertical farm. By stacking containers on top of each other or side by side, the farm can be customized according to the user's needs. The cultivation is also done on a vertical plane, so they can be classified as a VF. A greenhouse (GH) is a glass building where plants are grown under controlled conditions. In an urban environment, greenhouses are often built on the roofs of buildings. There are two levels of greenhouses, "low-tech" greenhouses, where the building envelope and natural ventilation are optimized, but no additional equipment is installed, and "high-tech" greenhouses, where supplemental lighting is provided for plant growth, the latest HVAC systems are installed and computerized monitoring is used [51].

Figure 6 shows a VF from Sky Green Technology, a CF from Cropbox, and a GH from Gotham Greens. The professional methods of UA thus offer the possibility to use the smallest areas, up to several thousand square meters, in cities.

Vertical Farm (VF)



Source: [Sky Greens – Technology](#)

Container Farm (CF)



Source: [Strawberry Cropbox](#)

Greenhouse (GH)



Source: [Gotham Greens](#)

Figure 6 Interior view of a vertical farm (VF), a container farm (CF), and a greenhouse (GH).

Soil-less growing systems are systems where plants are cultivated without the use of soil. The growth is facilitated through substrate or water culture of plants [55]. Based on the literature reviewed, three main soil-less growing systems were identified.

Hydroponics: In hydroponic systems, plants are cultivated without soil in nutrient-enriched water either on floating platforms or with a thin, flowing nutrient film across a horizontal surface. The nutrients required by the plants are transported by a nutrient solution to the roots of the plant, where they are absorbed [56]. This can be done on a single level. Such cases can be found in hydroponic GH, or on multiple levels, resulting in hydroponic VF, and are referred to as vertical hydroponics.

Aeroponics: Aeroponics is a variation of hydroponics in which the roots of plants are sprayed with mists or nutrient solutions. An aeroponic system is a closed-loop air–water–nutrient setup that enables rapid plant growth using minimal water and direct sunlight, without the use of soil or other growing media. The key distinction is that hydroponics relies on water as the growth medium, whereas aeroponics uses no growth medium at all.[21].

Aquaponics: Aquaponics combines the cultivation of plants and fish and can be considered as a closed-loop system [56]. In this system, the nutrient-rich water from the fish tanks is used to fertilize plants, and the plant cycle is equivalent to a hydroponic system.

These systems have different challenges and limiting factors, to name a few examples: supplemental lighting is fundamental for year-round production of vegetables at high latitudes [48], which results in high operating costs [57] and energy consumption [54], robust and resilient business models are still under development to address these issues [21]. Table A 4 in Appendix B provides a more detailed overview of the publications studied in the context of technologies for urban food production.

Challenges and Potentials of Urban Farming

Urban farming is increasingly seen as a viable solution to challenges related to local food security, land scarcity, and climate mitigation strategies. The subsequent discussion will provide a more detailed examination of the various forms of urban farming to assess their potential use under different conditions, such as location, built environment, and the land/buildings typologies that can be allocated for food growing.

It discusses the advantages and disadvantages of each form and the evaluation focuses on three key dimensions: (1) area needed to implement such systems, (2) energy consumption of the different cultivation methods and (3) expected yield.

A significant contribution to the understanding of agricultural technology in urban contexts is provided by Parkes et al. (2022) in the publication “*Narratives and Benefits of Agricultural Technology in Urban Buildings: A Review*”. The study represents one of the most comprehensive

and systematic attempts to compile empirical information on Controlled Environment Agriculture (CEA) and soilless growing systems applied within or on urban buildings and open land in an urban context.

Through an extensive literature review spanning the period from 2015 to 2022, the authors examined the diversity of technological solutions employed in UA, identified prevailing narratives regarding their environmental benefits, and critically assessed the availability of peer-reviewed data to substantiate these claims.

Geographically, the study demonstrated a strong concentration of installations in high-income regions. The majority were located in North America (33 sites), followed by Europe (26 sites) and Asia (nine sites, including one in Australia). This spatial distribution reflects the reliance of CEA systems on significant capital investment and access to venture funding, which is more readily available in economically developed contexts. Prominent examples include Gotham Greens and Lufa Farms in North America, Infarm and PlantLab in Europe, and Sky Greens in Asia. These cases illustrate a global trend in which advanced agricultural technology solutions are concentrated in regions with both the financial and infrastructural capacity to sustain them.

The work of Parkes et al. (2022) provides a valuable conceptual and empirical foundation for subsequent studies on urban agricultural technologies. It establishes a structured framework for analyzing urban farming systems by environment type, facility type, growing and cultivation system, and integration within the urban environment. While in the review study, initially 124 installations were identified, the authors excluded 56 sites in the final analysis because they were no longer in operation or had a website domain which was not active any more. For this work, the complete dataset of 124 sites served as the starting point.

By expanding the scope of the search, possible correlations between variables such as farm size, type, method of cultivation and date of closure were explored.

Each location in the original review study was re-examined through separate internet research and deep AI search. The data set was supplemented with an exploration of the following parameters: (i) whether the facility was still in operation in 2025 and geographical coordinates, (ii) cultivation methodologies mapped to Table 2 categories, the dimensions of the facility in square meters, and the final consumer price for products and energy use.

The following steps were taken to accomplish this objective:

1. Checking the website to see if it was still active and how accurate the information provided on the website was.
2. In the event of discrepancies on the website, more detailed research was conducted to determine whether online sources could be found that would confirm the closure of the facility or the entire company.

This was done to obtain the most accurate overview possible of when the company ceased its business activities. Given the rapid fluctuations in food prices, the food price for certain products merely serves as a metric to assess the extent of disparity in comparison to conventional food items. Specifically, if energy expenditures can be reduced, e.g., through the implementation of novel and more efficient technologies, a cost adjustment to market prices can be anticipated.

Based on the subset of the Parkes et al. (2022) site inventory updated to 2025, 97 sites worldwide were identified for the purpose of this work. Semi-controlled systems account for the largest share (46 sites; 47%), followed by fully controlled plant-factory systems (34 sites; 35%). Unconditioned outdoor approaches represent a smaller portion (15 sites; 15%), while hybrid cases remain rare (two sites; 2%).

Across categories, distinct technological and spatial patterns are evident. Fully controlled sites are primarily located in building structures (65%) and rely entirely on soilless cultivation (97%), dominated by hydroponics (65%) and aquaponics (24%). Semi-controlled systems are overwhelmingly greenhouse-based (100%) and are typically situated on open land (63%) or rooftops (35%); they likewise favor soilless cultivation (98%). By contrast, unconditioned systems are predominantly rooftop-based (73%) and mainly soil-based (73%) among cases with known growing-system data.

Differences also emerge in scale and operational continuity. Semi-controlled sites show the largest typical footprint (median 6,968 m², Interquartile Range (IQR) 1,289–19,510 m²), compared with fully controlled systems (median 1,195 m², IQR 88–5,028 m²) and unconditioned outdoor sites (median 790 m², IQR 216–1,527 m²). In the 2025 status update, semi-controlled operations showed the highest continuation rate with 41 out of 46 still in operation, whereas fully controlled systems exhibited higher closure (14 out of 33 in operation).

Restricting the analysis to North America data only (n = 61), semi-controlled systems accounted for the largest share (35 sites; 57%), followed by fully controlled plant-factory systems (15 sites; 25%) and unconditioned outdoor approaches represented a smaller portion (10 sites; 16%).

Across categories, distinct technological and spatial patterns were evident. Fully controlled sites were primarily located in building structures (60%) and relied entirely on soilless cultivation (100%), dominated by hydroponics (53%) and aquaponics (40%). Semi-controlled systems were overwhelmingly greenhouse-based (100%) and were typically situated on open land (69%) or rooftops (31%); they likewise favored soilless cultivation (97%). By contrast, unconditioned systems were predominantly rooftop-based (70%) and mainly soil-based (90%) among cases with known growing-system data.

Differences also emerged in scale and operational continuity. Semi-controlled sites showed the largest typical footprint (median 9,290 m², IQR 1,951–19,510 m²), compared with fully controlled systems (median 2,044 m², IQR 118–5,110 m²) and unconditioned outdoor sites (median 465 m²,

IQR 156–894 m²). In the 2025 status update, semi-controlled operations showed the highest continuation rate (31 out of 35 in operation), whereas fully controlled systems exhibited higher closure (5 out of 15 in operation).

Table 3 - Table 6 shows a summary of the results for all cases studied and for farms in North America only.

Table 3 Method of cultivation CEA system, group size and operational status (2025): All cases vs. North America

	All Cases		North America	
	Group size	In operation 2025	Group size	In operation 2025
Semi-controlled	46/97 (47%)	41/46 (89%)	35/61 (57%)	31/35 (89%)
Fully controlled	34/97 (35%)	14/33 (42%)	15/61 (25%)	5/15 (33%)
Unconditioned	15/97 (15%)	11/14 (79%)	10/61 (16%)	7/10 (70%)
Hybrid	2/97 (2%)	2/2 (100%)	1/61 (2%)	1/1 (100%)
TOTAL	97 total		61 total	

Table 4 Method of cultivation CEA system, size in m²: All cases vs. North America

	All Cases	North America
	Size m ² (median; IQR)	Size m ² (median; IQR)
Semi-controlled	median 6,968; IQR 1,289–19,510 (n=46)	median 9,290; IQR 1,951–19,510 (n=35)
Fully controlled	median 1,195; IQR 88–5,028 (n=30)	median 2,044; IQR 118–5,110 (n=14)
Unconditioned	median 790; IQR 216–1,527 (n=15)	median 465; IQR 156–894 (n=10)
Hybrid	median 22,399; IQR 17,099–27,700 (n=2)	median 11,799; IQR 11,799–11,799 (n=1)

Table 5 Method of cultivation CEA system vs. facility type: All cases vs. North America

	All Cases Facility Type				North America Facility Type			
	Greenhouse	Warehouse	Shipping container	In building	Greenhouse	Warehouse	Shipping container	In building
Semi-controlled	46/46 (100%)	0/46 (0%)	0/46 (0%)	0/46 (0%)	35/35 (100%)	0/35 (0%)	0/35 (0%)	0/35 (0%)
Fully controlled	0/34 (0%)	27/34 (79%)	4/34 (12%)	3/34 (9%)	0/15 (0%)	10/15 (67%)	2/15 (13%)	3/15 (20%)
Unconditioned	0/15 (0%)	0/15 (0%)	0/15 (0%)	0/15 (0%)	0/10 (0%)	0/10 (0%)	0/10 (0%)	0/10 (0%)
Hybrid	2/2 (100%)	0/2 (0%)	0/2 (0%)	0/2 (0%)	1/1 (100%)	0/1 (0%)	0/1 (0%)	0/1 (0%)

Table 6 Method of cultivation CEA system vs. growing system: All cases vs. North America

	All Cases Growing System				North America Growing System			
	Hydroponics	Aquaponics	Aeroponics	Soil	Hydroponics	Aquaponics	Aeroponics	Soil
Semi-controlled	36/46 (78%)	9/46 (20%)	0/46 (0%)	1/46 (2%)	30/35 (86%)	4/35 (11%)	0/35 (0%)	1/35 (3%)
Fully controlled	22/34 (65%)	8/34 (24%)	3/34 (9%)	1/34 (3%)	8/15 (53%)	6/15 (40%)	1/15 (7%)	0/15 (0%)
Unconditioned	2/15 (13%)	2/15 (13%)	0/15 (0%)	11/15 (73%)	0/10 (0%)	1/10 (10%)	0/10 (0%)	9/10 (90%)
Hybrid	1/2 (50%)	1/2 (50%)	0/2 (0%)	0/2 (0%)	1/1 (100%)	0/1 (0%)	0/1 (0%)	0/1 (0%)

The indicative ranges reported in Table 7 - Table 9 draw on a combination of evidence from Parkes et al. (2022) and additional values compiled through the present study's desk-based update and targeted online research (2025). Since information regarding energy consumption, costs, and yield varies greatly, the tables summarize representative ranges rather than uniform measurements from a single data set. Their purpose is to provide a comparative overview of how major urban food-production technology classes differ with respect to energy intensity, yield potential, and indicative production costs, thereby supporting cross-technology benchmarking and trade-off assessment under different urban deployment conditions.

Table 7 Indicative energy intensity of urban food-production technologies (kWh per kg of product)

Technology	Energy Use (kWh/kg)	Key Drivers
Vertical Farm	250–350	LED lighting, HVAC load
Container Farm	200–300	Artificial lighting, compact design
Greenhouse	30–80	Climate control, solar gain
Community Garden	<10	Manual labor, no artificial systems

Fully controlled environments are the most energy-intensive due to artificial lighting and environmental regulation, but they offer year-round production. Semi-controlled systems (greenhouses) achieve lower energy intensity by utilizing natural light and ventilation, particularly in mild climates.

Table 8 Indicative yield potential of urban food-production technologies (kg per m² per year)

Technology	Yield (kg/m ² /year)	Main drivers
Vertical Farm	80–120	Multilayer hydroponic cultivation
Container Farm	50–80	Compact, modular production
Greenhouse	20–40	Seasonal variations
Community Garden	3–10	Soil limitations, unregulated environment

Vertical systems optimize space use and achieve the highest productivity per footprint, making them particularly relevant in dense urban cores.

Table 9 Indicative production cost ranges of urban food-production technologies (CAD/kg)

Technology	Estimated final consumer Costs (CAD/100g)	Main Cost Factors
Vertical Farm	3.5–6.0	Energy, automation, capital cost
Container Farm	4.0–7.0	Equipment, maintenance
Greenhouse	1.0–2.5	Heating, labor
Community Garden	<1.0	Low input, volunteer labor

While vertical and container farms are more costly, they can be economically viable when producing high-value crops (e.g. herbs, microgreens) or integrated with renewable energy sources.

2.2.3 Literature addressing food demand and local food supply chains

Objective: *Analyze the food demand and local food supply chains (from production sales locations like supermarkets or farmer markets) as a function of the socio-economic situation at the district level.*

In total, 25 papers were identified for full-text analysis. The papers fall into two categories: (1) papers that examine the shopping behavior of different user groups, how neighborhood affects food consumption, and the impact of urban food supply on the provision of healthy food (19 papers), and (2) papers that focus on logistic and economic factors (six papers). Table 10 shows the publications of the first category and their focus topic. The socio-economic conditions are emphasized here, i.e. it is not only technical aspects that need to be considered, but also conditions such as proximity to the nearest supermarket or income level that have an impact on consumers' decisions.

Table 10 Reference and focus topic of the publications examined for the secondary-objective 2 (first category)

Reference	Focus topics
[58]	Identification of the profile of a typical online grocery shopper and mapping of factors that possibly influence consumers' decision to shop organic food online.
[59]	Individuals' food shopping behavior and activity within the retail food environment
[60]	Analysis of availability of food store outlets in the US and associations with neighborhood characteristics on race, ethnicity, and socioeconomic status.
[61]	Examine the variability in grocery shopping patterns and the factors that predict them among low-income minority women in public housing.
[62]	Investigation whether geographical location or store type was associated with healthy and unhealthy food availability in grocery stores.
[63]	Characterization of the local food environment in New York City's Washington Heights and Inwood to examine the access to healthy food for Hispanic population.
[64]	Investigation of the association between neighborhood-level economic hardship, the retail food environment, fast food consumption, and obesity prevalence.
[65]	- Relationship between the population-weighted mean distances to supermarkets - Associations of obesity and fruit and vegetable consumption with distance to supermarkets in metropolitan and nonmetropolitan areas.
[66]	Measure of food environment quality that characterizes urban neighborhoods by the relative amounts of healthy (e.g. fruits and vegetables) to unhealthy foods (e.g. energy-dense snacks).
[67]	Examine the association and variation of school neighborhood food environment and obesity across gender and urbanicity at multiple geographic scales.
[68]	Relationship between community characteristics and household food security status among elementary school children in Wisconsin
[69]	Influence of local food environments on the food provided in family child care homes and the impact on healthy food.
[70]	Neighborhood food environment and food acquisition behavior and the links to food pantry use.
[71]	- Investigation of two diet related health programs. - Social practice theory to investigate how the introduction of local food and slow cookers altered low-income individuals' food provisioning practices.
[72]	Identification of the social missions of urban farms.
[73]	- Explores food acquisition and shopping habits using multidimensional measures and examines its association with body mass index. - Identifies distinct patterns in food acquisition and shopping habits in a nationally representative sample. - Examines whether socioeconomic status, nutritional factors, and reasons underlying store choice were associated with the identified patterns. - Evaluates the association between the identified patterns and obesity.

[74]	Analysis of use of supermarkets according to socioeconomic characteristics and diet quality index-international according to supermarket use.
[75]	Examines the socio-economic characteristics and motivations of shoppers using different retail formats (large supermarkets, medium-sized supermarkets, or traditional outlets in Tunisia.
[76]	Examines the association between sociodemographic factors, physical activity engagement, and the selected food purchasing practices among people living in a low socioeconomic peri-urban and rural area of two provinces of South Africa.

The other six papers address the problem from the perspective of food logistics, economic factors, how food is produced and delivered, and how food waste can be reduced at the consumer level. Most of the publications focused more broadly on food environments and the effects different settings have on consuming healthy or unhealthy food. Prajapati *et al.* [77] focused on vehicle routing in the e-commerce industry, mainly the first-mile pickup and the last-mile delivery logistics problem. Verlinde and Macharis [78] studied the delivery of goods to supermarkets out of business hours and the willingness of stakeholders to adopt new delivery schedules. Ochoa *et al.* [79] and van der Meer [80] focused on small-scale farmers, mainly from peri-urban areas, and how they can benefit from coordinated and short food supply chains. Ma *et al.* [81] analyzed the motivational factors of farmers in China to participate in sustainable agriculture. Kölmel *et al.* [82] investigated the platform "Foodsharing", which aims to reduce food waste, focusing on the challenges of scaling such bottom-up approaches. Although various technical solutions, such as online platforms for more direct food marketing or automated route planning, are available, there are still hurdles that make it difficult for actors to implement new concepts.

2.2.4 Literature addressing spatial system dynamics

Objective: Development of a Spatial System Dynamics (SSD) model that combines geospatial information and stock flow modeling.

In total, 35 papers were identified for full-text analysis. Several methods were developed to understand the system's behavior in two ways: the spatial characteristics and the temporal behavior. Such models are designed and developed to understand and predict future urban growth [83–86], changes in the state of cells, which represent specific areas in the city or urban environment [87–91] or the interaction between individuals or groups [92–98] by linking the geographic information with some rules or simulation models.

Figure 7 shows the basic concept of a spatio-temporal simulation workflow. Field data is collected as a raster or vector layer, which describes the spatial network, and numerical data describes the properties of the cells, shapes, lines, or points. The dynamic simulation engine, which can be

simple mathematical transition rules, more complex agent-based models (ABM), or system dynamics models, takes the initially created map and calculates a new system state for each time step. The simulation result is the spatial network structure, including the state of cells, polygons, lines, or points.

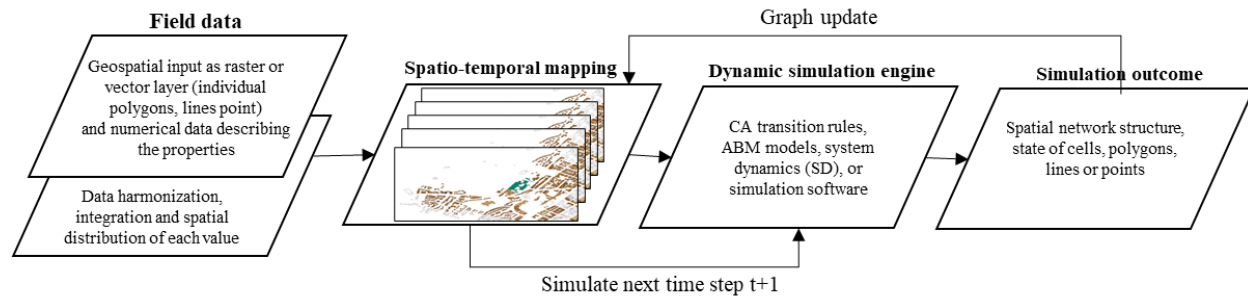


Figure 7 Basic concept of spatio-temporal simulation

Fundamental to this is that maps and data are used to give spatial context and to parameterize the models. Basically, there are two types of time and space changes: (1) objects change their state in time and space, i.e., they move on the map, and (2) cells or objects are always at the same location and change their state over time.

Several publications deal with software architecture [99–101] and optimization problems [102], the integration of more complex simulation software packages into GIS [103–105], the development of geo-games [106, 107] and geospatial participatory modeling [108]. Only one publication was in the publication collection, which considered the coupling of SD and GIS [109]. The implemented SD model uses the Vensim software package. Table A 6 in Appendix B provides a more detailed overview of the publications examined in the context of spatial system dynamics.

The literature review shows that research relevant to this thesis is divided into four areas. First, decision support systems (DSS) for urban food systems emphasize the need for tools that enable participatory processes and provide rapid, interactive feedback, while existing applications often focus either on interaction between stakeholders (using SD and/or GIS) or on narrowly defined technical assessments (often at the building level), with few approaches combining both perspectives at the urban level. Second, the literature on urban food production technologies provided detailed classifications of professionally controlled environmental systems (e.g., vertical farms, container farms, greenhouses) and community-based horticultural approaches, but also highlighted strong practical limitations, particularly the energy requirements, operating costs, and uncertain long-term profitability of high-tech urban farming, which is confirmed by the updated inventory in this work, which examined operational continuity through 2025. Third, studies on food demand, food retail, and local supply chains emphasized that the availability and accessibility

of healthy foods was strongly influenced by socio-economic conditions and purchasing behavior at the neighborhood or district level. Logistics-oriented studies often addressed new concepts and the efficient distribution of food, but rarely connected them to equitable access to food. Fourth, the literature on spatial system dynamics showed mature approaches to spatiotemporal simulation and a growing number of works on software architectures and geospatial simulation platforms, but explicit, bidirectional coupling of system dynamics with geospatial information systems was still rare.

Chapter 3. Methodology

This chapter describes the methodological workflow used in this thesis to move from the literature-based problem framing to an operational, scenario-ready analysis. The chapter clarifies how evidence from the technology review and the Montréal case study is methodologically integrated into the thesis, and documents the steps used to develop and test the Spatial System Dynamics (SSD) model, which is later applied to simulate household food insecurity at the borough level.

The chapter's structure aims to clarify the interconnection between research questions, methodological decisions, and results. Section 3.1 outlines the research design and summarizes how each research question is addressed. Section 3.2 describes the system dynamics modeling procedure and the specific steps followed to develop the SSD model. Section 3.3 presents the high-level causal loop diagram that defines the main feedback mechanisms, which is then translated into a stock-and-flow structure in the subsequent section. The technical details of the developed DSS, its implementation, and software architecture are described in Chapter 4.

3.1 Methodological approach and research design

This thesis follows a design-oriented research workflow that translates insights from the literature into an operational framework and a simulation model suitable for scenario-based decision support. The methodological approach is structured around the three research questions, each producing a specific output that aims to support decision makers in the analysis of Montréal urban food systems. An overview of the research questions, methods, data sources, and outputs is provided in Table 11.

Table 11 Mapping of research questions to methods, data sources, and outputs

Research question	Methods	Key data / sources	Output
RQ1: What urban food production technologies are available, and what key technical requirements and constraints determine their practical feasibility in cities?	Structured literature review and typology development; evidence synthesis of challenges/potentials; supplementary systematic web-based review to update and enrich the Parkes et al. (2022) installation inventory (status in 2025).	Peer-reviewed literature and reports on UA technologies; Parkes et al. (2022) inventory as baseline; publicly available site-level information (company pages, news/secondary sources) used to verify operational status and extract attributes (e.g., facility type, growing system)	Decision-support typology and feasibility assessment of UA systems to identify potential locations in urban areas.
RQ2: How does the urban food environment impact the availability and accessibility of healthy food?	Montréal case-study data integration and indicator construction; categorization of food outlets; spatial aggregation at district/borough level.	Montréal food establishment data; Census socio-economic indicators; 211 food aid requests; administrative boundaries (plus supporting spatial layers as needed).	Baseline assessment of availability and accessibility based on spatial indicators derived from Montréal datasets (food outlets, socio-economic vulnerability, food aid requests).
RQ3: How can a system model be developed to describe the interdependencies of urban food production and policy changes to increase food security for vulnerable people?	SSD model development (causal loop diagram to stock-and-flow); parameterization using case-study indicators; model checks; scenario design and simulation.	Model structure from literature; Montréal case-study inputs;	SSD model and scenarios supporting decision-making on food security interventions.

RQ1 is addressed through the structured literature review presented in Chapter 2, complemented by an additional targeted search to obtain more detailed evidence on the challenges and potentials of urban farming systems. The synthesis develops a typology of urban agriculture systems (including greenhouses, vertical farms, container farms, and community gardens) and consolidates evidence on technical requirements and constraints that determine feasibility in practice. The output of RQ1 is therefore an evidence-based feasibility assessment and classification of urban food production technologies, which serves as a decision-support framework: it structures urban agriculture systems into a clear typology and operationalizes the link to the built environment so users can explore GIS layer where the information about the buildings is stored (e.g., building typology (residential, industrial, commercial), building age, volume, etc.) and select candidate urban agriculture systems and locations.

In this thesis, the primary role of the RQ1 output is therefore not the quantification of production volumes, but the provision of a structured typology of urban agriculture system types that enables stakeholders to interactively explore built-environment GIS layers and identify suitable urban agriculture systems for specific contexts.

RQ2 is addressed through the Montréal case-study data integration and preparation workflow using the datasets described in Chapter 5. The work focuses on collecting, cleaning, harmonizing, and categorizing food supply location data and linking these layers with district-level socio-economic information, food-aid request records, and administrative boundaries. The output is therefore not a behavioral or causal analysis of access, but a spatially consistent and decision-support-ready baseline dataset that allows stakeholders to explore the urban food environment and its socio-economic context and provides a robust empirical basis for subsequent scenario design and interpretation.

RQ3 is addressed by developing a Spatial System Dynamics (SSD) model that integrates the main mechanisms identified in the literature and the case study. The SSD model formalizes feedback structures and time dynamics, enabling scenario analysis of interventions that affect food access, availability, and food security outcomes. The model does not aim to calculate crop yields or exact production volumes; instead, the influence of urban food production is represented in aggregated form through the development of local production capacity (e.g., as the growth of urban agriculture) and its effects within the geographical accessibility subsystem.

The remainder of this chapter outlines the methodological steps used to develop the SSD model and introduces relevant model parameters. In addition, Chapter 4 introduces the Design Science Research Methodology (DSRM) as the overarching methodology guiding the development and evaluation of the thesis artifacts (in particular, the decision support system).

3.2 System dynamics as modeling method

This section introduces system dynamics as the core modeling method and summarizes how it is applied to develop the SSD model. The model is developed within the software Vensim in the PLE Plus version. The highest level of the model description is the Causal Loop Diagram (CLD), where causal links among the variables are represented and balancing and reinforcing mechanisms are described. Based on the CLD, the stock and flow models for the subsystems are developed. In the model, stocks are represented as countable entities and are elements of the built environment, representing the links between system dynamics models and GIS data. The stocks in the model track the accumulation of food-selling points, points of public transport, and food-production points such as urban farms in the area of interest. The model is comprised of three interconnected sub-systems, which consider elements of geographical accessibility, household finances and resources and household circumstances. Reinforcement loops in the model are primarily identified in loops containing stock elements, such as the number of supermarkets and healthy food stores. The model is used to compare different urban areas and to derive strategies to increase food security. Detailed documentation of the model, including a description of each variable and its rationale, the main equations, integration of the datasets, and the assumptions on the dynamic behavior of the model, can be found in Appendix C.

The development of an SD model is not a linear process and can be divided into six individual steps, as shown in Figure 8.

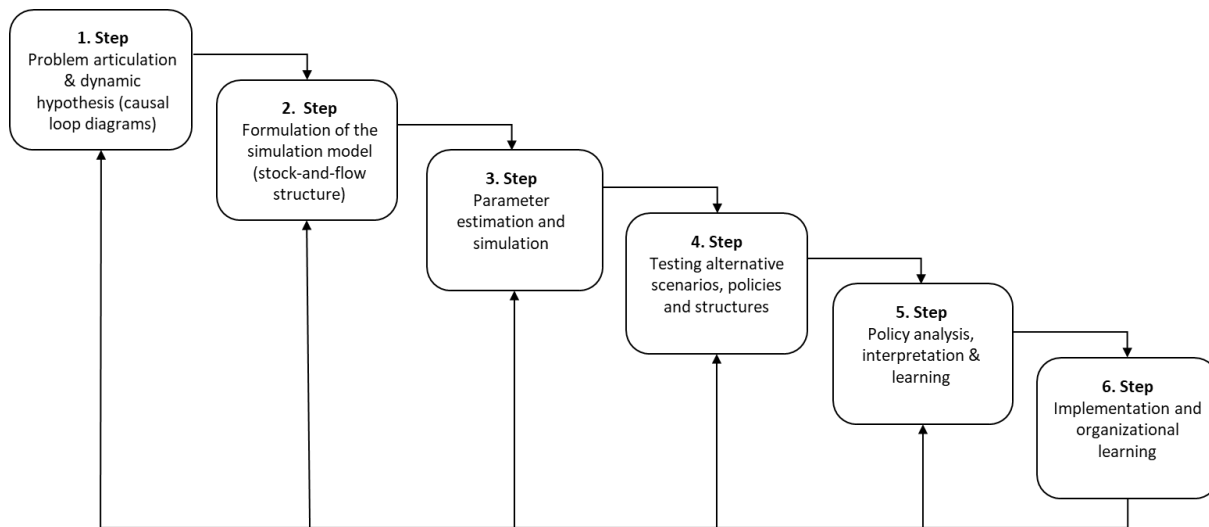


Figure 8 The six steps to develop a system dynamics model adapted from [22]

In the first step, the environment under investigation is described in a CLD. The CLD helps to describe and understand if the model addresses the research questions and formulates the main

dynamics in the system. Once the model reaches a certain stage of detail, it is transferred into a stock and flow model. With the stock and flow model, the first analysis of the system behavior can be performed. Testing restrictions in the presence of a known model behavior provides a preliminary insight into its functionality.

To illustrate this, we can think about the scenario of determining the impact of the opening hours of supermarkets, restaurants, and/or grocery stores on access to food. In the event of the opening hours being set to zero, access to food is effectively eliminated. In essence, the absence of operational retail establishments results in the inability to acquire food.

Following the initial testing of the model behavior, the next step is the model parameterization phase. The model parameterization facilitates the initial assessment of the magnitude of the values calculated by the model. This process provides further insight into the model's behavior, simultaneously revealing any inconsistencies within the model.

The fourth step in the process involves the modeling of scenarios. In this phase, a range of scenarios can be simulated, with the focus on learning from the model. The implementation of diverse scenarios facilitates the formulation of strategies to achieve the desired outcome.

The fifth and final step in the research process is to discuss the results. As part of the analysis, the results obtained are checked for plausibility and explained. However, the implementation of the scenarios in the real world is no longer part of the research process.

Based on the Design Science Research Methodology (DSRM), the SSD model was developed by first analyzing existing literature from the perspective of the applicability of the models described to the topic of urban food security.

There are several SD models published, which take food security into account to a certain degree [110–113], but none of them adequately describes how spatial urban objects can be integrated into system dynamics simulation. The model closest to the objective of the thesis currently published is the model developed by Sawyer *et al.* [112]. The authors presented a system map with five subsystems (SS1-5) to identify the system dynamics that maintain and reinforce a food environment that influences dietary intake in low-income groups. The subsystems are presented as causal loop diagrams, as the subsystems may have the same elements or feedback loops; they are interlinked. The system presented is organized around four dimensions of the food environment: accessibility, availability, affordability, and acceptability. Figure 9 shows the developed system map, including the five sub-systems.

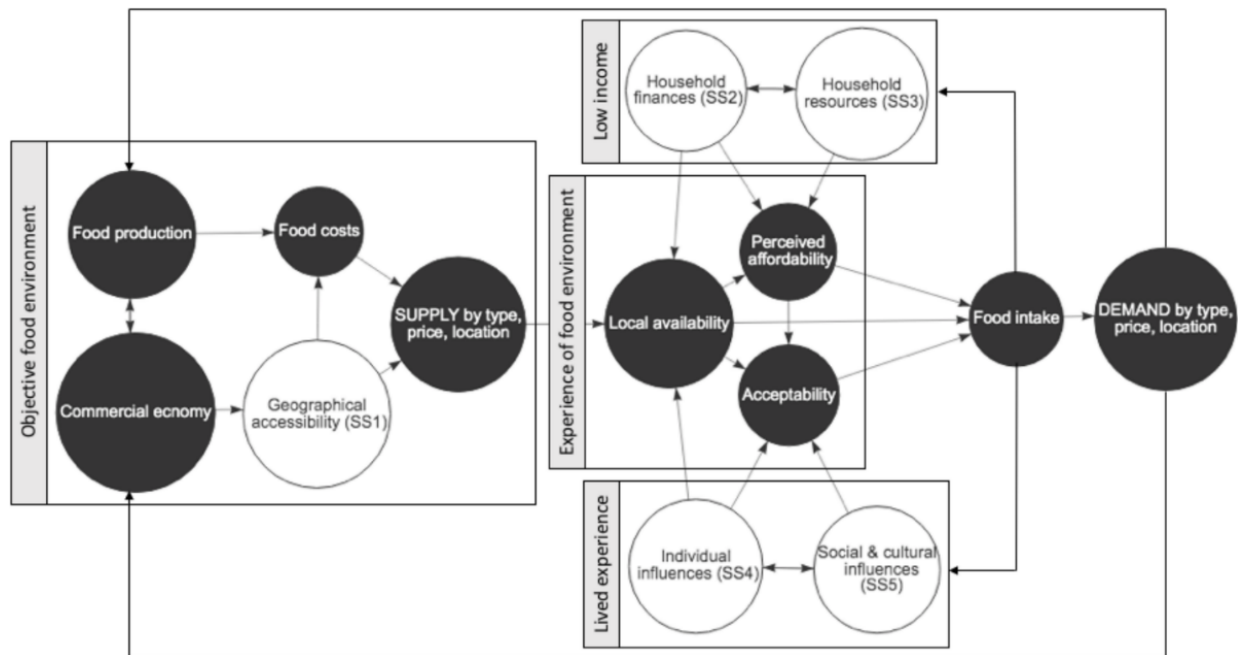


Figure 9 Overview of system driving food intake in low-income groups [112]

The geographical accessibility subsystem (SS1) describes the interplay between the food environment and geographical access. Elements like local market pressure to provide more healthy foods within an area, supermarket and healthy food store density or accessibility of healthy food in the local area are elements of the subsystem. SS2 and SS3 focus on the finances and resources at the household level. Household finances are influenced by vulnerability to fluctuations in living costs and costs of living. In SS4, the interplay between the food environment and individual influences of people is modeled, including elements like cooking skills, nutrition knowledge, or learned preferences for healthy food. The last subsystem, SS5 focuses on the links between food environments and social and cultural influences. The model describes the relationships between the food system in which people live and its impact on food insecurity in a comprehensive way.

However, it also has limitations: with the existing model, it is not possible to simulate the influence of various policy measures. The model developed by Sawyer *et al.* [112] is presented as a causal loop diagram, which provides valuable insights into the complex interrelations and feedback mechanisms between elements of the food environment. While this representation captures the structure of the system and highlights the key drivers and reinforcing mechanisms, it remains qualitative in nature. Consequently, it does not allow for quantitative analysis or the simulation of dynamic behavior over time, limiting its ability to evaluate the impact of policy interventions such as improved accessibility through better public transport, strategies to open supermarkets or ban fast-food outlets in specific areas, or reducing the costs of living.

Nevertheless, the model serves as an excellent starting point. It offers a comprehensive, literature-based overview of the major determinants influencing dietary intake within low-income populations and organizes them across the four dimensions of the food environment: accessibility, availability, affordability, and acceptability. Building upon this conceptual foundation, the system dynamics model developed in this thesis extends the qualitative structure into an executable stock-and-flow model. This transformation enables quantitative simulation and dynamic analysis, allowing the investigation of how changes in policies, environmental conditions, or socio-economic factors evolve over time and influence food security outcomes.

Based on this approach, the SSD model developed in this work builds upon the principles of Sawyer *et al.* [112] while introducing new structural components that integrate spatial data and quantify feedback effects across three interconnected subsystems.

To be able to do this, the model needs to be expanded in various ways. It is necessary to transform the existing CLD into a stock and flow model, assigning the stocks to exact elements from the physical infrastructure of a city, and to develop the corresponding equations that are incorporated into the model for each element. Only then is it possible to perform calculations.

As the SSD model aims to gain better insights into the links between the physical built environment people live in and household food insecurity, it includes three sub-systems. ***(1) the subsystem of geographical food accessibility, (2) the subsystem of household finances, and (3) household circumstances.*** It does not contain elements on a personal level, like the food or health literacy of individuals. It is therefore a model that is particularly suitable for studies at the district level and focuses on the impact at the household level. It aims to capture the causal structure of local food systems with essential feedback loops and with (degrees of) stock-flow consistency.

The following assumptions are made to be able to do this:

- Stocks are countable entities and elements of the built environment that connect system dynamics models with GIS data.
- Dimensions of the food environment (accessibility and availability) are connecting KPIs for policy making.
- Flows change the stocks, and parameters change the flows, which are elements that can be used to develop strategies to improve equitable access to healthier food.

3.3 High-level conceptual model

Figure 10 shows the high-level conceptual model. The color and symbols of the arrows represent the relationships between the elements. The arrows are used to indicate the causal relationships between the two variables. The direction of the arrows indicates the direction of causality, i.e., from the cause variable to the influenced variable. The polarity between the variables is denoted by a positive (+) or negative (-) sign. A positive polarity indicates that the influencing variable moves in the same direction as the cause variable, which may be an increase or a decrease. It is imperative that both variables move in the same direction. Conversely, a negative polarity indicates that the variable being influenced moves in the opposite direction to the causal variable.

In an SD model, there are two types of feedback loops, balancing and reinforcing loops.

- **Balancing feedback loop:** a feedback loop in which the resultant effect of the causal links over time limits or constrains the movement of variables. Balancing loops seek equilibrium, trying to bring stocks to a desired state and keep them there. Also called a negative, compensating, goal-seeking or controlling feedback loop [114].
- **Reinforcing feedback loop:** a feedback loop in which the sum effect of the causal links tends to strengthen (reinforce) the movement of variable values in a given direction due to positive feedback [114].

The conceptual model reveals a food system characterized by deep interdependencies between infrastructure, economic behavior, retail dynamics, and individual decision-making. Rather than functioning as isolated variables, key factors such as transport access, income level, food availability, and consumer choice are linked through a series of feedback loops, some feedback loops act to stabilize the system (balancing loops), while others serve to amplify changes once they begin (reinforcing loops). At a systemic level, the model demonstrates how constraints in one domain, such as high living costs, inadequate public transport, or limited food retail density, can cascade through the system and reduce access to healthy food, particularly for vulnerable populations. These effects are often compounded by adaptive behaviors at the household level, such as the adoption of low-cost, nutrient-poor diets or reduced food purchases. While these behaviors may help households maintain short-term financial stability, they frequently undermine long-term health outcomes and reinforce structural inequities.

At the same time, the model identifies opportunities for system-wide transformation through self-reinforcing feedback loops. For instance, investments in urban food production or the strategic expansion of healthy food retail outlets can stimulate local demand, reshape perceptions of affordability, and increase the overall availability of healthy foods. These reinforcing loops offer significant potential to build momentum toward healthier, more equitable food systems, provided they are supported by enabling policies and initial investment.

Taken together, the systemic view reveals that food access is not merely a function of availability, but rather the outcome of complex, interrelated conditions shaped by policy, infrastructure, economics, and social behavior. As such, effective interventions must be systemic in scope and coordinated across multiple domains.

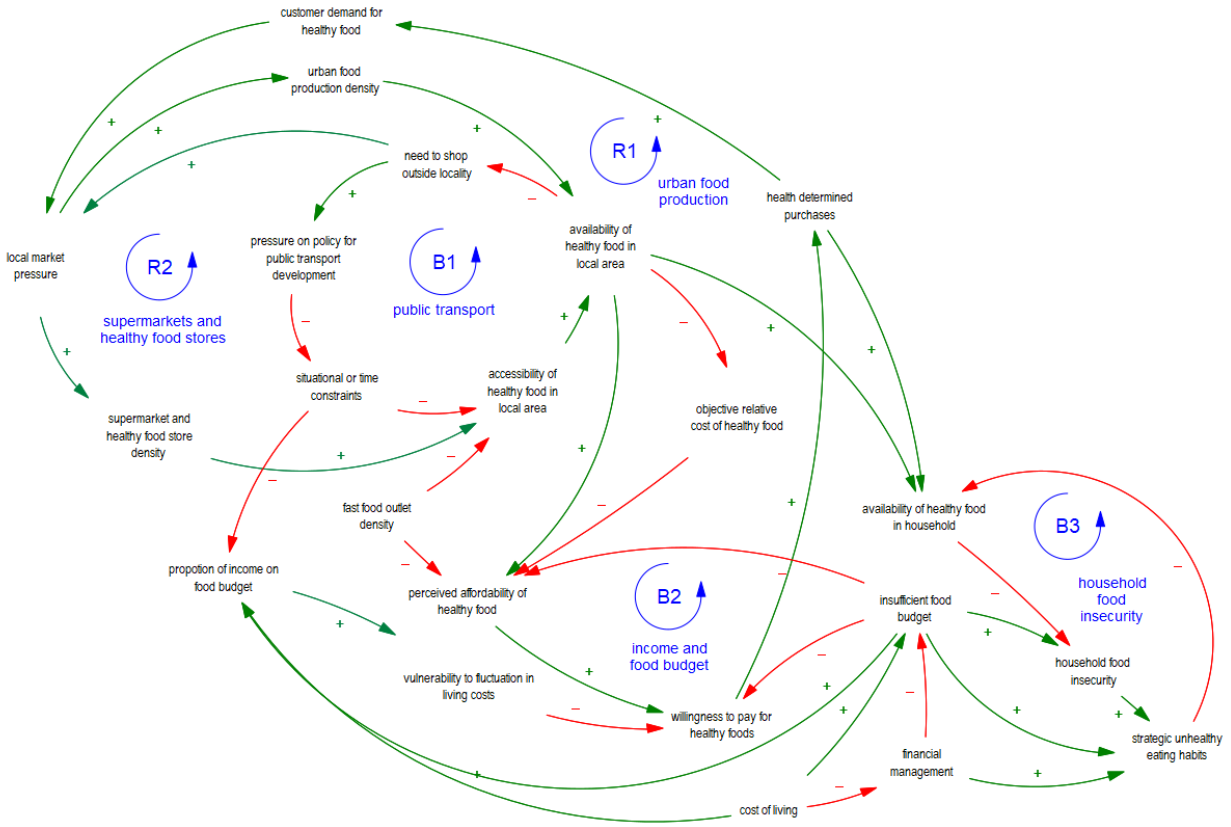


Figure 10 High-level Causal Loop Diagram (CLD) of the developed Spatial Food Systems Model

Following established system-dynamics practice as presented by John D. Sterman [22], the prominent feedbacks in Figure 10 are numbered and named B1–B3 for balancing loops and R1–R2 for reinforcing loops. The numbering and concise labels should help the readers and stakeholders to navigate through the main causal structures. The identifiers assigned to these loops (e.g., B1, R2) function as bookmarks rather than as a ranking of importance, while the names summarize each loop’s function in policy-relevant terms (e.g., public transport [B1], income and food budget [B2], household food insecurity [B3], urban food production [R1], supermarket and healthy food stores [R2]).

The high-level CLD was strategically abstracted; secondary links, pure parameters, and details within the subsystems were omitted to highlight the essentials. The subsequent subsections are devoted to an in-depth examination of the predominant mechanism within the balancing and reinforcing loops.

3.3.1 Public transport – balancing loop (B1)

The balancing loop B1 (public transport) describes a policy-driven mechanism that can stabilize access to healthy food when local conditions worsen. In the overarching causal loop diagram, this loop is presented as an abstraction: it deliberately simplifies the detailed stock and flow dynamics of public transportation in order to highlight the central causal mechanism and make the feedback structure easier to understand. Importantly, the loop does not determine whether healthy food stores physically exist in the area. The physical presence and development of supermarkets and healthy food stores is primarily described by the reinforcing loop R2 (supermarkets and healthy food stores). The variable need to shop outside a given locality is connected to both loops: it increases when local availability is low (a consequence of limited local retail supply as represented in R2), and it also acts as a trigger for public transport-related policy responses in B1.

The cycle is activated when the availability of healthy food decreases. A decrease in local availability increases the need to shop outside the locality (negative relationship), as households must travel to obtain healthy food. As more people rely on shopping outside the locality, pressure on policymakers to expand public transportation increases (positive relationship). In the diagram, this policy response is represented as a reduction in situational or time constraints (negative relationship), reflecting the idea that improved public transportation can reduce the time, effort, and mobility barriers associated with food shopping. Fewer situational or time constraints improve the physical accessibility of healthy food (negative relationship between constraints and accessibility), which in turn increases the availability of healthy food in the local environment (positive relationship). As local availability improves, the need to shop outside the community decreases (negative relationship), closing the circle.

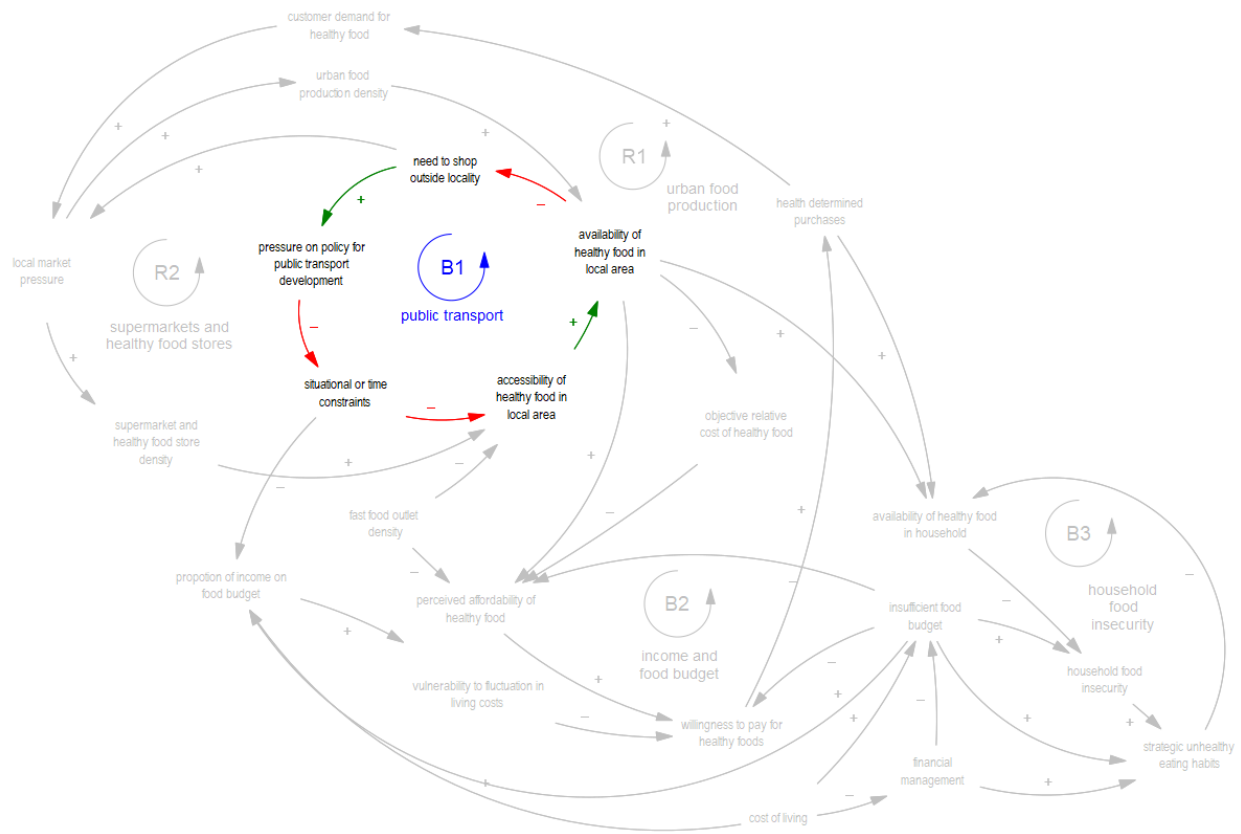


Figure 11 Balancing loop (B1) focusing on public transport and food accessibility

Possible interventions to improve food availability:

- Enhance public transport affordability and transport station density, particularly in underserved neighborhoods.
- Support policies that reduce time constraints, such as flexible work hours or expanded retail hours.
- Invest in infrastructure that promotes local food demand, including small markets and community-supported agriculture close to transport nodes.
- Prioritize policy agility, ensuring transport development can respond to real-time shifts in public need.

3.3.2 Income and food budget – Balancing loop (B2)

Balancing loop B2 focuses on how economic constraints, particularly household income, cost of living, and food budget limitations, interact with food purchasing behavior to influence access to healthy food in local communities. This loop highlights a self-regulating system that works to maintain balance, but often at the cost of food security and health equity.

Vulnerability to fluctuations in living expenses is a key element in this balancing loop. As living costs rise, more income must be allocated to cover basic needs, shrinking the budget available for food. This limited budget reduces individuals' willingness to pay for healthy foods, as healthier options are often perceived (and sometimes priced) as more expensive. A lower willingness to pay leads to fewer health-determined purchases, reducing the demand for healthy food in local markets.

As demand declines, the availability of healthy food in local area decreases, either because retailers reduce healthy stock, or because such outlets close altogether. This decline forces residents to shop outside their locality, introducing new situational and time constraints.

These constraints further increase the proportion of income spent on food, either due to higher prices, longer travel distances, or fewer cost-saving opportunities. This, in turn, heightens a household's vulnerability to economic shocks.

This is a self-limiting (balancing) loop, meaning the system reacts to disruptions by stabilizing itself, but often in a way that limits positive change. In this case, as food costs rise or income falls, the system balances by reducing access and consumption of healthy food, rather than correcting the underlying income inequality or cost burden.

In effect, the loop constrains a household's ability to improve dietary habits, particularly in low-income settings where budgets are already stretched thin.

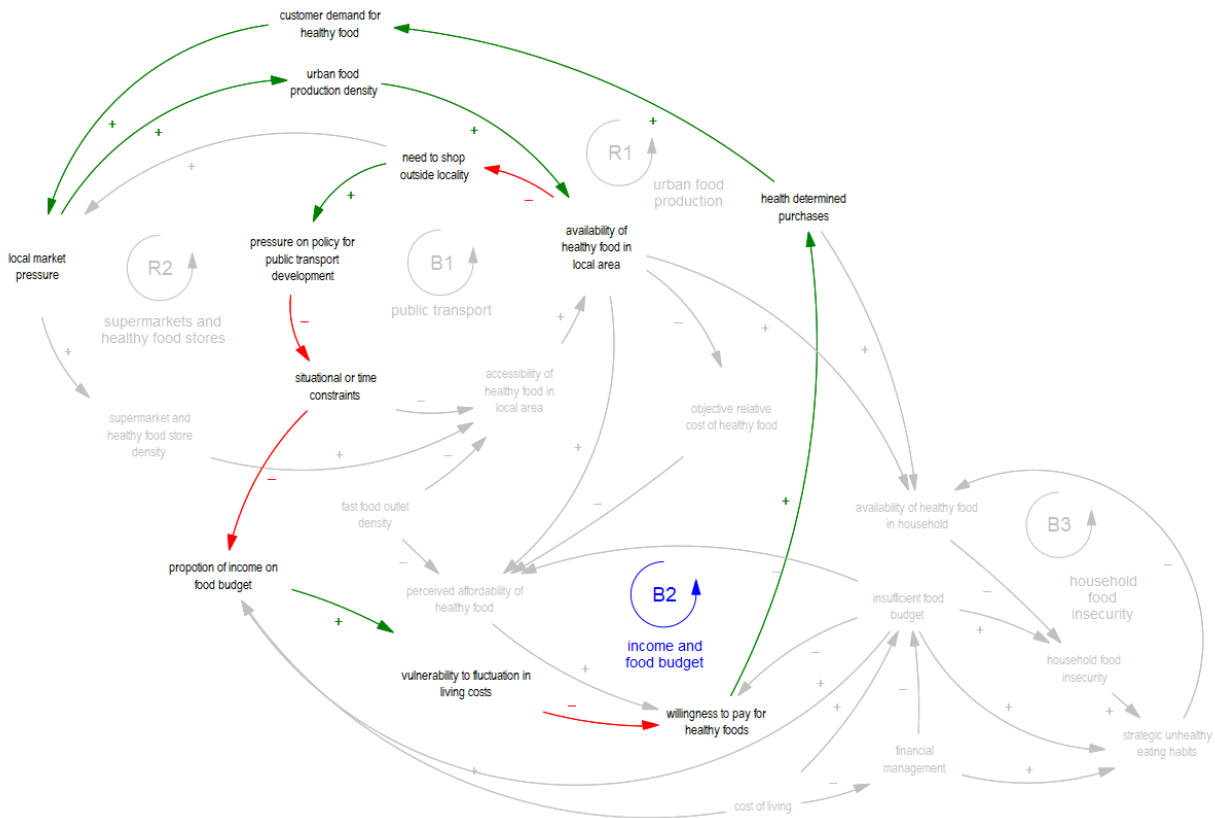


Figure 12 Balancing loop (B2) focusing on income and food budget

Possible interventions to improve income and food budget constraints:

This loop reveals how financial instability is a major barrier to healthy food access. Without sufficient income or budget flexibility, households are trapped in a cycle of reduced access, lower demand, and declining availability.

To disrupt this loop in a constructive way, interventions should focus on.

- Enhancing food affordability (e.g. subsidies, price caps, discount programs).
- Increasing household income or reducing living costs (e.g., housing, utilities).
- Strengthening food purchasing power through policies like universal basic income, food assistance, or price support.
- Improving local access to reduce the need for travel and time-intensive shopping.

By addressing the root cause of income-based constraints, this loop can be transformed from a barrier into a foundation for an equitable, sustainable, and health-supporting food system.

3.3.3 Household food insecurity – Balancing loop (B3)

Balancing loop B3 captures the complex and often difficult decisions households make when facing food insecurity due to economic hardship, rising living costs, and limited access to healthy food. This loop represents a self-regulating system in which households adjust their food consumption and financial behavior to stabilize access to food, often through short-term trade-offs with long-term health implications.

At the center of the loop is the availability of healthy food in the household, which is directly influenced by the availability of healthy food in the local area and by household food purchasing behavior. When local availability is low or the household budget is insufficient, the availability of healthy food in the household declines, leading to a rise in household food insecurity.

As food insecurity intensifies, households often respond with strategic, unhealthy eating habits, such as buying cheaper, calorie-dense, low-nutrient foods, reducing meal portions, or skipping meals entirely [115]. These are survival strategies intended to stretch limited resources.

Such behavior can help households temporarily manage their finances, improving financial management and relieving pressure on their food budget. If successful, this financial adjustment can partially improve food availability, stabilizing food insecurity in the short term.

In this way, the loop balances itself, when food insecurity increases, households employ cost-saving strategies to regain control over their situation. However, the balancing comes at a cost, nutritional quality and health outcomes are often compromised to achieve financial relief.

As a balancing loop, B3 represents an effort by the household system to self-correct in response to food stress. However, the strategies used to restore balance, such as unhealthy eating patterns, are not sustainable and may lead to diet-related non-communicable diseases, including obesity, diabetes, hypertension, and cardiovascular diseases [116]. Thus, while the loop achieves short-term stabilization, it can inadvertently reinforce long-term vulnerability, particularly for low-income families, elderly individuals, and those with limited access to affordable, healthy food.

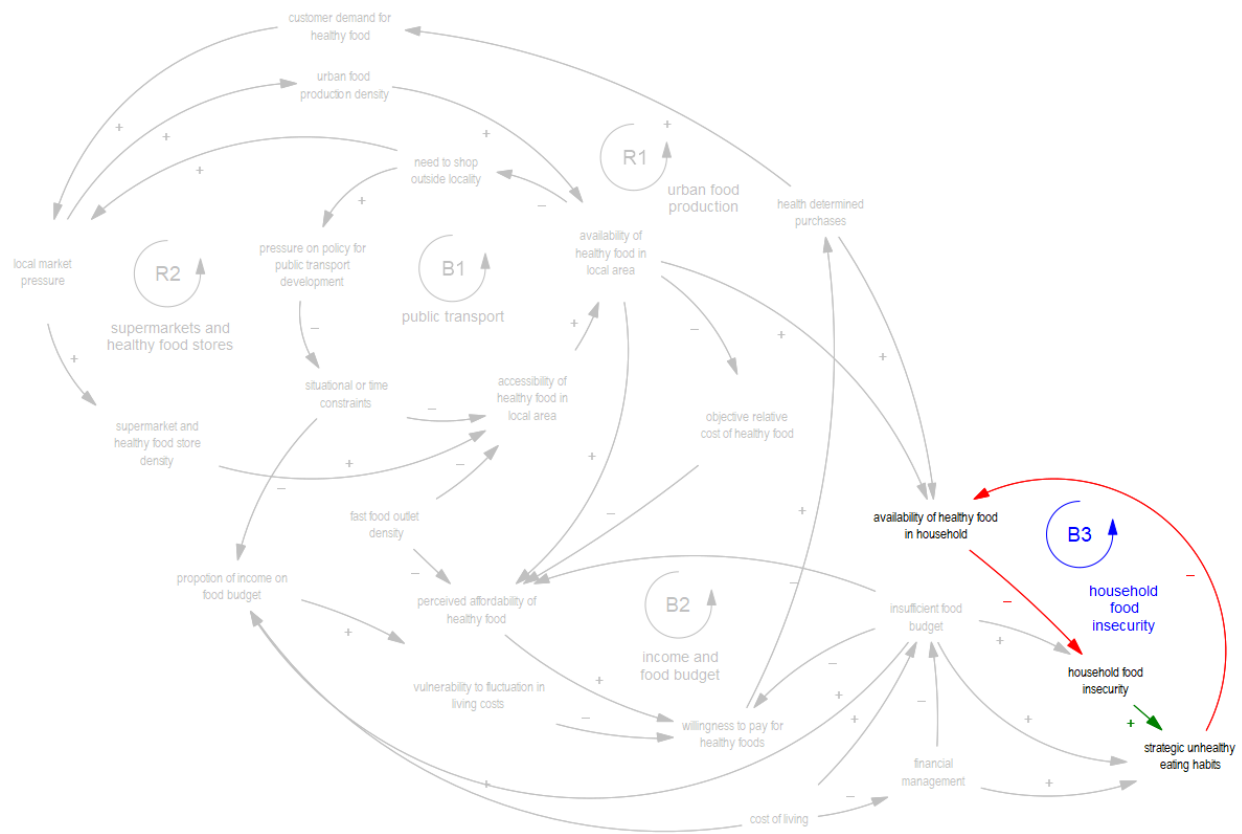


Figure 13 Balancing loop (B3) focusing on household food insecurity

Possible interventions to improve household food insecurity:

This loop highlights the tension between survival and well-being in food-insecure households. To prevent the need for harmful coping strategies and support long-term food security, targeted interventions are needed at several leverage points.

- Strengthen household food budget through income support, food assistance programs, and cost-of-living relief.
- Promote affordable access to healthy food, especially in underserved areas.
- Improve financial literacy and resource management, helping households plan and prioritize spending without sacrificing nutrition.
- Integrate health and social services, recognizing food insecurity as both an economic and public health issue.

Balancing loop (B3) reveals how households facing food insecurity strive to maintain stability in the face of financial constraints. However, without structural support, these efforts often come at

the cost of diet quality, health, and long-term resilience. A sustainable response requires policies that address not only the availability of healthy food but also the economic and behavioral realities that shape household decision-making under stress.

3.3.4 Urban food production – Reinforcing loop (R1)

The urban food production reinforcing loop (R1) describes a positive feedback system where an increase in one variable leads to a chain reaction that further amplifies the original change. This reinforcing feedback loop illustrates how urban food production can play a pivotal role in shaping the availability, affordability, and demand for healthy food in local areas. As a self-reinforcing system, the dynamics within this loop support a cycle where improvements in one part of the food environment generate momentum for further positive change.

The loop begins with an increase in urban food production density through mechanisms such as community gardens, rooftop farms, vertical indoor farms, or small-scale urban farming initiatives. As urban production grows, the availability of healthy food in the local area increases, making it easier for residents to access fresh and nutritious options close to home. Improved availability supports more health-determined purchases as residents are empowered to choose foods based on nutritional value rather than convenience or proximity alone. These choices, in turn, enhance consumers' willingness to pay for healthy food, driven by increased awareness of their benefits and greater satisfaction with access and quality.

This rising willingness contributes to a higher perceived affordability of healthy food, as healthier options become more normalized and competitive in the local market. In response, local market pressure grows, encouraging vendors and producers to further expand healthy food offerings. This intensified demand leads to increased customer demand for healthy food, which feeds back into strengthening the initial conditions of urban food production density.

This is a classic positive feedback loop, each amplifies the next, resulting in a cycle that can build momentum over time. As more healthy food is produced locally, the system supports itself by generating increasing demand and willingness to invest in nutritious food options. This loop has the potential to transform urban food environments, but only if initial barriers such as land access, startup costs, and policy restrictions are addressed.

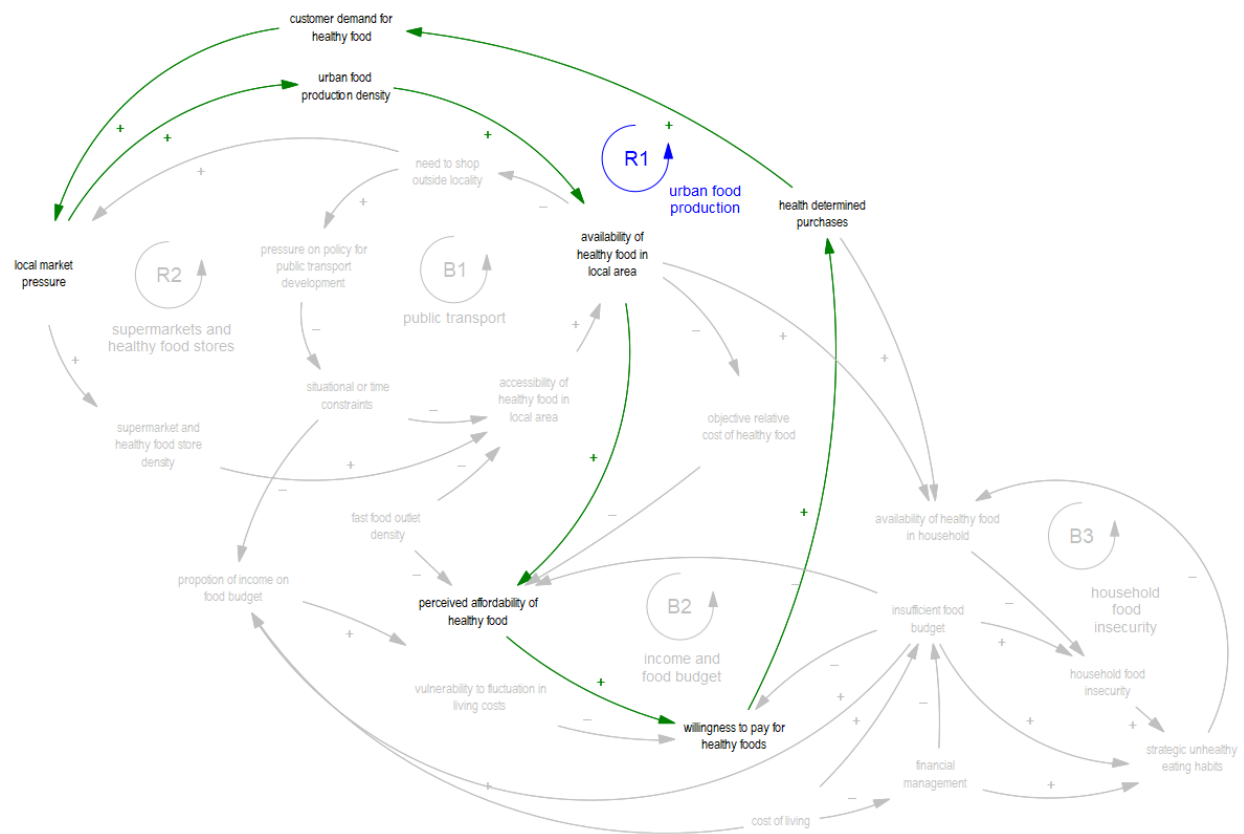


Figure 14 Reinforcing loop (R1) focusing on urban food production options

This reinforcing loop underscores the strategic value of investing in urban agriculture and local food systems.

Possible interventions to improve urban food production density:

- Policy-makers can support urban food production by enabling access to urban growing spaces, offering incentives for community food initiatives, and supporting food education programs.
- Community organizations can leverage this loop by promoting health literacy, encouraging participation in local growing efforts, and creating pathways for residents to influence local food supply chains.
- Local businesses and markets benefit from aligning with the loop's momentum, offering healthier options, and engaging more with urban growers.

3.3.5 Supermarkets and healthy food stores – Reinforcing loop (R2)

This reinforcing loop describes how the density of supermarkets and healthy food stores creates a positive feedback cycle that strengthens local food access, consumer demands, and the market's capacity to meet those demands. This reinforcing feedback loop illustrates how the expansion of supermarkets and healthy food stores can initiate and sustain a positive cycle of improved food access, increased consumer demand, and strengthened local food systems. At its core, this loop captures how market-driven dynamics, when aligned with public health objectives, can contribute to healthier and more equitable food environments.

The loop begins with an increase in the density of supermarkets and healthy food stores in a local area. It improves the availability of healthy foods by creating more retail space for healthy, nutritious products, aligning retail space with local demand. As healthy options become more prevalent and convenient, consumers are more likely to make health-determined purchases, choosing foods based on nutritional value rather than proximity or price alone.

These purchasing behaviors enhance consumers' willingness to pay for healthy foods, driven by greater health awareness, satisfaction, and trust in local offerings. Over time, this contributes to a shift in the perceived affordability of healthy food as more consumers view these products as accessible, valuable, and worth the investment.

In turn, this shift increases local market pressure, signaling to retailers and suppliers that there is robust and growing demand for healthy foods. This motivates the continued development and expansion of supermarkets and healthy food outlets, closing the loop and reinforcing the investment in food retail infrastructure. This is a self-reinforcing loop; each improvement in access, availability, or demand further amplifies the next, creating a cycle of health-promoting behavior and infrastructure development. As more healthy food becomes accessible and desirable, demand continues to grow, prompting further expansion of supply.

This loop has significant potential to transform food deserts and food swamps into food-secure environments offering healthier and more sustainable options, especially when initial barriers such as high setup costs, zoning restrictions, or supply chain limitations are addressed.

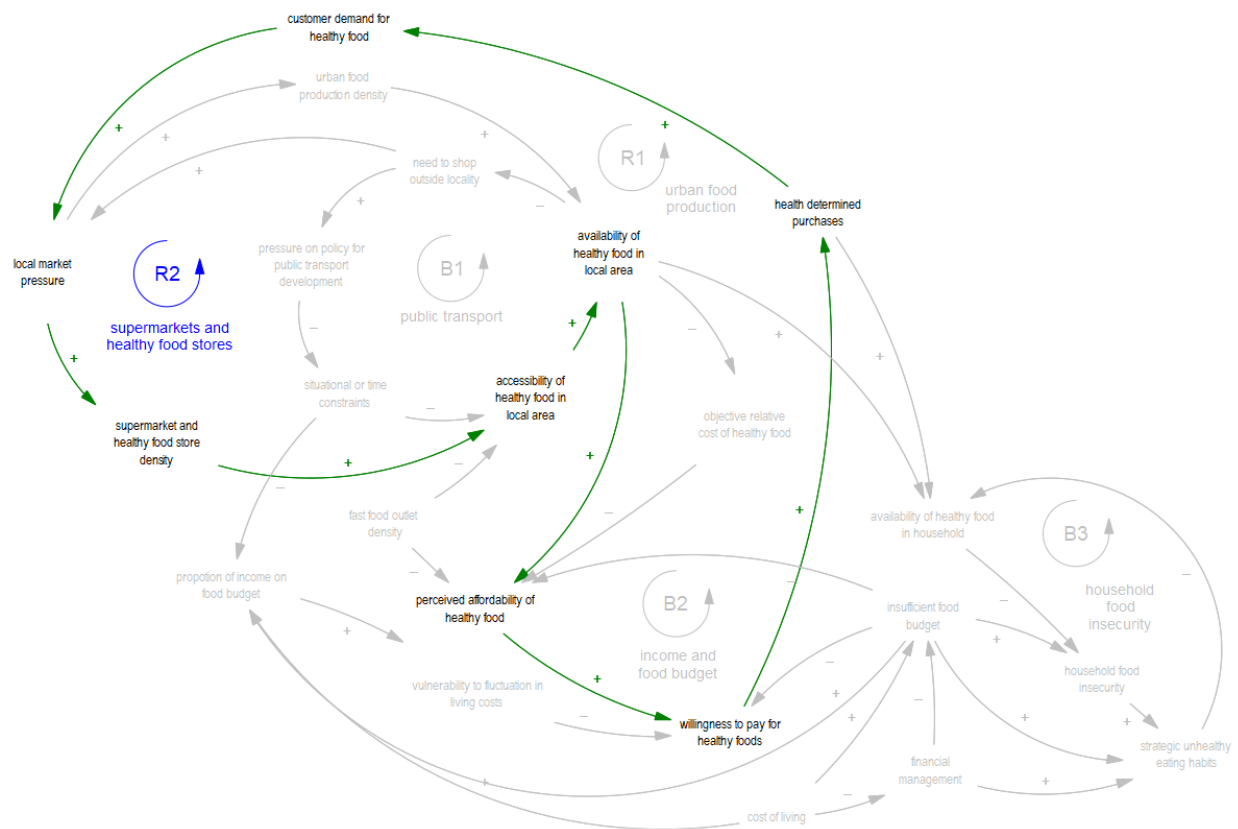


Figure 15 Reinforcing loop (R2) focusing on urban food production options

Possible interventions to improve supermarket and healthy food store development:

- Public investment and policy support can play a key role in initiating this loop, especially in underserved areas where market forces alone may be insufficient.
- Strategies that promote affordable pricing, diverse food offerings, and culturally appropriate options can accelerate consumer uptake and support the perceived value of healthy food.
- Partnerships between local governments, retailers, and communities can help sustain and guide growth in ways that meet public health and equity goals.
- Consumer education campaigns can enhance willingness to pay and shift perceptions about affordability, further energizing the feedback loop.

By promoting conditions that allow this reinforcing loop to thrive, communities can build resilient, health-oriented food systems that are responsive to local needs and sustainable in the long term.

3.4 Converting the conceptual model into a simulation model (Stock and Flow Model)

In Section 3.3, the underlying conceptual model is presented using a causal loop diagram. The model demonstrates the dynamic interactions between different variables that influence the accessibility and availability of food. The conceptual model under consideration integrates three balancing loops (B1, B2, and B3) and two reinforcing loops (R1 and R2). Each of these loops is designed to address specific aspects of the local food environment. The subsequent discussion will focus on the stocks and flows in the system. In the stock-and-flow model, elements such as the number of supermarkets, fast food outlets, or public transport stations are represented as stocks. The addition or removal of supermarkets, for example, influences the stock of supermarkets in the model, which represents the flow. This means that the number of stores increases if the neighborhood or district under investigation offers suitable conditions for investors or supermarket chains to build new supermarkets. Factors such as the social/geographical segregation of the population and the sense of security in an area are conditions that can have a positive or negative effect on the number of stores.

3.4.1 Subsystem geographical accessibility

The subsystem geographical access is the direct link between geographical data coming from GIS, which contains the dimensions of accessibility and availability of healthy foods in the local area. The accessibility addresses whether or not households and individuals have sufficient physical and economic access to food. For example, if the density of fast-food outlets increases, the accessibility to healthy foods decreases.

Figure 16 illustrates the subsystem of geographical access to food. The stocks are denoted by rectangles, while inflows or outflows are symbolized by pipes pointing into or out of the stock.

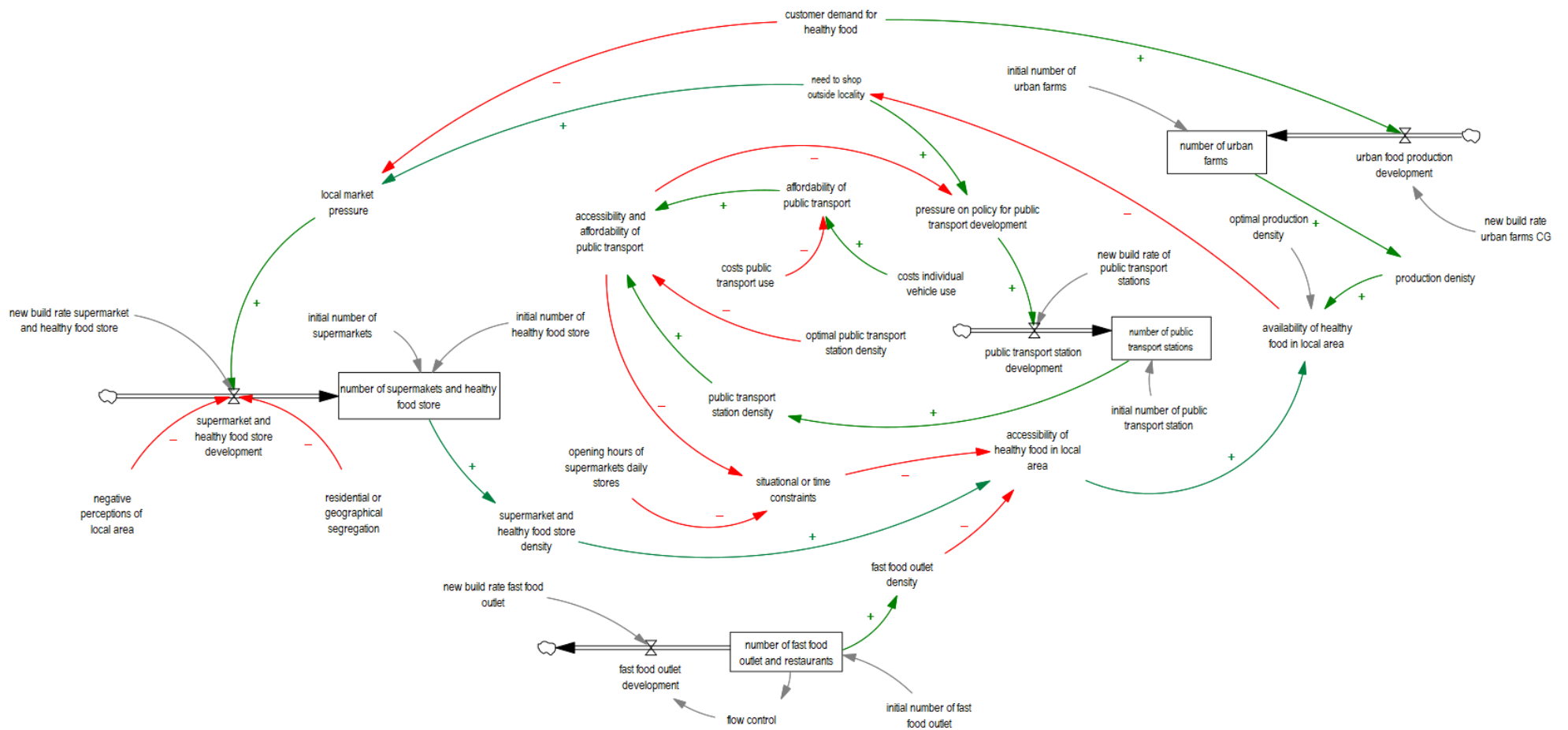


Figure 16 Subsystem geographical access, including the stock and flows in the system

Starting from the left, where the number of supermarkets and healthy food stores is shown as a stock, the inflow to this stock corresponds to the development of supermarkets and healthy food stores (see Figure 17).

This describes the dynamics surrounding the development of supermarkets and healthy food stores. This stock is growing due to an influx driven by the rate of new store construction and local market pressure. If local market pressure for such offerings is high, the number of stores increases, i.e., higher local demand leads to increased store development.

Other factors that are taken into account here are the negative perception of the local environment and spatial or geographical segregation. A highly positive perception of an area results in the expansion of outlets offering healthy options. The model also takes into account the initial conditions, which are determined by the existing number of supermarkets and healthy food stores. The initial stock is reduced by inflows or outflows until it is minimal (poor conditions) or maximal (optimal conditions). How well an area is supplied is expressed by the variable density of supermarkets and shops selling healthy food within the residential area.

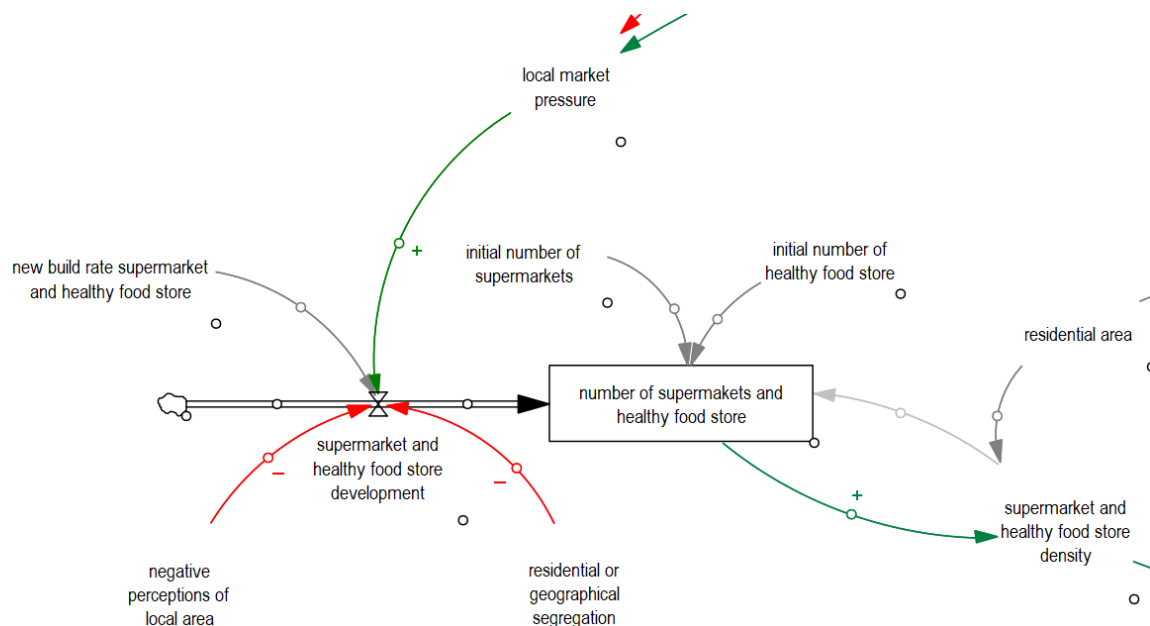


Figure 17 Details on the Stock and Flow structure for the number of supermarkets and healthy food stores.

Figure 18 shows the stock-and-flow structure used to represent the expansion of unhealthy food provision in a local area through businesses where unhealthy food options represent the majority in their offering. The central stock, number of fast-food outlets and restaurants, captures the

accumulated presence of fast-food outlets over time and is initialised by the initial number of fast-food outlets. The development rate is driven by the factor to build more outlets (new build rate fast food outlet). The flow-control link between the stock and the flow is only a control mechanism to prevent the variable fast-food outlet density from taking negative values.

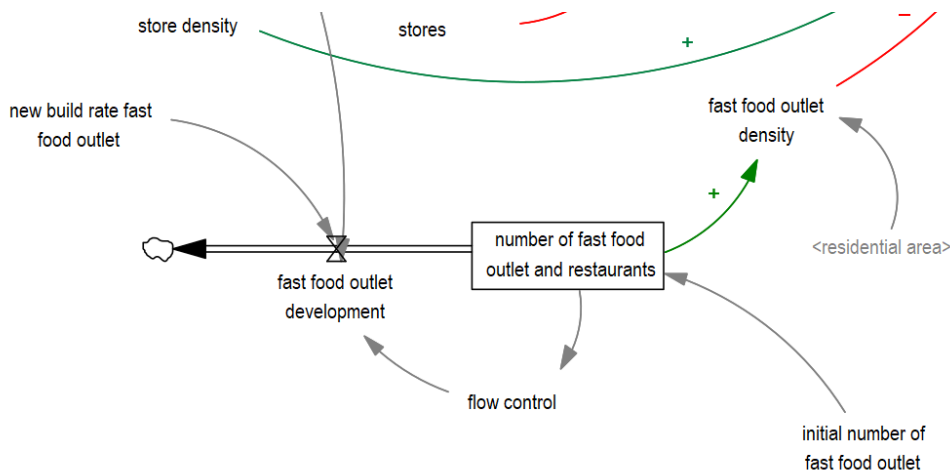


Figure 18 Details on the Stock and Flow structure for the number of fast food outlet and restaurants

The dynamics around public transport infrastructure and its impact on local food accessibility is shown in Figure 19. At its core, the stock is the “*number of public transport stations*”, driven by an inflow, the “*new build rate of public transport stations*” (public transport station development). This development rate has a positive polarity to the variable “*pressure on policy for public transport development*”, stemming from the “*need to shop outside the locality*”. This need arises when local food accessibility and availability decline.

The variable “*optimal public transport station density*” has a direct impact on the variable “*accessibility and affordability of public transport*”. The “*optimal public transport station density*” can be derived from the 15-minute city concept, i.e., an area should have a density that allows people to reach a stop within 15 minutes. However, excessive high public transport availability can lead to higher costs over time, as adjusting transport costs is a gradual process. These costs negatively affect affordability, potentially generating a feedback loop that constrains public transport development.

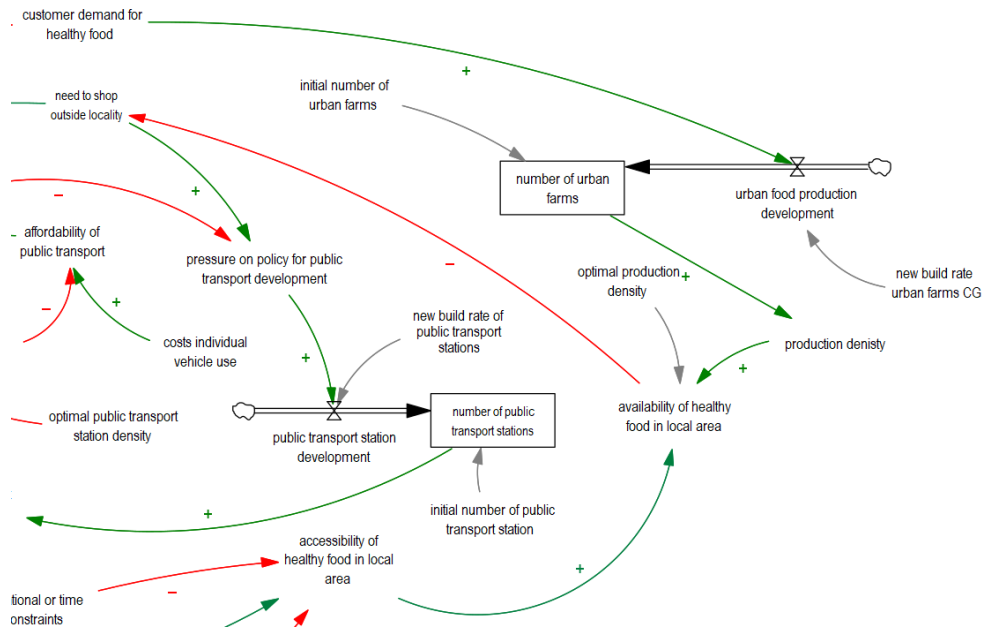


Figure 20 Stock and flow highlighting the dynamics of urban food production

3.4.2 Subsystem household finances

The household finances subsystem translates cost-of-living pressures into food-purchasing power and, ultimately, into the availability of healthy food within households. While this subsystem does not introduce additional stocks of the built environment, it operationalizes the balancing mechanisms B2 (income and food budget) and B3 (household food insecurity) and links them to the spatial stocks defined in Section 3.4.1 via availability of healthy food in the local area and fast-food outlet density. Figure 21 shows the causal structure.

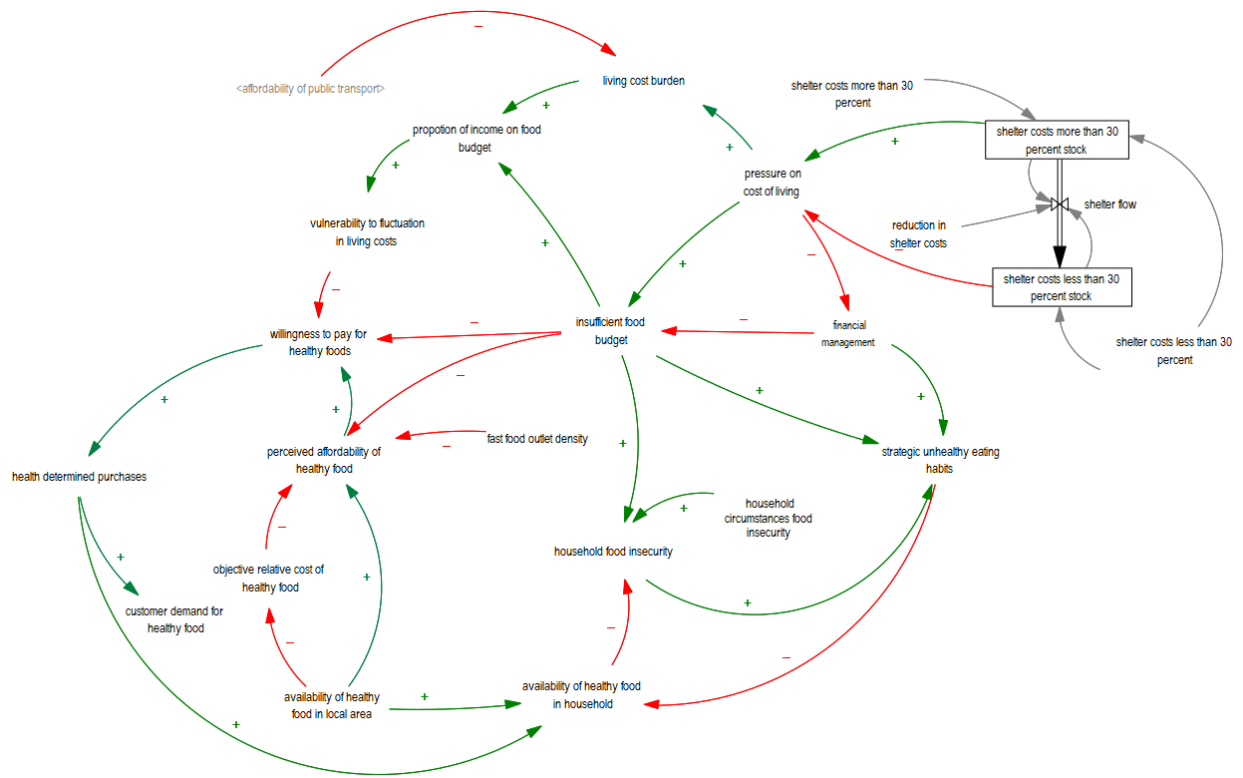


Figure 21 Subsystem household finances

Starting from the upper right in Figure 21, the share of “*shelter costs more than 30 percent*” raise “*pressure on cost of living*”, which increases “*insufficient food budget*” and “*living cost burden*”. Conversely, when “*shelter costs less than 30 percent*” prevail, pressure is reduced. This branch illustrates how housing expenses in low-income contexts can limit spending on food.

A higher “*insufficient food budget*” depresses “*willingness to pay for healthy foods*”. Lower willingness translates into fewer “*health determined purchases*”, weakening “*customer demand for healthy food*”. Retailers often respond by reducing healthy offerings, so “*availability of healthy food in local area*” falls. In turn, this depresses “*availability of healthy food in household*”, resulting in higher household food insecurity. This purchasing-power pathway implements balancing loop B2 in the stock-and-flow model by channeling financial stress into reduced local demand and availability.

Further, the “*objective relative cost of healthy food*” and the density of fast food outlets lower the perceived affordability of healthy food, which further reduces willingness to pay even when incomes are unchanged. This perception channel is the main interface to the geographical subsystem. The “*fast food outlet density*” and “*availability of healthy food in local area*” feed directly into affordability perceptions in this subsystem.

On the right-hand side of Figure 21, households under budget pressure adopt strategic unhealthy eating habits (e.g., cheaper calorie-dense options, portion reduction, skipping meals). These strategies can temporarily improve financial management and ease the burden of an insufficient food budget. This implements balancing loop B3, a self-stabilizing response that secures calories at the expense of diet quality and longer-term health.

Two variables provide tight couplings to the subsystem geographical accessibility: (i) availability of healthy food in local area is determined by spatial stocks (supermarkets/healthy stores, urban farms) and feeds directly into household purchasing; (ii) fast food outlet density is driven by the stock of fast food outlets and acts here as an affordability/attractiveness mechanism. Together, these links allow spatial interventions (R1, R2) to propagate into household budgets and purchasing behavior.

3.4.3 Subsystem household circumstances

The household circumstances subsystem quantifies structural vulnerability to food insecurity arising from household composition, housing tenure, and immigration status. In contrast to the geographical subsystem, this subsystem is implemented as a set of risk indices, weighted combinations of category shares calibrated from data, rather than as additional physical stocks. The indices roll up into household circumstances food insecurity, which then contributes directly to overall household food insecurity. Figure 22 provides the causal layout.

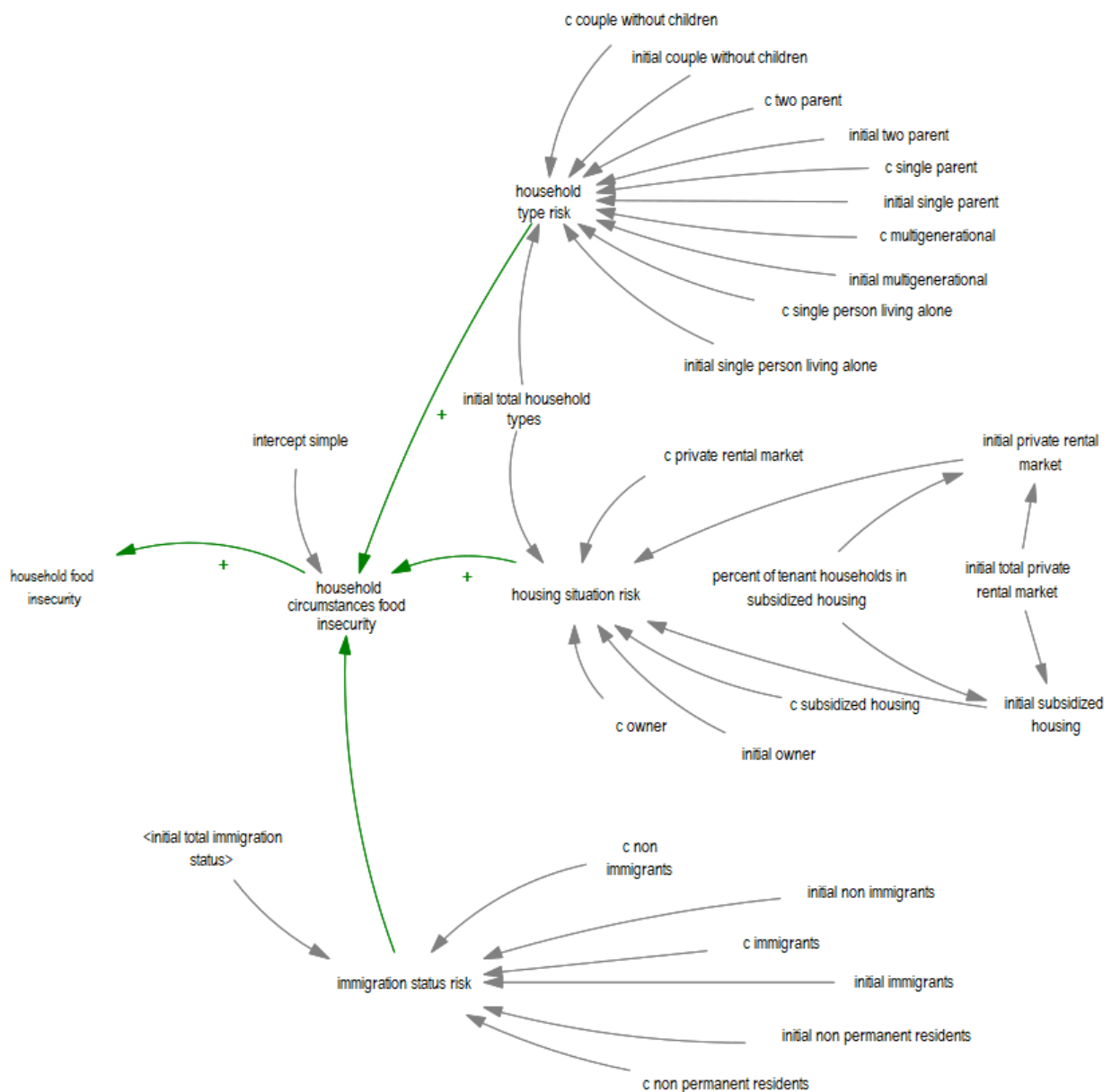


Figure 22 Subsystem household circumstances

(a) Household-type risk

The household type risk aggregates the baseline composition of households couple without children, two-parent, single parent, multigenerational, and single person living alone. Each category enters with a parameter c (e.g., c two parent, c single parent) and an initial value capturing the local distribution (e.g., initial single parent). An intercept (simple) represents baseline risk

independent of composition. Together, these produce a household-type contribution to the overall circumstances risk.

(b) Housing-situation risk

The housing situation risk summarizes tenure conditions using category parameters with corresponding initial levels (e.g., initial owner, initial subsidized housing): c_{owner} , $c_{private\ rental\ market}$, and $c_{subsidized\ housing}$. The percentage of tenant households in subsidized housing and initial total private rental market help normalize shares. This branch captures how tenure status and the structure of the local rental market condition vulnerability to food insecurity.

(c) Immigration-status risk

The immigration status risk combines the local composition of non-immigrants, immigrants, and non-permanent residents using parameters (e.g., $c_{immigrants}$) and initial counts (initial immigrants, initial non permanent residents). As with the other branches, the parameters represent weights to be estimated or set from empirical evidence, while the initial values fix the local baseline.

The three partial risks feed into household circumstances food insecurity, which then increases overall household food insecurity. Initial total household types provides the denominator for shares and ensures internal consistency when the model is applied to different areas. Because the parameters are explicit (the c terms and the intercept), the subsystem can be re-calibrated for alternative cities or time periods without altering the model structure.

Although this subsystem does not change spatial stocks directly, it conditions how households experience the environment described in the subsystem geographical accessibility and the household finances.

Further information on the details of how the data was analyzed and processed for the parameterization of the SD model can be found in Chapters 5.2.2 and 5.2.4

Chapter 4. Decision Support System Framework

Chapter 3 provides details of the developed system dynamics model to simulate urban food security for vulnerable people.

In this chapter, the developed framework is presented in more detail.

The development of reliable Decision Support Systems (DSS) requires a sound scientific methodological foundation and robust technical architecture. The DSS is built in a microservices-based architecture and aims to perform Spatial System Dynamics (SSD) simulations. This decision was made in order to create a scalable system. The rationale behind this design decision can be attributed to two primary factors.

Firstly, although conventional System Dynamics (SD) models offer powerful functions for representing feedback loops, nonlinear interactions, and temporal dynamics from a methodological perspective [24, 25, 110–113], they are inherently non-spatial. On the other hand, Geographic Information Systems (GIS) capture spatial data and patterns [27, 117], but are not designed to represent and calculate systemic feedback structures. SSD integrates these perspectives and enables simulation models to incorporate location-specific data while ensuring that systemic logic of system dynamics is respected. The implementation of the SSD coupling is realized through moderate coupling, which means that both simulation models and geodata are linked via a shared database. This choice is made in order to achieve a balance between the degree of integration, flexibility, and computational feasibility.

Secondly, from a technical perspective, the DSS uses a microservices architecture. In contrast to a monolithic system, in which all functions are closely intertwined, the DSS consists of several independent services, each responsible for a specific function, such as data management, simulation execution, or visualization. These services communicate via standardized interfaces (APIs), a microservice architecture enables independent development, deployment, and scaling. This design facilitates the parallelization of development tasks, dynamic resource allocation, and the seamless integration of new components over time.

The use of open standards and open-source software increases the adaptability of the DSS. System dynamics models are represented using XMILE [118], a standardized exchange format, ensuring interoperability and model transparency. Geodata is managed using common database systems (PostgreSQL/PostGIS), while simulation and orchestration are performed in a Linux-based environment compatible with modern containerization tools such as Docker.

The DSS Framework is one of the major artifacts developed within this thesis and fulfills three requirements:

1. **Methodological rigor:** The integration of SD and GIS into an SSD simulation environment is achieved through the implementation of a coupling strategy that uses a shared database.
2. **Technically scalable:** The implementation of a microservices-based architecture has the potential to accommodate both a high number of users and extensive simulations.
3. **Maintainability and extensibility:** The utilization of open standards (XMILE, RESTful APIs) and modular components that facilitate long-term adaptability is fundamental.

The initial demonstration of the DSS is conducted in the domain of urban food systems, with the island of Montréal functioning as the case study environment. However, the artifact's technical and methodological principles are not domain-specific and can be transferred to other contexts that require spatially explicit dynamic modeling, such as energy or water systems.

The subsequent sections of this chapter provide a comprehensive elaboration on the conceptual framework and the constituent components of the DSS.

Section 4.1 discusses the theoretical and methodological foundations, including the DSRM, SSD, and coupling strategies. Section 4.2 presents the system architecture, focusing on the microservices and the individual layers of the DSS. Section 4.3 outlines component interactions and workflows. Section 4.4 shows the workflow for creating Python-ready code based on XMILE files created with Vensim. Section 4.5 discusses advantages and challenges.

4.1 Theoretical and methodological foundations

4.1.1 Design Science Research Methodology (DSRM)

Developing Information Systems (IS) artifacts requires both a theoretical grounding and a methodological framework that ensures relevance and rigor. The Design Science Research Methodology (DSRM) provides such a framework. DSRM is based on the premise that IS research must analyze existing phenomena and produce innovative artifacts that solve relevant problems [23]. These artifacts can be models, methods, constructs, or instantiations. The Decision Support System (DSS) is the central artifact of this thesis.

The following table provides an illustration of how the seven guidelines of the DSRM are applied in this thesis.

Table 12 The seven guidelines of the DSRM and the way of applying the guidelines for the SSD – DSS

Guideline No.	Description from [23]	Way of applying the guideline
1: Design as an Artifact	<i>“Design-science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation.”</i>	The artifact produced is the Decision Support System (DSS), implemented as a Spatial System Dynamics (SSD) tool with a microservices-based architecture. It constitutes both a methodological construct (SSD coupling strategy) and a technical instantiation (software architecture).
2: Problem Relevance	<i>“The objective of design-science research is to develop technology-based solutions to important and relevant business problems.”</i>	The DSS addresses the relevant problem of decision-making in urban food system planning, where spatial heterogeneity and dynamic feedback must be considered simultaneously. The system provides technology-based support for exploring scenarios and trade-offs.
3: Design Evaluation	<i>“The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods.”</i>	Evaluation was performed through: (i) technical testing (stress tests, scalability of users), (ii) model validation (extreme condition testing in Vensim before XMILE export), and (iii) case application (scenario analysis in Montréal and comparison of baseline simulation with published data). These methods demonstrate the utility, quality, and efficacy of the DSS.
4: Research Contributions	<i>“Effective design-science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and/or design methodologies.”</i>	Contributions include: (i) Artifact contribution: a working DSS integrating SSD and microservices, (ii) Foundational contribution: demonstrating moderate coupling as a viable integration strategy, and (iii) Methodological contribution: a pipeline of how to integrate Vensim models using XMILE into an SSD framework.
5: Research Rigor	<i>“Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact.”</i>	Rigor was ensured by: (i) applying system dynamics best practices (unit checks, sensitivity analysis), (ii) using formal standards (XMILE, RESTful APIs, PostGIS), and (iii) employing structured evaluation methods (technical tests, case studies, usability checks).

6: Design as a Search Process	<i>“The search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment.”</i>	The design followed an iterative search process: testing different coupling strategies, exploring multiple technical options (monolithic vs. microservices), and selecting moderate coupling and microservice architecture as the most effective means of achieving scalability, flexibility, and integration with spatial data.
7: Communication of Research	<i>“Design-science research must be presented effectively both to technology-oriented as well as management-oriented audiences.”</i>	The DSS is communicated to the interested technical audiences, such as developers and researchers via a GitHub repository, which details the architecture, pipelines, etc. and scientific publications. The developed data products are made available via public access to the CERC Datahub.

The conceptual framework of DSRM ensures that the development of the DSS is not an isolated process; rather, it is integrated into a structured, iterative research process. It also situates the DSS within the field of IS research, where the production of artifacts is valued not only for practical utility but also for extending scientific knowledge.

4.1.2 Coupling strategies: Advantages and disadvantages

A key methodological question when linking different tools, such as SD and GIS in this case, is how the tools can interact with each other. The linking strategy determines how data and information are exchanged, processed, and synchronized, and how flexible the basic architecture of the system will be. There are different ways to exchange data and information between software components.

In the field of simulation software, there are four main options: 1. Loose coupling, 2. Moderate coupling, 3. Tight coupling, and 4. Embedded. Each strategy has an impact on the performance, maintainability, and scalability of the overall system.

Loose coupling is the simplest form of integration, where data is exchanged between the individual components via external files, typically in text or CSV format. The approach of loose coupling is advantageous because it is both straightforward and technology-independent, with the capacity for almost every application to read and write such files. However, it is important to note the significant limitations of loose coupling. Firstly, data exchange is asynchronous, which prevents real-time interaction. Secondly, performance is poor when processing large data sets. Thirdly, the process is cumbersome when repeated frequently. While loose coupling is adequate for exploratory

or one-time analyses, it is not suitable for a DSS intended to support continuous, scalable decision-making. Examples for loose coupling implementation can be found in Perez and Dragicevic [90].

In contrast, tight coupling involves strong dependencies between software components [119], frequently through shared standards or programming interfaces. In such cases, system dynamics models and spatial data interact during runtime, thereby enabling real-time simulations that are both spatially and dynamically explicit. Tight coupling is characterized by its ability to deliver high performance and depth of integration. However, it is important to note that this approach is often accompanied by increased complexity and limited flexibility. The implementation of such systems is frequently reliant on proprietary software. This approach produces dependencies that can restrict scalability and long-term sustainability. Tight coupling also complicates the process of updating or replacing individual components without compromising the integrity of the entire system.

The process of embedding involves the complete integration of a system into the programming environment of another. For instance, SD functionalities may be integrated directly into a GIS tool, or GIS functionalities may be embedded into an SD modeling environment. Although the process of embedding can facilitate seamless functionality, it does so at the expense of modularity, resulting in a highly specialized solution that is challenging to extend or generalize. In practice, the process of embedding frequently results in systems that are closely associated with particular software environments, thereby restricting their relevance to more limited use cases. C. Neuwirth and A. Peck [120, 121] presented a methodology for coupling Vensim and ArcGIS. Through a Dynamic Link Library (.dll), Vensim was embedded in ArcGIS, and with this, both software packages were combined.

There are several disadvantages in using Vensim and ArcGIS as simulation, data management, and visualization packages: (1) both are proprietary and need licenses to use the complete functionalities, (2) the maintenance of the .dll will require continuous updates if the software versions are changing, (3) the integration into an urban platform which is using Linux and Python as the central operating system and programming language is limited to the functionalities the software provides and (4) scalability, computation power, and parallelization of simulation (e.g. working with multiple users at the same time) is limited as the software architecture is not designed for the deployment in a cloud infrastructure.

Moderate coupling is a concept that offers a middle ground between the loose coupling and tight coupling approaches. With this strategy, both system dynamics models and geodata tools access a shared database that serves as a central hub for storing, retrieving, and exchanging data. The simulation engine retrieves data from the database, runs the models, and writes the results back. Visualization and GIS tools subsequently access the updated database to display the results. This strategy combines the flexibility of loose coupling with some of the performance benefits of tighter integration. It is important to note that moderate coupling facilitates the decoupling of components.

This means that the system dynamics engine, GIS tool, and visualization modules can evolve independently, provided that they adhere to the common database schema. Figure 23 illustrates the four ways of integrating an SD engine (left) with GIS/Visualization (right), ordered by increasing degree of coupling and complexity. In the loosely coupled configuration, information is exchanged via serialized files (e.g., CSV, JSON, TXT), yielding an asynchronous workflow with inherently non-real-time synchronization. The moderately coupled configuration relies on a shared database, where interoperability is mediated through a common schema; this approach preserves partial component independence while enabling periodic or near-real-time data refresh. In the tightly coupled configuration, integration is achieved through runtime interfaces (API/SDK), permitting direct bidirectional communication, low-latency interaction, and higher performance, at the cost of increased implementation complexity and stronger dependency (often vendor-specific) constraints. The embedded configuration consolidates both functionalities within a single software environment, maximizing user experience but decreasing modularity and limiting portability and extensibility across platforms.

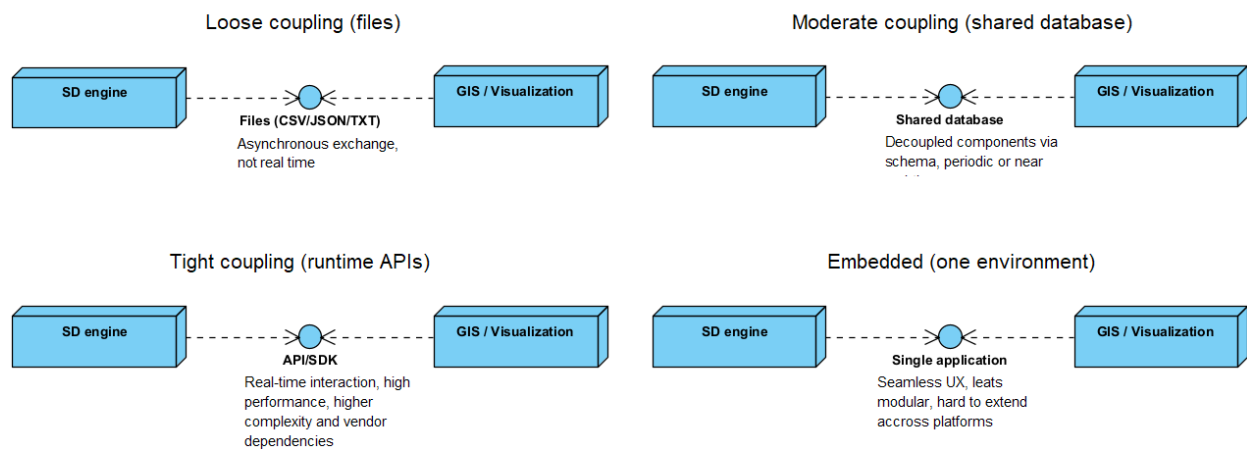


Figure 23 Illustration of the different coupling strategies: Loose coupling, Moderate coupling, Tight coupling, and Embedded (own illustration).

The DSS concept presented in this dissertation employs moderate coupling. The following three advantages can be identified:

1. **Flexibility and modularity:** Components can be updated, replaced, or scaled without requiring changes to other parts of the system. For example, the simulation engine could be replaced by another SD tool, as long as it can read and write to the shared database.
2. **Technical feasibility:** Modern database systems, especially PostgreSQL with the PostGIS extension, enable efficient processing of both relational and geospatial data. This allows for the seamless storage of simulation inputs and outputs alongside spatial datasets.

3. **Scalability:** Moderate coupling and microservices fits well with cloud-native architectures, where multiple microservices can interact via a central database. Simulation servers, visualization services, and user interfaces can work in parallel and access the same shared data resources.

The predominant disadvantage associated with moderate coupling is the potential performance bottleneck that arises from the database. In scenarios where multiple services interact with substantial data sets simultaneously, the optimization of queries and the management of database scaling become pivotal considerations. However, recent advancements in cloud database technologies have led to the introduction of solutions such as clustering, replication, and horizontal scaling, which can mitigate these risks.

In summary, moderate coupling offers the optimal balance between performance, modularity, and scalability for the applications outlined in this thesi. This approach overcomes the limitations of tight coupling, which can lead to rigidity and inefficiency, while ensuring a degree of generalizability that is often lacking in embedded systems. This choice is both a methodological and technical decision that shapes the architecture of the DSS.

4.1.3 Standards and interoperability

The utilization of open standards is critical for the extensibility, interoperability, and maintainability of any DSS. Standards serve a dual purpose; they ensure technical compatibility and, moreover, they promote transparency, reproducibility, and long-term sustainability. The DSS developed as part of this thesis incorporates several important standards that enable the effective integration of SD models, geodata, and microservice-based architectures.

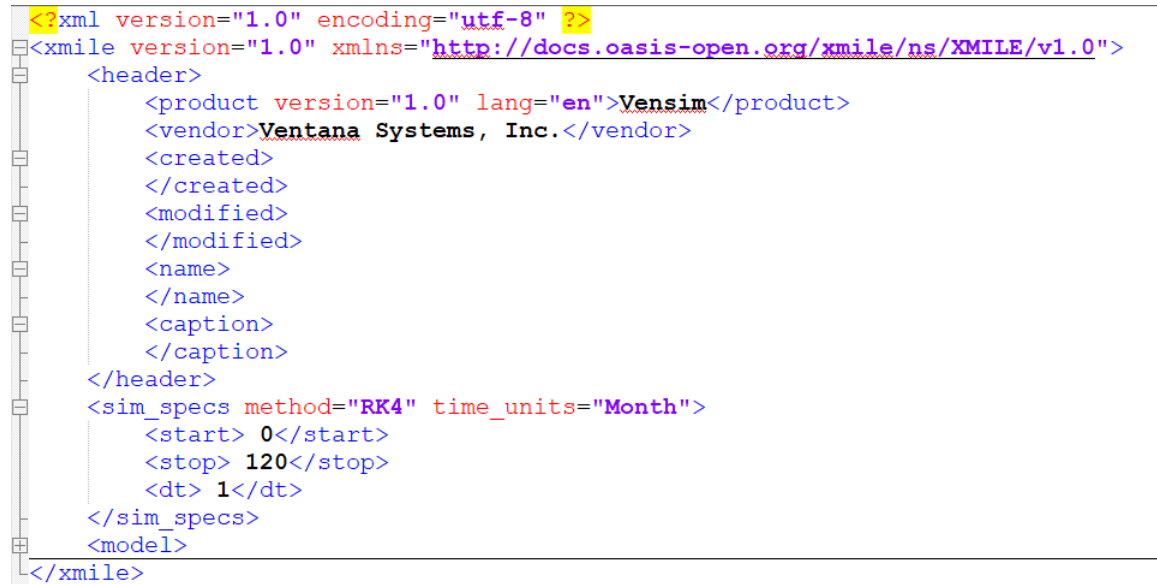
System Dynamics Standards: XMILE.

XMILE, which stands for eXtensible Model Interchange Language is used as the standard format for encoding SD models. XMILE is an open XML-based standard for describing and exchanging SD models. XMILE provides a structured, machine-readable representation of stocks, flows, parameters, and equations, thereby rendering models transparent and interoperable across tools. The adoption of XMILE by the DSS ensures that models can be reused, modified, or shared without being tied to a specific proprietary software environment. This enhances both scientific reproducibility and technical adaptability [118].

Figure 24 shows the main structure of the XMILE file. The header includes general information, required information is the vendor and product name, optional information includes parameters such as model name <name>, date created <created>, date modified <modified>, or caption.

Vensim by default only writes the required information into the XMILE file during the export. The simulation specification section is defined by the <sim_specs> tag, and must include the time units of the model as well as, the start and end time of the simulation. In the example below, the time units are months, and the simulation period is 120 months, which is 10 years.

The XMILE file contains the whole information of the model



```
<?xml version="1.0" encoding="utf-8" ?>
<xmile version="1.0" xmlns="http://docs.oasis-open.org/xmile/ns/XMILE/v1.0">
  <header>
    <product version="1.0" lang="en">Vensim</product>
    <vendor>Ventana Systems, Inc.</vendor>
    <created>
    </created>
    <modified>
    </modified>
    <name>
    </name>
    <caption>
    </caption>
  </header>
  <sim_specs method="RK4" time_units="Month">
    <start> 0</start>
    <stop> 120</stop>
    <dt> 1</dt>
  </sim_specs>
  <model>
</xmile>
```

Figure 24 Main structure of an XMILE model

The main block in the XMILE file, where the model equations, stocks, flows, and auxiliaries are described, is the <model> block. Figure 25 shows the first lines of the model block of the “*food insecurity model*” presented in Chapter 3. Each variable includes three main elements <units>, <doc> and <eqn>. The documentation function is particularly important for ensuring that models remain comprehensible at a later date. When modeling in Vensim, comments can be added to each individual variable, and these comments are then included in the XMILE file.

```

<?xml version="1.0" encoding="utf-8" ?>
<xmile version="1.0" xmlns="http://docs.oasis-open.org/xmile/ns/XMILE/v1.0">
  <header>
    <sim_specs method="RK4" time_units="Month">
      <start> 0</start>
      <stop> 120</stop>
      <dt> 1</dt>
    </sim_specs>
    <model>
      <variables>
        <stock name="number_of_fast_food_outlet_and_restaurants">
          <units>Number</units>
          <doc></doc>
          <eqn>
            initial_number_of_fast_food_outlet
          </eqn>
          <inflow>
            fast food outlet development
          </inflow>
        </stock>
        <stock name="number of public transport stations">
        </stock>
        <stock name="number of supermarkets and healthy food store">
        </stock>
        <stock name="number of urban farms">
        </stock>
        <stock name="shelter costs less than 30 percent stock">
        </stock>
        <stock name="shelter costs more than 30 percent stock">
        </stock>
        <aux name="accessibility_and_affordability_of_public_transport">
          <units>Dmm1</units>
          <doc>In areas characterised by inadequate transport infrastructure, public transportation
          <eqn>
            (1/(1+EXP(-10*((public_transport_station_density / optimal_public_transport_station_density - 0.5))))
            * 3.14159 + 3.14159) / 2 + 0.5)) / 2
          </eqn>
        </aux>
        <aux name="accessibility_of_healthy_food_in_local_area">
          <units>Dmm1</units>
          <doc>If fast food outlet density is increasing the accessibility is decreasing.
          FAO definition Access: addresses whether or not households and individuals have sufficient physical and ec
          This variable describes the the physical accessibility</doc>
        </aux>
      </variables>
    </model>
  </header>
</xmle>

```

Figure 25 View of a model block in an XMILE file

Geospatial Standards: PostGIS and pgAdmin

The DSS employs the PostGIS database extension of PostgreSQL to manage the data [122]. PostGIS extends the functionality of the relational database PostgreSQL to enable the processing of geodata objects, facilitating efficient queries such as intersections, buffers, and overlays. Furthermore, the system is compliant with the standards defined by the Open Geospatial Consortium (OGC), including the Web Map Service (WMS) and the Web Feature Service (WFS). The standards ensure that geodata can be integrated not only within the DSS, but also with external GIS applications.

As the data is not stored in individual files but in a database, queries can be written directly in the SQL query language to retrieve the required information. This has a particular impact on the performance of the system. For database administration, pgAdmin [123] is used, which provides a Graphical User Interface (GUI) for PostgreSQL. Figure 26 shows the GUI of pgAdmin and an example query to calculate the total number of fast-food outlets in Ville-Marie (NUM=20).

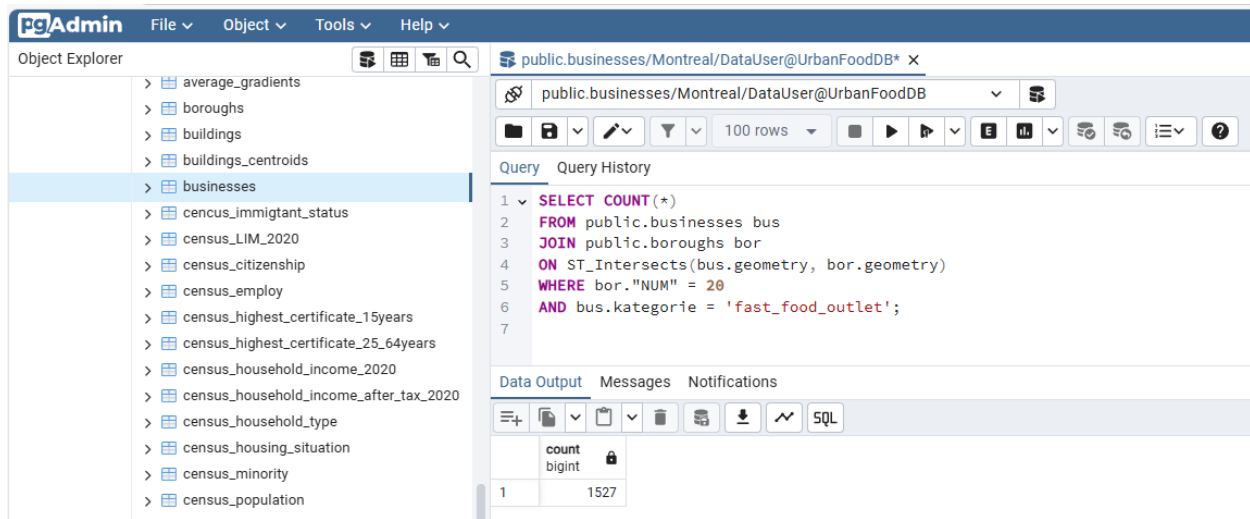


Figure 26 View of the pgAdmin GUI and a query on the fast-food outlets of Ville-Marie (NUM=20)

The query counts the number of businesses classified as fast food outlets (*bus.kategorie* = 'fast_food_outlet') that are located within the borough whose identifier (*bor."*NUM*"*) equals 20.

The table *public.businesses* contains the business data (see Chapter 5.2.1), with each business having a point location geometry column. The *JOIN public.boroughs bor ON ST_Intersects(bus.geometry, bor.geometry)* executes a spatial join between businesses and boroughs, the *ST_Intersects* returns a TRUE if the geometries and points overlap or touch. This ensures that each business is matched to the borough in which it is physically located. *WHERE bor."*NUM*" = 20* filters the results to a specific borough (with the identifier NUM=20, in this case Ville-Marie). The *AND bus.kategorie = 'fast_food_outlet'* further restricts to only those businesses categorized as fast food outlets. In the last step, the *SELECT COUNT(*)* counts how many such businesses meet all the above conditions. The output is a single integer representing the number of fast food outlets located inside the borough with NUM = 20.

The decision to run queries based on numbers rather than names is driven by the fact that data records in Montréal are available in both French and English, with different spellings in each language. However, the numbers remain consistent across different data records.

Individual queries can be tested in pgAdmin. Once the database query has been developed, it can easily be integrated into the *connect_query_db.py* script via copying and pasting.

Service Communication Standards: RESTful APIs

Communication between a client (for example, an external service) that wants to use the DSS and the microservice performing the simulation takes place via a RESTful API. Implementing a REST (Representational State Transfer) interface provides significant advantages for interoperability and integration. By exposing functions such as data retrieval and simulation execution through REST endpoints, the DSS enables interaction between heterogeneous services without requiring knowledge of its internal architecture.

The DSS REST API web server is accessible through a base URL that serves as an entry point. Endpoints are defined to handle standard HTTP methods (`GET`, `POST`, `PUT`, `DELETE`). Clients typically send data as JSON in `POST` or `PUT` requests, and the server returns responses in JSON format. This design facilitates seamless integration of external systems with the DSS.

Example of the communication between the external client and the DSS REST API web server:

The DSS exposes its functionality through a RESTful API. Clients interact with the API by sending HTTP requests to a base URL. In this example, `String1` is the base URL. The client first requests the available simulation scenarios by sending a `GET` request to the `/scenarios` endpoint. This response lists the available scenarios in the `food_security` model that the client can use as a starting point for simulation. The response JSON shows the scenarios that are available for the system dynamics simulation.

```
String1 = 'domain where the API is reachable'
response = requests.get(String1 + '/scenarios')
response.json()
{'food_security': ['food_stores', 'interactive_scenario', 'base']}
```

To write a new scenario, the client first defines the area of interest using the number of the borough. In the next step, variables in the models that can be changed are defined, such as the rate of new supermarket construction or the density of transport stations. The data is sent in JSON format using an HTTP `POST` request to the `/write_scenario` endpoint.

```
NUM = 20
res = requests.post(
    url=f'{String1}/write_scenario',
    json = f'{{"city": "Montréal", "borough_name": "Ville-Marie", "NUM": {NUM}, \
        "newBuildRateSupermarketAndHealthyFoodStore": 0.5, \
        "newBuildRateFastFoodOutlet": 2, \
        "newBuildRatePublicTransport": 3, \
        "newBuildRateUrbanFarms": 0.2, \
        "timeToAdjustCostsOfPublicTransport": 1, \
        "optimalTransportStationDensity": 5}}}'
)
```

The DSS processes the new scenario and returns a JSON response describing the simulation model and updated constants. This output confirms that the new scenario has been registered in the DSS, with updated constants reflecting the client's input.

```
res = res.json()
res
{'food_security': {'model': 'simulation_models/food_security',
'scenarios': {'base': {'constants': {'initialCoupleWithoutChildren': 13040.307258328516,
'initialMultigenerational': 238.9882479013189,
'initialNonImmigrants': 32940.35645619583,
'initialNonPermanentResidents': 20117.281609697577,
'initialNumberOfFastFoodOutlet': 1527,
}},
'food_stores': {},
'interactive_scenario': {}},
'source': 'simulation_models/food_security.xml'}}
```

Communication between QGIS and PostGIS services: Direct SQL protocol

In addition to RESTful communication with external services, the DSS architecture also includes direct database connections. The GIS client (e.g., QGIS) connects to the PostGIS database using the PostgreSQL wire protocol over TCP/IP. This connection does not rely on HTTP or RESTful endpoints but instead executes SQL queries directly against the spatial database.

Through this direct SQL communication, QGIS can access geospatial data stored in PostGIS, perform spatial joins and filters, and visualize the results in map layers. Since the database exposes its schema and functions directly, the client needs to understand the database structure and use SQL (and PostGIS spatial functions) to retrieve and manipulate the data.

While this approach provides powerful query capabilities and tight integration with geospatial functions, it lacks the abstraction and interoperability of REST APIs. External systems must have credentials and database knowledge to connect, which can reduce portability compared to a RESTful interface.

4.2 System architecture and technical design

The conceptual and methodological choices outlined in the previous section of moderate coupling, reliance on open standards, and the adoption of DSRM as a guiding framework, directly shape the technical architecture of the DSS. The system is designed not as a monolithic application but as a platform based on microservices. This architecture ensures modularity, scalability, and long-term maintainability, while at the same time providing the technical infrastructure required to implement Spatial System Dynamics (SSD).

The main idea behind the work is to present a DSS framework that builds on state-of-the-art technologies, uses open-source software or standards as much as possible, and is flexible enough to be connected to third-party tools like QGIS.

The conceptual model of the DSS is structured into three interrelated layers: (1) the Business Layer, (2) the Software, Code, and Infrastructure Layer, and (3) Data and Models Layer. These layers collectively demonstrate how raw data and computational models are transformed into actionable insights for decision-makers in the domain of food security. Figure 27 shows the concept of the DSS as a business process diagram.

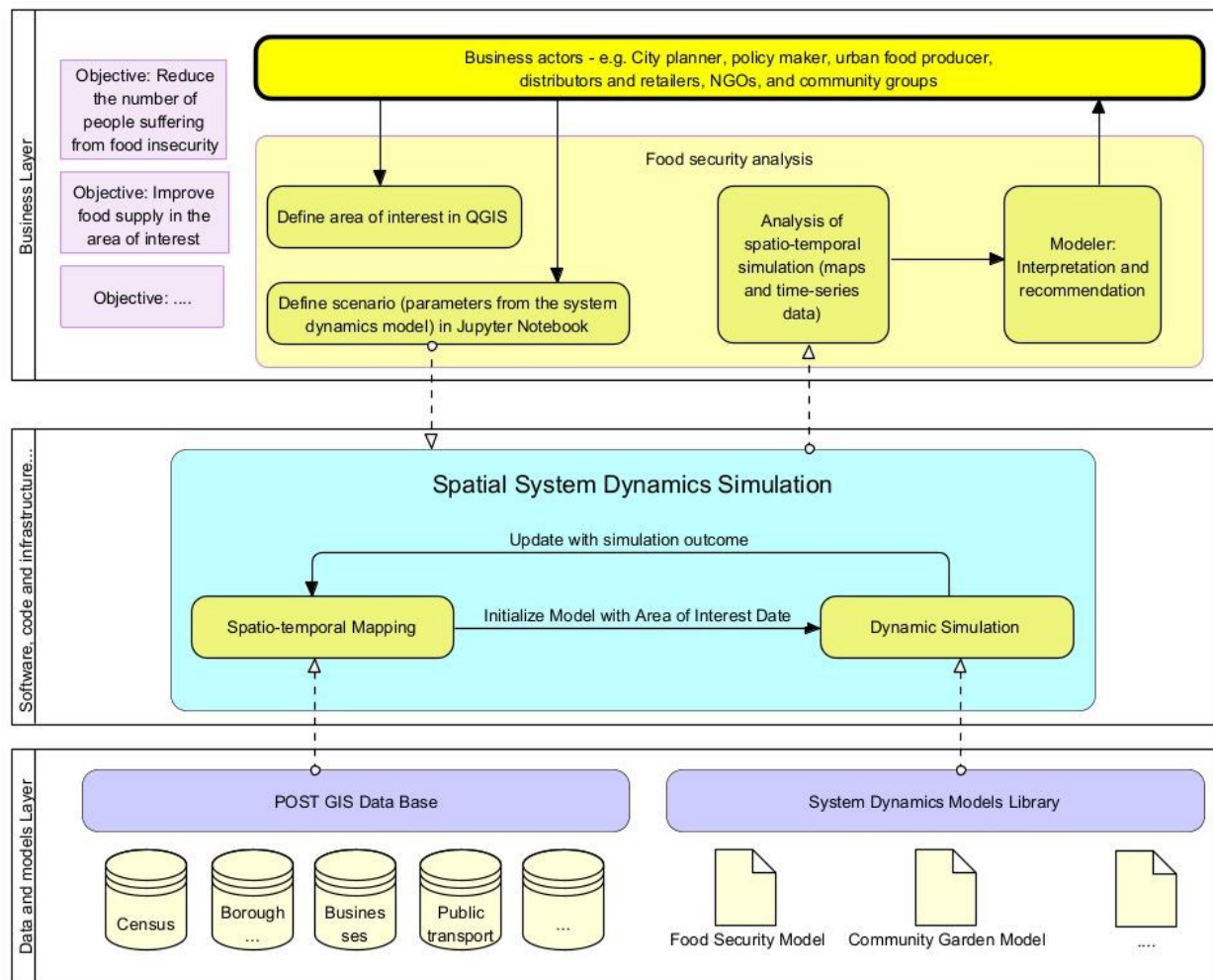


Figure 27 Concept of the Decision Support System (DSS), model as a business process diagram with the software Visual Paradigm

Data and Models Layer

At the foundation of the DSS is the Data and Models Layer, which includes a System Dynamics Model Library and a GIS Data Base required for the simulations. This layer integrates diverse datasets, including census information, borough-level data, business records, and public transport data, among others. These heterogeneous datasets are stored and managed in a PostgreSQL with PostGIS extension database, enabling efficient handling of spatially explicit information. In addition to the data, the System Dynamics Model Library hosts conceptual and mathematical models that represent different systems relevant to the topic of interest, e.g., food security.

The data component is responsible for ingesting, storing, and serving the heterogeneous datasets required by the DSS. These datasets can be grouped into two categories:

1. **Geospatial data:** Includes spatially explicit information such as public buildings, businesses, information on community gardens, and/or administrative boundaries.
2. **Tabular and statistical data:** Encompasses datasets such as census data, price information of energy, GHG emission factors, and/or information on specific food. These datasets are integrated into the same PostgreSQL environment, enabling joint queries with spatial data where necessary.

By centralizing data access in a shared database, the DSS operationalizes the principle of moderate coupling.

Software, Code, and Infrastructure Layer

The intermediate software, code, and infrastructure layer operationalizes the transformation of data into simulation outputs. Central to this layer is the Spatial System Dynamics Simulation Core environment. It is composed of two interconnected processes: spatio-temporal mapping and dynamic simulation. The spatio-temporal mapping process initializes the model with the defined area of interest and corresponding data retrieved from the database queries. This ensures that the simulation is spatially contextualized. The dynamic simulation process then executes the system dynamics models, producing temporal trajectories of key variables that capture system behavior over time. The outcomes of these simulations are fed back into the spatio-temporal mapping.

This layer also manages the computational infrastructure required for model execution. It represents the technical backbone of the DSS, ensuring that models and data interact seamlessly to produce meaningful outputs.

Business Layer

The Business Layer represents the decision-making context in which the DSS is applied. It begins with the articulation of high-level objectives, such as reducing the number of people suffering from food insecurity or improving food supply within a given area of interest. These objectives frame the use of the DSS and guide subsequent analyses. Business actors like city planners, policy makers, urban food producers, distributors, retailers, NGOs, or community groups interact with the DSS at this layer. Their engagement is mediated through two main tools: (1) QGIS, used to define the spatial area of interest, and (2) Jupyter Notebooks, used to specify system dynamics parameters and scenarios. The simulation results, produced in the infrastructure layer, are analyzed in terms

of maps and time-series data, which support food security assessments. Finally, modelers interpret these outputs and provide recommendations tailored to the stakeholders' needs.

The business layer thus contextualizes the technical outputs of the DSS within real-world decision processes. By linking simulation results to strategic objectives, this layer ensures that the system delivers actionable insights to a diverse set of stakeholders working to address food security challenges.

Together, the three layers illustrate the end-to-end process of the DSS: From raw data and models (Data and Models Layer), through technical processing and simulation (Software and Infrastructure Layer), to interpretation and decision-making (Business Layer). This layered approach highlights the modularity of the DSS architecture, ensuring both technical robustness and practical relevance for policy and planning.

4.2.1 Principles of microservices

Microservices architecture represents a paradigm shift in the design of complex software systems. Unlike traditional monolithic architectures, in which all functionalities are implemented in a single, interdependent codebase, microservices decompose a system into multiple independent services. Each service is responsible for a narrowly defined functionality, such as database management, model execution, or visualization, and communicates with other services through standardized interfaces, like RESTful APIs.

Several characteristics make microservices particularly suited for an SSD-DSS:

1. **Autonomy of components:** Each microservice is self-contained, with its own codebase, dependencies, and runtime environment. This autonomy allows different development teams to work on different services without interfering with one another.
2. **Independent deployment and scaling:** Because services are decoupled, they can be deployed, updated, and scaled independently. For example, if the simulation service faces high demand during scenario analysis, it can be scaled horizontally without affecting the database management service.
3. **Resilience and fault isolation:** Failures in one service do not necessarily propagate to the entire system. This isolation increases the robustness of the DSS, ensuring that, for instance, a visualization error does not disrupt ongoing simulations.
4. **Technology heterogeneity:** Microservices enable the use of different programming languages and frameworks for different components. The DSS can integrate geospatial services implemented in Python with simulation engines coded in C++ or Java, as long as they adhere to the same communication protocols.

4.2.2 Infrastructure

The DSS operates on a Linux-based distributed infrastructure, providing stability, security, and compatibility with containerization technologies. Each microservice is encapsulated in a Docker container. Docker utilizes packaging of code, managing dependencies, and runtime configurations into a portable unit. This guarantees that services behave consistently across development, testing, and production environments. This infrastructure operationalizes the methodological principles established earlier. The reliance on microservices and containerization ensures that the DSS is modular, scalable, and maintainable. By building on open-source technologies, the system avoids proprietary lock-in and ensures long-term sustainability.

Together, these design choices realize the objectives set out in DSRM: methodological rigor, technical scalability, and long-term adaptability. The next section will explain how these components interact during operation, detailing workflows for data ingestion, simulation execution, and visualization.

Deployment Architecture

Figure 28 shows the deployment diagram of the different components in the DSS, it models the physical and virtual execution environments, software components, and artifacts, as well as their interactions.

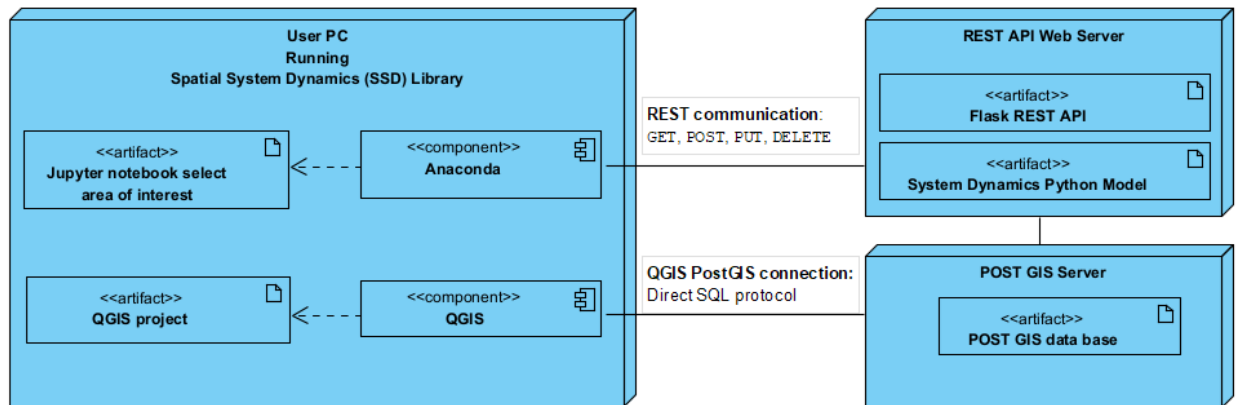


Figure 28 Deployment diagram for the different components to be able to run an SSD simulation

User PC

The User PC constitutes the client-side execution environment and serves as the main point of interaction between the user and the DSS framework. Two major components are deployed on this node.

- The first is the Anaconda component, which provides the Python based runtime environment. Within this component, the associated artifact is the Jupyter notebook for selecting the area of interest. This artifact represents the interactive user interface that allows researchers to define and configure the spatial domain under investigation.
- The second component is QGIS. Its associated artifact, the QGIS project, provides advanced capabilities for visualization, spatial analysis, and cartographic representation of model outputs. Through this, users are able to interpret simulation results in a spatially explicit manner and link them to real-world geographic contexts.

Together, Anaconda and QGIS integrate an interactive model configuration with geospatial visualization on the User PC.

REST API Web Server

The REST API Web Server functions as the computational and communication hub of the architecture. It hosts two artifacts:

- The Flask REST API, which acts as middleware between the client and the server, exposing simulation functionalities through standardized web service endpoints.
- The System Dynamics Python Model, which encapsulates the core logic of the SD model. This model artifact contains the mathematical formulations and computational routines necessary for executing simulations based on user-defined inputs.

The REST API Web Server processes incoming requests from the User PC, triggers the corresponding model execution, and transmits results back to the client. It ensures interoperability by adhering to RESTful principles and provides a scalable solution for handling multiple user requests.

PostGIS Server

The PostGIS Server provides the system's spatial database infrastructure. It contains the PostGIS database artifact, which serves as a repository for both input data and simulation outputs. The database is spatially enabled, allowing efficient storage, retrieval, and querying of geospatial

datasets. The REST API Web Server interacts directly with the PostGIS Server, retrieving the data necessary to initialize and run simulations and storing the results of executed models. This separation between computation and data management ensures consistency, persistence, and scalability.

Interactions Between Nodes

The interaction between nodes follows a client–server paradigm. The User PC communicates with the REST API Web Server via a RESTful interface. Users configure model parameters and spatial domains in the Jupyter notebook and submit these through the REST API. The Web Server then executes the System Dynamics Python Model, retrieving and storing spatial data via the PostGIS Server. Once computations are complete, results are returned to the User PC, where they can be visualized in QGIS or further analyzed interactively in Jupyter notebooks.

The deployment architecture of the SSD framework is designed to separate user interaction, computational modeling, and spatial data management into distinct but interconnected nodes. The User PC serves as the environment for configuration and visualization, the REST API Web Server as the computational and communication layer, and the PostGIS Server as the persistent data repository. This modular and distributed design promotes interoperability, scalability, and maintainability, thereby ensuring that the DSS framework can be flexibly applied in diverse research contexts.

4.3 Component Interactions

While the architecture of the DSS defines the structure and responsibilities of the individual layers, the value of the system emerges only through their interaction. The design choices described in the previous section moderate coupling, microservices, and open standards become operational when data flows seamlessly across the layers, when simulations incorporate spatially explicit parameters, and when results are transformed into interpretable visualizations for end-users.

This section details the workflows that connect the three layers of the DSS (data, simulation, and application) and explains how standardized communication protocols and orchestration mechanisms ensure smooth and scalable operation.

4.3.1 Data ingestion and preparation

The interaction process is initiated by the integration of data into the data layer. The data is sourced from a variety of repositories, including geodata repositories (OpenStreetMap), statistical databases (Statistics Canada), web scraping pipelines (Yelp), and user-provided files (CERC research team). Each data set is subjected to a pipeline consisting of three primary steps:

1. **Extraction:** The data is retrieved from its source, which may include open data portals, APIs from statistical offices, or web crawling resources.
2. **Transformation:** It is rare for raw datasets to be suitable for direct integration. The transformation step is pivotal in standardising formats, rectifying errors, and harmonising coordinate systems for spatial data.
3. **Loading:** The resultant data is then loaded into the PostgreSQL/PostGIS database, which functions as a central repository.

Figure 29 illustrates the data integration and preparation workflow. For each data set, a separate Jupyter Notebook is developed and is available in the following GitHub repository and in the data portal of Concordia University. Each Jupyter Notebook is accompanied by detailed documentation that specifies the provenance of the data, the date of data access, the publisher, and the steps taken during the data transformation process. This information plays a crucial role in preserving origin and version information, thereby facilitating reproducibility of simulation results and research outputs.

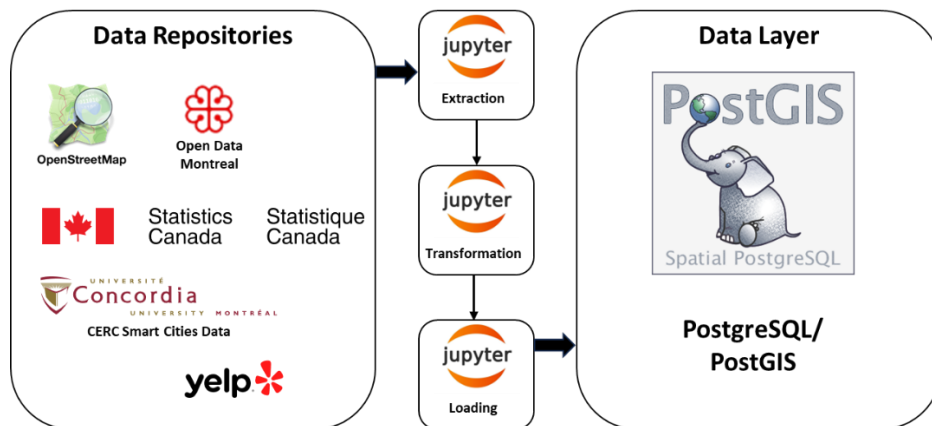


Figure 29 Illustration of the data integration and preparation workflow

4.3.2 Integration of simulation models workflow

The SD model is first developed and parameterized in Vensim (see Chapter 3). In this stage, the model structure (stocks, flows, auxiliaries and feedback loops) and its equations are defined and tested inside the Vensim environment. After verification in Vensim, the model is exported as an XMILE file (see Chapter 4.1.3). As illustrated in Figure 30, the exported XMILE file is then used as an input to the Business Prototyping Toolkit for Python (BPTK-Py) compiler [124]. The compiler parses the XMILE file and translates the SD model into executable Python code. This step bridges the visual block modeling from Vensim and the execution environment (Python). Once the SD model is available as a Python code the model is uploaded into the Spatial System Dynamics Simulation Core. In this final step (right side of the figure), the Python-based SD model can be executed as part of the simulation core and connected to spatial data through the GIS connector. This enables running the same SD logic programmatically while coupling model inputs/outputs to spatial data.

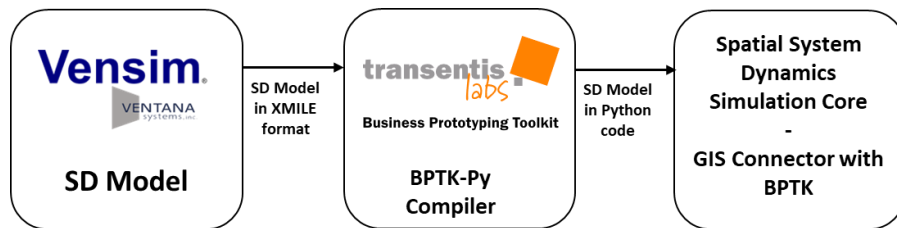


Figure 30 Illustration of the SD model integration into the SSD Simulation Core

4.4 Pipeline for creating XMILE models

Vensim PLE Plus is used as the primary modeling tool for the development of SD models. Vensim provides a graphical environment for constructing causal loop diagrams and stock-and-flow models, enabling researchers to represent feedback structures, accumulations, and nonlinear dynamics in a transparent way. Once developed and validated, the model can be exported in XMILE (XML Modeling Interchange LanguageE) format. The XMILE models are then compiled using the BPTK-Py toolkit compiler, which generates executable Python scripts. Finally, these Python-based models are integrated into the Spatial System Dynamics (SSD) framework, where they can interact with geospatial data and other services in the DSS.

The following subsections describe each step of this pipeline in detail: model creation in Vensim, testing and validation, exporting to XMILE, converting with BPTK-Py, and integration into the SSD framework.



Figure 31 Pipeline for Creating XMILE Models for Integration into the SSD Framework

Step 1: Model creation in Vensim PLE Plus

The pipeline begins with the construction of SD models in Vensim PLE Plus (both causal loop diagrams and stock and flow models), where the model behavior is tested in an initial phase. Developing models in Vensim enables collaborative model creation with relevant stakeholders, as visual modeling provides a clear illustration of the key dynamics of the system (see Chapters 3.3 and 3.4).

Step 2: Testing and validation in Vensim

Once a stock-and-flow model is created, it must be validated. A critical aspect of validation is testing extreme conditions. Extreme condition tests involve simulating the system under boundary scenarios where the expected behavior is known, ensuring that the model behaves plausibly. For example:

Zero development scenario: If the construction of new public transport stations is set to zero, the stock representing total stations should remain constant.

Extreme condition tests provide confidence in the structural integrity of the model. Vensim also includes diagnostic tools for checking unit consistency and sensitivity analysis, further strengthening model reliability before export.

Step 3: Exporting models in XMILE format

After validation, the Vensim model is exported in XMILE format. The export process in Vensim PLE Plus is straightforward: the model diagram is saved in XMILE format, producing an XML file that encodes stocks, flows, auxiliaries, equations, and parameters (see Chapter 4.1.3). This XMILE file becomes the central representation of the model for subsequent steps in the pipeline.

Step 4: Converting Models with BPTK-Py

Once the XMILE file has been created, the next step is to interpret and execute it using the compiler of BPTK-Py.

The process involves:

1. Loading the XMILE file: BPTK-Py reads the exported XML structure, parsing stocks, flows, and equations into its internal representation.
2. Generating a Python model: The toolkit automatically creates a Python script that mirrors the logic of the XMILE model. This makes the model executable in a Python environment and allows direct access to Python's scientific ecosystem like NumPy, Pandas or Matplotlib.
3. Running simulations: With the generated Python script, simulations can be executed directly within Python. Parameters can be varied programmatically, results stored in data frames, and sensitivity analyses automated.

By bridging XMILE and Python, BPTK-Py provides the key step that enables SD models to be integrated into broader computational frameworks, such as the SSD-based DSS.

Integration into the SSD Framework

The final step in the pipeline is the integration of the Python-based SD model into the Spatial System Dynamics (SSD) framework. Here, the model interacts with geospatial data and other services via the DSS architecture. The integration demonstrates the power of the pipeline: models created in Vensim are not stuck to a closed environment but become interoperable, extensible, and directly usable within a DSS.

The pipeline for creating XMILE models and integrating them into the SSD framework follows a clear sequence:

1. Model creation in Vensim PLE Plus: developing causal loop and stock-and-flow models.
2. Testing and validation: ensuring plausible dynamics under extreme conditions.
3. Export to XMILE: producing an open-standard XML representation.
4. Conversion with BPTK-Py: generating an executable Python script.
5. Integration into SSD: embedding the Python model in the DSS for spatially explicit simulations.

This pipeline combines the strengths of Vensim (ease of modeling), XMILE (open standardization), BPTK-Py (Python integration), and the SSD framework (spatial and systemic integration). It exemplifies the methodological and technical choices of this thesis: transparency, interoperability, scalability, and extensibility.

4.5 Advantages and challenges

The technical and methodological decisions underlying the DSS moderate coupling, microservices architecture, and the use of open standards are not arbitrary but were made deliberately to strike a balance between performance, scalability, and maintainability. However, as with any design strategy, the implementation of these decisions is not without its challenges. It is necessary to understand these trade-offs in order to evaluate the robustness of the DSS and identify areas for improvement in future iterations.

4.5.1 Advantages

Flexibility and modularity: The most significant advantage of the DSS is to be found in its modular architecture. The decomposition of the system into independent microservices, each with a narrowly defined responsibility, enables the DSS to achieve a level of flexibility that is unattainable in monolithic systems. The services (simulation server, data ingestion pipelines, and visualisation modules) can be updated, replaced, or scaled independently. This modularity guarantees the system's capacity to adapt to emerging requirements, such as the incorporation of additional datasets, the adoption of novel modeling paradigms, and/or the refinement of visualization techniques.

Scalability: Containerization enables the DSS to scale both vertically (adding resources to a single service) and horizontally (instantiating multiple service instances). For simulation or optimization workloads, which are often computationally intensive, this elasticity ensures that multiple users can run scenarios concurrently without degradation in performance. This scalability makes the DSS suitable not only for research contexts but also for operational decision-making involving multiple stakeholders.

Transparency and reproducibility: The implementation of open-source software and open standards, including XMILE for model encoding, PostGIS for spatial data management, and RESTful APIs for communication, is pivotal in ensuring transparency and reproducibility. Models encoded in XMILE can be exchanged between different tools, PostGIS-structured databases can be queried by external GIS applications, and APIs allow external systems to interact with the DSS without knowledge of its internal architecture. This level of transparency is of particular importance in scientific contexts, where the principles of reproducibility and verifiability are considered fundamental.

Interoperability: Through its API-driven design, the DSS achieves a high level of interoperability. Services developed in different languages and environments can coexist as long as they adhere to the API specifications. This not only enhances technical flexibility but also lowers barriers for integrating external tools. For instance, machine learning services for predictive modeling could be added as independent new microservices.

Resilience and fault isolation: In monolithic systems, failures frequently propagate across the entire application. In contrast, the microservices architecture of the DSS ensures fault isolation. A malfunction in one service, for example in a visualization component, does not necessarily compromise the simulation server or the database.

Decision relevance: The methodological integration of SD with geospatial data ensures that the DSS produces results that are directly relevant to decision-making. The integration of systemic feedback with spatial heterogeneity enables the DSS to generate insights that are more comprehensive and practical than those yielded by standalone SD or GIS tools. The technical architecture provides a foundation for this methodological ambition by ensuring that data, models, and visualizations interact in nearly real time.

4.5.2 Challenges

Architectural complexity: The architectural complexity of the structure is worthy of note. The very modularity that provides flexibility also introduces architectural complexity. A system composed of multiple microservices poses significant challenges to orchestration, monitoring, and error handling. It is essential for developers to maintain consistency in API specifications, manage container deployments, and monitor interactions between services. For small teams, this increased complexity may represent a significant overhead compared to monolithic systems.

Integration overhead: The utilization of moderate coupling through a shared database offers flexibility but also introduces integration overhead. The database is a common interface to which simulation servers, visualization services, and data ingestion pipelines all rely. In the absence of adequate query optimization or when the schema becomes excessively complex, the database risks becoming a bottleneck. Furthermore, ensuring that data transformations preserve consistency across spatial and dynamic datasets requires rigorous governance.

Performance bottlenecks: The reliance on a central database can result in I/O (input/output) performance limitations, which can hinder scalability under conditions of heavy load. Concurrent read/write operations from multiple services have the potential to impede the execution of queries, particularly for substantial geospatial datasets. Whilst database clustering and replication offer potential solutions, they also introduce additional configuration complexity.

Learning curve and maintenance effort: The learning curve and the maintenance effort are two factors that must be taken into consideration. The implementation of containerization practices necessitates the expertise of professionals skilled in this domain. Teams with no prior experience of Docker pipelines may encounter a considerable learning curve. Moreover, the ongoing maintenance of the system, the updating of containers, the monitoring of resource consumption, and the management of security patches require a sustained operational effort. In the context of

research prototypes, this investment may be considered suboptimal unless the system is intended for long-term utilization.

Governance and data quality: The DSS is reliant on heterogeneous datasets. Ensuring data quality and governance is a non-trivial challenge. Inaccuracies in the input data can propagate through the simulation and compromise the relevance of the decisions derived from it. The establishment of clear protocols for data validation, provenance tracking, and versioning is therefore critical.

Adoption barriers: Finally, while the DSS offers technical sophistication, stakeholders may find it difficult to adopt due to its perceived complexity. Individuals lacking in technical IT expertise may necessitate training to utilize the DSS effectively. Furthermore, organizations that are accustomed to proprietary, monolithic tools may be reluctant to adopt an open-source, microservices-based system, even if it offers long-term advantages.

Chapter 5. Primary and Secondary Data

In this Chapter, the datasets used to parameterize the system dynamics model (see Chapter 3) are described in more detail. The data sets are divided into two categories: primary data and secondary data. Primary data represents data that was collected in the context of the work; it serves to close the gaps in the secondary data or to supplement the secondary data. Primary data were collected for places of food consumption, such as restaurants or fast-food outlets, and food-acquiring points like supermarkets, small shops, and healthy food stores.

The secondary data is collected from several freely available sources, including official databases, surveys, reports, and scientific studies (e.g. Open data portal from the City of Montréal, Statistics Canada). Secondary data is quantitative and geo-referenced, if possible, to allow characterization of external factors. The data is used to represent current socio-spatial trends and phenomena across areas in Montréal.

Since the simulation results depend heavily on the underlying input data, separate Jupyter notebook scripts are developed for each data set that describes where the data comes from (data source), how the data was processed, and what adjustments were made to the data. The Jupyter notebooks enable external parties such as other scientists, data managers in cities, or other software developers to understand and interpret the data and create their own data sets for their applications.

Since a complete description of all steps would exceed the scope of this work, in this chapter the most important data sets are described.

A notable challenge encountered when working with information and data in Montréal is the limited availability of bilingual resources, with certain data exclusively available in French. In order to establish a comprehensive and well-organized database, as well as to facilitate the efficient

processing of information, it was necessary to translate the data sets that were initially available only in French into English. However, to ensure the reproducibility of the research, the original data set and the translated data set were archived, enabling modifications to be made at any time.

5.1 Data Flow Diagram for data integration into DSS

Figure 32 presents a data-flow diagram (DFD) that formalizes how primary and secondary sources were acquired, transformed, and consolidated in the PostGIS-based DSS used to run spatial system-dynamics simulations. The DFD specifies the collection, processing, and merging steps prior to persistence in the spatial database that supports geospatial querying and model execution. The complete diagram is also available as a machine-readable Visual Paradigm XML project, enabling import and reuse. The workflow represented in the DFD is encoded in the accompanying XML project file (`Data_flow_daigram.xml`), developed using Visual Paradigm. This file formally specifies all entities, data stores, processes, and data flows shown in the diagram, ensuring that the workflow can be reproduced or imported into other modeling environments.

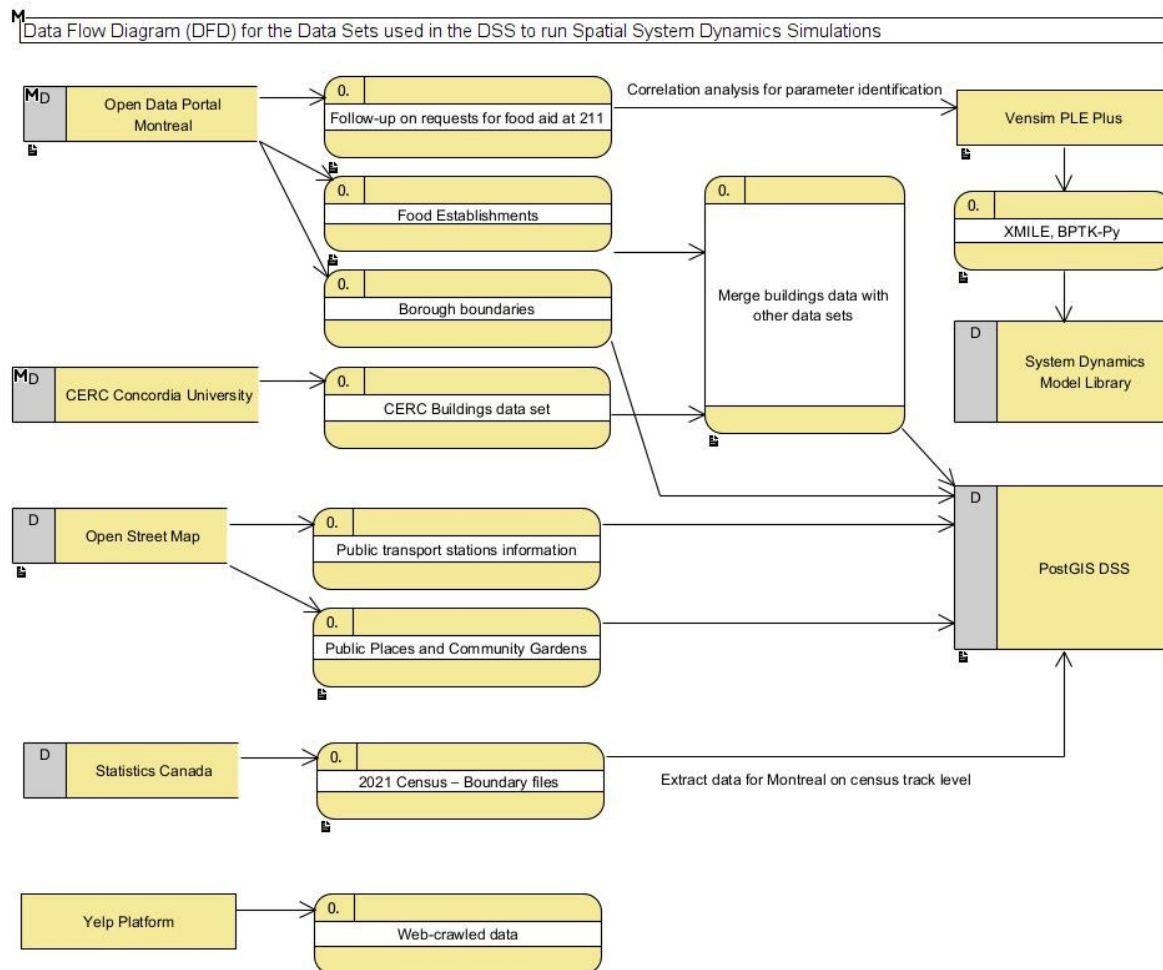


Figure 32 Data flow diagram for the data sets used in the DSS to run SSD simulations.

DFD elements and their instantiation in this work.

The data-flow diagram (DFD) uses four canonical element types: data stores (D), processes (P), external entities (E), and data flows (F). A data store (D) is a passive repository that persists data between transformations; stores are only read from or written to by processes. A process (P) is an active transformation that converts inputs to outputs (e.g., cleaning, spatial joins, schema harmonization, model compilation). An external entity (E) is a system outside the DSS boundary that supplies or consumes data but does not persist it within the DSS (e.g., authoring or execution tools). A data flow (F) is a directed, labeled connection that specifies the movement of a defined payload (and its representation) between elements.

In Figure 32, six data stores are represented. On the left are four external source stores (Statistics Canada, OpenStreetMap, Open Data Portal Montréal, and CERC Concordia University) from which raw datasets are retrieved. On the right are the two internal repositories where results are

persisted: the PostGIS DSS (processed, geo-referenced inputs for analysis) and the System Dynamics Model Library (compiled SD models and versions). Data are extracted from the external stores and passed through processes (P) such as *Public transport stations information*, *Public places and community gardens*, *Merge buildings data with other datasets*, and *Extract data at the census-tract level*. External entities (E), notably Vensim PLE Plus and the XMILE/BPTK-Py execution stack, exchange model structures and parameters with the DSS but do not act as persistent repositories. The data flows (F) trace these movements end-to-end (e.g., source store → processing step → PostGIS DSS; Vensim/XMILE ↔ model library), making the transformation chain explicit and reproducible.

Overview of the Data Flow

The DFD illustrates the following data exchange and transformation processes:

- Open Data Portal Montréal provides three key datasets: Follow-up on Requests for Food Aid at 211, Food Establishments, and Borough Boundaries. These datasets serve as the foundation for spatial and socio-economic analyses. The Follow-up on Requests for Food Aid at 211 data supports a regression analysis to identify model parameters that are used in the subsystem household circumstances (see Chapter 3.4.3).
- CERC Concordia University supplies the CERC Buildings dataset, which is integrated with other datasets to produce a comprehensive inventory of the built environment. This dataset is particularly important for assessing the spatial distribution of food establishments and merging information of food establishments with building data .
- OpenStreetMap contributes geospatial data on Public Transport Stations and Public Places and Community Gardens, enhancing the representation of mobility and accessibility within the study area.
- Statistics Canada provides the 2021 Census Boundary Files, which define the spatial reference framework for the study. These files allow the extraction of census-tract-level data for Montréal, ensuring compatibility with other datasets used in the DSS.

Given the scope and complexity of the data integration and modeling workflow, it is not feasible to describe each processing step and transformation in full detail within this chapter. To maintain transparency and reproducibility, all datasets, preprocessing scripts, and configuration files are openly available in the accompanying [GitHub repository](#). The following subsections, therefore, focus selectively on key datasets and processing steps that are most relevant for understanding and interpreting the simulation results presented in Chapter 6. The objective is not only to clarify how data supports the modeling effort but also to align this work with the Design Science Research Methodology (DSRM). In particular, the data integration and model parameterization processes address the DSRM guidelines on Design as an Artifact, Problem Relevance, Design Evaluation,

and Research Rigor (see Table 12, Chapter 4.1.1). Together, these subsections provide the empirical and methodological foundation necessary to interpret the DSS simulations and to demonstrate the artifact's validity and contribution within the DSRM framework.

5.2 Detailed Description of Key Datasets

The following section provides a focused description of selected datasets and processing steps that form the analytical foundation of the DSS. While numerous datasets were collected and harmonized during the development of the SSD model, this section concentrates on those that are most critical for understanding the model structure, input assumptions, and simulation outcomes. Each subsection describes the data source, its main characteristics, the preprocessing and transformation procedures applied, and its specific role within the DSS workflow. By highlighting these key datasets, the section aims to enhance the interpretability of the simulation results and to demonstrate how the data architecture operationalizes the principles of the Design Science Research Methodology (DSRM), particularly in terms of design evaluation, research rigor, and communication of research.

5.2.1 Food Establishments

The City of Montréal provides a dataset on food establishments under the responsibility of its Food Inspection Division, which operates under the mandate of the Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec (MAPAQ) for inspections. The data is sourced daily from MAPAQ permits, Certificates of occupancy issued by the City of Montréal and field observations. This recording is interesting because it contains details of the businesses where food is sold and/or consumed; specially, whether the shops are still open or have already closed, the address of the shops, their coordinates and the type of shop [125].

As the SD model uses supermarkets, healthy food stores, and fast-food outlets as input variables to simulate the temporal development of those establishments as stocks, the type of business is used to categorize the businesses into healthy food stores, supermarkets, fast food restaurants, restaurants, catering, and others.

The original data set for the permissions comprises a total of 73 categories for the establishments. In order to facilitate a more comprehensive overview, the 73 categories have been divided into the following classes: healthy food store, supermarket, fast food outlet, restaurant, out-of-home catering, and other. This approach was required due to the SD model's usage of supermarkets, healthy food stores, and fast food restaurants as input variables to simulate the temporal development of these establishments as stocks. The method by which the assignment was made is illustrated in Table A 11 in Appendix D and described in more detail in Chapter 5.2.5.

The objective was to reduce the initial 73 categories into the six classes which can be used in the SD model. For instance, grocery stores that offer prepared foods, grocery stores, and supermarkets were classified as supermarkets. Brasseries, lounge bars, taverns, take-out restaurants, and full-service restaurants were classified as restaurants. There are certain advantages and disadvantages in using a simplified classification. Whilst the integration into the SD model is less complex in the event of a reduced number of classes, this does result in the loss of information.

Figure 33 illustrates the distribution of open food establishments across the boroughs of Montréal, categorized into the six classes. Ville-Marie has the highest number of food establishments, exceeding 2,500, with restaurants forming the largest proportion, followed by fast food outlets and supermarkets. Le Plateau-Mont-Royal, Villeray–Saint-Michel–Parc-Extension, Côte-des-Neiges–Notre-Dame-de-Grâce, and Rosemont–La Petite-Patrie also show high concentrations, each hosting over 1,000 establishments. In most boroughs, restaurants and supermarkets constitute substantial portions of the total, whereas healthy food stores and other categories remain relatively small. Peripheral and less densely populated boroughs, such as Senneville, Hampstead, and Montréal Ouest, have very few food establishments overall. The data indicate a marked concentration of diverse food service options in central and densely populated boroughs, with variety and volume diminishing toward the city’s periphery.

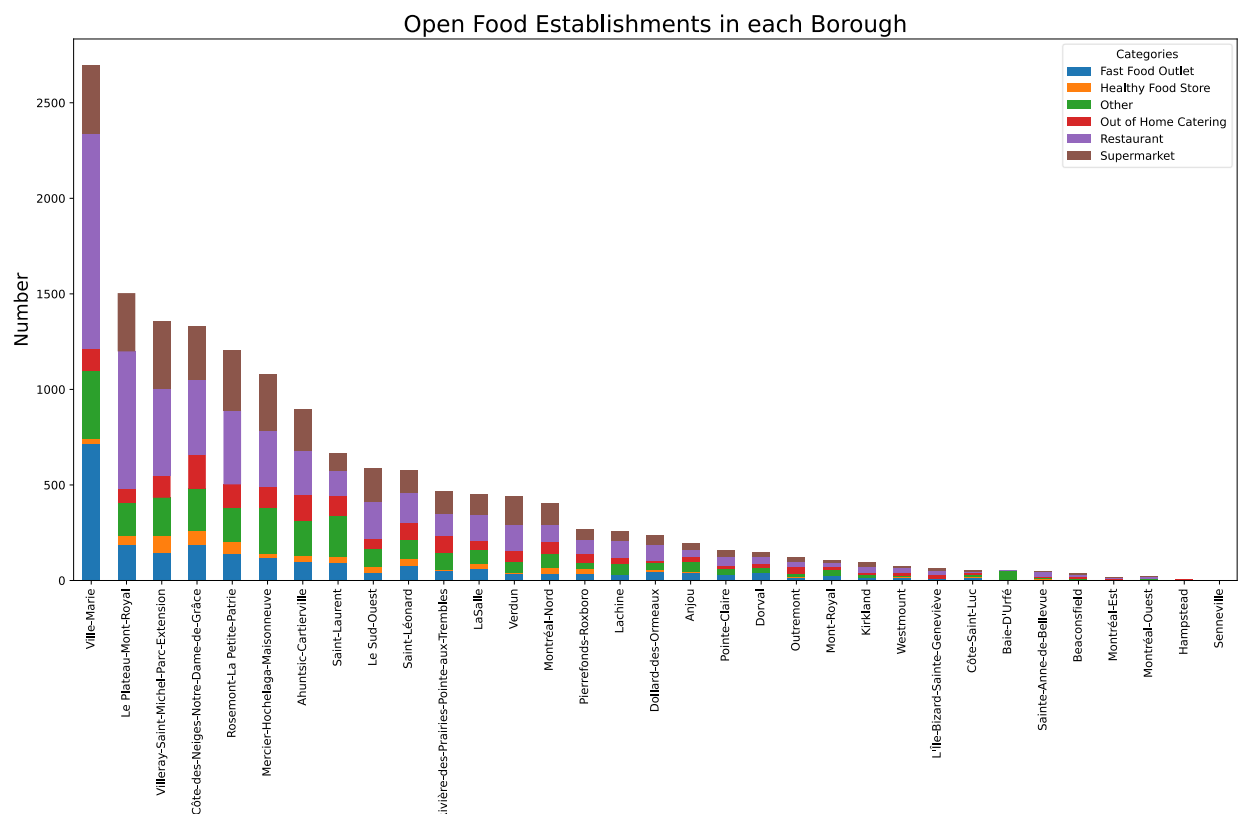


Figure 33 Open food establishments in each borough

Figure 34 shows the patterns of business openings and closures between 2016 and 2023. The openings and closures varied considerably across different categories of food establishments. Fast food outlets showed relatively stable levels of activity, with both openings and closures generally remaining below 15 per month and displaying only minor fluctuations over time. Restaurants were more active in the earlier years of the period (2016-2020), with monthly openings occasionally exceeding 25, but both openings and closures gradually declined toward the later years. Supermarkets experienced pronounced spikes in activity during the initial years, with more than 20 openings in some months, followed by a shift toward lower and steadier levels. Healthy food stores consistently recorded low counts, rarely exceeding five openings or closures in a month. Out-of-home catering services exhibited moderate activity, typically with fewer than 15 openings each month and similar patterns in closures. In contrast, other food establishments displayed relatively stable opening rates but occasional sharp surges in closures, with one month reaching nearly 100.

Overall, the trends indicate that while openings and closures often moved in tandem within each category, the magnitude and frequency of these changes were highly dependent on the type of food establishment.

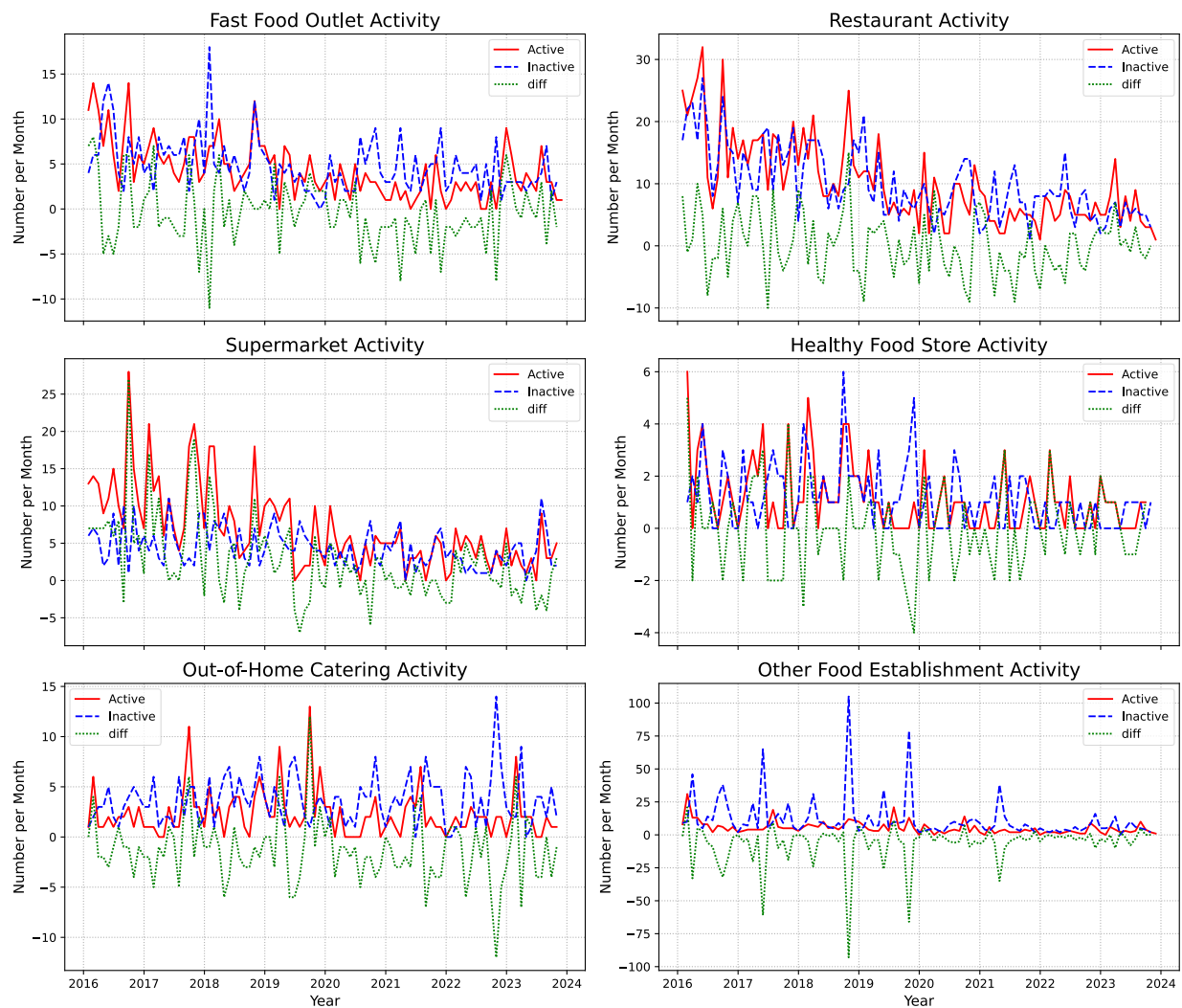


Figure 34 Food establishments activity in Montréal for the years 2016 – 2023

From 2016 to 2023, cumulative patterns of openings and closures revealed notable differences across food establishment categories (see Figure 35). In the case of fast food outlets, cumulative openings and closures increased at a broadly similar pace, both reaching over 400 by December 2023, with only a modest gap between the two. Restaurants followed a comparable trajectory, with cumulative counts for openings and closures both approaching 1,000 by the end of the period, and the difference between them remaining relatively small. Supermarkets showed a different pattern: cumulative openings rose steadily to exceed 600, while closures increased more slowly, creating a widening positive gap over time. Healthy food stores maintained low cumulative counts, with both openings and closures ending just above 100; however, the small gap between them narrowed toward the later years. Out-of-home catering establishments displayed a reverse trend, with closures surpassing openings over time, leading to a growing negative difference that exceeded

100 by 2024. The “other food establishments” category exhibited the most extreme divergence, with cumulative closures surpassing 1,000 while openings remained around 500, producing a large and persistent negative gap throughout the period. Overall, the cumulative data indicate that while some categories experienced relatively balanced growth and decline, others, particularly out-of-home catering and other food establishments were characterized by long-term net losses.

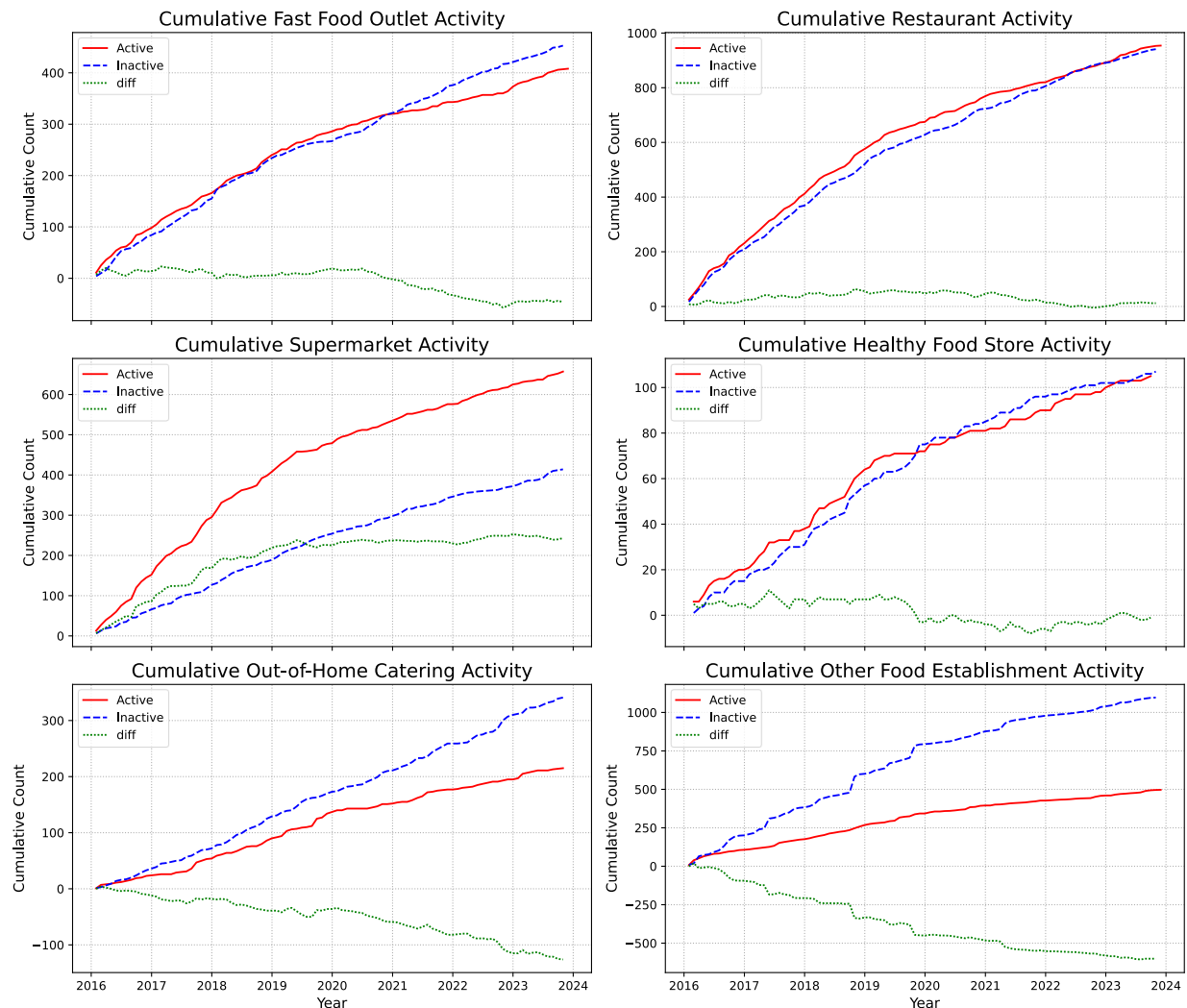


Figure 35 Cumulative food establishments activity in Montréal for the years 2016 - 2023

Between 2016 and 2023, patterns of openings and closures across food establishment categories revealed both short-term fluctuations and long-term cumulative trends, highlighting differences in sector stability and growth. Monthly activity data show that fast food outlets maintained relatively steady levels of openings and closures, generally below 15 per month, with only minor fluctuations.

Restaurants were more dynamic in the early years, sometimes exceeding 25 openings per month, but both openings and closures gradually declined toward the later period. Supermarkets experienced pronounced peaks in the early years, with over 20 openings in some months, before shifting to lower and steadier levels. Healthy food stores consistently recorded low activity, rarely exceeding five openings or closures in a month. Out-of-home catering services exhibited moderate monthly changes, typically under 15 openings, with closures tracking closely. In contrast, the “other food establishments” category showed relatively low opening numbers but occasional sharp spikes in closures, reaching as high as 100 in a single month.

Cumulative data over the same period revealed longer-term imbalances for some sectors. In fast food outlets and restaurants, cumulative openings and closures increased at similar rates, resulting in only modest differences between the two by 2023.

Supermarkets displayed sustained net growth, with cumulative openings exceeding 600 while closures remained significantly lower. Healthy food stores maintained low cumulative totals for both openings and closures, with differences narrowing toward the end of the period. Out-of-home catering establishments experienced net losses over time, as closures steadily outpaced openings. The largest and most persistent gap appeared in other food establishments, where cumulative closures exceeded 1,000 compared with around 500 openings, producing a substantial long-term decline. Taken together, the monthly and cumulative trends indicate that while some categories, such as supermarkets, showed net expansion, others, particularly out-of-home catering and other food establishments, underwent sustained contraction.

The dataset described here serves as the conceptual basis for the analysis of food establishments in Montréal. However, to enable spatially precise integration into the PostGIS database and the SSD model, additional processing steps were required, including geocoding, building-level matching, and linguistic standardization. These procedures are detailed in Chapter 5.2.5 Mapping of food establishment data with building data.

5.2.2 Follow-up on requests for food aid at 211

The Montréal Follow-up on requests for food aid at 211 service, a program administered by the City of Montréal, has been established to address food insecurity within the local population and facilitate access to food aid for those in need. The program is administered in collaboration with 211 Greater Montréal, a comprehensive referral service, which ensures that individuals and families in need can receive timely and appropriate assistance. The dataset contains all inquiries (phone, chat, and email) made to 211 Greater Montréal in 2021 and 2022 [126].

The dataset is structured around three interrelated components: requests, follow-ups, and needs, each capturing a different layer of information tied together by unique call identifiers (ID Call) as shown in Table 13.

The request data includes over 11,000 entries that provide basic details of each call. It contains data such as the call date, location (province, municipal district, region), and demographic information like the caller's age, gender, language, and mode of communication.

The follow-up data, with 572 entries, goes deeper into the callers' socio-economic context and the outcomes of their requests. It includes information on household income sources, education levels, living and immigration situations, and previous experiences with food aid. It also tracks whether help was obtained, how long it took, if additional support was sought, and reasons why aid might not have been received. Satisfaction with the support process is also documented.

The needs data is the biggest data set, with over 12,000 entries focusing on the specific types of needs expressed during the calls. Each entry includes a taxonomy code and name identifying the type of need, whether or not it was fulfilled, and, if not, the reason why.

Together, these three data sets provide a comprehensive picture of individual help-seeking experiences, from the initial request to detailed socio-economics (follow-up) and the specific needs that were or were not met.

Table 13 Details on the Follow-up on requests for food aid at 211

Requests (11.106 recodings)	Follow-up (572 recodings)	Needs (12.331 recodings)
- ID Call - Date - Province - Municipal district - Region - Age - Gender - Mode of communication - Language	- ID Call - Source household income - Education level - Household situation - Housing situation - Citizenship immigration status - History of food aid use - Obtained aid through resources - After how many days help - After how many days obtained help - Return to resources help - Overall satisfaction level - Why not get help	- ID Call - Taxonomy Code - Taxonomy Nom - Needs fulfilled - Reason need not met - ID Needs

The data on the food aid request provides insight into the areas of the city where people experience food insecurity. The request data set is used to analyze the total number of food aid requests by borough (Figure 36). Mercier–Hochelaga–Maisonnette records the highest demand, with over 1,200 requests, followed by Rosemont–La Petite-Patrie, Montréal-North, and Villieray–Saint-

Michel–Parc–Extension, each exceeding 1,000 requests. Ahuntsic–Cartierville and Côte-des-Neiges–Notre-Dame-de-Grâce also report high levels of requests, ranging between 850 and 900. Ville-Marie, Le Plateau-Mont-Royal, and Le Sud-Ouest show moderate demand, with values between 550 and 700. Mid-range boroughs, including Rivière-des-Prairies–Pointe-aux-Trembles, Saint-Léonard, LaSalle, Anjou, Lachine, and Verdun, register between 200 and 500 requests. Lower demand is observed in Pierrefonds–Roxboro, Côte-Saint-Luc, and other smaller boroughs, where counts drop below 200. The lowest values, under 50 requests, are found in affluent or sparsely populated boroughs such as Hampstead, Sainte-Anne-de-Bellevue, Beaconsfield, Montréal-West, Baie-d’Urfé, and Senneville.

The distribution suggests that food aid needs are concentrated in economically disadvantaged and densely populated boroughs, while wealthier or less populated areas show minimal demand for food aid.

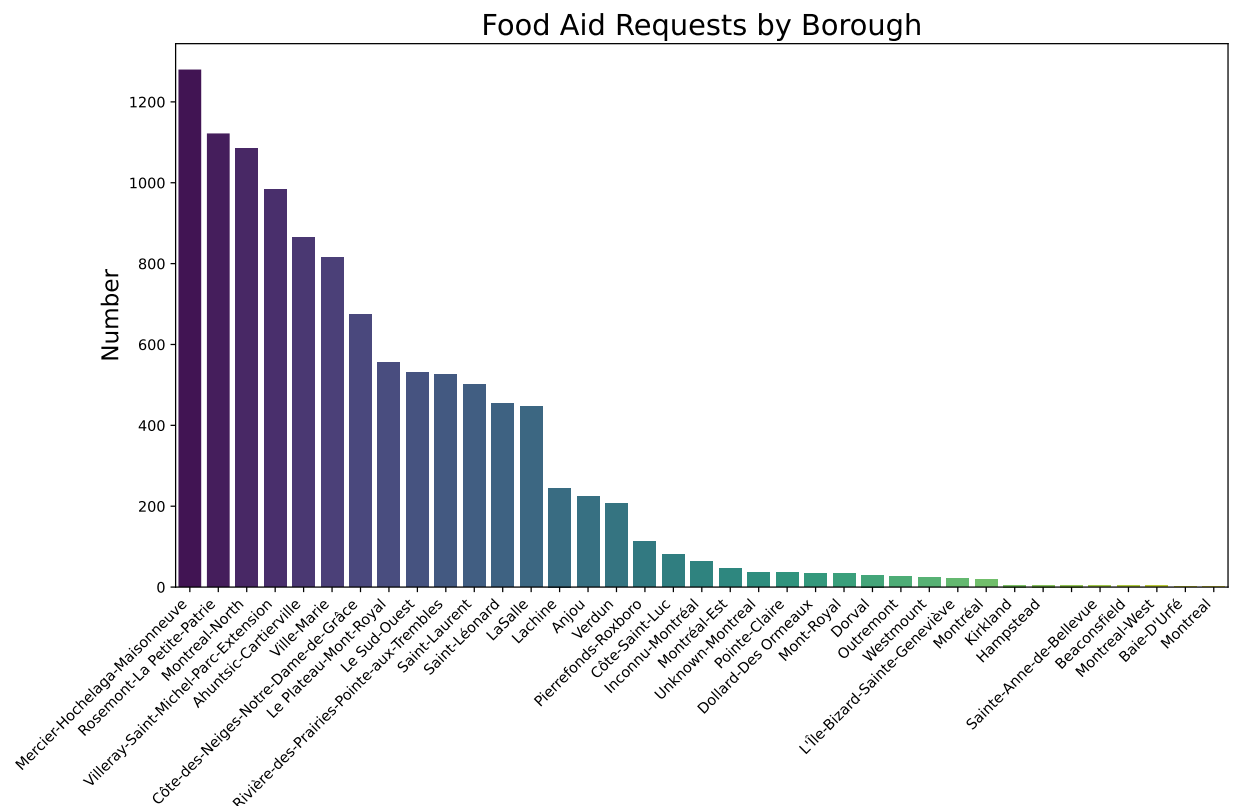


Figure 36 Food aid requests by borough

The analysis of the follow-up recordings provides insight into the sociodemographic and economic characteristics of the respondents. In terms of household situation (see Figure 37), the most frequently reported category was “two-parent households” (n = 171), followed closely by “single

person living alone” (n = 161). “Single-parent households” accounted for 62 cases, while “common-law couples” (n = 45) and “couples without children” (n = 33) were less common. Multigenerational households represented 22 cases, and a small number of respondents declined to answer (n = 3). Notably, 75 cases had no recorded information.

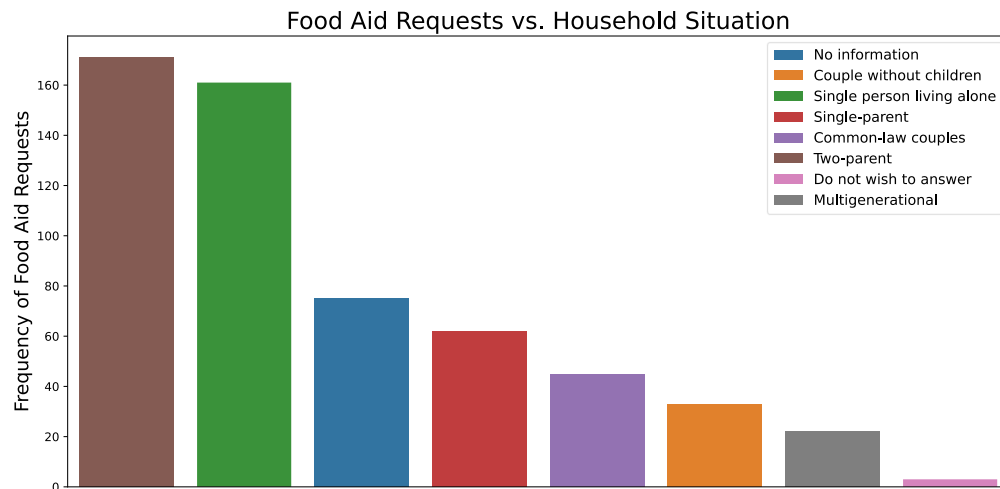


Figure 37 Frequency of food air requests vs. household situation

Figure 38 shows the numbers based on different housing situations, where “private rental market” dominated, reported by 359 respondents, followed by “subsidized housing” (n = 77). A substantial number of cases lacked information (n = 97). Smaller proportions were recorded for “owner-occupied housing” (n = 10), “private residences for seniors” (n = 4), and “cooperative housing” (n = 2). Of particular significance, 15 respondents reported being homeless.

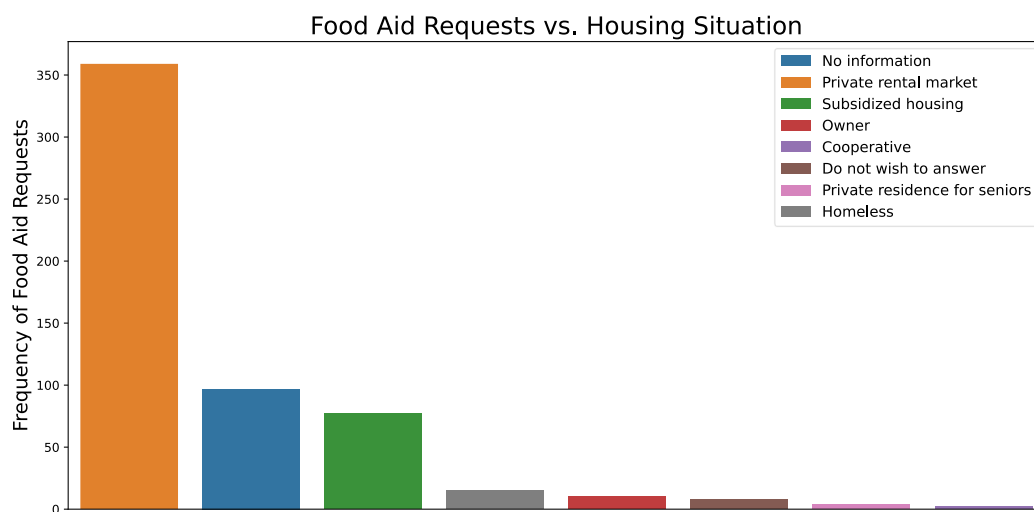


Figure 38 Frequency of food air requests vs. housing situation

Educational level varied widely across the sample. “Secondary education” was the most frequent category (n = 153), followed by “professional (DEP)” (n = 79), “university – 1st cycle” (n = 73), “primary education” (n = 71), and “college (technical)” (n = 56). More advanced degrees were less common, with 21 respondents holding a “university – 2nd cycle” degree and six holding a “university – 3rd cycle” degree. In 101 cases, no educational information was available, and 12 respondents declined to answer.

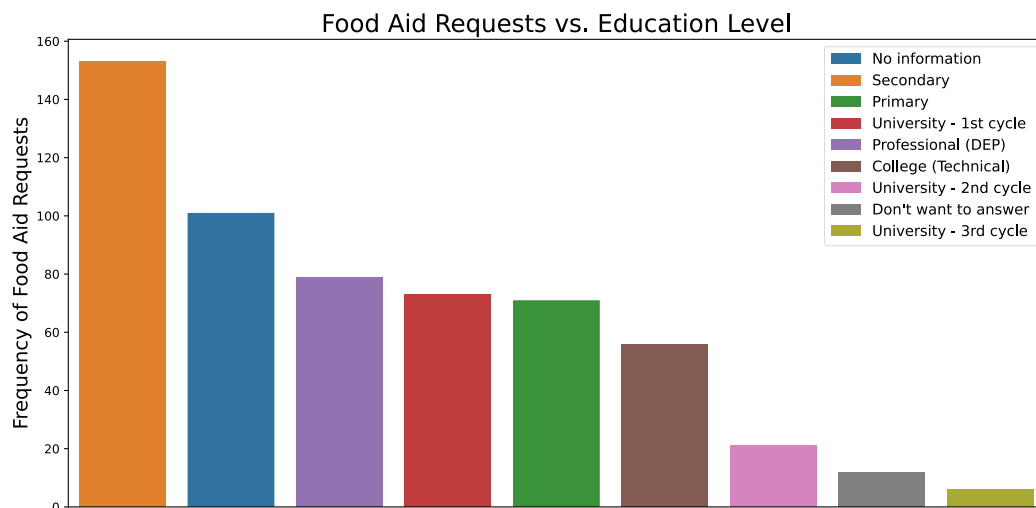


Figure 39 Frequency of food air requests vs. education level

Regarding the main source of household income, “social assistance” was by far the most reported source (n = 239), highlighting a substantial dependency on public support. This was followed by “no income” (n = 70), “full-time employment” (n = 43), and “old-age pension” (n = 39). Other income sources included “part-time employment” (n = 28), “unemployment insurance” (n = 20), “disability plans” (n = 13), “family allowance” (n = 11), and “other” (n = 12). Minimal representation was observed for “student loans and grants” (n = 6), and six respondents did not wish to disclose their income source. In 85 cases, no information was recorded.

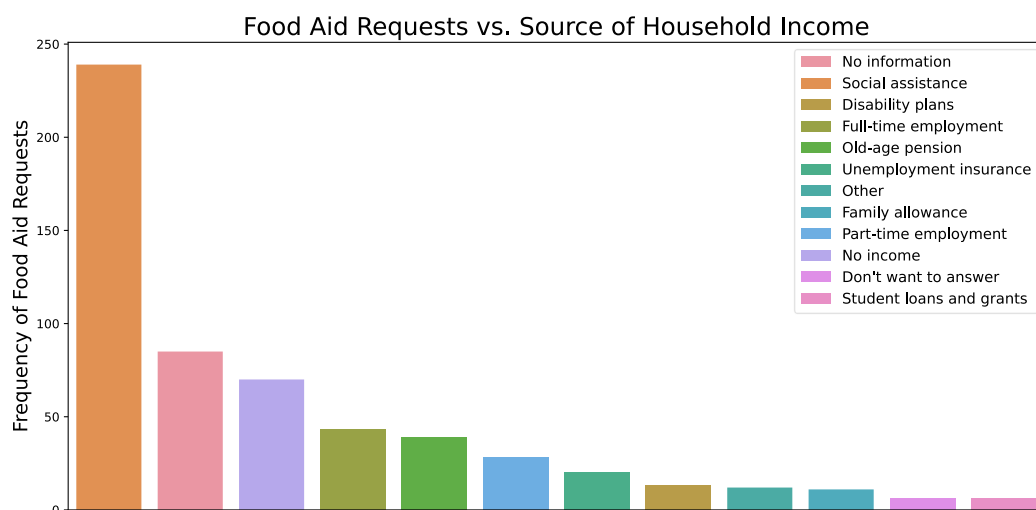


Figure 40 Frequency of food air requests vs. source of household income

Overall, the data suggest that the population captured in the follow-up recordings is socioeconomically diverse but characterized by a high prevalence of rental housing, modest levels of educational attainment, and significant reliance on social assistance or absence of income.

Figure 41 shows the analysis of the median age and number of food aid requests by borough. The data highlights marked variation in service request volumes across Montréal's boroughs. Mercier-Hochelaga-Maisonneuve stands out with the highest number of records (1,080), suggesting significant demand or need in that area. It is followed closely by Rosemont–La Petite-Patrie with 955 requests, and Montréal-North with 908. These boroughs with high absolute numbers also show relatively mid-range median ages, all in the early-to-mid 40s, suggesting a broad, working-age population making use of services.

On the other hand, several boroughs show minimal numbers of requests e.g. Dorval, Mont-Royal, Montréal-East or Westmont. This variation paints a picture of uneven service use or less need for food aid in specific areas of the city, with a clear concentration in more densely populated, working-class boroughs, and far less activity in either very affluent or very small boroughs.

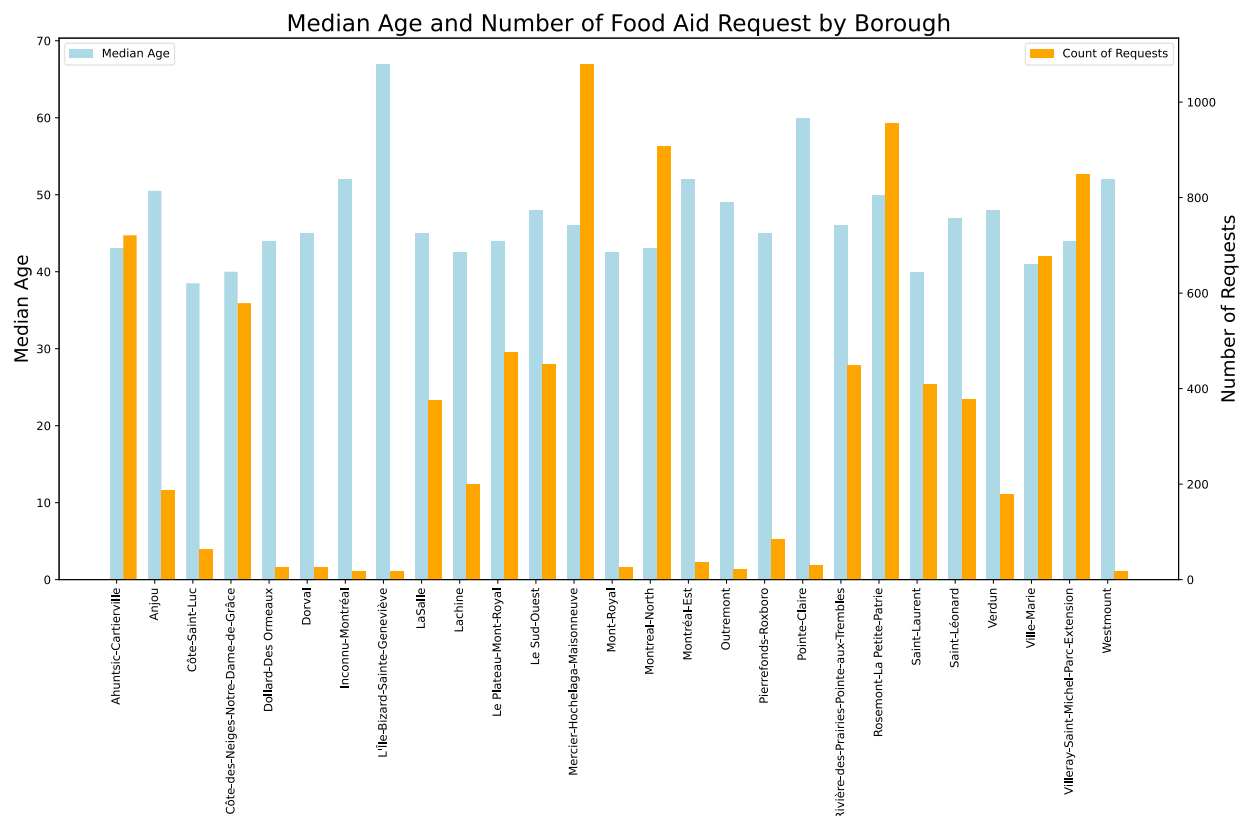


Figure 41 Median age and number of food air requests by borough (Follow-up food aid request data)

The map in Figure 42 provides an overview of the spatial distribution of food aid requests across Montréal. It is essential to interpret the results with caution for boroughs with very low request counts. Several boroughs, such as Baie-D'Urfé (NUM = 71, $n = 2$), Beaconsfield (NUM = 7, $n = 4$), Hampstead (NUM = 10, $n = 5$), Kirkland (NUM = 3, $n = 5$), Montréal-West (NUM = 75, $n = 4$), Sainte-Anne-de-Bellevue (NUM = 76, $n = 4$), L'Île-Dorval (NUM = 73, $n = 0$), and Senneville (NUM = 77, $n = 0$), report a low number of requests, fewer than 20 requests across the entire dataset. At such low levels, the data cannot be considered reliable. Such low number of requests are considered to be insufficient to reflect underlying needs, population characteristics, or spatial patterns of household food insecurity.

Low counts typically arise in small, low-density, or high-income boroughs, where residents may have different support networks, access different services, or be less likely to contact 211 as a first point of help. In these cases, the absence of requests is not equivalent to the absence of need; instead, it reflects sample sparsity, potential under-reporting, and structural differences in help-seeking behaviour. Consequently, boroughs with fewer than 20 records are treated as having no

valid or interpretable data, and they are not included in comparative analyses or used to draw conclusions about spatial patterns of food insecurity in Montréal.

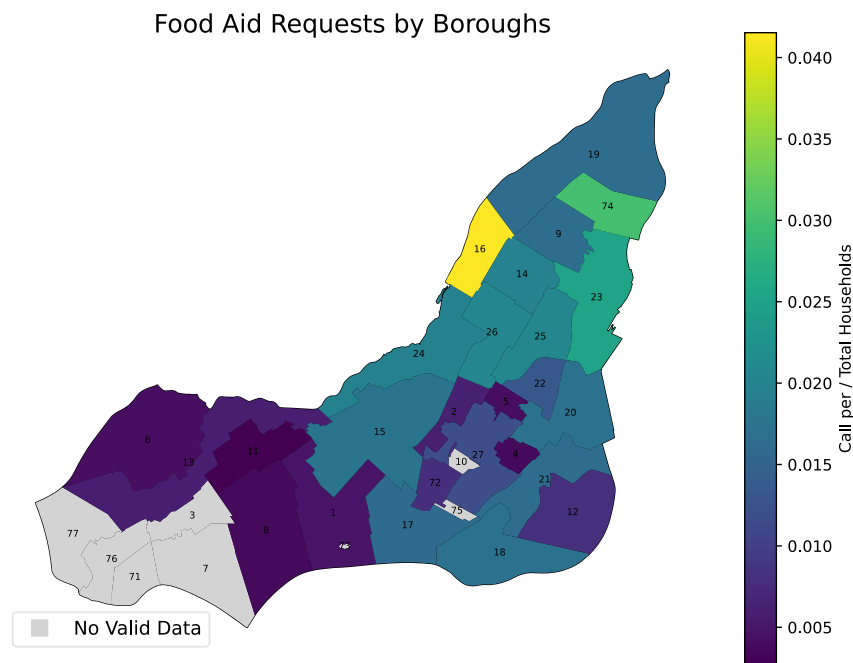


Figure 42 Spatial distribution of food aid requests across Montréal, calls per total number of households

5.2.3 Statistics Canada 2021 Census

Statistics Canada provides the 2021 Census Boundary Files, which constitute a crucial spatial reference layer for the DSS. The Statistics Canada 2021 Census boundary and attribute data form the core demographic and socio-economic foundation of the DSS. The data were obtained from the Statistics Canada data portal (2021 Census of Population). The files include both geographic shapefiles defining census tracts and attribute tables describing population, dwelling, income, education, and employment characteristics.

A Python workflow was developed to extract only the variables relevant for the parametrization of the SD model. The extraction process is documented in the accompanying Jupyter notebook (Census_analysis.ipynb), with the function `select_data()`, census tables using `CHARACTERISTIC_ID` codes corresponding to the specific indicators of interest that can be filtered. Table 14 provides an overview of the thematic categories and attributes retained from the census data set and the purpose of the data set within the DSS.

Table 14 Overview of the thematic categories and attributes retained from the Statistics Canada data

Thematic Group	Examples of Variables Extracted	CHARACTER-ISTIC_ID Range	Purpose within DSS
Population and Age	Total population (2016, 2021), % change, median and average age	1–40	To analyze demographic change and age distribution across census tracts.
Private Dwellings	Total and occupied dwellings, household size, census families	4–77	To represent residential density and household structure in spatial simulations.
Income (2019–2020)	Median total income, after-tax income, government transfers, COVID-19 benefits	111–125, 204–216	To analyze economic status and inequality indicators.
Household Income Groups	Income brackets from under \$5,000 to \$200,000+	260–280	To create income class distributions for neighborhood typologies.
Low Income (LIM/LICO)	Low-income measures by age group	335–364	To quantify poverty levels and link them to food aid and accessibility indicators.
Education	Highest certificate or degree (15+ and 25–64 years)	1998–2029	To estimate educational attainment and its relation to economic and social patterns.
Employment	Participation, employment, and unemployment rates	2228–2230	To represent labor market activity as an external driver in system dynamics.
Citizenship and Immigration	Canadian citizenship, immigrant status, year of immigration	1522–1537	To assess diversity and population turnover.
Visible Minorities and Religion	Ethnic group proportions and major religious affiliations	1683–1697, 1949–1973	To describe socio-cultural heterogeneity across Montréal.

Each dataset was preprocessed by filtering only Montréal’s census tracts, joining them with geographic boundaries, and exporting the results as GeoJSON files for integration into the DSS database. This approach ensures that only relevant, high-quality, and interpretable variables are imported into the DSS, thereby reducing redundancy and maintaining a strong conceptual link between spatial data and the SD model structure. It is important to note that not all census-derived datasets are directly used as input parameters in the system dynamics model. While demographic and economic indicators such as population, household structure, and income levels are incorporated into the SD model to parameterize simulation variables, other datasets are integrated into the DSS primarily to support spatial exploration and prioritization by end users.

Variables such as Low Income (LIM/LICO), Visible Minority, and Religion are stored in the PostGIS database but are not explicitly represented as dynamic components in the simulation. Instead, these layers serve a contextual and analytical function to allow users, through tools like QGIS, to identify and visualize areas of socio-economic vulnerability, demographic diversity, or equity concern. This enables stakeholders to define priority zones for intervention, comparison, or further scenario testing within the DSS environment.

In this way, the census data performs a dual role: providing quantitative inputs for model parameterization and offering spatial insights for decision-making support.

5.2.4 Mapping of food aid request data to the census data

The Montréal Follow-up on Requests for Food Aid at 211 dataset provides detailed socio-economic and demographic information on individuals and households seeking food assistance. However, the categories used in the 211 dataset do not correspond directly to those used in the Statistics Canada Census 2021 data. To enable integration and analysis within the SSD simulation, a structured mapping process between the two data sources was required.

The census data are stored in the PostGIS database and include spatially referenced tables such as `census_household_type`, `census_housing_situation`, and `census_immigrant_status`. These tables allow the derivation of spatially aggregated socio-economic indicators for each borough of Montréal, which are then used to parameterize the SSD model.

The mapping process consisted of four steps:

- 1. Identification of Relevant Categories in the 211 Dataset**

Categories describing housing situation, citizenship and immigration status, and household composition were extracted from the 211 Montréal dataset. These categories reflect the socio-economic conditions of the population requesting food aid, such as the private rental market, subsidized housing, refugee, or single-parent households. It should be noted that the dataset also includes responses where no information was available or where respondents selected “Do not wish to answer.” These entries are retained in the 211 datasets for completeness, but cannot be mapped to any Census category.

- 2. Review of corresponding census variables**

The full list of 2021 census characteristics was reviewed to identify equivalent statistical definitions. Reference was made to Statistics Canada’s data dictionary to ensure that selected categories corresponded to comparable population groups or housing situations.

3. Establishment of mapping tables

For each 211 category, the most appropriate Census category and its CHARACTERISTIC_ID were identified (*see Mapping Tables of 211 Montréal Food Aid Request to the Census 2021*).

For example, the 211 category private rental market was mapped to the Census variable “Total - Tenant households in non-farm, non-reserve private dwellings - 25% sample data” (CHARACTERISTIC_ID = 1490). Similarly, single-parent household was aligned with “One-parent-family households” (CHARACTERISTIC_ID = 105), and Refugee was grouped under the broader Census category “Immigrants” (CHARACTERISTIC_ID = 1529). Some categories, such as homeless, private residence for seniors, or cooperative housing, could not be mapped because the Census does not collect or publish this information directly. Entries marked as “No information” or “Do not wish to answer” were also excluded from the mapping since they lack definable Census equivalents.

4. Implementation in PostGIS queries

The mapped categories were integrated into SQL queries that extract borough-level or area of interest data from the Census layers. Each query calculates the population-weighted total of the relevant characteristic within a geometry using spatial intersections, as illustrated for the calculation of the total immigrants in the function below:

```
WITH borough_geom AS (  
    SELECT ST_Union(geometry) AS geom  
    FROM public.boroughs  
    WHERE "NUM" = :num_value  
)  
SELECT  
    COALESCE(  
        SUM(cs."C1_COUNT_TOTAL" *  
            (ST_Area(ST_Intersection(cs.geometry, b.geom)) /  
            NULLIF(ST_Area(cs.geometry), 0))  
        ),  
        0  
    ) AS count  
FROM public.census_immigrant_status cs  
JOIN borough_geom b ON ST_Intersects(cs.geometry, b.geom)  
WHERE cs."CHARACTERISTIC_NAME" = 'Total - Immigrant status and period of  
immigration for the population in private households - 25% sample data';
```

This ensures that the SSD model receives harmonized and geographically aggregated indicators for initialization of the simulation model.

The mapping was a necessary step to enable the semantic and structural alignment of both datasets. While the 211 Montréal dataset provides detailed, service-based observations about vulnerable populations, the census data provides standardized, spatially explicit demographic and housing data at census tract levels.

The mapping of both data sources allows:

- **Model parameterization:** The SSD model relies on census-derived indicators such as the number of tenant households, proportion of one-parent families, or the share of immigrants to establish its initial conditions.
- **Spatial integration:** Using the PostGIS spatial functions, census geometries are overlaid with borough boundaries, enabling borough-level aggregation and comparison with 211 Montréal food aid data.
- **Decision support and visualization:** Within the DSS and QGIS environment, the mapped indicators allow users to visualize and prioritize areas with higher vulnerability, for example, regions with higher proportions of low-income tenants or single-parent households.

The mapping revealed that some categories of the 211 Montréal dataset cannot be fully represented using Census data. For instance, homelessness, cooperative housing, and private residences for seniors were not explicitly captured in the Census.

Consequently, the SSD model does not currently simulate food insecurity among the homeless population, an important limitation that calls for further data collection by local agencies, food security networks or food banks. Moreover, the Census aggregates broad categories such as immigrants, without distinguishing between specific groups like refugees or temporary workers. Future research should explore integrating administrative data from Immigration, Refugees and Citizenship Canada (IRCC) or municipal registries to improve model granularity and representativeness.

Finally, responses marked as “Do not wish to answer” or “No information available” reflect the data collection reality in social support systems and should be considered when interpreting model outputs, as these represent populations that may experience data invisibility, despite being potentially at risk of food insecurity. The summarized results of the mapping process presented above are complemented by detailed tabular information provided in Mapping Tables of 211 Montréal Food Aid Request to the Census 2021.

The Appendix lists, for each 211 Montréal category, the corresponding Census 2021 characteristic and its associated CHARACTERISTIC_ID, along with the number of occurrences in the 211

dataset. It also identifies categories for which no Census equivalent exists, such as homeless, private residence for seniors, or cooperative housing, as well as responses where participants indicated “No information” or “Do not wish to answer.”. These entries are important for understanding the completeness and representativeness of the data used in the model.

5.2.5 Mapping of food establishment data with building data

The objective of this workflow was to produce a spatially accurate and semantically harmonized dataset of food establishments that could be integrated into PostGIS. This integration enables spatially explicit analyses of food environments and supports the assessment of accessibility to different types of food outlets at the building scale across the territory of Montréal. Figure 43 shows the data flow diagram for the workflow applied.

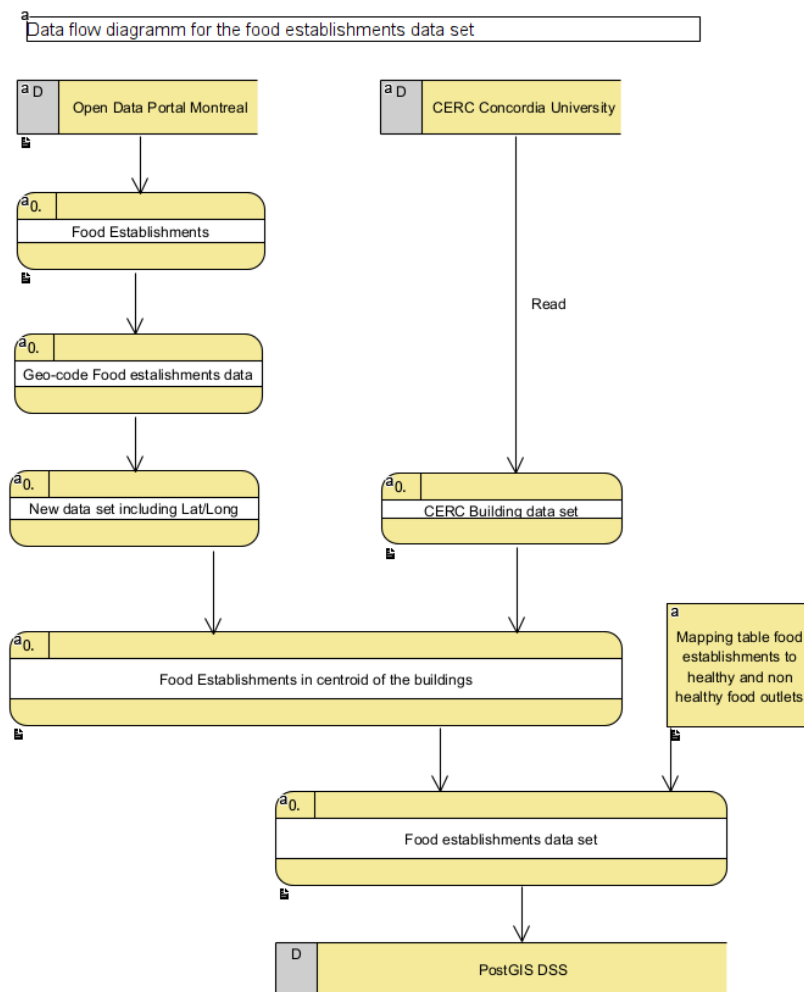


Figure 43 Data flow diagram for the mapping of food establishments, with building information and categories of food establishments used for the system dynamics simulation

A key challenge encountered in this process was the spatial inaccuracy of the original food establishments dataset provided by the City of Montréal. The dataset, obtained from the Open Data Portal Montréal, included basic business information such as business_id, name, address, city, state, five different operational status¹, date of last status and approximate geographic coordinates. However, the coordinates did not correspond to actual building locations but were typically placed along street lines. Consequently, a direct spatial correspondence between food establishments and buildings was not possible, which limited the potential for a more detailed spatial analysis and integration into the DSS environment.

To address this limitation, a reverse geocoding procedure was applied. This step transformed the approximate street-based coordinates into precise address-based locations (as the address of the establishment was included in the data set), enabling the spatial alignment of food establishments with the CERC Building Dataset developed by Concordia University. By associating each establishment with the centroid of the corresponding building, it became possible to enrich the dataset with a range of building-level attributes, including unique building identifiers (bldg_ID) or building codes. This spatial integration ensured that each food establishment could be more accurately situated within the built environment. Figure 44 shows the businesses' locations before applying reverse geocoding (left) and after (right). The new business's location lies in the center of a building footprint.

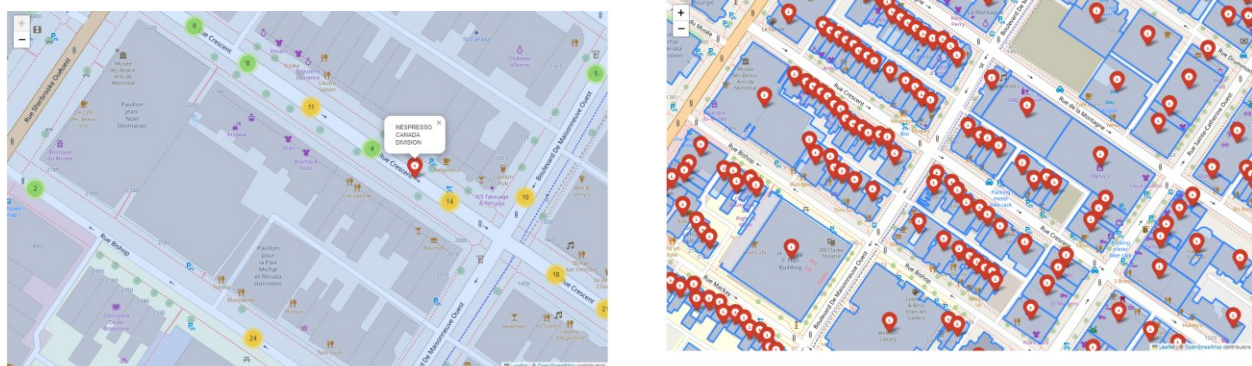


Figure 44 Before geocoding (left) and after geocoding (right)

Following spatial integration, the dataset underwent linguistic and categorical standardization to ensure consistency and interoperability across analytical platforms. Because the source data were

¹ (1) Open: In operation, (2) Closed: Permanently closed, (3) Closed Change of Operator: Change of Ownership, (4) Processing: Recently opened and awaiting inspection and (5) Under Federal Inspection: Change of Inspection Jurisdiction

originally recorded in French, all establishment names and types were translated into English. The translation facilitates broader usability of the dataset within multilingual research and decision-support contexts.

Subsequently, food establishment types were mapped to standardized analytical categories in order to support comparative and health-oriented analyses of the urban food environment. Each establishment was classified into one of six major groups: healthy food store, supermarket, fast food outlet, restaurant, out of home catering, and others.

This categorization not only enabled differentiation between healthy and less healthy food outlets but also provided the conceptual structure required for further modeling and integration into the system dynamics model. The resulting dataset integrates information on business characteristics, building attributes, multilingual names, and standardized food outlet categories. The enhanced attribute structure comprising fields such as "bldg_ID", "English", "French", "kategorie", and "geometry", allows for precise spatial referencing and analytical flexibility. The final dataset was imported into the PostGIS database, thereby enabling spatial queries, visualization, and integration with other urban datasets such as census and socio-economic indicators.

Overall, this workflow transformed a fragmented and spatially imprecise data source into a coherent, georeferenced, and multilingual dataset ready for analytical use. By linking food establishment data with building-level information, the process establishes a robust foundation for investigating relationships between the built environment, food accessibility, and socio-economic conditions in Montréal. The complete data flow is illustrated in Figure 43 (Data flow diagram for the food establishments dataset), which outlines the transformation from raw data acquisition to the integration of the cleaned dataset within the PostGIS DSS.

Table 15 shows a segment of the mapping between the original food establishment types and the categories used in the system dynamics model, while the full mapping list of categories can be found in Table A 11 in Appendix D.

Table 15 Segment from the mapping table of food establishments to categories of the system dynamics model

French	English	Healthy food store	Super-market	Fast Food Outlet	Restaurant	Out of home catering	Other
Distributrice automatique	Automatic vending machine						x
Épicerie avec préparation	Grocery with preparation		x				
Restaurant	Restaurant				x		
Brasserie	Brasserie				x		
Restaurant service rapide	Quick service restaurant			x			
Supermarché Boulangerie	Supermarket Bakery	x	x				

The mapping required some interpretive adjustments to reflect how these businesses operate in practice and to align them with the broader health-related categories used in the analysis. The categorization aimed to capture the predominant type of food offered and its relevance for evaluating healthy and less healthy food environments. However, the original data from the City of Montréal did not always provide sufficient detail to make clear distinctions between business types. For example, establishments such as Tim Hortons or McDonald's appeared in both the restaurant and fast-food outlet categories. This variation depended on how they were recorded in the source data, some entries referred to outlets with indoor seating, while others did not. In this study, the classifications were not manually adjusted; the categories were retained as provided in the dataset. This represents a limitation of the mapping, because such inconsistencies may influence the precision of category-based analyses. Similarly, bakeries were placed under healthy food stores based on the assumption that they primarily sell fresh and minimally processed food products. The classification of brasseries was less straightforward, since they typically serve both quickly prepared and freshly cooked meals, placing them somewhere between the restaurant and fast-food outlet categories. These considerations highlight the interpretive nature of the mapping process and the importance of acknowledging such limitations when analyzing Montréal's food environment using the system dynamics model developed in this work.

5.3 Summary and Integration

This chapter presented the data architecture supporting the Spatial System Dynamics (SSD) model and the Decision Support System (DSS). Together, the datasets described in Chapters 5.2.1 through 5.2.5 form a comprehensive empirical foundation for simulating and analyzing Montréal's urban food environment.

The Food Establishments dataset from the City of Montréal provides the structural basis for representing food supply points across the city. Through subsequent processing (Chapter 5.2.5), these data were spatially refined, linked to building geometries, and semantically harmonized into the six analytical categories of healthy food store, supermarket, fast food outlet, restaurant, out-of-home catering, and other to support the simulation of sectoral dynamics.

The Follow-up on Requests for Food Aid at 211 dataset contributed an essential social dimension, offering detailed insights into the demographic and socio-economic characteristics of residents seeking food assistance. Its mapping to Statistics Canada's 2021 Census (Chapter 5.2.4) enabled semantic alignment and borough-level integration, allowing food aid data to be analyzed in relation to standardized demographic and housing indicators.

The Census data itself provided the demographic and socio-economic backbone of the DSS, defining population structures, income distributions, and other contextual variables used for both model calibration and spatial exploration. Together with CERC's building data and OpenStreetMap layers, the census ensures that all datasets operate within a consistent geographic framework.

Finally, the data flow model developed in Visual Paradigm formalizes how these sources interact. Encoded in XML and integrated into the PostGIS DSS, this model documents all data stores, processes, and relationships, ensuring transparency and reproducibility in line with open-science principles. Overall, the data integration process transformed a heterogeneous collection of municipal, institutional, and primary data sources into a coherent, interoperable, and multilingual database. This harmonized structure not only underpins the SSD simulations presented in Chapter 7 but also provides a replicable methodological framework for other cities aiming to link food environment data, social indicators, and system dynamics modeling within an integrated spatial decision-support context.

Chapter 6. Spatial System Dynamics Simulations

To demonstrate the functionality and relevance of the DSS, the city of Montréal was selected as a case study to illustrate its use. Montréal offers a suitable use case for the following reasons. Firstly, the City of Montréal operates its own open data portal, where data sets are publicly available (see Chapter 5). Secondly, the city, mainly the island of Montréal, has areas of food swamps and food deserts, thus establishing itself as a suitable location for the experimental evaluation of decision support tools designed to facilitate the design of equitable, healthier, and more sustainable urban food systems. Finally, Montréal is of sufficient size to present authentic computational challenges while remaining adequately manageable.

Importantly, the choice of Montréal is not meant to restrict the DSS to a single case. Rather, it serves as a proof-of-concept: the framework architecture is domain- and location-independent, and Montréal provides a concrete example through which methodological and technical principles can be demonstrated.

This chapter presents the application of the DSS and the corresponding simulation results for selected areas in Montréal. Initially, calculations were conducted for the entire island of Montréal. The focal point of this investigation is, to first test the model's behavior under extreme conditions and second to get initial insights into the situation in Montréal.

In the subsequent phase, the model will be utilized to simulate all boroughs in Montréal, with the initial conditions being held constant. The objective of this step is to provide a comprehensive analysis of the disparities between the boroughs. Finally, a variety of strategies were implemented in three distinct boroughs. One area is characterized as a "food swamp" (Ville-Marie), the other is designated as a "food desert" (Beaconsfield), while the third one can be classified as a mixed area (Montréal-Nord).

6.1 Initial Simulations to Understand the Model Behavior

In system dynamics, several methods exist for validating model behavior, depending on the model purpose and model structure. Structure validity can be tested with two methods, (1) direct structure tests and (2) structure oriented behavior tests which include, for example, tests like extreme-condition tests, behavior sensitivity tests, or modified behavior-prediction [127]. The best way would be to compare the model behavior directly with historical time series data. The challenge in using historical data for model evaluation is that data for food insecurity on such a granular level (city or borough level) does not exist or is not publicly available. Several pieces of information are available at the provincial level, such as the report by Tarasuk et al. [5], which indicates that 13.1% of households in Quebec experienced some level of food insecurity.

To run the first simulations and establish a baseline, the model was parametrized. Model parameters were divided into three different categories:

1. Parameters that are changeable in the model and are derived from data from Statistics Canada, Open Data Portal Montréal, OpenStreetMap, and buildings data from the CERC team (see Chapter 5.1).
2. Parameters that are changeable in the model and are based on assumptions.
3. Parameters that are used for initialization but are not changeable by the user, the model calculates the changes, or the parameters are kept constant over the simulation.

Table 16 through Table 18 summarize the parameterization of the SSD model for the initial simulation of the Montréal case study. The differentiation between data-derived, assumed, and constant parameters provides transparency regarding the model's empirical foundation, uncertainty, and calibration strategy.

Table 16 presents parameters directly informed by empirical data sources. These parameters form the quantitative backbone of the model, linking simulation dynamics to observed urban structures and behaviors. For instance, the new build rate for supermarkets and healthy food stores (0.112 per month per km²) and the negative rate for fast-food outlet growth (-0.0179 per month per km²) reflect observed urban development trends and provide a realistic baseline for assessing accessibility to healthy food environments.

Moreover, the cost parameters for public and private transport (0.873 and 0.625 CAD/km, respectively) capture the economic dimensions of food accessibility and mobility. These values are essential for simulating behavioral responses related to travel mode choice and food procurement. The inclusion of supermarket opening hours (0.5) represents temporal availability, acknowledging that accessibility is not purely spatial but also constrained by operational time windows. Together, these empirically grounded variables establish a data-informed baseline that enhances the model's structural validity.

Table 16 Parameters derived from data and used for the initial run of the SSD simulation

Parameter in the SD model	Value	Units
New Build Rate Supermarket and Healthy Food Store	0.112	Number / (Month*km ²)
New Build Rate Fast Food Outlet	-0.0179	Number / (Month*km ²)
Costs Public Transport Use	0.873	CAD / km
Costs Individual Vehicle Use	0.625	CAD / km
Opening Hours of Supermarkets Daily Stores	0.5	-

Table 17 contains parameters for which no direct empirical data were available and, therefore, were established through informed assumptions. These parameters, such as the public transport station build rate (0.001 per month per km²) and optimal densities for transport and production (8 stations or units per km²), define the system's equilibrium tendencies. Their role in the model is primarily exploratory: they enable sensitivity and policy testing, helping to identify thresholds at which systemic behavior shifts occur.

Social factors, such as negative perceptions of local areas and residential segregation (both set at 0.5), introduce qualitative aspects of urban inequality into the system's structure. Although not directly measurable, these variables are crucial for reproducing the non-linear feedback loops between perception, accessibility, and investment. Because they are assumption-based, these parameters represent potential sources of uncertainty and should be the focus of sensitivity and robustness analyses in subsequent validation stages.

Table 17 Parameters based on assumptions and used for the initial run of the SSD simulation

Parameter in the SD model	Value	Units
New Build Rate Public Transport	0.001	Number / (Month*km ²)
New Build Rate Urban Farms CG	0	Number / (Month*km ²)
Optimal Public Transport Station Density	8	Number / km ²
Negative Perceptions of Local Area	0.5	-
Residential or Geographical Segregation	0.5	-
Optimal Production Density	8	Number / km ²
Reduction in Shelter Costs	0	% per Month

Table 18 lists constants that define the structural and demographic context of the simulated system. These include spatial characteristics (e.g., local area = 500.2 km², residential area = 223.2 km²) and baseline quantities for different household types, housing cost burdens, and immigration status. Such parameters anchor the model to the real-world conditions of Montréal, ensuring that dynamic processes unfold within realistic bounds. For example, the inclusion of households spending more than 30% of income on shelter (217 399) introduces a socioeconomic constraint directly tied to food insecurity risk.

The initial stock values for supermarkets (2 682), healthy food stores (568), and fast-food outlets (5 959) established the competitive structure of the urban food system at the start of the simulation. These constants serve as initial conditions for exploring how policy interventions or infrastructure developments might alter the distribution of food access over time.

Table 18 Parameters derived from data and used for the initial run of the SSD simulation, and are constants for the Montréal Island

Parameter in the SD model	Value	Units
Local Area	500.2	km ²
Residential Area	223.2	km ²
Initial Number of Healthy Food Store	568	Number
Initial Number of Supermarkets	2682	Number
Initial Number of Fast Food Outlet	5959	Number
Initial Number of Public Transport Station	9374	Number
Shelter Costs Less Than 30 Percent	688 894	Number of Households
Shelter Costs More Than 30 Percent	217 399	Number of Households
Initial Couple Without Children	176 944	Number
Initial Two Parent	194 789	Number
Initial Single Parent	85 924	Number
Initial Multigenerational	13 354	Number
Initial Single Person Living Alone	36 9359	Number
Initial Total Household Types	91 4004	Number
Initial Total Private Rental Market	55 2259	Number
Initial Owner	361 804	Number
Percent of Tenant Households in Subsidized Housing	0.079	%
Initial Total Immigration Status	1 173 634	Number
Initial Non Immigrants	653 849	Number
Initial Non Permanent Residents	138 379	Number

Collectively, the three parameter categories represent a deliberate balance between empirical grounding, conceptual assumptions, and structural constants. This layered approach allows the SSD model to operate as both a descriptive tool (reflecting current conditions) as well as an exploratory tool (testing interventions and extreme scenarios).

Figure 45 presents the simulated trajectories of food accessibility, availability, and household food insecurity over a ten-year period for Montréal Island. The model was initialized to represent the status quo, meaning that no policy interventions or structural changes were introduced during the simulation. Each variable was normalized on a scale from 0 to 1 to facilitate interpretability. For accessibility and availability, a value of 0 indicates a complete absence of access or physical availability of food, while a value of 1 represents full accessibility and maximum food availability within the modeled system. In contrast, the food insecurity variable was inversely defined: a value of 1 indicates that 100% of households experience food insecurity, whereas 0 represents complete food security.

With the values set, only a marginal enhancement in the metrics could be observed, with accessibility rising from 0.556 to 0.609, availability from 0.198 to 0.225, and food insecurity from

0.128 to 0.124. The minor improvement can be attributed to the marginal reduction in fast food outlets and the corresponding addition of supermarkets. In the absence of valid data on socio-economic factors, no changes were made to this structure.

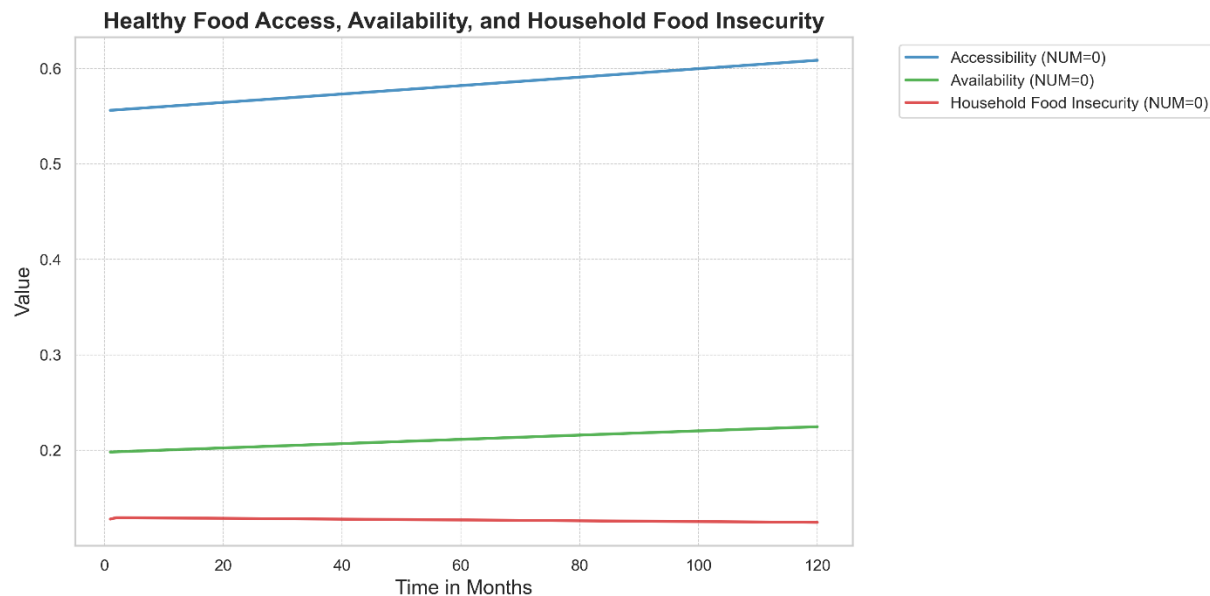


Figure 45 Initial simulation results for the island of Montréal (food accessibility, availability, and household food insecurity) NUM=0 is the complete island.

The slow increase of the three indicators over time demonstrated that the model behaved consistently under steady-state conditions, confirming its internal coherence and structural validity. The relatively high level of accessibility (0.556) compared to the lower availability (0.198) suggests that, while transportation and mobility options allow most residents to reach food outlets, the diversity and spatial density of healthy food sources remained constrained. The simulated household food insecurity level of 12.8% closely aligned with the empirically reported rate of 13.1% for Québec (Tarasuk et al., 2022), indicating that the model plausibly reproduced real-world baseline conditions despite being calibrated at the city scale. This correspondence supports the model's credibility for representing food system dynamics in Montréal and provides a reliable reference point for subsequent experiments. Future scenario simulations can thus meaningfully explore how targeted interventions, such as expanding urban agriculture, enhancing supermarket coverage, or improving public transportation infrastructure, affect food accessibility and household vulnerability across different boroughs.

In the context of extreme condition testing, these parameters serve as stress points for evaluating the model's internal consistency. By systematically varying empirically derived and assumed

values beyond the realistic range, it is possible to test whether system responses remain logical and coherent. This method ensures that the SSD framework maintains structural validity even under implausible or boundary conditions, a necessary step before its application for policy analysis.

6.2 Model Behavior under Extreme Conditions

To assess the robustness and validity of the SSD model, a series of extreme condition tests was conducted. This approach involved exposing the model to boundary or implausible input values that extended beyond the range of normal operating conditions. The purpose of these tests was to verify that the model behaved logically and consistently even under unrealistic or extreme scenarios, thereby ensuring structural soundness and internal validity.

6.2.1 Minimizing household food insecurity in the local area

Physical accessibility to healthy foods can be increased by a number of parameters. If we assume that all supermarkets and stores offering healthy foods are open 24 hours a day, then situational or time-related restrictions are reduced, thereby increasing accessibility. Another factor is the presence of fast-food outlets. In the best-case scenario, there are no fast-food outlets offering unhealthy foods. The two assumptions that no unhealthy food is available and that access is possible 24 hours a day should maximize accessibility. To achieve this, the parameters “*opening hours of supermarkets and daily stores*” and “*new build rate of fast food outlets*” should be set accordingly.

The value for “*opening hours of supermarkets and daily stores*” must be maximum, i.e. = 1. The value for “*new build rate fast food outlet*” was chosen so that after 10 years there are no more fast-food outlets. For Montréal, this corresponds to a reduction rate of -0.215 Number/month and km², which means that 2.58 outlets per km² should disappear per year. Figure 46 shows the simulated results of food accessibility, availability, and household food insecurity. The accessibility reaches a value of 0.928, which means a nearly maximum accessibility, and Figure 46 shows only the simulated household food insecurity. It declines exponentially in the first 40 months and reaches a steady state condition at 11.1 %. This means that although the accessibility is at a maximum, the household food insecurity is only decreasing by 1.7 %.

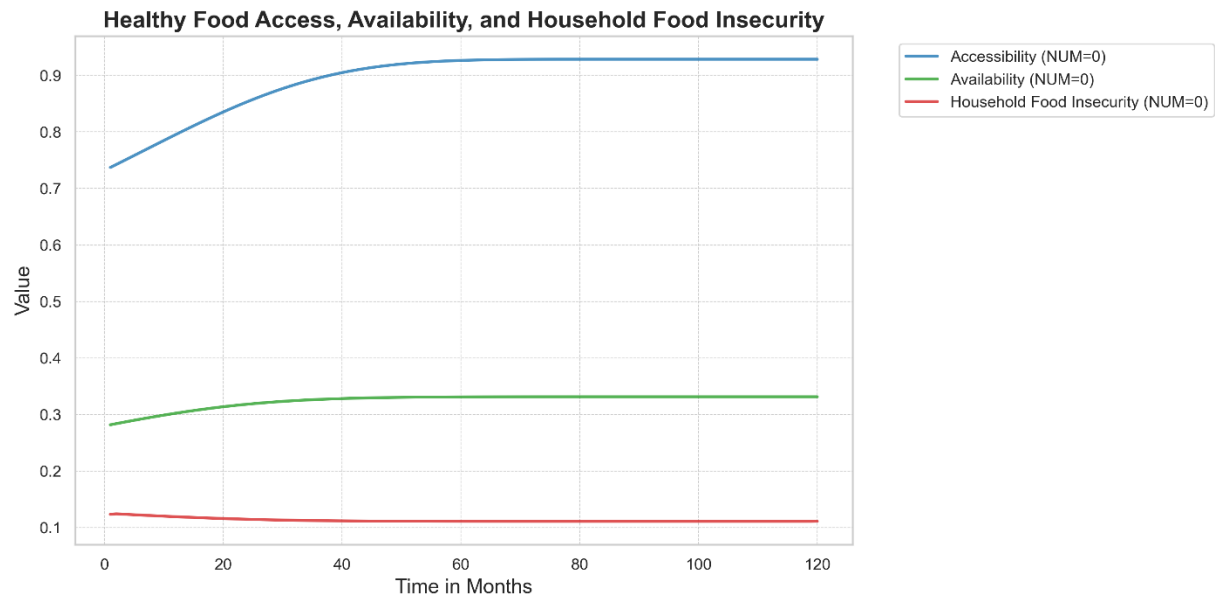


Figure 46 Simulated food accessibility, availability, and household food insecurity for the island of Montréal, NUM=0. For opening hours of supermarkets and daily stores = 1, and new build rate fast food outlet = -0.215.

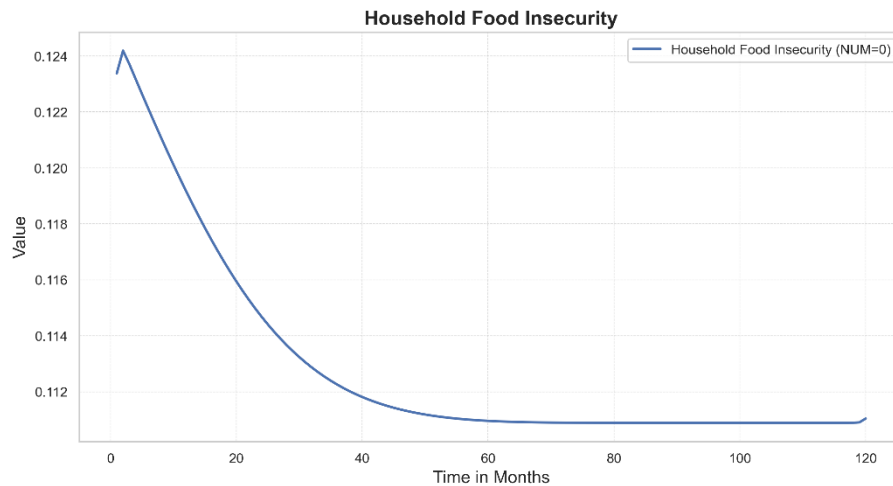


Figure 47 Simulated household food insecurity for Montréal if physical access to food is at maximum.

To further decrease household food insecurity, the food availability needs to be increased. This can be done by increasing points in the city where food is produced and/or stored, like urban farms, community gardens, etc.. Availability describes whether food exists or can be physically accessed,

taking into account production systems, reserves, markets, and transportation. With a “*new build rate urban farms CG*” of 0.1 the production density, and thus availability, can be increased to a value of 0.662 (Figure 48). The household food insecurity can be reduced to 3.7%. As shown in Figure 49, the time to reach this state is about 60 months.

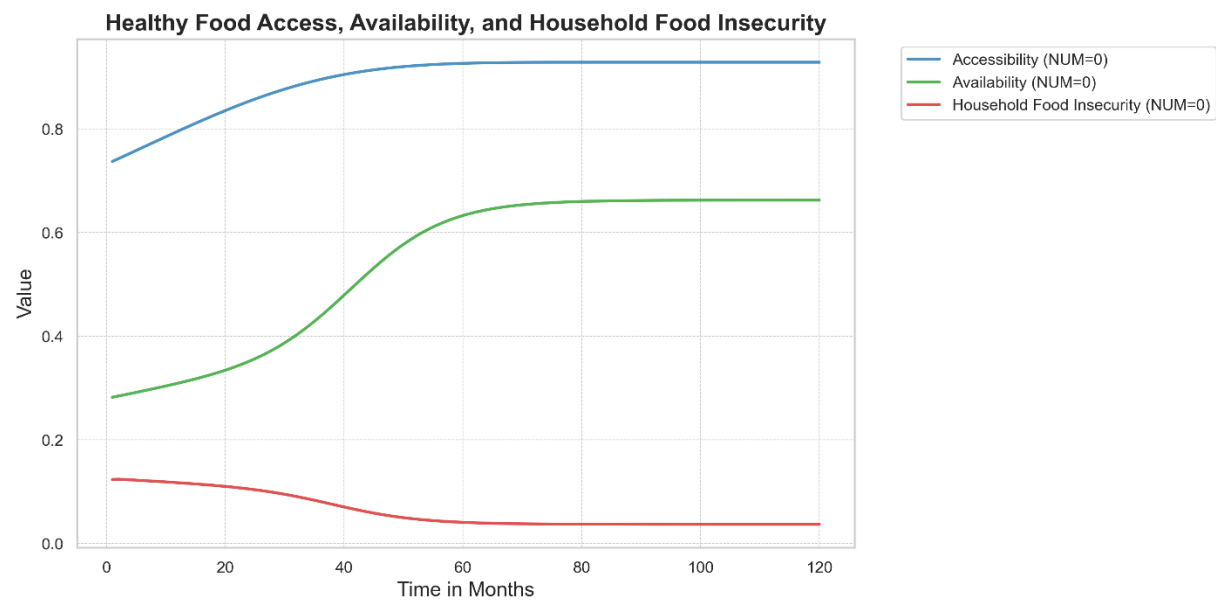


Figure 48 Simulated food accessibility, availability, and household food insecurity for the island of Montréal, NUM=0. For opening hours of supermarkets and daily stores = 1, and new build rate fast food outlet = -0.215 and new build rate urban farms CG = 0.1.

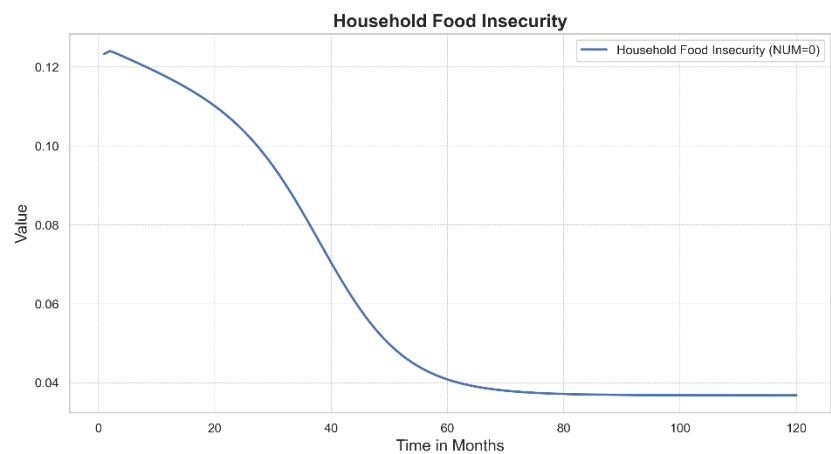


Figure 49 Simulated household food insecurity for Montréal if physical access to food and availability are at maximum.

The changes made so far have been implemented in the geographical access subsystem. Another factor that plays an important role is the shelter costs incurred by a household. Households with high shelter costs (usually > 30% of income spent on housing) have significantly higher food insecurity. The “*reduction in shelter costs*” parameter in the model can be used to enter the target percentage per month. A value of 2 percent/month means that 24 percent of households that spend more than 30 percent of their income on housing are reduced each year.

In Montréal, around 217 399 households pay more than 30% of their income on shelter costs, and 688 894 households pay less than 30%. This means that around 23.9% are in a situation that, from a financial point of view, is critical to become food insecure.

To reduce the households that pay more than 30 % on shelter costs, a monthly reduction of the stock (households paying more than 30% for shelter costs) of 3.7 % is needed. Figure 50 shows the simulated household food insecurity, with all these changes, a household food insecurity of 3.0 % is the minimum that can be reached.

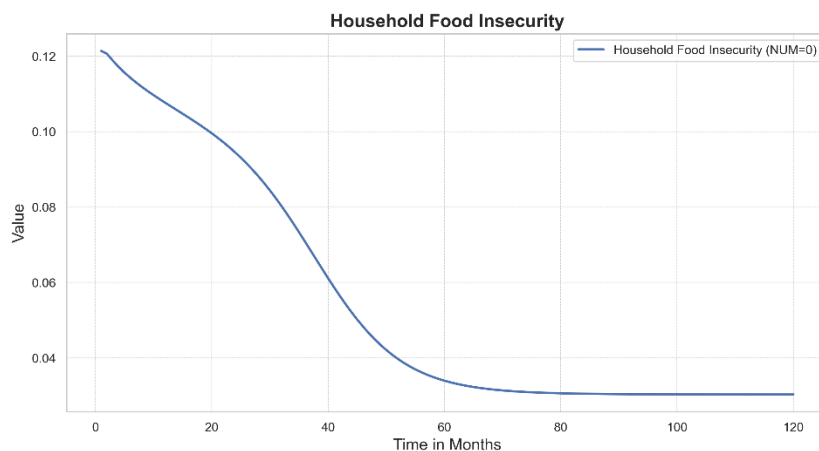


Figure 50 Simulated household food insecurity for Montréal if physical access to food and availability are at maximum, and shelter costs are reduced.

6.2.2 Maximizing household food insecurity in the local area

In addition to testing how far the system can be pushed toward optimal conditions, extreme condition testing also requires exploring the opposite direction conditions under which household food insecurity becomes as severe as possible. This is essential for evaluating the internal consistency and robustness of the SSD model across the full spectrum of feasible and non-feasible parameter values. Just as the previous section demonstrated the theoretical lower bound of food insecurity by maximizing accessibility, availability, and reducing financial pressure, the same

model structure allows for systematically reversing these parameters to identify the corresponding upper bound.

To maximize household food insecurity, the parameters that previously contributed to a favorable environment were now intentionally stressed toward their most adverse values. This follows the same logic used in the previous section, but instead of enhancing accessibility and availability or reducing economic vulnerabilities, these conditions were weakened. For instance, physical accessibility to healthy food can be minimized by reducing opening hours of supermarkets and daily stores to their lowest value, limiting the temporal window through which households can obtain food. Similarly, the “*new build rate of fast food outlets*” can be set to an extreme positive value, resulting in a rapid expansion of unhealthy food environments and a corresponding erosion of access to nutritious food options.

Food availability can be suppressed by preventing the construction of urban farms, community gardens, or other local production facilities, or by setting the “*new build rate urban farms CG*” to zero or even negative values to simulate a declining production base. Under these assumptions, the spatial and structural capacity of the city to produce or store food collapses over time, further increasing household vulnerability.

Conducting these inverse extreme conditions allows the model to demonstrate whether it remains structurally coherent when exposed to highly unfavorable scenarios. If the model responds logically, showing rapidly declining accessibility and availability, accompanied by a sharp rise in food insecurity, this provides further evidence of its robustness.

Together, these extreme scenario experiments help validate the SSD model and ensure its suitability for analyzing a wide range of real-world and hypothetical food system dynamics.

Figure 51 presents the simulated trajectories of food accessibility, availability, and household food insecurity for the island of Montréal ($NUM = 0$) under conditions designed to maximize household vulnerability. The parameter settings correspond to the inverse of the “best-case” scenario: supermarket and healthy-food store opening hours were reduced to zero, the construction rate of fast-food outlets was strongly positive (0.215 outlets per month per km^2), no new urban farms or community gardens were added (new build rate urban farms $CG = 0$), and shelter cost pressures increased over time due to a negative monthly reduction rate (-0.01). These assumptions created a combined spatial, economic, and structural environment expected to severely limit food system performance.

The simulated accessibility exhibits a continuous decline from an initial value of approximately 0.373 to around 0.123 by the end of the ten-year period. The downward trend reflects the compounding effects of diminishing healthy-food access points, nonexistent opening hours, and rising density of fast-food outlets that crowd out healthier options. The model captures how even small monthly reductions in accessibility parameters accumulate significantly over long periods.

Food availability showed an even sharper deterioration. Starting from roughly 0.104 at the beginning of the simulation, availability steadily declined to just under 0.015 by month 120. This trajectory reflected the lack of new urban farms or community gardens and the absence of any growth in local food production capacity. As the model structure links availability to production, storage, and spatial food presence, the imposed constraints led to a monotonic erosion of the system's capacity to provide healthy food resources.

In contrast, household food insecurity rose substantially under these adverse conditions. Beginning at approximately 0.136, close to the initial baseline observed in earlier scenarios, the insecurity index increased slowly in the early simulation years as structural pressures accumulated. The curve demonstrated a marked increase between months 40 and 60, which can be attributed to nonlinear feedback loops between accessibility, availability, and financial constraints on households. By the end of the ten-year period, household food insecurity reached approximately 0.658, meaning that 65% of households experienced some level of food insecurity under these extreme conditions.

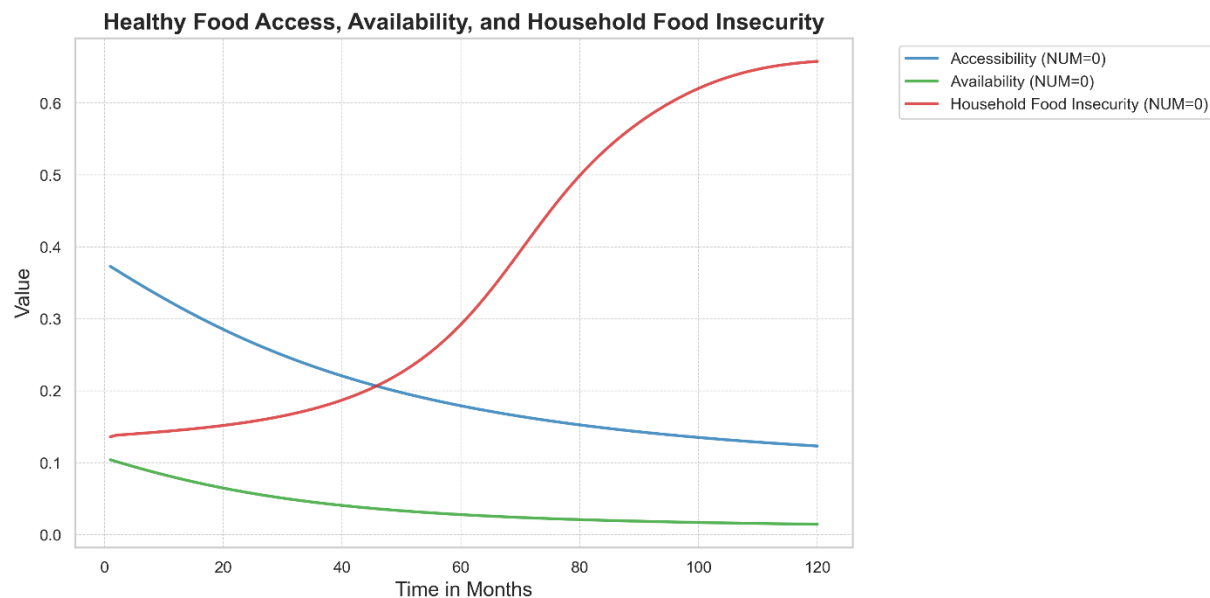


Figure 51 Simulated food accessibility, availability, and household food insecurity for the island of Montréal, NUM=0. For opening hours of supermarkets and daily stores = 0, and new build rate fast food outlet = 0.215, new build rate urban farms CG = 0.0 and reduction in shelter costs = -0.01.

The divergence of the three indicators highlights the asymmetric sensitivity of the system: while accessibility and availability degrade gradually, household food insecurity responded with increasing intensity over time. This behavior reflected the model's internal logic, in which

economic stressors (increasing shelter costs), spatial degradation (reduced access), and structural shortage (declining availability) reinforced each other. The result was a rapidly escalating vulnerability after a critical threshold was crossed.

Overall, the maximization scenario demonstrates that the SSD model responded consistently and logically under highly unfavorable boundary conditions. The simulation provided a clear upper bound for household food insecurity and illustrated how combinations of spatial, economic, and infrastructural pressures interacted to exacerbate food system vulnerability in urban environments.

6.3 Simulation of Borough Food Insecurity

The extreme condition tests showed the robustness of the model, revealing how favorable and unfavorable parameter settings drive the system toward theoretical lower and upper bounds of household vulnerability. These experiments established the model's ability to behave logically under both plausible and highly adverse configurations, thereby strengthening confidence in its structural validity.

Building on this foundation, the following section focuses on the factors that influence food insecurity at the borough level. It introduces a series of simulation scenarios designed to explore how different interventions, trends, and spatial strategies may influence Montréal's food system dynamics at the borough level.

6.3.1 Baseline simulation for the borough-specific household food insecurity

The baseline simulation represents the “status-quo” trajectory of household food insecurity across the Island of Montréal over a 10-year period. All parameters were held constant at their initial values, meaning that no policy interventions, no changes in food outlet construction rates, no adjustments to shelter costs, and no modifications to transit accessibility were introduced during the simulation (see also Section 6.1). This setup allows the model to reproduce the system's internal dynamics as they are currently structured and to reveal spatial inequalities that arise from existing socio-demographic conditions, food environment characteristics, and transport accessibility patterns. The baseline scenario, therefore, provides a reference point from which specific borough analysis can be performed and borough characteristics can be compared. Figure 52 illustrates the household food insecurity levels in each borough at the beginning and end of the simulation, indicating minimal variation in the results. This perspective offers a more detailed analysis than the simulation for the entire Island of Montréal, facilitating a more nuanced examination of the factors contributing to food insecurity.

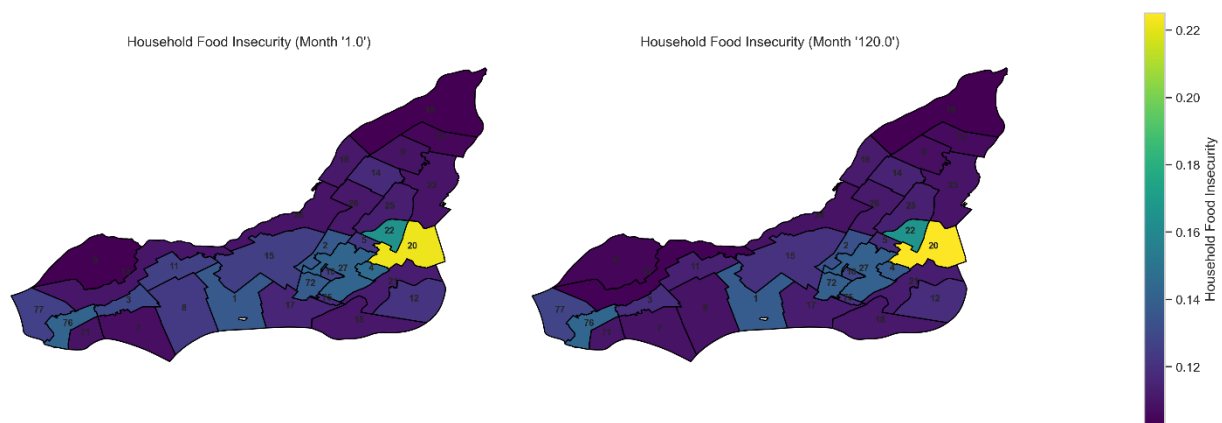


Figure 52 Borough-specific household food insecurity at t=0 and t=120 (after 10 years)

The baseline simulation highlights substantial spatial variation in household food insecurity (HFI) across the Island of Montréal. While the island-wide mean at the start of the simulation was approximately 12.8 %, several boroughs deviated markedly from this value due to structural differences in their local food environments, socio-demographic conditions, and accessibility profiles. Table 19 shows a comparison of the main characteristics for the boroughs with the highest and lowest household food insecurity (HFI).

In particular, five boroughs, Ville-Marie (NUM = 20), Le Plateau-Mont-Royal (NUM = 22), Westmount (NUM = 4), Sainte-Anne-de-Bellevue (NUM = 76), and Côte des Neiges Notre Dame de Grâce (NUM = 27), exhibited the highest levels of simulated HFI, with initial HFI values ranging from 0.142 to 0.222. Boroughs with the highest levels of simulated HFI generally exhibited a combination of low healthy-food availability, reduced accessibility to grocery retailers, and an imbalanced food environment characterized by a higher relative density of fast-food outlets. In addition, such boroughs often show socio-demographic vulnerability, where high proportions of low-income households and elevated housing cost pressures reduced disposable income available for food, increasing the likelihood of food-insecure conditions even when food outlets were present within the borough, which can be seen in the ratio of shelter costs in Table 19. This multi-dimensional interplay of physical, economic, and mobility-related barriers was reflected in the elevated HFI values observed at the start of the simulation.

By contrast, boroughs with the lowest HFI displayed more favorable structural conditions. They benefited from strong accessibility conditions for example in Rivière-des-Prairies-Pointe-aux-Trembles (NUM=19) and a spatial configuration that minimized the temporal and financial constraints of food acquisition. Furthermore, lower socio-economic vulnerability, combined with a more balanced ratio between healthy food outlets and fast-food establishments (see Ratio Density), reduced pressure on household resources and supported stable access to nutritious foods. Together, these factors contributed to markedly lower initial HFI values and underscores the

importance of the broader urban food environment and socio-economic context in shaping borough-level food insecurity.

Table 19 Comparison of the main characteristics for the boroughs with the highest and lowest household food insecurity (HFI)

NUM	Borough	HFI	HFI _{circ}	Avail- ability	Access- ibility	Healthy Store Density	Fast Food Density	Ratio Density	Ratio shelter
20	Ville-Marie	0.222	0.096	0.064	0.283	89.97	394.77	0.228	0.374
22	Le Plateau-Mont-Royal	0.164	0.099	0.133	0.431	60.04	135.96	0.442	0.316
4	Westmount	0.146	0.087	0.240	0.639	6.51	10.44	0.623	0.321
76	Sainte-Anne-de-Bellevue	0.142	0.084	0.058	0.267	3.83	25.30	0.151	0.229
27	Côte-des-Neiges-Notre-Dame-de-Grâce	0.142	0.103	0.184	0.529	20.67	39.65	0.521	0.282
23	Mercier-Hochelaga-Maisonneuve	0.109	0.094	0.275	0.720	18.81	24.49	0.768	0.211
7	Beaconsfield	0.108	0.066	0.251	0.663	0.82	1.26	0.653	0.142
74	Montréal-Est	0.105	0.094	0.288	0.752	6.87	5.13	1.340	0.188
6	L'Île-Bizard-Sainte-Geneviève	0.103	0.074	0.280	0.732	1.79	2.19	0.815	0.169
19	Rivière-des-Prairies-Pointe-aux-Trembles	0.103	0.079	0.283	0.741	6.34	7.23	0.877	0.162

6.3.2 Food deserts, food swamps and mixed conditions: Selected boroughs for a more detailed analysis

The spatial distribution of food outlets in urban environments is far from uniform, and these structural disparities shape how households experience food insecurity at the local scale. Two archetypal configurations, food deserts and food swamps, are especially relevant for interpreting the borough-level simulation results. A food desert describes an area where physical availability to nutritious foods is limited, typically due to low densities of supermarkets, healthy food retailers, or local production sites. Even when accessibility through transport is relatively high, the absence of proximate healthy food options can generate persistent structural constraints on household food security. In contrast, a food swamp is an environment where unhealthy or highly processed food outlets are densely concentrated relative to healthy alternatives. In such contexts, households may technically have access to food, but the local retail composition overwhelmingly promotes low-cost, energy-dense, and nutritionally poor options.

The simulated borough-level characteristics reflect these dynamics. Montréal exhibits characteristics of both food deserts, such as peripheral areas, and food swamp zones, particularly in central regions, which manifest differently in the underlying model variables, such as healthy-food availability, accessibility, store density ratios, and socio-economic exposure (e.g., housing cost burdens). These structural patterns influence how households interact with their local food environment and thus shape the baseline levels of household food insecurity (HFI) observed across the island.

To illustrate these contrasting conditions, three boroughs, Ville-Marie, Montréal-Nord, and Beaconsfield, were selected for detailed analysis. These boroughs represent distinct types of food environments and provide insight into how identical strategies can yield divergent food insecurity outcomes:

- Ville-Marie (NUM = 20), located in the dense urban core, combined extremely high fast-food density (394.8 outlets/km²) and relatively low availability of healthy food (0.064). Despite strong public transport accessibility, its highly imbalanced food environment typified a food swamp, where unhealthy options outcompeted nutritious ones. The borough also exhibited the highest percentage of households paying more than 30% of income on shelter (37.4 %), intensifying financial vulnerability.
- Montréal-Nord (NUM = 16) presented a contrasting profile: it had much lower food retail density overall but displayed relatively high accessibility to healthy foods (0.752). Yet, structural socio-economic pressures, such as a 23.5% shelter-cost burden and a high household circumstances food insecurity (housing, household, and immigration status risks), created an environment where financial pressure was the highest constraint and driver to food insecurity.
- Beaconsfield (NUM = 7), in contrast to both, illustrated a form of suburban food desert: low densities of both healthy food stores (0.822 stores/km²) and fast-food outlets (1.4 stores/km²) meant that food environments were sparse rather than saturated. While accessibility was high (0.663) and socio-economic vulnerability was comparatively low (14% shelter-cost burden), the physical scarcity of food outlets created structural reliance on mobility and higher transport costs for food provisioning.

These three boroughs, therefore, represented different structural mechanisms through which food insecurity could emerge: oversupply of unhealthy foods, socio-economic vulnerability combined with mixed food environments, and sparse food infrastructure. The following section analyses these conditions in detail, demonstrating how the same interventions may lead to divergent outcomes depending on whether a borough more closely resembles a food desert, a food swamp, or a mixed-form food system.

The strategy integrates improvements in the physical food environment, mobility infrastructure, local food production, and socio-economic conditions. By adjusting multiple structural drivers simultaneously, the intervention is designed to show how the same strategy can yield different results. Thus highlighting the need of more granular strategies.

The first component of the strategy targets the local food retail environment, increasing the construction rate of supermarkets and healthy-food stores ($\text{newBuildRateSupermarketAndHealthyFoodStore} = 0.112$) while allowing moderate growth of fast-food outlets ($\text{newBuildRateFastFoodOutlet} = 0.179$). Although the latter represents a continued expansion of less healthy food environments, the increased establishment rate of healthy-food outlets is expected to enhance availability and counterbalance existing food swamp conditions, particularly in dense urban boroughs such as Ville-Marie.

Second, improvements to mobility and accessibility are introduced through a positive build rate of public transport stations ($\text{newBuildRatePublicTransport} = 0.001$) combined with slightly reduced costs for public transport use (0.37 CAD/km) relative to private vehicles (0.72 CAD/km). This reflects a mobility-focused intervention that aims to enhance equitable food access, especially in boroughs where food stores are spatially dispersed, as is the case in Beaconsfield.

A third component strengthens the local food production base, with a non-zero construction rate for urban farms and community gardens ($\text{newBuildRateUrbanFarmsCg} = 0.001$). This addition responds particularly to food desert conditions, where healthy-food availability is structurally limited due to low retail density. By increasing local production, the strategy supports improvements in availability and resilience.

Furthermore, the strategy includes measures addressing social and perceptual drivers of food access, reducing negative perceptions of local areas and weakening residential or geographical segregation (both set to 0.1). These factors influence mobility patterns, willingness to travel to food outlets, and the ability of households to integrate into resource-rich parts of the borough. Lowering these barriers supports a more equitable distribution of food access.

The temporal availability of food is also enhanced through extended supermarket and store opening hours ($\text{openingHoursOfSupermarketsDailyStores} = 0.7$), increasing the temporal flexibility for households, particularly those with non-standard working hours, to access healthy foods.

Finally, the strategy introduces a modest monthly reduction in the proportion of households experiencing high shelter-cost burdens ($\text{reductionInShelterCosts} = 0.001$). Since disproportionate housing expenses are a major determinant of food insecurity, even small reductions in this structural pressure gradually improve the financial capacity of households to purchase food.

Taken together, this strategy represents a multi-lever intervention that simultaneously addresses availability, accessibility, mobility, local production, temporal constraints, social barriers, and

financial vulnerability. By applying the same strategy to boroughs with different food-system characteristics, Ville-Marie as a food swamp, Montréal-Nord as a mixed environment with socio-economic vulnerability, and Beaconsfield as a food desert, it becomes possible to assess how structural conditions mediate intervention effects. The results, therefore, illustrate not only the absolute impact of each intervention but also the extent to which boroughs with distinct food environments respond differentially to the same set of strategic measures.

The simulation results for the three boroughs showed that applying the same multi-component strategy led to markedly different trajectories of accessibility, availability, and household food insecurity (HFI). While all variables were normalized between 0 and 1, their time paths revealed whether the intervention mainly stabilized existing conditions or shifted the local food system toward higher or lower vulnerability. (Figure 53 - Figure 55).

In Beaconsfield (NUM = 7), the strategy did not reduce household food insecurity; instead, HFI increased from 0.094 to 0.123 over the simulation period. This indicates that the intervention was not sufficient to improve outcomes in this borough, despite Beaconsfield's comparatively low shelter-cost burden and otherwise less vulnerable socio-economic profile. As a suburban food-desert type borough, Beaconsfield is characterized by sparse food infrastructure, with low densities of both healthy food stores and fast-food outlets, and a strong reliance on mobility for food access. The results, therefore, suggest that the strategy did not meaningfully overcome these structural disadvantages. Rather than moving toward greater food security, Beaconsfield's trajectory points to a worsening situation over time, indicating that low socio-economic pressure alone does not compensate for limited local food availability and suburban spatial constraints.

In Ville-Marie (NUM = 20), the picture was different. At the start of the simulation, the borough combined comparatively the lowest accessibility (0.518) and availability (0.178) with the highest HFI level of the three cases (0.19.1). Under the strategy, accessibility and availability changed only slightly and even decrease marginally (– 0.3 % and – 0.2 %, respectively). Nevertheless, HFI declined from 0.191 to 0.161, corresponding to a 15.7 % relative reduction. The gradual and almost linear decrease in HFI suggested that improvements in other subsystems, particularly the modest reduction in shelter-cost burden, the build-up of urban agriculture, and lower negative perceptions and segregation, were able to alleviate household vulnerability even though the physical food environment remained structurally imbalanced and fast-food dense. In other words, in a food swamp context such as Ville-Marie, socio-economic relief and diversification of the food landscape could reduce food insecurity without producing strong changes in the aggregate accessibility and availability indicators.

The Montréal-Nord (NUM = 16) simulation illustrated a third pattern. This borough started with the highest accessibility (0.987) and the highest availability (0.335) among the three cases, but with an intermediate HFI level (0.098). Over time, accessibility and availability deteriorated substantially: accessibility dropped by about 45% (to 0.680) and availability by 29% (to 0.258). In

contrast to Ville-Marie, HFI increased from 0.098 to 0.114 (+ 14 %). The trajectories were non-linear: accessibility and availability remained almost stable during the first 40–60 months and then declined more rapidly, while HFI began to rise slowly after around 60 months and accelerated toward the end of the simulation. This behaviour indicates that Montréal-Nord was pushed away from its initial position. The combination of continued fast-food growth, changing store composition, and population-related pressures gradually eroded the previously high accessibility and availability, and once critical thresholds in the food environment were crossed, the reinforcing feedbacks between declining access and existing socio-economic vulnerability drove HFI upwards. Montréal-Nord therefore moved from a relatively well-served but socio-economically fragile setting toward a more structurally disadvantaged situation.

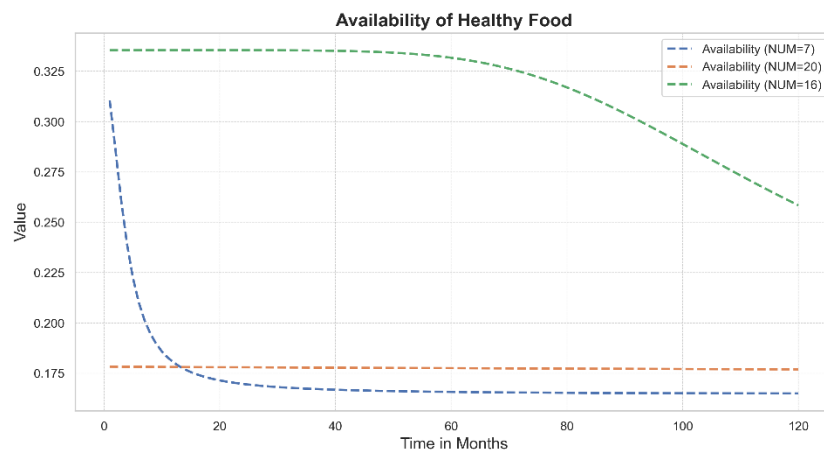


Figure 53 Simulated food availability for the three selected boroughs

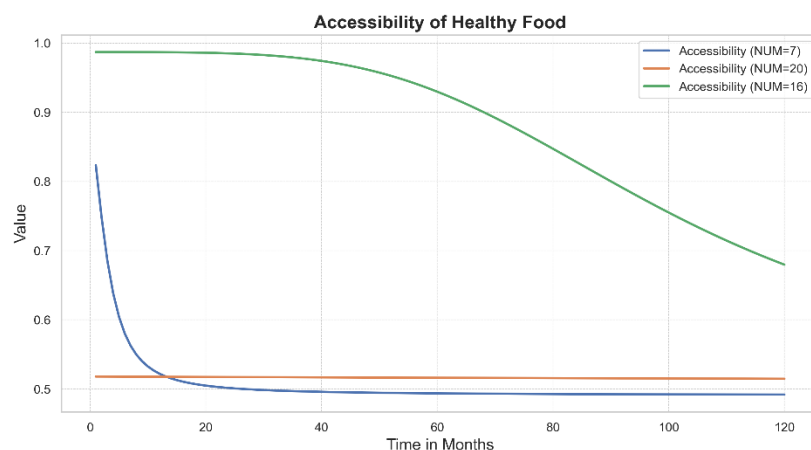


Figure 54 Simulated food accessibility for the three selected boroughs

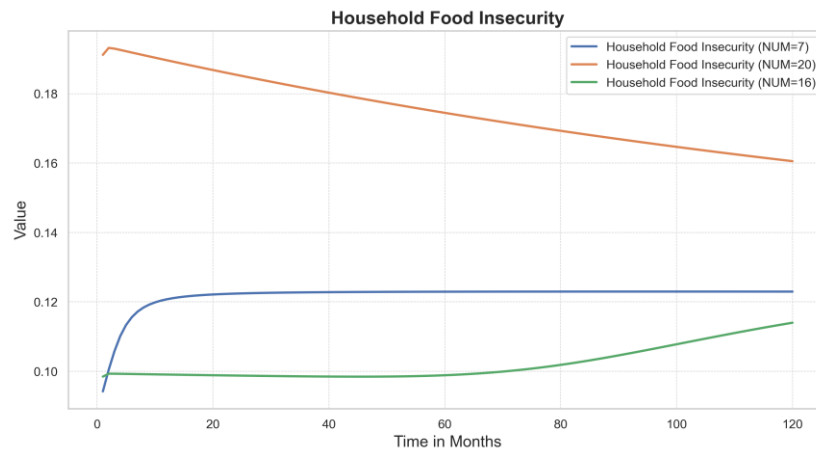


Figure 55 Simulated household food insecurity for the three selected boroughs

6.3.3 Sensitivity analysis for the three selected boroughs

To better explain the divergent household food insecurity (HFI) trajectory in Figure 55, a one-at-a-time sensitivity analysis was conducted for the three selected boroughs. Each strategy parameter was varied by $\pm 10\%$ around the strategy setting, and the resulting change in HFI was measured relative to the baseline simulation at month 1, month 36, month 72, and month 120. Because HFI is normalized between 0 and 1, the absolute deviations were small in magnitude; however, the ranking of parameters revealed which levers matter most at different stages of the simulation.

The comparison showed that the sensitivity structure is strongly time-dependent. In all three boroughs, opening hours of supermarkets and daily stores produced the largest immediate deviation in HFI at month 1. After this initial phase, the pattern diverges sharply: in Beaconsfield, opening hours remained the dominant parameter throughout the simulation followed by the increase of fast-food density; in Ville-Marie, reduction in shelter costs became the main driver from month 36 onward; and in Montréal-Nord, the dominant parameter shifted from opening hours at month 1, to shelter-cost reduction at month 36, and then to the new build rate of fast-food outlets by months 72 and 120. This temporal shift mirrors the different HFI dynamics observed in Figure 55.

In Beaconsfield ($NUM = 7$), opening hours of supermarkets and daily stores was the dominant parameter at every observed time step (Figure 56). At month 1, a 10% reduction in opening hours increases HFI by about 0.00071, while a 10% increase lowers it by about 0.00037. The effect remained almost unchanged at months 36, 72, and 120, with maximum deviations of approximately 0.00076, 0.00075, and 0.00075. By contrast, the new build rate of fast-food outlets was relevant mainly at the beginning of the simulation (about ± 0.00047 at month 1) and became almost negligible by month 120 (around ± 0.00001). Reduction in shelter costs became the second-most influential parameter in the long run, but its magnitude remained very small (around

± 0.00001 at month 120). This indicates that Beaconsfield's HFI trajectory was driven primarily by temporal accessibility rather than by gradual changes in food-retail construction or socio-economic parameters. The borough's sparse suburban structure therefore appears most sensitive to whether existing food outlets can be reached within household time constraints.

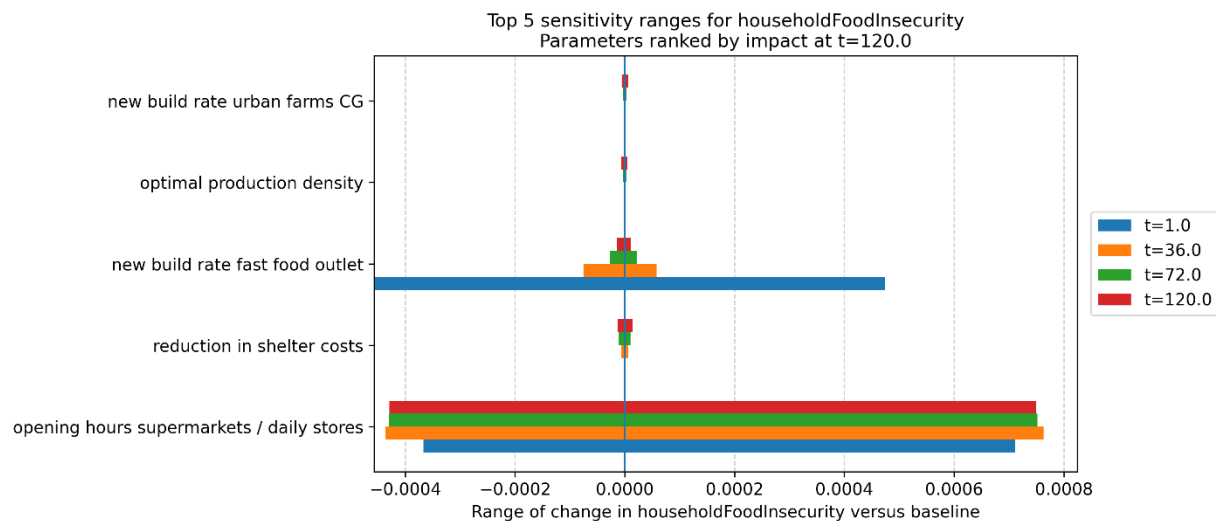


Figure 56 Sensitivity analysis for HFI, Beaconsfield (NUM = 7)

Ville-Marie (NUM = 20) showed a different sensitivity pattern (Figure 57). At month 1, opening hours still had the largest immediate effect on HFI, with a maximum deviation of about 0.00015. From month 36 onward, however, a reduction in shelter costs became the dominant parameter by a clear margin. A 10% decrease in the shelter-cost reduction parameter raised HFI by about 0.00115 at month 36, 0.00190 at month 72, and 0.00244 at month 120, whereas a 10% increase lowered HFI by about 0.00113, 0.00182, and 0.00228, respectively. All other parameters remained much smaller; even at month 120, the second-largest effect, opening hours, reached only about 0.00037. This pattern suggested that the gradual decline in HFI in Ville-Marie is driven primarily by economic relief rather than by changes in retail construction rates. In a borough already characterized by dense food provision but the highest shelter-cost burden, housing-related affordability appeared to be the main lever for reducing food insecurity over time.

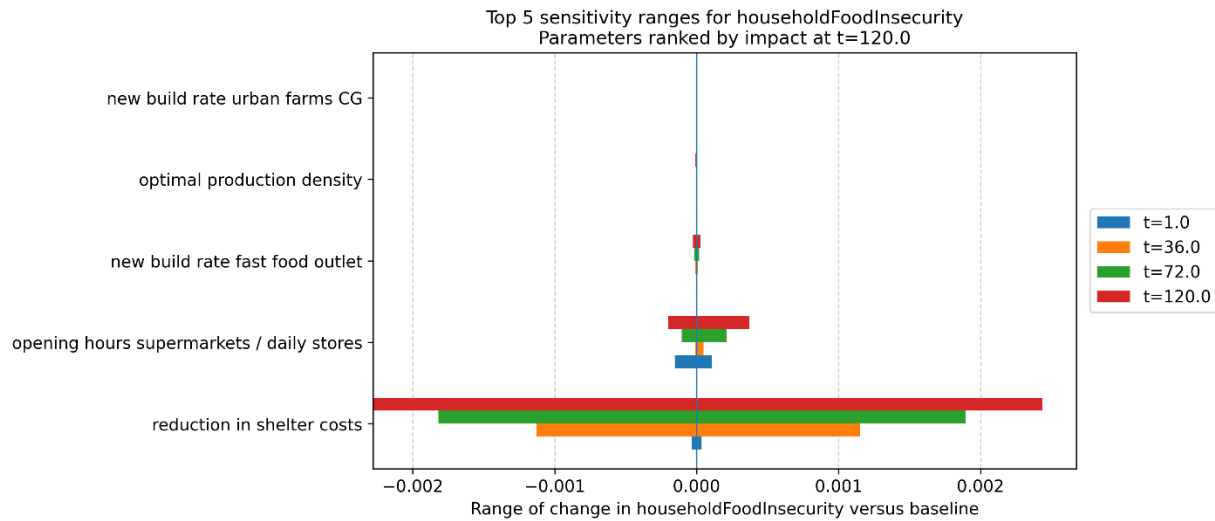


Figure 57 Sensitivity analysis for HFI, Ville-Marie (NUM = 20)

Montréal-Nord (NUM = 16) displayed the most dynamic sensitivity structure (Figure 58). At month 1, opening hours had the strongest immediate effect on HFI, with a maximum deviation of about 0.00010. By month 36, reduction in shelter costs became the most influential parameter (about ± 0.00008). In the later stages of the simulation, the dominant driver shifts decisively to the new build rate of fast-food outlets: a 10% reduction lowers HFI by about 0.00110 at month 72 and 0.00379 at month 120, while a 10% increase raised HFI by about 0.00157 and 0.00319 respectively. Opening hours remained the second most influential parameter, but at a much lower level (about 0.00105 at month 120). This indicated that Montréal-Nord's worsening HFI trajectory is increasingly shaped by the composition of the food environment rather than by short-term access conditions alone. Once the retail system became more fast-food dominated, the effect on HFI intensified and eventually outweighed the benefits of modest socio-economic relief.

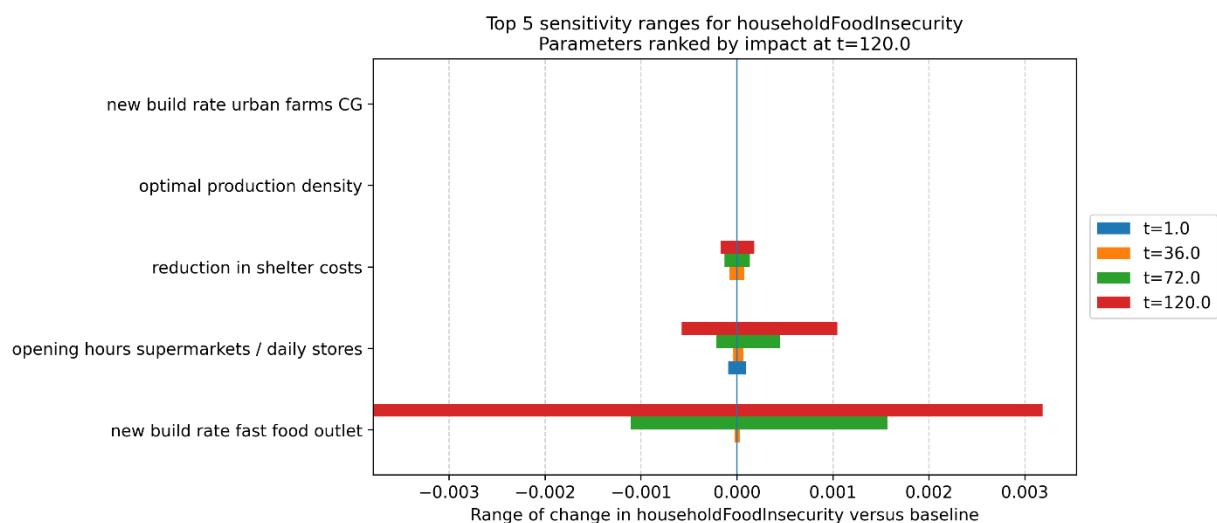


Figure 58 Sensitivity analysis for HFI, Montréal-Nord (NUM = 16)

Table 20 summarizes which parameter exerted the strongest influence on HFI at the four selected points in time (months 1, 36, 72, and 120) for each borough. The comparison highlights that the dominant driver of HFI is not constant over the simulation period, but shifts depending on the local borough context. While opening hours dominated the early simulation stage in all three boroughs, later stages showed clear divergence: Beaconsfield remained most sensitive to opening hours and fast-food build rate, Ville-Marie became primarily driven by shelter-cost reduction, and Montréal-Nord shifted from shelter costs to the fast-food build rate. This temporal change in dominant sensitivity helps explain why the HFI trajectories in Figure 55 differ so strongly across the three boroughs.

Table 20 Parameter with the strongest influence on HFI at months 1, 36, 72, and 120 for each selected borough.

Borough	Month 1	Month 36	Month 72	Month 120
Beaconsfield (NUM = 7)	Opening hours and Fast-food build rate	Opening hours	Opening hours	Opening hours
Ville-Marie (NUM = 20)	Opening hours	Shelter costs	Shelter costs	Shelter costs
Montréal-Nord (NUM = 16)	Opening hours	Shelter costs	Fast-food build rate	Fast-food build rate

Taken together, the sensitivity analysis clarifies why the same intervention strategy produced very different HFI trajectories. Beaconsfield is characterized by a persistent dependence on temporal access, Ville-Marie by the cumulative importance of shelter-cost relief, and Montréal-Nord by a growing sensitivity to fast-food expansion in the later simulation stages. The timing of these

dominant drivers is consistent with the observed dynamics: the near-linear decline in Ville-Marie corresponds to the steadily rising effect of shelter-cost reduction, the late acceleration of HFI in Montréal-Nord matched the strong long-run sensitivity to fast-food growth, and Beaconsfield's early increase followed by a plateau is consistent with a system dominated by opening hours and only weakly responsive to most other levers. A further notable result was that several parameters, including the new build rate of supermarkets and healthy-food stores, the new build rate of public transport, negative perceptions of the local area, and residential/geographical segregation, showed no detectable direct effect on HFI within the tested $\pm 10\%$ range. This does not mean that these parameters are irrelevant for the broader food system, but it does indicate that, for HFI in these three boroughs under the tested strategy, the strongest leverage points are borough-specific and time-dependent. The results, therefore, supported the need for spatially differentiated as well as temporally sequenced policy responses.

6.4 Summary and Discussion of the Spatial System Dynamics (SSD) model

This chapter demonstrated the application of the Spatial System Dynamics (SSD) model and the decision support system (DSS) for analysing food system dynamics across the Island of Montréal. The simulations served three complementary purposes: (1) to evaluate the model's internal consistency through extreme-condition testing; (2) to establish a baseline representation of borough-level disparities in household food insecurity (HFI); and (3) to examine how a uniform intervention strategy unfolded in boroughs with distinct structural characteristics. Collectively, these steps highlight the flexibility and explanatory capacity of the SSD framework and its suitability for urban food-system planning.

The initial simulations of the entire island reproduced plausible levels of food accessibility, availability, and household food insecurity (HFI), with the baseline HFI aligning closely with empirical estimates for Québec. Extreme-condition tests further confirmed the structural validity of the model. Under highly favourable settings, maximal opening hours, elimination of fast-food outlets, expansion of urban agriculture, and reduced shelter-cost burdens, the system moved toward a theoretical lower bound of approximately 3 % HFI. Conversely, under maximally adverse settings, Montréal approached a severe upper bound of around 65% HFI. These boundary experiments demonstrated that the model responds logically and proportionately across a wide parameter space, strengthening confidence in its robustness and interpretability.

The baseline borough-level simulations revealed spatial heterogeneity. While some boroughs exhibited favourable combinations of accessibility, availability, and low housing-cost pressures, others, particularly dense central districts or socio-economically vulnerable areas, showed considerably higher HFI. This spatial diversity underscores the importance of location-specific food system characteristics, such as retail composition, transport connectivity, and socio-demographic vulnerability.

By selecting Ville-Marie, Montréal-Nord, and Beaconsfield as representative food-environment types (i.e. food swamp, socio-economically constrained mixed environment, and food desert, respectively) the chapter examined how a single multi-component strategy performed under contrasting local conditions. The results clearly showed that boroughs did not respond uniformly. In Ville-Marie, the same measures produced a meaningful reduction in HFI despite limited changes in accessibility and availability, indicating that socio-economic levers could offset highly imbalanced food retail landscapes. In Montréal-Nord, however, accessibility and availability eroded over time despite the intervention, ultimately increasing HFI, suggesting that underlying structural pressures could overpower moderate improvements unless targeted with greater intensity.

Overall, the findings highlight a central insight: city-wide strategies may improve aggregate conditions but cannot be expected to generate uniform benefits across diverse urban contexts. Structural characteristics, such as fast-food saturation, socio-economic vulnerability, or spatial sparsity of food outlets, strongly mediate the effectiveness of interventions. As a result, policy design for urban food systems must account for localised feedback structures rather than assuming that identical interventions can produce comparable outcomes. The SSD approach provides a valuable platform for uncovering these dynamics, testing strategies before implementation, and supporting the development of more granular, borough-specific policies to reduce food insecurity across Montréal.

Chapter 7. Conclusions

This thesis developed and demonstrated a Spatial System Dynamics (SSD) enabled decision support system (DSS) to analyse how the urban food environment and policy levers jointly shape household food insecurity for vulnerable populations. Using Montréal as a case study, the work operationalized the linkage between System Dynamics (SD) and Geospatial Information Systems (GIS) through moderate coupling, and evaluated the approach through model checks (including extreme-condition testing), baseline simulation and scenario experiments. The results confirm that food insecurity dynamics are shaped by interacting physical and socio-economic drivers, and that city-wide strategies may improve aggregate conditions but cannot be expected to generate uniform benefits across boroughs.

7.1 Main Contributions

This thesis contributes on three levels: (i) methodological contributions that operationalize Spatial System Dynamics (SSD) within a Design Science Research Methodology (DSRM) process; (ii) technical contributions in the form of reusable IT artifacts (software, workflows, and data products); and (iii) empirical insights from applying the framework to Montréal that demonstrate the relevance of spatial heterogeneity and dynamic feedbacks for food security planning.

7.1.1 Identified gaps in existing systems and how they are addressed

- System dynamics models can represent feedbacks and temporal dynamics, but are inherently non-spatial; GIS captures spatial patterns, but is not designed to represent systemic feedback structures. The thesis addresses this gap through an SSD approach that links simulation and geodata via moderate coupling.
- Existing urban food system models (e.g., qualitative causal loop diagrams) provide valuable structure but do not allow quantitative simulation of policy interventions. The thesis transforms the conceptual structure into an executable stock-and-flow model suitable for scenario analysis.
- Coupling strategies involve trade-offs between performance, flexibility, and maintainability. The thesis selects and implements moderate coupling (shared PostGIS database) as a middle ground that supports spatially explicit simulations while preserving component modularity.
- Urban food security decision-making relies on heterogeneous datasets and typically lacks reproducible integration workflows. The thesis develops documented (Extract, Transform, Load (ELT)) data pipelines, mapping and geocoding workflows and integrates them into the DSS environment.
- Decision support tools for urban food systems often lack transparency and interoperability. This thesis implements open standards (XMILE, PostGIS, REST) and a Vensim→XMILE→BPTK-Py→Python pipeline to enable model reuse and reproducible execution.

Table 21 Mapping of identified gaps, contribution and thesis outputs

Identified gap	Thesis contribution	Concrete output	Location
SD simulations (non-spatial) and GIS (non-dynamic) are rarely combined to support decision-making.	Develop an SSD–DSS architecture using moderate coupling and microservices.	Microservices-based DSS with shared PostgreSQL/PostGIS database for dynamics simulation and GIS analysis.	Ch. 4 (SSD foundations, coupling, architecture)
Qualitative CLDs cannot simulate the effects of specific policy measures over time.	Extend the literature-based CLD into an executable stock-and-flow model focused on built-environment levers.	Spatial Food Systems Model (SFSM) with subsystems for accessibility, household finances, and household circumstances.	Ch. 3 (model) & Ch. 6 (simulation)
Proprietary SD environments limit reuse and integration into broader analytical workflows.	Create an interoperable model pipeline to execute SD models in Python and integrate them into the DSS.	Vensim→XMILE→BPTK-Py→Python integration workflow.	Ch. 4 (pipeline)
Heterogeneous urban food data is difficult to harmonize across languages, spatial scales, and schemas.	Develop reproducible workflows for data ingestion, semantic mapping, reverse geocoding, and aggregation.	ETL pipelines, mapping tables, reverse geocoding procedures.	Ch. 5 (data) & Appendix A (artifact inventory)
Average values at the state or city level mask inner-city differences and are difficult to use for measures at a micro level.	Demonstrate borough-level heterogeneity and evaluate a uniform strategy across contrasting boroughs.	Baseline borough disparity results and comparative strategy simulations (Beaconsfield, Ville-Marie, Montréal-Nord).	Ch. 6 (food desert and food swamp simulations)
Need for transferable IS research contributions beyond a single case study.	Produce a coherent artifact portfolio (software, workflows, datasets) and document design decisions following DSRM guidelines.	Artifact inventory including software, method/workflow artifacts, and data assets.	Ch. 4 (DSRM) & Appendix A (artifact inventory)

7.1.2 Key results obtained in the Montréal case study

Baseline plausibility: the island-wide simulation reproduces an HFI level of 0.128 (12.8%), close to the published Québec estimate (13.1%), while indicating moderate accessibility (0.556) but low availability of healthy food (0.198). Extreme-condition testing: under highly favourable assumptions HFI approaches ~3%, whereas under maximally adverse assumptions it can rise towards ~65%, establishing plausible bounds and internal consistency checks for scenario analysis.

Spatial heterogeneity: borough-level baseline simulations show strong disparities, with initial HFI ranging from 0.103–0.108 in low-HFI areas (e.g., Senneville, Beaconsfield) to 0.222 in Ville-Marie.

Context-dependent strategy impacts: in a uniform multi-lever strategy run, HFI increased in the early months in Beaconsfield (+2.3%), decreased substantially in Ville-Marie (-3%), but increased in Montréal-Nord (+1.6%), reflecting different structural starting conditions and feedback dynamics.

7.1.3 Contribution to the knowledge base

Methodological contribution: operationalization of SSD as a practical integration of SD and GIS through moderate coupling, demonstrating a viable balance between integration depth and modularity for decision support.

Design contribution: a standards-compliant, microservices-based DSS architecture that enables reproducible, extensible simulations and geospatial visualization.

Modeling contribution: an executable system dynamics model for urban food security that enables quantitative testing of policy interventions, extending beyond qualitative causal loop diagrams.

Substantive contribution: evidence that food insecurity dynamics and intervention effectiveness vary strongly across urban space; city-wide strategies therefore require context-sensitive prioritization rather than assuming uniform effects.

7.1.4 Artifact contributions (DSRM)

SSD–DSS framework implemented as microservices (simulation server, REST API layer, spatial database, and GIS visualization workflows). Interoperable model-execution workflow (Vensim→XMILE→BPTK-Py→Python) enabling SD models to be executed in Python and embedded in the DSS.

Documented data integration workflows (ETL pipelines, mapping tables, reverse geocoding, aggregation queries) to transform heterogeneous datasets into harmonized DSS inputs.

Curated and integrated Montréal case-study datasets (Open Data Montréal food establishments, 211 food aid requests, census layers, building data, and supporting spatial layers) enabling spatially explicit simulations and analysis.

7.2 Limitations

The results and artifacts presented in this thesis should be interpreted in light of several limitations. These limitations concern (i) the scope and parameterization of the system dynamics model, (ii) architectural trade-offs of the developed DSS, and (iii) constraints in data availability and preprocessing that affect calibration, representativeness, and the precision of spatial indicators.

7.2.1 Limitations in the System Dynamics Model

The model scope was intentionally focused on built-environment and socio-economic levers through three interconnected subsystems (food accessibility, household finances, and household circumstances). It did not include personal-level factors (e.g., cooking skills, nutrition knowledge, learned preferences) and therefore did not aim to represent individual behaviour and individual situational constraints in detail.

Validation and calibration were constrained by the limited availability of historical and granular (borough-level) food insecurity data for Montréal. As a result, plausibility checks relied on comparisons to published aggregate estimates (e.g., Québec-level HFI) rather than detailed time-series calibration.

Several parameters for the initial simulations were based on assumptions due to missing empirical inputs. While sensitivity analysis and extreme-condition testing improved confidence in model logic, absolute levels and long-term trajectories remain dependent on parameter choices.

The RQ1 output was designed primarily as a feasibility-oriented typology and decision-support catalogue for urban agriculture systems rather than as a detailed quantification of production volumes. Accordingly, the model represented urban agriculture as a lever within a simplified system representation.

7.2.2 Limitations in the developed DSS

Architectural complexity: the microservices design improves flexibility and scalability but increases orchestration and error-handling requirements, which can be a significant overhead.

Integration overhead and potential bottlenecks: moderate coupling through a shared database provides flexibility, but the database can become a performance bottleneck under heavy concurrent

workloads and requires careful schema design, query optimization, and governance to preserve consistency across spatial and dynamic datasets.

Portability considerations: while the DSS exposes RESTful interfaces, some GIS interactions rely on direct SQL access to the PostGIS database, which requires database knowledge and credentials and can reduce portability compared to fully abstracted API-based access.

Operational effort: containerization and service maintenance require sustained effort (updates, resource monitoring, security patches) and technical expertise, which may exceed the needs of lightweight research prototypes unless long-term operation is intended.

7.2.3 Limitations in data availability and data processing

Data gaps at fine spatial scale: granular food insecurity indicators were not consistently available at the borough level, which limited direct calibration and evaluation of spatial simulation outputs.

Representativeness of social data: the 211 food aid dataset contained categories that could not be mapped to census variables (e.g., homelessness) and included responses such as “No information available” or “Do not wish to answer”. This data invisibility affected representativeness.

Spatial accuracy of food establishment records: the City of Montréal dataset provided approximate coordinates that required reverse geocoding to match establishments to building geometries; residual geocoding and matching errors could influence fine-scale accessibility calculations.

Category consistency and information loss: food establishment types were simplified from 73 categories into six analytical classes for simulation. This simplification improved tractability but entailed information loss, and the source data sometimes contained inconsistent categorization (e.g., chains appearing under different types). In this study, categories were retained as provided and not manually adjusted, which could affect the precision of category-based analyses.

Static contextual layers: several census-derived indicators were stored in the DSS to support spatial exploration and prioritization but were not represented as dynamic components in the simulation, which limited the model’s ability to endogenously represent all socio-demographic factors.

7.3 Future Work

The development of the SSD framework, the case study model from Montréal, and the implementation of the DSS artifacts serve as a foundation from which future research can build.

The following directions are particularly relevant in light of the current scope, assumptions and data constraints identified in this thesis.

Stakeholder-based validation and scenario co-design: The framework and the system dynamics model should be tested together with relevant stakeholders and domain experts (e.g., community experts, urban planners, city representatives) to validate causal assumptions, assess the feasibility of calculations and scenarios, and refine intervention definitions to reflect implementable policy options.

Improved empirical parameterization: Several parameters currently rely on assumptions or proxy constructs (e.g., geographical segregation and other socio-spatial influences). Future studies should determine such parameters more precisely using additional empirical data and targeted analyses, and assess their influence through systematic sensitivity analyses.

Transferability and comparative city studies: The workflow and technical implementation are well documented and can in principle be transferred to other cities. While census and OpenStreetMap data are available across Canada, future work should evaluate which complementary datasets are accessible through municipal open data portals in other locations and define reusable “data adapters” for collection. Applying the method to multiple Canadian cities and comparing the results would provide deeper insights into structural determinants and contextual effects that influence food insecurity.

Real-world evaluation with planners and policymakers: The practical implementation of the DSS would provide valuable insights into its application by urban planners and political decision makers. This implementation would ascertain whether the DSS supports their workflows and how its outputs influence prioritization and communication. Such studies should include usability testing and an assessment of decision quality and trust in model outputs.

AI-enabled interaction and MCP integration: Given the rapid development of AI, especially large language models, connecting the DSS to AI assistants via the Model Context Protocol (MCP) offers promising possibilities, such as natural-language querying of spatial indicators, guided scenario construction, and transparent explanation of model behaviour, while maintaining traceability to underlying data and assumptions.

Additional extensions suggested by this thesis: Further work could (i) extend the model scope to better represent currently excluded populations (e.g., homelessness) and refine mappings between service categories and census indicators; (ii) incorporate uncertainty quantification and robustness analysis to support risk-aware decision making; and (iii) enhance the DSS with automated data-update pipelines, performance/scalability improvements and additional visualization/benchmarking functions to support routine use.

CONTRIBUTION OF AUTHORS

This thesis is compiled in accordance with Concordia University's Faculty of Graduate Studies regulations, and it incorporates sections that have been published or are pending publication in peer-reviewed journals and conference proceedings.

This thesis adheres to the regulations of Concordia University's Faculty of Graduate Studies. The candidate independently conceived, curated data, developed the modeling process, wrote initial drafts, and authored all publications listed below. The advisor and any co-authors, if applicable, provided guidance and assisted in finalizing the publications.

The following papers have already been published since the start of the PhD thesis.

1. Braun, R.; Hertweck, D.; Eicker, U. (2022): An approach to cluster the research field of the food-energy-water nexus to determine modeling capabilities at different levels using text mining and cluster analysis. In Energy Nexus, p. 100101. DOI: <https://doi.org/10.1016/j.nexus.2022.100101>.
2. Braun, R.; Padsala, R.; Malmir, T.; Mohammadi, S.; Eicker, U. (2021): Using 3D CityGML for the Modeling of the Food Waste and Wastewater Generation-A Case Study for the City of Montréal. In Frontiers in big data. DOI: <https://doi.org/10.3389/fdata.2021.662011>.

Chapter 8. References

- [1] T. Ben Hassen and H. El Bilali, "Three years into the pandemic: Insights of the COVID-19 impacts on food security and nutrition in low and middle-income countries," *Heliyon*, vol. 10, no. 7, e28946, 2024, doi: 10.1016/j.heliyon.2024.e28946.
- [2] C. Béné, D. Bakker, M. J. Chavarro, B. Even, J. Melo, and A. Sonneveld, "Global assessment of the impacts of COVID-19 on food security," *Global Food Security*, vol. 31, p. 100575, 2021, doi: 10.1016/j.gfs.2021.100575.
- [3] S. Devadoss and W. Ridley, "Impacts of the Russian invasion of Ukraine on the global wheat market," *World Development*, vol. 173, p. 106396, 2024, doi: 10.1016/j.worlddev.2023.106396.
- [4] Z. Dardona, M. Amame, and S. Boussaa, "Assessing the effects of 2023–2024 conflict on food security, dietary habits, and nutritional well-being among the population of Gaza," *Discov Public Health*, vol. 22, no. 1, 2025, doi: 10.1186/s12982-025-00761-w.
- [5] M. Lagi, K. Z. Bertrand, and Y. Bar-Yam, "The Food Crises and Political Instability in North Africa and the Middle East," *SSRN Journal*, 2011, doi: 10.2139/ssrn.1910031.
- [6] G. Soffiantini, "Food insecurity and political instability during the Arab Spring," *Global Food Security*, vol. 26, p. 100400, 2020, doi: 10.1016/j.gfs.2020.100400.
- [7] M. F. Bellemare, "Rising Food Prices, Food Price Volatility, and Social Unrest," *American J Agri Economics*, vol. 97, no. 1, pp. 1–21, 2015, doi: 10.1093/ajae/aau038.
- [8] World Bank, *Poverty and Hunger. Issues and Options for Food Security in Developing Countries.: A World Bank policy study*. Washington, D.C., U.S.A.
- [9] FAO, *Rome Declaration on World Food Security and World Food Summit Plan of Action :World Food Summit* (in engchiarafrespa). Rome: FAO.
- [10] FAO, "The State of Food Insecurity in the World 2001: Food insecurity – when people live with hunger and fear starvation," The Food and Agriculture Organization of the United Nations, 2001. Accessed: Feb. 25 2023. [Online]. Available: <https://www.fao.org/agrifood-economics/publications/detail/en/c/122100/>
- [11] European Commission, "COMMISSION STAFF WORKING DOCUMENT Drivers of Food Security," Council of the European Union - Secretariat-General, Jan. 2023. Accessed: Feb. 25 2023. [Online]. Available: https://commission.europa.eu/publications/analysis-main-drivers-food-security_en
- [12] Agriculture and Agri-Food Canada, "Food Policy for Canada: Everyone at the Table," Agriculture and Agri-Food Canada, 2019. Accessed: Nov. 4 2023. [Online]. Available: <https://agriculture.canada.ca/en/departement/initiatives/food-policy/food-policy-canada>
- [13] Smith M.: Pointing J. and Maxwell S., "Household Food Security: Concepts and Definitions.: An Annotated Bibliography," *Institute of Development Studies, University of Sussex, Brighton*, 1993.

- [14] T. Lang and D. Barling, "Food security and food sustainability: reformulating the debate," *The Geographical Journal*, vol. 178, no. 4, pp. 313–326, 2012, doi: 10.1111/j.1475-4959.2012.00480.x.
- [15] High Level Panel of Experts on Food Security and Nutrition (HLPE), *Food security and nutrition: building a global narrative towards 2030: A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome*. [Online]. Available: https://knowledge4policy.ec.europa.eu/publication/food-security-nutrition-building-global-narrative-towards-2030_en?utm_source=chatgpt.com
- [16] RUAF CIC, "Shaping food security narratives: A strategic tool for climate action," 2026. Accessed: Mar. 30 2026. [Online]. Available: <https://ruaf.org/2026/03/06/ruaf-launches-new-report-on-food-security-narratives-for-climate-action/>
- [17] M. D. Anderson, "Expanding food democracy: a perspective from the United States," *Frontiers in Sustainable Food Systems*, Volume 7 - 2023, 2023. [Online]. Available: <https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2023.1144090>
- [18] FAO, IFAD, UNICEF, WFP, and WHO, "The State of Food Security and Nutrition in the World 2023. Urbanization, agrifood systems transformation and healthy diets across the rural–urban continuum.," The Food and Agriculture Organization of the United Nations, Rome, 2023. Accessed: Oct. 29 2023. [Online]. Available: <https://www.fao.org/documents/card/en/c/cc3017en>
- [19] Tarasuk V., Li T., and Fafard St-Germain AA., "Household food insecurity in Canada, 2021: Research to identify policy options to reduce food insecurity (PROOF)," Toronto:, 2022. Accessed: Nov. 4 2023. [Online]. Available: <https://proof.utoronto.ca/>
- [20] Hannah Ritchie and Max Roser, "Land Use," *Our World in Data*, 2013.
- [21] K. Al-Kodmany, "The vertical farm: A review of developments and implications for the vertical city," *Buildings*, vol. 8, no. 2, 2018, doi: 10.3390/buildings8020024.
- [22] John D. Sterman, *Business Dynamics: Systems Thinking and Modeling for a Complex World*: Jeffrey J. Shelsfud, 2000.
- [23] A. R. Hevner, S. T. March, J. Park, and S. Ram, "Design Science in Information Systems Research," *MIS Quarterly*, vol. 28, no. 1, pp. 75–105, 2004, doi: 10.2307/25148625.
- [24] E. C. Francisco, Ignacio, P. S. D. A., A. L. Piolli, and Dal Poz, M. E. S., "Food-energy-water (FEW) nexus: Sustainable food production governance through system dynamics modelling journal of cleaner production," *Journal of Cleaner Production*, vol. 386, 2023, doi: 10.1016/j.jclepro.2022.135825.
- [25] K. M. Rich, M. Rich, and K. Dzyyee, "Participatory systems approaches for urban and peri-urban agriculture planning: The role of system dynamics and spatial group model building," *Agricultural Systems*, vol. 160, pp. 110–123, 2018, doi: 10.1016/j.agsy.2016.09.022.
- [26] M. Dijkshoorn-Dekker, V. Linderhof, T. J. M. Mattijssen, and N. Polman, "Food secure metropolitan areas: The transition support system approach," *Sustainability (Switzerland)*, vol. 12, no. 13, 2020, doi: 10.3390/su12135376.

- [27] G. Arciniegas *et al.*, "A participatory tool for assessing land footprint in city-region food systems—A case study from Metropolitan Copenhagen," *Frontiers in Sustainable Food Systems*, vol. 6, 2022, doi: 10.3389/fsufs.2022.846869.
- [28] L. Y. Li, X. Li, C. Chong, C. H. Wang, and X. N. Wang, "A decision support framework for the design and operation of sustainable urban farming systems," *Journal of Cleaner Production*, vol. 268, 2020, doi: 10.1016/j.jclepro.2020.121928.
- [29] Y. L. Teo and Y. L. Go, "Techno-economic-environmental analysis of solar/hybrid/storage for vertical farming system: A case study, Malaysia," *RENEWABLE ENERGY FOCUS*, vol. 37, pp. 50–67, 2021, doi: 10.1016/j.ref.2021.02.005.
- [30] M. Contractor, G. Luna, S. Patel, and S. Steinberg, "Decision Support and Planning Tool to Facilitate Urban Rooftop Farming," in 2020.
- [31] T. Thiesen, M. G. Bhat, H. Liu, and R. Rovira, "An Ecosystem Service Approach to Assessing Agro-Ecosystems in Urban Landscapes," *LAND*, vol. 11, no. 4, 2022, doi: 10.3390/land11040469.
- [32] M. C. Kirnbauer and B. W. Baetz, "Allocating urban agricultural reuse strategies to inventoried vacant and underutilized land," *Journal of Environmental Informatics*, vol. 20, no. 1, pp. 1–11, 2012a, doi: 10.3808/jei.201200215.
- [33] M. C. Kirnbauer and B. W. Baetz, "A prototype community-based planning tool for evaluating site suitability for the temporary reuse of vacant lands," *International Journal of Urban Sustainable Development*, vol. 6, no. 2, pp. 221–240, 2014b, doi: 10.1080/19463138.2014.899230.
- [34] D. L. Erickson, S. T. Lovell, and V. E. Mendez, "Identifying, quantifying and classifying agricultural opportunities for land use planning," *LANDSCAPE AND URBAN PLANNING*, vol. 118, pp. 29–39, 2013, doi: 10.1016/j.landurbplan.2013.05.004.
- [35] M. Ghodsvali, G. Dane, and B. de Vries, "An integrated decision support system for the urban food-water-energy nexus: Methodology, modification, and model formulation," *Computers, Environment and Urban Systems*, vol. 100, 2023, doi: 10.1016/j.compenvurbsys.2023.101940.
- [36] R. E. Vega-Azamar, R. Romero-López, M. Glaus, N. A. Oropeza-García, and R. Hausler, "Sustainability assessment of the residential land use in seven boroughs of the Island of Montreal, Canada," *Sustainability (Switzerland)*, vol. 7, no. 3, pp. 2454–2472, 2015, doi: 10.3390/su7032454.
- [37] A. Dias, D. Lemos, X. Gabarrell, and L. Arroja, "Comparison of tools for quantifying the environmental performance of an urban territory," *Journal of Industrial Ecology*, vol. 22, no. 4, pp. 868–880, 2018, doi: 10.1111/jiec.12614.
- [38] V. de Laurentiis, D. V. L. Hunt, S. E. Lee, and C. D. F. Rogers, "EATS: a life cycle-based decision support tool for local authorities and school caterers," *International Journal of Life Cycle Assessment*, vol. 24, no. 7, pp. 1222–1238, 2019, doi: 10.1007/s11367-018-1460-x.

- [39] J. A. Verstegen, D. Karssenberg, F. van der Hilst, and A. Faaij, "Spatio-temporal uncertainty in Spatial Decision Support Systems: A case study of changing land availability for bioenergy crops in Mozambique," *COMPUTERS ENVIRONMENT AND URBAN SYSTEMS*, vol. 36, no. 1, pp. 30–42, 2012, doi: 10.1016/j.compenvurbsys.2011.08.003.
- [40] S. M. Downs, S. Ahmed, J. Fanzo, and A. Herforth, "Food Environment Typology: Advancing an Expanded Definition, Framework, and Methodological Approach for Improved Characterization of Wild, Cultivated, and Built Food Environments toward Sustainable Diets," *FOODS*, vol. 9, no. 4, 2020, doi: 10.3390/foods9040532.
- [41] F. Terribile *et al.*, "A Web-based spatial decision supporting system for land management and soil conservation," *Solid Earth*, vol. 6, no. 3, pp. 903–928, 2015, doi: 10.5194/se-6-903-2015.
- [42] E. Mino *et al.*, "Tools for edible cities: A review of tools for planning and assessing edible nature-based solutions," *Water (Switzerland)*, vol. 13, no. 17, 2021, doi: 10.3390/w13172366.
- [43] D. V. Aladin, E. V. Aladina, D. A. Chuvikov, O. O. Varlamov, and L. E. Adamova, "Creating a "logical intelligent plant care system" in digital agriculture based on Mivar approach," in 2022.
- [44] C. M. Bacon and G. A. Baker, "The rise of food banks and the challenge of matching food assistance with potential need: towards a spatially specific, rapid assessment approach," *Agriculture and Human Values*, vol. 34, no. 4, pp. 899–919, 2017, doi: 10.1007/s10460-017-9783-y.
- [45] N. Robert and K. Mullinix, "Municipal policy enabling regional food systems in British Columbia, Canada: Assessing focal areas and gaps," *JOURNAL OF AGRICULTURE FOOD SYSTEMS AND COMMUNITY DEVELOPMENT*, vol. 8, pp. 115–132, 2018, doi: 10.5304/jafscd.2018.08B.003.
- [46] I. Marques-Perez and B. Segura, "Integrating social preferences analysis for multifunctional peri-urban farming in planning. An application by multi-criteria analysis techniques and stakeholders," *AGROECOLOGY AND SUSTAINABLE FOOD SYSTEMS*, vol. 42, no. 9, pp. 1029–1057, 2018, doi: 10.1080/21683565.2018.1468379.
- [47] R. Surls *et al.*, "Gearing up to support urban farming in California: Preliminary results of a needs assessment," *Renewable Agriculture and Food Systems*, vol. 30, no. 1, pp. 33–42, 2015, doi: 10.1017/S1742170514000052.
- [48] O. D. Palmitessa, M. A. Pantaleo, and P. Santamaria, "Applications and Development of LEDs as Supplementary Lighting for Tomato at Different Latitudes," *AGRONOMY-BASEL*, vol. 11, no. 5, 2021, doi: 10.3390/agronomy11050835.
- [49] J. He, Ed., *Integrated vertical aeroponic farming systems for vegetable production in space limited environments: Acta Horticulturae*, 2017. [Online]. Available: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85036671316&doi=>

- 10.17660%2fActaHortic.2017.1176.5&partnerID=40&md5=03e0bde308a0382051939e2f98504999
- [50] J. He and L. Qin, "Microclimate control to increase productivity and nutritional quality of leafy vegetables in a cost-effective manner," *International Journal of Agricultural and Biological Engineering*, vol. 15, no. 3, pp. 55–61, 2022, doi: 10.25165/j.ijabe.20221503.7367.
- [51] K. Benis, I. Turan, C. Reinhart, and P. Ferrao, "Putting rooftops to use - A Cost-Benefit Analysis of food production vs. energy generation under Mediterranean climates," *CITIES*, vol. 78, pp. 166–179, 2018, doi: 10.1016/j.cities.2018.02.011.
- [52] R. R. Shamshiri *et al.*, "Advances in greenhouse automation and controlled environment agriculture: A transition to plant factories and urban agriculture," *International Journal of Agricultural and Biological Engineering*, vol. 11, no. 1, pp. 1–22, 2018, doi: 10.25165/j.ijabe.20181101.3210.
- [53] L. Graamans, E. Baeza, A. van den Dobbelsteen, I. Tsafaras, and C. Stanghellini, "Plant factories versus greenhouses: Comparison of resource use efficiency," *Agricultural Systems*, vol. 160, pp. 31–43, 2018, doi: 10.1016/j.agry.2017.11.003.
- [54] W. K. Mok, Y. X. Tan, and W. N. Chen, "Technology innovations for food security in Singapore: A case study of future food systems for an increasingly natural resource-scarce world," *TRENDS IN FOOD SCIENCE & TECHNOLOGY*, vol. 102, pp. 155–168, 2020, doi: 10.1016/j.tifs.2020.06.013.
- [55] M. G. Parkes, D. L. Azevedo, T. Domingos, and R. F. M. Teixeira, "Narratives and Benefits of Agricultural Technology in Urban Buildings: A Review," *Atmosphere*, vol. 13, no. 8, 2022, doi: 10.3390/atmos13081250.
- [56] K. Plat, A. Meyer, P. Schneider, and K. Perret, Eds., *Potential for sustainable urban food production in a medium scale city in Germany: World Sustainability Series*, 2018. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85071456790&doi=10.1007%2f978-3-319-73028-8_13&partnerID=40&md5=d5e80ba3adc7d5dd385e823ed896b030
- [57] N. Engler and M. Krarti, "Review of energy efficiency in controlled environment agriculture," *Renewable and Sustainable Energy Reviews*, vol. 141, 2021, doi: 10.1016/j.rser.2021.110786.
- [58] M. Zámková, S. Rojík, M. Prokop, S. Činčalová, and R. Stolin, "Czech Consumers' Preference for Organic Products in Online Grocery Stores during the COVID-19 Pandemic," *INTERNATIONAL JOURNAL OF ENVIRONMENTAL RESEARCH AND PUBLIC HEALTH*, vol. 19, no. 20, 2022, doi: 10.3390/ijerph192013316.
- [59] A. Gustafson, J. W. Christian, S. Lewis, K. Moore, and S. Jilcott, "Food venue choice, consumer food environment, but not food venue availability within daily travel patterns are associated with dietary intake among adults, Lexington Kentucky 2011," *NUTRITION JOURNAL*, vol. 12, 2013, doi: 10.1186/1475-2891-12-17.

- [60] L. M. Powell, S. Slater, D. Mirtcheva, Y. Bao, and F. J. Chaloupka, "Food store availability and neighborhood characteristics in the United States," *Preventive Medicine*, vol. 44, no. 3, pp. 189–195, 2007, doi: 10.1016/j.ypmed.2006.08.008.
- [61] V. Shier, S. Miller, and A. Datar, "Heterogeneity in grocery shopping patterns among low-income minority women in public housing," *BMC PUBLIC HEALTH*, vol. 22, no. 1, 2022, doi: 10.1186/s12889-022-14003-0.
- [62] C. Kemp, J. Collins, and C. Palermo, "Is the type and location of grocery stores a predictor of healthy and unhealthy food availability? A cross-sectional study," *Nutrition and Dietetics*, vol. 76, no. 3, pp. 277–283, 2019, doi: 10.1111/1747-0080.12541.
- [63] Co, M. C. Jr. and S. Bakken, "Influence of the Local Food Environment on Hispanics' Perceptions of Healthy Food Access in New York City," *Hispanic Health Care International*, vol. 16, no. 2, pp. 76–84, 2018, doi: 10.1177/1540415318788068.
- [64] M. Laxy, K. C. Malecki, M. L. Givens, M. C. Walsh, and F. J. Nieto, "The association between neighborhood economic hardship, the retail food environment, fast food intake, and obesity: Findings from the Survey of the Health of Wisconsin Disease epidemiology - Chronic," *BMC PUBLIC HEALTH*, vol. 15, no. 1, 2015, doi: 10.1186/s12889-015-1576-x.
- [65] A. Michimi and M. C. Wimberly, "Associations of supermarket accessibility with obesity and fruit and vegetable consumption in the conterminous United States," *International Journal of Health Geographics*, vol. 9, 2010, doi: 10.1186/1476-072X-9-49.
- [66] P. L. Hutchinson, J. Nicholas Bodor, C. M. Swalm, J. C. Rice, and D. Rose, "Neighbourhood food environments and obesity in southeast Louisiana," *Health and Place*, vol. 18, no. 4, pp. 854–860, 2012, doi: 10.1016/j.healthplace.2012.03.006.
- [67] P. Jia, H. Xue, X. Cheng, and Y. Wang, "Effects of school neighborhood food environments on childhood obesity at multiple scales: A longitudinal kindergarten cohort study in the USA," *BMC Medicine*, vol. 17, no. 1, 2019, doi: 10.1186/s12916-019-1329-2.
- [68] J. S. Bartfeld, J.-H. Ryu, and L. Wang, "Local characteristics are linked to food insecurity among households with elementary school children," *Journal of Hunger and Environmental Nutrition*, vol. 5, no. 4, pp. 471–483, 2010, doi: 10.1080/19320248.2010.527278.
- [69] L. M. Braun, D. Ward, D. Hales, A. Vaughn, and T. Erinosho, "Food Outlet Density, Distance, and Food Quality Offered to Preschool-Aged Children at Family Child Care Homes," *Journal of Nutrition Education and Behavior*, vol. 54, no. 2, pp. 109–117, 2022, doi: 10.1016/j.jneb.2021.09.009.
- [70] A. S. Hosler, X. Cong, and A. Alharthy, "Food Pantry Use and Its Association with Food Environment and Food Acquisition Behavior among Urban Adults," *Journal of Hunger and Environmental Nutrition*, vol. 16, no. 3, pp. 356–369, 2021, doi: 10.1080/19320248.2020.1848687.
- [71] J. E. Gaddis, A. K. Coplen, M. Clark-Barol, A. Martin, C. K. Barrett, and L. Lubowicki, "Incorporating local foods into low-income families' home-cooking practices: The critical role of sustained economic subsidies," *JOURNAL OF AGRICULTURE FOOD SYSTEMS*

- AND COMMUNITY DEVELOPMENT*, vol. 10, no. 1, pp. 117–132, 2020, doi: 10.5304/jafscd.2020.101.019.
- [72] C. Dimitri, L. Oberholtzer, and A. Pressman, "Urban agriculture: connecting producers with consumers," *British Food Journal*, vol. 118, no. 3, pp. 603–617, 2016, doi: 10.1108/BFJ-06-2015-0200.
- [73] X. Ma, B. A. Bell, K. White, J. Liu, and A. D. Liese, "Food Acquisition and Shopping Patterns in the United States: Characteristics and Relation to Body Mass Index in the US Food Acquisition and Purchase Survey," *Journal of the Academy of Nutrition and Dietetics*, vol. 122, no. 4, 745-757.e2, 2022, doi: 10.1016/j.jand.2021.09.013.
- [74] S. Tessier *et al.*, "Regular users of supermarkets in Greater Tunis have a slightly improved diet quality," *Journal of Nutrition*, vol. 138, no. 4, pp. 768–774, 2008, doi: 10.1093/jn/138.4.768.
- [75] S. Tessier *et al.*, "Food shopping transition: socio-economic characteristics and motivations associated with use of supermarkets in a North African urban environment," *Public Health Nutrition*, vol. 13, no. 9, pp. 1410–1418, 2010, doi: 10.1017/S1368980010000601.
- [76] S. O. Onagbiye, T. Lungiswa, and P. Thandi, "Association between selected food purchase practices, physical activity and sociodemographic factors among people living in a low socioeconomic periurban and rural area of South Africa," *Open Public Health Journal*, vol. 13, no. 1, pp. 44–51, 2020, doi: 10.2174/1874944502013010044.
- [77] D. Prajapati, F. T. S. Chan, Y. Daultani, and S. Pratap, "Sustainable vehicle routing of agro-food grains in the e-commerce industry," *International Journal of Production Research*, vol. 60, no. 24, pp. 7319–7344, 2022, doi: 10.1080/00207543.2022.2034192.
- [78] S. Verlinde and C. Macharis, "Who is in Favor of off-hour Deliveries to Brussels Supermarkets? Applying Multi Actor Multi Criteria Analysis (MAMCA) to Measure Stakeholder Support," in 2016, pp. 522–532. [Online]. Available: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85021269562&doi=10.1016%2fj.trpro.2016.02.008&partnerID=40&md5=60e68de9a9003f06cc2f6fc6fc6d1b14>
- [79] C. Y. Ochoa, A. Mataran, R. M. Olmo, J. M. Lopez, and R. Fuentes-Guerra, "The Potential Role of Short Food Supply Chains in Strengthening Periurban Agriculture in Spain: The Cases of Madrid and Barcelona," *SUSTAINABILITY*, vol. 11, no. 7, 2019, doi: 10.3390/su11072080.
- [80] C. van der Meer, *Exclusion of small-scale farmers from coordinated supply chains - Market failure, policy failure or just economies of scale: AGRO-FOOD CHAINS AND NETWORKS FOR DEVELOPMENT*, 2006.
- [81] Y. Ma, L. D. Chen, X. F. Zhao, H. F. Zheng, and Y. H. Lu, "What motivates farmers to participate in sustainable agriculture? Evidence and policy implications," *INTERNATIONAL JOURNAL OF SUSTAINABLE DEVELOPMENT AND WORLD ECOLOGY*, vol. 16, no. 6, pp. 374–380, 2009, doi: 10.1080/13504500903319047.

- [82] R. Kölmel, C. Baedeker, and J. Böhm, "Diffusion of a social innovation: Spatial aspects of "foodsharing" distribution in Germany," in *Innovative Logistics Services and Sustainable Lifestyles: Interdependencies, Transformation Strategies and Decision Making*, 2019, pp. 195–208. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85063928509&doi=10.1007%2f978-3-319-98467-4_9&partnerID=40&md5=7d62033b3a70a904e46bb055d0ed1756
- [83] S. Mohammady, Delavar, and P. Pahlavani, *URBAN GROWTH MODELING USING AN ARTIFICIAL NEURAL NETWORK A CASE STUDY OF SANANDAJ CITY, IRAN: 1ST ISPRS INTERNATIONAL CONFERENCE ON GEOSPATIAL INFORMATION RESEARCH*, 2014.
- [84] S. Mansour, E. Ghoneim, A. El-Kersh, S. Said, and S. Abdelnaby, "Spatiotemporal Monitoring of Urban Sprawl in a Coastal City Using GIS-Based Markov Chain and Artificial Neural Network (ANN)," *REMOTE SENSING*, vol. 15, no. 3, 2023, doi: 10.3390/rs15030601.
- [85] Y. L. Liu, Q. S. He, R. H. Tan, Y. F. Liu, and C. H. Yin, "Modeling different urban growth patterns based on the evolution of urban form: A case study from Huangpi, Central China," *Applied Geography*, vol. 66, pp. 109–118, 2016, doi: 10.1016/j.apgeog.2015.11.012.
- [86] S. Abolhasani, M. Taleai, M. Karimi, and A. R. Node, "Simulating urban growth under planning policies through parcel-based cellular automata (ParCA) model," *International Journal of Geographical Information Science*, vol. 30, no. 11, pp. 2276–2301, 2016, doi: 10.1080/13658816.2016.1184271.
- [87] R. M. Basse, O. Charif, and K. Bódis, "Spatial and temporal dimensions of land use change in cross border region of Luxembourg. Development of a hybrid approach integrating GIS, cellular automata and decision learning tree models," *Applied Geography*, vol. 67, pp. 94–108, 2016, doi: 10.1016/j.apgeog.2015.12.001.
- [88] V. Kocabas and S. Dragicevic, "Assessing cellular automata model behaviour using a sensitivity analysis approach," *COMPUTERS ENVIRONMENT AND URBAN SYSTEMS*, vol. 30, no. 6, pp. 921–953, 2006, doi: 10.1016/j.compenvurbsys.2006.01.001.
- [89] T. Anderson and S. Dragicevic, "A Geosimulation Approach for Data Scarce Environments: Modeling Dynamics of Forest Insect Infestation across Different Landscapes," *ISPRS International Journal of Geo-Information*, vol. 5, no. 2, 2016, doi: 10.3390/ijgi5020009.
- [90] L. Perez and S. Dragicevic, "Landscape-level simulation of forest insect disturbance: Coupling swarm intelligent agents with GIS-based cellular automata model," *Ecological Modelling*, vol. 231, pp. 53–64, 2012, doi: 10.1016/j.ecolmodel.2012.01.020.
- [91] Y. K. Godellou, A. A. Alesheikh, A. A. S. Mohammed, and K. Chapi, "Excellent approach to modeling urban expansion by Fuzzy Cellular Automata - Agent Base Model," in 2014. [Online]. Available: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-84923113802&doi=10.1117%2f12.2063097&partnerID=40&md5=0dfc0149cbcedf2ac3edf29588ad35be>

- [92] T. Anderson and S. Dragičević, "A Geographic Network Automata Approach for Modeling Dynamic Ecological Systems," *Geographical Analysis*, vol. 52, no. 1, pp. 3–27, 2020, doi: 10.1111/gean.12183.
- [93] T. Anderson, A. Leung, L. Perez, and S. Dragičević, "Investigating the Effects of Panethnicity in Geospatial Models of Segregation," *Applied Spatial Analysis and Policy*, vol. 14, no. 2, pp. 273–295, 2021, doi: 10.1007/s12061-020-09355-2.
- [94] J. Wang, J. Xiong, K. Yang, S. Peng, and Q. Xu, "Use of GIS and agent-based modeling to simulate the spread of influenza," in 2010. [Online]. Available: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-77958024085&doi=10.1109%2fGEOINFORMATICS.2010.5567658&partnerID=40&md5=f43c54d183e997b2da1ef5e5a4875565>
- [95] P. Chen and M. L. Liu, *Integration agent-based models and GIS as a virtual urban dynamic laboratory: GEOINFORMATICS 2007: GEOSPATIAL INFORMATION TECHNOLOGY AND APPLICATIONS, PTS 1 AND 2*, 2007.
- [96] B. Davies, I. Romanowska, K. Harris, and S. A. Crabtree, "Combining Geographic Information Systems and Agent-Based Models in Archaeology: Part 2 of 3," *Advances in Archaeological Practice*, vol. 7, no. 2, pp. 185–193, 2019, doi: 10.1017/aap.2019.5.
- [97] R. Olszewski, P. Palka, A. Turek, B. Kietlinska, T. Platkowski, and M. Borkowski, "Spatiotemporal Modeling of the Smart City Residents' Activity with Multi-Agent Systems," *APPLIED SCIENCES-BASEL*, vol. 9, no. 10, 2019, doi: 10.3390/app9102059.
- [98] M. Darvishi and G. Ahmadi, *Validation techniques of agent based modelling for geospatial simulations: 1ST ISPRS INTERNATIONAL CONFERENCE ON GEOSPATIAL INFORMATION RESEARCH*, 2014.
- [99] Q. F. Guan, X. Shi, M. Q. Huang, and C. G. Lai, "A hybrid parallel cellular automata model for urban growth simulation over GPU/CPU heterogeneous architectures," *International Journal of Geographical Information Science*, vol. 30, no. 3, pp. 494–514, 2016, doi: 10.1080/13658816.2015.1039538.
- [100] J. Maso, X. Pons, and A. Zabala, "Building the World Wide Hypermap (WWH) with a RESTful architecture," *International Journal of Digital Earth*, vol. 7, no. 3, pp. 175–193, 2014, doi: 10.1080/17538947.2012.669414.
- [101] R. Y. Liu, N. Liu, W. Z. Bao, and Y. Zhu, *Network-oriented massive spatio-temporal data model and its applications: GEOINFORMATICS 2006: GEOSPATIAL INFORMATION TECHNOLOGY*, 2006.
- [102] Q. Huang and W. Song, "A land-use spatial optimum allocation model coupling a multi-agent system with the shuffled frog leaping algorithm," *COMPUTERS ENVIRONMENT AND URBAN SYSTEMS*, vol. 77, 2019, doi: 10.1016/j.compenvurbsys.2019.101360.
- [103] S. J. Rey *et al.*, "Open Geospatial Analytics with PySAL," *ISPRS International Journal of Geo-Information*, vol. 4, no. 2, pp. 815–836, 2015, doi: 10.3390/ijgi4020815.

- [104] M. Cannata, J. Neumann, and R. Rossetto, "Open source GIS platform for water resource modelling: FREEWAT approach in the Lugano Lake," *SPATIAL INFORMATION RESEARCH*, vol. 26, no. 3, pp. 241–251, 2018, doi: 10.1007/s41324-017-0140-4.
- [105] F. Y. Lin, T. P. Lin, and R. L. Hwang, "Using geospatial information and building energy simulation to construct urban residential energy use map with high resolution for Taiwan cities," *ENERGY AND BUILDINGS*, vol. 157, pp. 166–175, 2017, doi: 10.1016/j.enbuild.2017.01.040.
- [106] O. Ahlqvist, N. Khodke, and R. Ramnath, "GeoGame analytics - A cyber-enabled petri dish for geographic modeling and simulation," *COMPUTERS ENVIRONMENT AND URBAN SYSTEMS*, vol. 67, pp. 1–8, 2018, doi: 10.1016/j.compenvurbsys.2017.08.013.
- [107] O. Ahlqvist, T. Löffing, J. Ramanathan, and A. Kocher, "Geospatial Human-environment Simulation through Integration of Massive Multiplayer Online Games and Geographic Information Systems," *Transactions in GIS*, vol. 16, no. 3, pp. 331–350, 2012, doi: 10.1111/j.1467-9671.2012.01340.x.
- [108] J. Vukomanovic, M. M. Skrip, and R. K. Meentemeyer, "Making It Spatial Makes It Personal: Engaging Stakeholders with Geospatial Participatory Modeling," *LAND*, vol. 8, no. 2, 2019, doi: 10.3390/land8020038.
- [109] I. Hijazi, A. Donaubaue, A. Hamm, A. Falkenstein, and T. H. Kolbe, "Urban Growth Simulation Using Urban Dynamics and Citygml: A Use Case from the City of Munich," in 2022, pp. 97–104. [Online]. Available: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85141047046&doi=10.5194%2fisprrs-annals-X-4-W2-2022-97-2022&partnerID=40&md5=cce320229408353c4ac2c2cec4674213>
- [110] H. J. Herrera de Leon and B. Kopainsky, "Do you bend or break? System dynamics in resilience planning for food security," *Syst. Dyn. Rev.*, vol. 35, no. 4, pp. 287–309, 2019, doi: 10.1002/sdr.1643.
- [111] J. Randers and D. Collste, *The Earth4All model of human wellbeing on a finite planet towards 2100*, 2023. Accessed: Feb. 4 2025. [Online]. Available: <https://eartharxiv.org/repository/view/5111/>
- [112] A. D. M. Sawyer *et al.*, "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," *International Journal of Behavioral Nutrition and Physical Activity*, vol. 18, no. 1, p. 96, 2021, doi: 10.1186/s12966-021-01164-1.
- [113] I. J. Martinez-Moyano and G. P. Richardson, "Best practices in system dynamics modeling," *Syst. Dyn. Rev.*, vol. 29, no. 2, pp. 102–123, 2013, doi: 10.1002/sdr.1495.
- [114] D. N. Ford, "A system dynamics glossary," *Syst. Dyn. Rev.*, vol. 35, no. 4, pp. 369–379, 2019, doi: 10.1002/sdr.1641.
- [115] J.-A. Puddephatt, G. S. Keenan, A. Fielden, D. L. Reaves, J. C. G. Halford, and C. A. Hardman, "'Eating to survive': A qualitative analysis of factors influencing food choice and

- eating behaviour in a food-insecure population," *Appetite*, vol. 147, p. 104547, 2020, doi: 10.1016/j.appet.2019.104547.
- [116] W. Willett *et al.*, "Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems," *The Lancet*, vol. 393, no. 10170, pp. 447–492, 2019, doi: 10.1016/S0140-6736(18)31788-4.
- [117] R. Braun, R. Padsala, T. Malmir, S. Mohammadi, and U. Eicker, "Using 3D CityGML for the Modeling of the Food Waste and Wastewater Generation-A Case Study for the City of Montréal," *Frontiers in big data*, vol. 4, p. 662011, 2021, doi: 10.3389/fdata.2021.662011.
- [118] OASIS, *XML Interchange Language for System Dynamics (XMILE) Version 1.0: OASIS Standard*. [Online]. Available: <https://docs.oasis-open.org/xmile/xmile/v1.0/xmile-v1.0.html> (accessed: Sep. 30 2026).
- [119] L. LIU and M. T. ÖZSU, Eds., *Encyclopedia of Database Systems*. Boston, MA: Springer US, 2009.
- [120] C. Neuwirth and A. Peck, "A conceptual spatial system dynamics (SSD) model for structural changes in grassland farming," in *International Congress on Modelling and Simulation*, Adelaide, Australia, Dec. 2013.
- [121] C. Neuwirth, A. Peck, and S. P. Simonovi, "Modeling structural change in spatial system dynamics: A Daisyworld example," *Environmental Modelling & Software*, vol. 65, pp. 30–40, 2015, doi: 10.1016/j.envsoft.2014.11.026.
- [122] PostGIS PSC & OSGeo, *PostGIS*. [Online]. Available: <https://postgis.net/> (accessed: Oct. 3 2025).
- [123] Dave Page, *pgAdmin: PostgreSQL Tools*. [Online]. Available: <https://www.pgadmin.org/> (accessed: Oct. 28 2025).
- [124] Oliver Grasl, *Business Prototyping Toolkit for Python*. [Online]. Available: https://github.com/transentis/bptk_py
- [125] Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec (MAPAQ), *Food establishments data set*. [Online]. Available: <https://donnees.montreal.ca/dataset/etablissements-alimentaires>
- [126] 211 Greater Montreal - City of Montreal, *Follow-up on requests for food aid at 211*. [Online]. Available: <https://donnees.montreal.ca/dataset/demandes-aide-alimentaire> (accessed: Jan. 23 2026).
- [127] Y. Barlas, "Formal aspects of model validity and validation in system dynamics," *Syst. Dyn. Rev.*, vol. 12, no. 3, pp. 183–210, 1996, doi: 10.1002/(SICI)1099-1727(199623)12:3<183::AID-SDR103>3.0.CO;2-4.
- [128] C. Chaichana, A. Man, S. Wicharuck, Y. Mona, and D. Rinchumphu, "Modelling of annual sunlight availability on vertical shelves: A case study in Thailand," *Energy Reports*, vol. 8, pp. 1136–1143, 2022, doi: 10.1016/j.egyr.2022.07.077.

- [129] I. Pertry, P. Bleyaert, P. Demyttenaere, and M. Demeulemeester, Eds., *Agrotopia, a living lab for high-tech urban horticulture within Europe: Acta Horticulturae*, 2018. [Online]. Available: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85056855613&doi=10.17660%2fActaHortic.2018.1215.29&partnerID=40&md5=1d3bc6f35f74355418b1c0fe39826bb0>
- [130] C. R. Caceres, S. Tornroth, M. Vesterlund, A. Johansson, and M. Sandberg, "Data-Center Farming: Exploring the Potential of Industrial Symbiosis in a Subarctic Region," *SUSTAINABILITY*, vol. 14, no. 5, 2022, doi: 10.3390/su14052774.
- [131] D. Buehler and R. Junge, "Global Trends and Current Status of Commercial Urban Rooftop Farming," *SUSTAINABILITY*, vol. 8, no. 11, 2016, doi: 10.3390/su8111108.
- [132] G. Ledesma, J. Nikolic, and O. Pons-Valladares, "Bottom-up model for the sustainability assessment of rooftop-farming technologies potential in schools in Quito, Ecuador," *Journal of Cleaner Production*, vol. 274, 2020, doi: 10.1016/j.jclepro.2020.122993.
- [133] S. Thomaier *et al.*, "Farming in and on urban buildings: Present practice and specific novelties of Zero-Acreage Farming (ZFarming)," *Renewable Agriculture and Food Systems*, vol. 30, no. 1, pp. 43–54, 2015, doi: 10.1017/S1742170514000143.
- [134] S. A. Walters and K. S. Midden, "Sustainability of Urban Agriculture: Vegetable Production on Green Roofs," *AGRICULTURE-BASEL*, vol. 8, no. 11, 2018, doi: 10.3390/agriculture8110168.
- [135] S. Song, Y. Hou, R. B. H. Lim, L. Y. F. Gaw, D. R. Richards, and H. T. W. Tan, "Comparison of vegetable production, resource-use efficiency and environmental performance of high-technology and conventional farming systems for urban agriculture in the tropical city of Singapore," *Science of the Total Environment*, vol. 807, 2022, doi: 10.1016/j.scitotenv.2021.150621.
- [136] M. M. Khan, M. T. Akram, R. Janke, R. W. Qadri, am Al-Sadi, and A. A. Farooque, "Urban Horticulture for Food Secure Cities through and beyond COVID-19," *SUSTAINABILITY*, vol. 12, no. 22, 2020, doi: 10.3390/su12229592.
- [137] M. H. Saad, N. M. Hamdan, and Sarker, "State of the Art of Urban Smart Vertical Farming Automation System: Advanced Topologies, Issues and Recommendations," *ELECTRONICS*, vol. 10, no. 12, 2021, doi: 10.3390/electronics10121422.
- [138] C. Eigenbrod and N. Gruda, "Urban vegetable for food security in cities. A review," *Agronomy for Sustainable Development*, vol. 35, no. 2, pp. 483–498, 2015, doi: 10.1007/s13593-014-0273-y.
- [139] K. Benke and B. Tomkins, "Future food-production systems: Vertical farming and controlled-environment agriculture," *Sustainability: Science, Practice, and Policy*, vol. 13, no. 1, pp. 13–26, 2017, doi: 10.1080/15487733.2017.1394054.
- [140] K. Al-Kodmany, Ed., *The Vertical Farm: Exploring Applications for Peri-urban Areas: Modeling and Optimization in Science and Technologies*, 2020. [Online]. Available: <https://>

- www.scopus.com/inward/record.uri?eid=2-s2.0-85079420888&doi=10.1007%2f978-3-030-37794-6_11&partnerID=40&md5=878b1a3f28f1a3ffd504d5599f0a0a34
- [141] M. Cicekli and N. T. Barlas, "Transformation of today greenhouses into high technology vertical farming systems for metropolitan regions," *Journal of Environmental Protection and Ecology*, vol. 15, no. 4, pp. 1779–1785, 2014. [Online]. Available: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-84946821185&partnerID=40&md5=0a6c72f38aa01e825837d9b33be851c1>
- [142] G. Buyukozkan, F. Gocer, and D. Uzturk, "A novel Pythagorean fuzzy set integrated Choquet integral approach for vertical farming technology assessment," *COMPUTERS & INDUSTRIAL ENGINEERING*, vol. 158, 2021, doi: 10.1016/j.cie.2021.107384.
- [143] G. Gianquinto, F. Orsini, N. Michelon, D. F. Da Silva, and F. D. de Faria, *Improving yield of vegetables by using soilless micro-garden technologies in peri-urban area of north-east Brazil: PROCEEDINGS OF THE VIIIITH INTERNATIONAL SYMPOSIUM ON PROTECTED CULTIVATION IN MILD WINTER CLIMATES: ADVANCES IN SOIL AND SOILLESS CULTIVATION UNDER PROTECTED ENVIRONMENT*, 2007.
- [144] T. C. Gray, "ARCHITECTURAL PROTOTYPES IN SUPPORT OF URBAN FARMING AND THE SUSTAINABLE CITY," *INTERNATIONAL TRANSACTION JOURNAL OF ENGINEERING MANAGEMENT & APPLIED SCIENCES & TECHNOLOGIES*, vol. 11, no. 15, 2020, doi: 10.14456/ITJEMAST.2020.289.
- [145] T. Anderson and S. Dragicevic, "Geographic network automata for representing complex evolving spatial systems," in 2018, pp. 5–8. [Online]. Available: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85061814623&doi=10.1145%2f3284038.3284040&partnerID=40&md5=60f6bd6483dbba815200952ec8c18f43>
- [146] T. Anderson and S. Dragićević, "Network-agent based model for simulating the dynamic spatial network structure of complex ecological systems," *Ecological Modelling*, vol. 389, pp. 19–32, 2018, doi: 10.1016/j.ecolmodel.2018.10.008.
- [147] T. Anderson and S. Dragicevic, "NEAT approach for testing and validation of geospatial network agent-based model processes: case study of influenza spread," *International Journal of Geographical Information Science*, vol. 34, no. 9, pp. 1792–1821, 2020, doi: 10.1080/13658816.2020.1741000.
- [148] T. Gilbert, S. Barr, P. James, J. Morley, and Q. Ji, "Software systems approach to multi-scale GIS-BIM utility infrastructure network integration and resource flow simulation," *ISPRS International Journal of Geo-Information*, vol. 7, no. 8, 2018, doi: 10.3390/ijgi7080310.
- [149] C. Carré and Y. Hamdani, "Pyramidal framework: Guidance for the next generation of gis spatial-temporal models," *ISPRS International Journal of Geo-Information*, vol. 10, no. 3, 2021, doi: 10.3390/ijgi10030188.

- [150] A. Jjumba and S. Dragicevic, "A development of spatiotemporal queries to analyze the simulation outcomes from a voxel automata model," *EARTH SCIENCE INFORMATICS*, vol. 9, no. 3, pp. 343–353, 2016, doi: 10.1007/s12145-016-0260-8.
- [151] B. Huang, L. Yao, and TRB, "Spatiotemporal object database approach to dynamic segmentation," in *INITIATIVES IN INFORMATION TECHNOLOGY AND GEOSPATIAL SCIENCE FOR TRANSPORTATION: PLANNING AND ADMINISTRATION*, 2003, pp. 118–125.
- [152] M. Bhatt and J. O. Wallgrun, "Geospatial narratives and their spatio-temporal dynamics: Commonsense reasoning for high-level analyses in geographic information systems," *ISPRS International Journal of Geo-Information*, vol. 3, no. 1, pp. 166–205, 2014, doi: 10.3390/ijgi3010166.

Appendix A. Artifact inventory

Table A 1 Artifact type, description of the artifact, and reference to the main sections in the thesis and purpose of the artifact

Artifact type	Description of the artifact	Appearance and purpose
Model / Construct	High-level Causal Loop Diagram (CLD) of the developed Spatial Food Systems Model. Causal Loop Diagram with B1–B3 (balancing) and R1–R2 (reinforcing) loops capturing accessibility, budgets, household insecurity, urban production, and retail density.	Chapter 3.3, Figure 10; Understanding of the processes around balancing and reinforcing loops. Enables fast understanding of the system model.
Model	Three subsystems as stock-and-flow structures. Stock and flow models capturing the main dynamics for (i) geographical accessibility, (ii) household finances, and (iii) household circumstances.	Chapter 3.4.1 - 3.4.3. Details of the variables within the model, with the objective of fostering a comprehensive understanding of the Vensim model and enabling its successful utilization in running simulations..
Documentation	Model documentation. Statement regarding limitations, model information, number of variables, units, time horizon of the simulation, and main equations.	System dynamics model documentation.
Instantiation / System	Decision Support System (DSS) integrating Spatial System Dynamics (SSD) within a microservices-based architecture.	Chapter 4 overview; positions the DSS as the central artifact, emphasizing methodological rigor, scalability, and maintainability.
Model / Construct	Three-layer DSS conceptual model (Business Layer; Software, Code & Infrastructure Layer; Data & Models Layer).	Chapter 4 – System Architecture and Technical Design; clarifies how raw data and models are transformed into insights for decision-makers.
Design principle / Integration pattern	Moderate coupling strategy using a shared database (PostgreSQL/PostGIS) between SD engine and GIS tools.	Chapter 4 – Coupling Strategies; balances flexibility, performance, and scalability with decoupled components.
Software component / Instantiation	Spatial System Dynamics Simulation Core (spatio-temporal mapping + dynamic simulation processes).	Chapter 4 – Software, Code & Infrastructure Layer; executes system dynamics and writes results back for visualization.
Documentation / Specification	REST API specification examples (base URL, /scenarios, /write_scenario) with JSON payloads and responses.	Chapter 4 – Service Communication Standards; enables reproducible access and client integration for scenario management.

Software component / Model instantiation	System Dynamics Python Model generated from XMILE via BPTK-Py; core simulation routines.	Chapter 4 – Integration of Simulation Models Workflow; operationalizes SD models inside the DSS.
User interface / Analysis notebook	Jupyter Notebook for area-of-interest selection and scenario parameterization.	Chapter 4 – Deployment Architecture (User PC); interactive UI to define spatial domain and inputs.
Process / Workflow	Data integration & preparation workflow (ETL notebooks: Extract → Transform → Load, with metadata/versioning).	Chapter 4 – Data Ingestion and Preparation; ensures data quality, provenance, and reproducibility.
Process / Workflow	Simulation model integration workflow: Vensim → XMILE → BPTK-Py → SSD core.	Chapter 4 – Integration of Simulation Models Workflow; standard path to bring SD models into the DSS.
Infrastructure / Deployment	Containerized microservices using Docker on Linux-based infrastructure.	Chapter 4 – Infrastructure; enables independent deployment, scaling, and resilience.
Diagram / Documentation	Data Flow Diagram (DFD) showing how primary and secondary data sources are collected, processed, merged, and stored in the DSS.	Chapter 6 – Data Integration and Flow within the DSS; visualizes end-to-end data ingestion and preparation for SSD simulations.
Standard-based specification / UML model file	Visual Paradigm XML project file (UML_model_food_system_17_3.xml) encoding DFD elements: External Entities (E), Processes (P), Data Stores (D), and Data Flows (F).	Chapter 6 – Data Flow; formal, importable specification that ensures reproducibility and portability of the workflow.
Dataset (Primary)	Field-compiled dataset of places of food consumption (restaurants, fast-food outlets) and food acquisition points (supermarkets, small shops, healthy food stores).	Chapter 6 – Primary data; closes gaps and supplements secondary sources for DSS inputs.
Dataset (Secondary)	Open Data Portal Montréal – Food Establishments (daily updates from MAPAQ permits, City occupancy certificates, field observations; 73 original categories).	Chapter 6 – Food Establishments; core dataset for categorizing outlets into six classes for SD stocks.
Dataset (Secondary)	Open Data Portal Montréal – Follow-up on Requests for Food Aid at 211 (Requests, Follow-ups, Needs tables; 2021–2022).	Chapter 6 – 211 Food Aid dataset; socio-economic and service-use indicators used for correlation analysis and vulnerability context.
Dataset (Secondary)	Open Data Portal Montréal – Borough Boundaries.	Chapter 6 – Overview of Data Flow; spatial framework for borough-level aggregation and visualization.
Dataset (Secondary)	CERC Concordia University – Buildings dataset.	Chapter 6 – Overview of Data Flow; supports building-level integration and accessibility analyses.
Dataset (Secondary)	OpenStreetMap – Public Transport Stations; Public Places and Community Gardens.	Chapter 6 – Overview of Data Flow; mobility/accessibility and public realm context layers for DSS.

Dataset (Secondary)	Statistics Canada – 2021 Census Boundary Files and Census Profile attributes (census tracts).	Chapter 6 – Statistics Canada 2021 Census; demographic and socio-economic backbone for calibration and spatial exploration.
Analysis notebook	Jupyter notebooks (one per dataset) documenting source, processing, and adjustments; e.g., Census analysis.ipynb.	Chapter 6 – Technical Implementation and Reproducibility; enables external replication and adaptation.
Script / Function library	census_select.py with select_data() to filter Census tables by CHARACTERISTIC_ID for variables of interest.	Chapter 6 – Statistics Canada 2021 Census; standardized extraction of indicators for DSS integration.
Repository / Reproducibility package	Public GitHub repository with datasets, preprocessing scripts, configuration files, and notebooks.	Chapter 6 – Technical Implementation and Reproducibility; full transparency and recomputeability.
Process / Governance	Bilingual data curation: translation of French-only datasets to English with archiving of both original and translated versions.	Chapter 6 – Bilingual data availability; ensures usability and reproducibility while retaining provenance.
Data store / Infrastructure	PostGIS DSS database as the central repository for inputs and model outputs (supports spatial queries and overlays).	Chapter 6 – Data Flow and Integration; operational backbone for moderate coupling and model execution.
Data store / Model library	System Dynamics Model Library (compiled Python models generated via BPTK-Py from XMILE).	Chapter 6 – Overview of Data Flow; reusable models for further analysis and simulation.
Mapping tables / Data model	Crosswalk aligning 211 Montréal categories (housing, household composition, immigration) to Census 2021 CHARACTERISTIC IDs; Appendix C.	Chapter 6 – Mapping of food aid request data to the Census; enables borough-level harmonization for SSD initialization.
SQL query / Aggregation function	Population-weighted aggregation queries using ST_Union, ST_Intersection, and ST_Area to compute counts by borough/geometry.	Chapter 6 – Mapping implementation in PostGIS; supplies harmonized indicators to the SSD model.
Process / Workflow	Reverse geocoding and building-level matching of food establishments to CERC Buildings; centroid association and attribute enrichment.	Chapter 6 – Mapping Food Establishment Data with Building Data; improves spatial accuracy for analysis and DSS integration.
Process / Workflow	Linguistic standardization (FR→EN) and categorical harmonization of food establishment types into six classes (healthy, supermarket, fast food, restaurant, out-of-home catering, other).	Chapter 6 – Mapping Food Establishment Data; supports health-oriented analysis and SD model stocks.
Reference table / Mapping list	Mapping table from original 73 food-establishment categories to six analytical classes (Table 9 segment; full list in Appendix C).	Chapter 6 – Table 9; reproducible classification for consistent model inputs.
Data export / Interchange	GeoJSON exports of preprocessed census and integrated layers for loading into the DSS/PostGIS environment.	Chapter 6 – Statistics Canada 2021 Census; standardizes outputs for spatial clients and services.

Appendix B. Query words, word clouds and network graphs

The following table shows the search words, the number of results, and duplicates of the literature survey for each objective.

Table A 2 Query words used for the search in SC and WoS and results of the bibliometric search

No	Query Wording (QW) for WoS and SC search	Total Results	Duplicates
1	For literature addressing decision support systems		
	SC: (TITLE-ABS-KEY (decision AND support AND tool) AND TITLE-ABS-KEY (urban AND food AND system))	66	34
	WoS: (ALL=(decision AND support AND tool)) AND ALL=(urban AND food system)	109	
2	For literature addressing technologies for urban food production		
	SC: (TITLE-ABS-KEY (technologies) AND TITLE-ABS-KEY (urban AND food AND production) AND TITLE-ABS-KEY (greenhouses OR open AND farming OR community AND gardens OR vertical AND farming))	21	12
	WoS: (ALL=(technologies)) AND (ALL=(urban AND food AND production)) AND (ALL=(greenhouses OR open AND farming OR community AND gardens OR vertical AND farming))	167	
3	For literature addressing food demand and local food supply chains		
	SC: (TITLE-ABS-KEY (urban AND food AND logistics) AND TITLE-ABS-KEY (supermarket OR (farmer AND markets)))	62	33
	WoS: (ALL=(urban AND food AND logistics)) AND ALL=(supermarket AND farmer AND markets)	68	
4	For literature addressing the spatial system dynamics		
	SC: (TITLE-ABS-KEY (geospatial AND information AND system) AND TITLE-ABS-KEY (spatial AND system AND dynamics))	274	97
	WoS: (ALL=(geospatial AND information AND system)) AND ALL=(spatial AND system AND dynamics)	640	

Main objective: Decision Support Systems

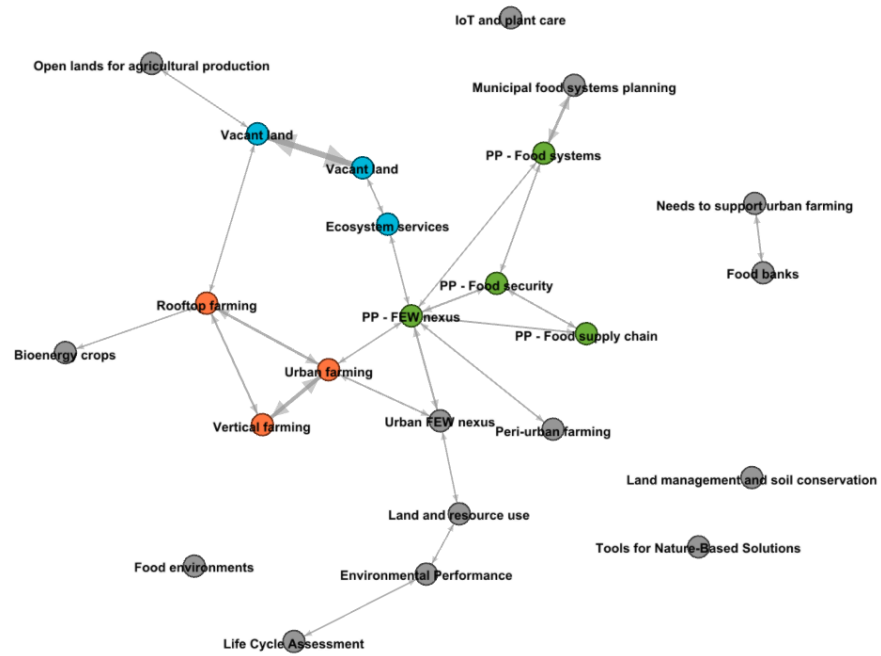


Figure A 1 Network graph of the selected papers for the overall objective, data set of 24 papers

Table A 3 Detailed overview of the publications studied for the main-objective

Reference	Focus topics	Level of work	Modeling method	Capabilities	Limitations
DSS and participatory processes (PP)					
[24]	- Food-energy-water (FEW) nexus - Food production governance	Green belt of the peri-urban region of the city of São Paulo	System dynamics (SD)	SD allows to model the complex system and to calculate the impact of different scenarios on a longer time period.	Although the complexity is modelled, the spatial information is missing.
[25]	- Participatory system - From supply to demand - Spatial group model building (SGMB)	Urban and peri-urban	SD models combined with participatory approaches	Overlaying quantitative models of urban food value chains alongside their land-use characteristics.	SD models were carried out with a small group (four people), so important elements in the model may have been forgotten. No updating of the maps.
[26]	- Participatory processes and transition support systems - Transition towards food security - Urban food security	Metropolitan area	- Combining stakeholder participation with model-driven decision support - Maps (GIS) for visualisation	- Involving stakeholders in informal governance processes, social innovation, and the co-production of knowledge in food system transitions - Stakeholder-inclusive approach to decision-making in food system transitions	No updating of the maps
[27]	- Participatory processes using GIS based tool - Agricultural land in close proximity to urban centers - Sustainable food systems through the lens of food supply resilience	Metropolitan area	Dynamic GIS, a combination Esri ArcMap 10.6 and communityViz Scenario 360TM	Features up-to-date European datasets to - assess the potential of current agricultural land use to provide food resources with special attention to the share of both plant- vs. animal-based products and meet the demand of city dwellers, and - enable stakeholders to geographically allocate land use change decisions concerning desirable food groups to move toward a sustainable city-region food system	Although the complexity is modelled, and the spatial information is granular the time is missing.
DSS and technical systems					

[28]	- Framework for the simulation, assessment, and optimization of urban farming systems - Provide convenient decision support for the stakeholders	Building	Dynamic simulation of the HVAC system	Full analysis of a HVAC urban farming system, including optimization of the system.	No spatial information, building scale and difficult to scale it up to an urban area.
[29]	- Optimized building geometry modeling integrated with energy yield estimation - Examination of the load demand in the vertical farming - Solar PV system for the vertical farms	Building	Dynamic simulation of the PV system	Evaluate the effect of grid-connected and standalone solar PV system configurations	No spatial information, building scale and difficult to scale it up to an urban area.
[30]	- Guide for users in designing a rooftop farm - Assessment tool covering critical requirements for rooftop farming e.g. weight bearing capacity and farm size	Building	- Tool based on a survey - Different categories for selection	Since the tool was developed through a questionnaire, it can consider specific circumstances that fit the study area.	Very specific tool, and the user must provide some information that may not be available. Scalability and general application to other areas are questionable.
DSS and the use of urban spaces					
[31]	- Ecosystem services (ES) indicators to assess alternative agro-ecosystems - Permaculture and Agro-ecosystems Sustainability, development of a score card	Urban: Comparison across different urban agriculture sites, e.g. urban farms, residential food gardens and public space farms/gardens	A tool that considers different indicators and calculates the indicators for the sites	- Calculation of ecosystem services (ES) indicators - Integration of ES indicators into urban planning and decision-making - Showing strengths and weaknesses through the indicators	The calculations are not based on a simulation model, so temporal and spatial changes are, therefore, difficult to predict. The interrelationships of the individual categories are also not clarified.

[33]	- Strategies on vacant urban lands and how to reuse it - 'Site suitability index' (or score) - Decision support tool for inventorying the spatial characteristics	Neighbourhood and community-based level	- Questionnaire and input fields developed in Microsoft Excel - Calculates site suitability indices based	Through the questionnaire, the places can be evaluated easily and quickly. Easy use of the tool.	The calculations are not based on a simulation model, so temporal and spatial changes are therefore difficult to predict. The interrelationships of the individual categories are also not clarified.
[32]	- Strategies on vacant urban lands and how to reuse it - 'Site suitability index' (or score) - Decision support tool for inventorying the spatial characteristics	Neighbourhood and community-based level	User can perform a series of "what-if" scenarios and sensitivity analyses to better articulate the potential trade-offs	- Identify potential alternative location-allocation solutions, which can be useful for initiating well-informed discussions related to suitable locations for vacant and underutilized land reuse. - Helpful in allocating reuse strategies to vacant and underutilized land - Visualizing strategies in a map	No temporal components in the calculations

Objective: Technologies for urban food production



Figure A 2 Word cloud of the for the data set of 28 papers, min.freq = 10. Objective: Technologies for urban food production



Figure A 3 Network graph of the selected papers for the objective: Technologies for urban food production, data set of 28 papers

Table A 4 Detailed overview of the publications studied for the objective: Technologies for urban food production

Reference	Focus topics	Technologies / technical requirements	Food products / crops	Challenges identified
[48]	- High-tech GH and artificial light applications. - Applications and development of LEDs in supplementary lighting (SL) of GH for tomato cultivation	- Light-emitting diodes (LED) installations - Overhead LED system + intracanopy LED installation - Daily light integral (DLI) in a GH	- Tomato - Pepper - Cucumber	- Limiting factors of GH cultivation in different climatic regions - Supplementary lighting (SL) is fundamental to produce vegetables such as tomato or cucumber all year round at high latitudes, whereas at middle latitudes, SL is strongly recommended to overcome the limiting factor of natural DLI and to obtain tomato yields comparable to those obtained in northern Europe with SL.
[128]	- Vertical farming (VF) - Model to predict the annual sunlight availability on vertical shelves	- RHINO modelling software - DLI calculation / simulation / modelling	DLI recommendation for: - Seedlings (plugs) - Early microgreen and late leafy greens and herbs - Lettuce, tomato, eggplant, cucumber, capsicum and strawberry	- Limited availability of solar energy at the lower shelves
[53]	Modelling and comparison of plant factories and greenhouses and quantify the resource requirement for lettuce production.	Complete HVAC system, including heating and cooling, CO2 regulation, light and ventilation.	- Lettuce	- Plant factories (PF) require a larger input of purchased energy compared to greenhouses - Direct use of solar energy has a greater impact on the total energy requirement than efficient use of energy. - Photovoltaic cells could be used to supply plant factories with renewable electricity.
[57]	Controlled Environment Agriculture (CEA), vertical farms (VF) and plant factories (PF).	- Energy efficiency technologies - Optimal indoor growing environments - Facility's envelope, HVAC, lighting, and incorporation of distributed generation technology	- Lettuce, tomatoes, herbs, micro-greens, shiitake mushrooms, cannabis, cucumber, pepper, strawberries, blueberry, rice	- High operating costs preventing farmers from turning a profit - High carbon footprints per crop, which hinder government efforts to mitigate carbon emissions - Significant need to evaluate the impact of various energy efficiency measures for CEA facilities - Improvements in lighting, dehumidification, and control technologies are needed to ensure CEA facilities can be less environmentally damaging

				- Limited modeling tools are available to specifically model the energy performance of CEA facilities
[129]	Research on greenhouse technologies	- The greenhouse aims to be energy neutral by exchanging residual heat and electricity with REO Veiling - Minimize energy use by applying the Dutch concept of “Next Generation Growing” - Integrated pest management - Reuse of nutrient waste solutions - Use of low-grade heat from the city waste incinerator	Different kinds of soilless vegetables	No access to the full publication, only to the abstract
[130]	Using excess heat from data center (DC) for greenhouses (GH)	- Excess heat from DCs to heat subarctic greenhouses (GHs) - Heat distribution systems Air-to-Air or Air-to-Water - Placement of GH on top of the DC, on side, distance or enclosing	No specific crops mentioned	- Ensure the reliability of local urban farms to meet the high proportion of vegetable demand throughout the year. - Increased price for local products - To have a competitive price in comparison to imported vegetables - High maintenance for the GH (e.g., roof snow cleaning) - Lack of capital for GH farmers to move to DC site (or vice versa) - Lack of specialized knowledge regarding thermal management and cooling control when designing DC business models - High DC security and an upstream effect create high requirements on the GH physical integration (e.g., create multiple access/entrance ways to the building) - Design and integration between a GH and a DC add extra costs - Heat transfer solutions and control systems add extra costs. Lack of suitable business models and service levels.

[55] Review paper	Soil-less growing systems in different regions of the world, aquaponics, hydroponics, vertical hydroponics and aeroponics	Water reuse, use of solar, direct sun and PV, LED supplement, CO2 Fertilization, organic waste reuse.	Full list of crop types given in the supplementary material	- The known drawback of ag-tech and indoor farming is the high energy demand, and consequently potentially higher GHG emissions - The operational costs to produce crops
[52]	Controlled environment agriculture (CEA), from greenhouses (GH) to high productivity vertical farms (VF). Strong focus on technologies ranging from HVAC to IoT for monitoring and opportunities for integration into buildings.	- Covering materials for greenhouses e.g. glass panels, net-screen film, Polyethylene (PE) plastic films, and ultraviolet (UV) stabilized PE-films. - Light control and artificial lights - IoT-based monitoring	No specific crops mentioned	Biggest challenges for the development of an efficient and viable CEA system are: - the creation of automation levels for energy management - reduction of environmental impact - maximizing use of natural resources
[51]	Systematic and integrated comparison of the productive uses of rooftops, enabling the evaluation of economic sustainability and net social welfare of a set of options over a 50-year life cycle.	- Rooftop farms for open-air food production - “Low-tech” Rooftop Greenhouse (RG) - “High-tech” Rooftop Greenhouse (RG) - Building-Integrated Photovoltaic (BIPV) energy systems	Organic- and non-organic tomato	- Outcomes highly site-specific, depending on yields, which vary according to local conditions such as solar radiation; and technology-specific, depending on the efficiency of the system. - Additional indicators such as land use or impacts on energy and freshwater resources should be considered in order to measure environmental impacts of each system in a more comprehensive way. Policy recommendations - Including productive rooftops into urban resilience plans - more flexible urban codes needed e.g. zoning codes in urban areas - Financial instruments to offer subsidies for roof reinforcements and green roof implementation - Fostering R&D and product quality certification
[131]	Focuses on large and commercial operations of urban rooftop farming (URF)	- Chemical Free Production - Energy Efficiency - Renewable Energy - Waste Heat - Water re-Use - Rainwater collection	- Lettuce - Chard - Pak choi - Tomatoes - Herbs	Commercial operation of URF, should they become profitable, is likely to attract notable private investment, allowing a significant level of high quality urban food production to be achieved.

		- Use of Greywater - Recycling of Nutrients - Exchange of Gases		
[132]	Rooftop-farm technologies application in school buildings.	- Minimum overload capacity 200 kg/m² - Overload capacity for green-roofs 490 kg/m² - Acceptable slope 2-5% - Accessible through staircases - Free of all mechanical fixings - Rainwater collection, heat and CO₂ control	- Lettuce	Land planning policies do not consider UA in their regulatory frameworks; and as such, there are no guidelines on its implementation nor its suitability.
[133]	Illustration and systemization present practices of ZFarming and discussion of specific novelties of ZFarming in the wider context of urban agriculture (UA).	Building uses combined with ZFarming e.g. health, transportation facilities, industry/warehouse, mixed-use, retail, community services, office, housing, farming-related food business, reserach/education, hotel/restaurant	No specific crops mentioned	Specific challenges are: - Suitability of the building: size of available space for growing and other activities, weight-bearing capacity, accessibility, logistics and infrastructure (e.g., freight elevator, water, energy), and the need for retrofitting; - Zoning and building regulations, permission processes: floor-to-area ratios, maximum allowable building heights, commercial farming as urban land-use, fire and energy codes, etc.; - Support by landlords - Financing - Technical issues
[56]	Potential of urban agriculture (UA) in Magdeburg, Germany.	- Urban organic agriculture system - Aquaponics	- Lettuce and herbs - Fish	- There are too few sustainable, organic and local urban food products on the market yet. - The needed energy for modern urban farming projects is still high in climate areas like the north of Germany. - The greatest challenges for a planned agricultural measure on a fallow land are the legacy of the area.
[134]	Vegetable production on green roofs.	- Biodiversity/Habitat - Growing Substrate - Irrigation Efficiency - Maintenance Activities - Nutrient Management	- Lettuce - Kale and radish - Tomato - Bean - Cucumber	- Reducing installation costs, large-scale assessments of weight load limitations for numerous buildings, and improvement of numerous management practices to ensure that the benefits of green

		- Pest Control - Plant Materials - Pollination Systems - Water Management	- Pepper - Basil, - Chive	roofs, such as energy savings and storm water management, are still provided to urban communities - Little information on how to best optimize yield of these crops in a green roof environment
[135]	High-technology and conventional farming systems for urban agriculture in Singapore. Comparison of production level and resource-use efficiency of 3 urban farming systems.	- Greenhouse construction - Maintenance of shipping container/indoor facilities - On-panel airflow ducts Growing channels LED boards - Work light - Supporting frames Supporting tracks - Circulation pump - Peristaltic dosing pump - Plumbing - Gutters - Growing medium Water - Electricity - N fertilizer - P fertilizer - K fertilizer - Ca fertilizer - Mg fertilizer	- Lettuce	- Compact indoor farms spent >100 times energy than Vnat given the same investment - Traditional farms could be established fast but exhausted the land allocated easily. - Local indoor farming had higher GWP than importing (2.51 kg CO₂-eq per FU) - Soil-based farming would have the highest water usage - Given that vertical farming would require more infrastructural support, the water and energy use in the manufacturing of the infrastructure may offset the water-saving benefit of vertical farming. - The current high energy and infrastructural costs of indoor farms have also resulted in a high per unit vegetable price to cover the cost of production, and therefore most indoor farms in Singapore are producing higher-value crops for the local market.
[49]	LED-integrated vertical aeroponic farming (VAF). System that can be used both indoors and in greenhouses, for vegetable production.	LED light	- Lettuce - Chinese broccoli - Chinese broccoli (<i>Brassica alboglabra</i>) - Nai Bai (<i>Brassica chinensis</i>) - Mizuna (<i>Brassica juncea</i> var. <i>japonica</i>) - Culinary herbs, such as red and green Chinese basil (<i>Perilla frutescens</i>), and sweet basil (<i>Ocimum basilicum</i>)	No access to the full publication, only to the abstract

[50]	LED-integrated vertical aeroponic farming (VAF).	- Cooling the plant roots - Root-zone CO₂ - Nutrient spraying	- Different leafy vegetables - Lettuce - Tuscan kale	Not discussed/mentioned
[54]	Technology innovations in urban farming, processing technology to reduce food wastage and spoilage, and alternative food sources that Singapore has adopted in addressing the rising challenge of food security.	Urban farming (UF), vertical farming (VF), Aquaponics and IoT Processing technology - Food waste valorisation - Biodegradable packaging - Natural preservatives Alternative food sources - Smart packaging with nanotechnology - Insect farming - Microalgae culture - Cultivated meat	- Water spinach - Different types of lettuce - Mints - Nile tilapia (<i>Oreochromis</i>)	- VF energy consumption, which is closely related to carbon footprint - VF artificial lighting would need to be supplemented which translates into higher capital and energy cost. - Aquaponics is difficult to sustain due to several factors such as temperature control, lack of sunlight, excessive wind and moisture of air - The main challenge for commercial aquaponics is to overcome its multi-disciplinarity, since it requires expertise from environmental, civil, mechanical engineering as well as knowledge in biochemistry, biotechnology, aquatic biology, process control, economics, finance and marketing - Pest and disease control is another challenging aspect of aquaponics - Aquaponics challenge of finding the perfect fish-plant couple where the nutrient profile provided by the fish excreta and the nutrients required by the plants overlaps significantly
[136]	Demonstrate the significance of urban horticulture, combined with new technologies to meet the needs of people in urban settings.	- Control of environmental pollution and waste management - Improvement of climate and microclimate - Conservation of biodiversity - Home gardening - Community gardens - Urban edible horticulture landscape - Living edible wall or vertical gardening - Rooftop gardens and greenhouses - Hydroponics - Aquaponics - Organoponics	- Vegetables (beans, tomatoes, lettuce, okra, eggplant, kale, carrots) - Fruits (Papaya, pineapple, avocado, guava, coconut) - Cabbages, ginger, chilies, pineapples, and mangoes - White cabbages, grapes, and apples - Dark green vegetables and fruit trees (according to climate and cultural practices)	Not discussed/mentioned

			- Vegetables (according to climate and consumer preferences) - Strawberries	
[137]	Comprehensive review of the concept of urban smart vertical farming (USVF) using various techniques to enhance productivity as well as its types, topologies, technologies, control systems, social acceptance, and benefits.	- Soil types - Lighting - Solar PV - (IoT)-Sensors and actors in USVF - IoT smart farming framework - IoT supported hardware controller board utilized in smart farming	No specific mentioned	- High starting cost - Low yield variability - Energy reliance and utilization - Producing heat by artificial lighting - Equipment location, space, and environmental issues - Form and dimensions of the increasing installation - Spacing between plants - Lighting systems should be evaluated for their heat management characteristics and configured to mitigate the warmth generated - Dirt and microorganisms from employees, environmental hazards in the nutrient medium, water cleanliness and protection - Post-farm handling activities such as sorting, trimming, and transportation
[138]	Review on the possibilities to utilize vacant urban spaces as efficiently as possible for urban agriculture. Demonstration of the possibilities for urban vegetable cultivation, technologies which still need to be developed, and their importance in sustainably guaranteeing food security in cities in the future.	Traditional growing systems - Home gardening - Community gardening - Continuous productive urban landscapes Innovative cropping systems - Soilless cultures - Organoponics Indoor farming systems - Building integrated agriculture - Vertical farming	No specific mentioned	- Resource efficiency of indoor farming systems, they are still very expensive - Vegetable species are out of season. Their production might need more energy than shipping produce from a country with more favorable growing conditions - Shifting the production to areas with less favorable growing conditions could increase the amount of fertilizer needed - Urban horticulture is not suitable for every area due to risks of contamination
[139]	Evaluation of the claims, possibilities,	- LED - Air conditioning - Solar panels - Water supply (recycling, grey water)	- Lettuce - Strawberries - Tomatoes - Grain	Vertical farming, limited range of crops suitable for this business model (originally mostly vegetables such as lettuce, strawberries, and tomatoes), together with the small proportion of

	and limitations of vertical farming and related food production models.		- Grape and tree fruit	the population that could be serviced and the expensive energy requirements.
[21] and [140]	High-tech vertical farming systems and sustainable benefits of the vertical farm (environmental, social and economic benefits)	"Computerized and monitoring systems; Cell phones, laptops, and tablets; Food growing apps; Remote control systems and software (farming-from-afar systems); Automated racking, stacking systems, moving belts, and tall towers; Programmable LED lighting systems; Renewable energy applications (solar panels, wind turbines, geothermal, etc.); Closed-loop systems, anaerobic digesters; Programmable nutrient systems; Climate control, HVAC systems; Water recirculating and recycling systems; Rainwater collectors; Insect-killing systems; Robots"	No specific mentioned	- Need for more developments that scale up projects so that the economic and commercial feasibility and return on investment (ROI) are offered at best rates. - Need to investigate the full life-cycle analysis (LCA) and the number of years to reach parity with a traditional farm. - Success of the vertical farm will depend not only on innovation in technologies but also on local conditions including demand on certain produce by population, availability of labors, and farming conditions. - Robust and resilient business models are needed. - Required technologies and technical expertise needed to implement the vertical farm in developing countries. - Economic feasibility, codes, regulations, and a lack of expertise.
[141]	Greenhouses and high technology vertical farming	- LED lamps - Purification of water - Fish farming - Artificial illumination - Robotic harvesting - Evaporation and recycling systems - 'SlurryCarb' machine (EnerTech) alternative power system	- Lettuce - Strawberries	Not discussed/mentioned
[142]	Establishes a multi-criteria decision-making (MCDM) framework to assess the VF systems.	Ambient light, temperature, humidity, CO2 concentration, water, and nutrients, can be manipulated to speed up the growth process to grow more fresh food	No specific mentioned	- The investment cost for a VF is still a challenging issue for entrepreneurs and municipalities. - Immature technology - High upfront cost - Limited crop types
[143]	Soilless systems' for home and community gardens	- Nutrient solutions (commercial hydro-soluble fertilizers)	- Tomato - Okra	To match yield and quality improvement and water use efficiency, and the possible future

		- Soilless systems (Garrafas and Caixa) - Garrafas is based on a wood structure and based on gravity flow - Tank of about 300 litres volume - Hydraulic pipes		developments. For tomato, it will be important to solve the problems linked to the reduced fruit-setting.
[144]	New architectural typologies designed to support urban farming.	- Fully automated mobile greenhouse - Automated heating, cooling, and ventilation systems as well as a four-zone irrigation system. - Container farm	No specific mentioned	No specific mentioned

Objective: Food demand and local food supply chains



Figure A 4 Word cloud of the for the data set of 25 papers, min.freq = 10. objective: Food demand and local food supply chains

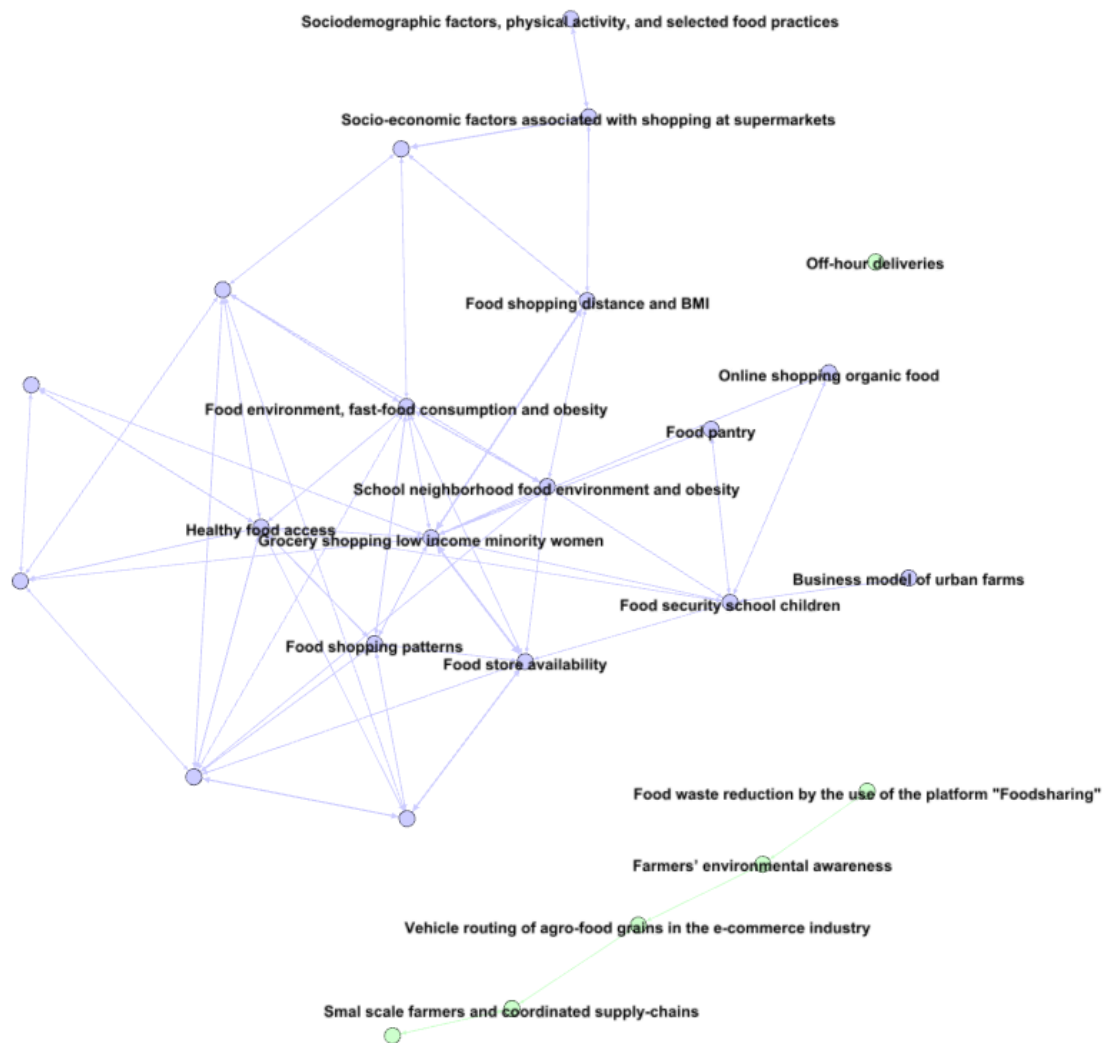


Figure A 5 Network graph of the selected papers for the objective: Food demand and local food supply chains, data set of 25 papers

Table A 5 Detailed overview of the publications studied for the objective: Food demand and local food supply chains

Reference	Focus topics	Methods	Main Findings
[58]	Identification of the profile of a typical online grocery shopper and mapping of factors that possibly influence consumers' decision to shop organic food online.	- Survey with a total of 757 responses - Statistiscal analysis of the survey data	- The frequency of online grocery shopping increases significantly with increasing education and income and decreases with increasing the number of household members. - Most shop for groceries online because of time savings, better product choice and more convenient and easier search. - 80.58% of the surveyed sample of customers buy organic food online. - Most respondents shop for groceries online in order to save time, have a wider choice of products and due to more convenient and easier searching. - The proportion of respondents shopping for groceries online is not significantly related to gender. - The higher the respondents' net monthly income, the more often they buy organic food online.
[59]	Individuals' food shopping behavior and activity within the retail food environment	- Cross-sectional survey among adults (n=121) age 18 years and over to assess demographics, food shopping behaviors, and dietary outcomes. - Food store audits using the Nutrition Environment Measurement Survey-Store Rudd (NEMS-S) in stores where respondents reported purchasing food (n=22). - Multivariate logistic regression to examine associations between six dietary variables with food venue availability within activity space; food venue choice; frequency of shopping; and availability of food within food venue.	1) Food venue availability within activity space – no significant associations. 2) Food Venue Choice – Shopping at farmers' markets or specialty grocery stores reported higher odds of consuming fruits and vegetables. - Frequency of shopping - Shopping at a farmers' markets and specialty stores at least once a week reported higher odds of consumption of fruits and vegetables. - Shopping frequently at a super market had higher odds of consuming sugar-sweetened beverages. 3) Availability of food within store – those who shop in supermarkets with high availability of healthy food has lower odds of consuming sugar-sweetened beverages.
[60]	Multivariate analysis of the availability of food store outlets in the US and associations with neighborhood characteristics on race, ethnicity and socioeconomic status (SES)	Commercial food store outlet data are linked across 28,050 zip codes to Census 2000 data.	- Low-income neighborhoods have fewer chain supermarkets with only 75% ($p<0.01$) of that available in middle-income neighborhoods. - Non-chain supermarkets and grocery stores are more prevalent in low-income and minority neighborhoods. - The results found herein support the underlying premise of previous studies that have reported that low-income households face higher food prices in large part as a result of a lack of supermarket availability in their neighborhoods.

[61]	Examine the variability in grocery shopping patterns, and the factors that predict them, among low-income minority women in public housing.	Questionnaire	- Considerable variability in grocery shopping patterns, including the types of grocery stores accessed, distance travelled, frequency of shopping, and reasons behind grocery store choice. - Initiatives to improve the neighborhood food environment should consider quality of food, cultural factors, and availability of foods desired by the surrounding community, in addition to price and proximity of grocery stores. - Reason for choosing grocery store, the most common reasons were price (34.2%), convenience of location (32.5%), quality of food (21.3%), choice of items (7.2%), cleanliness (3.2%), customer service (1.7%). - As distance to primary grocery store increased, the percentage of participants who shopped for quality of food increased and the percentage who shopped for convenience of location decreased. - Almost half of those who travelled four or more miles cited quality of food as their main reason for choosing a location (47.3%), compared to 13.9% of those who traveled less than one mile.
[62]	Investigatin whether geographical location or store type was associated with healthy and unhealthy food availability in grocery stores.	- A cross-sectional study using the Victorian Healthy Food Basket to measure food availability in a convenience sample of 112 stores in urban and regional Victoria, Australia. - Logistic regression analyses assessed whether location (regional, urban), distance from capital city central business district (km) and type of store (chain supermarket, independent supermarket and general store) predicted the number of missing healthy and unhealthy food items.	- Store type was a stronger predictor of stores having missing ‘healthy’ and ‘unhealthy’ food items than the store distance from a large urban centre. - General stores and independent supermarkets may be important settings for interventions to improve availability of healthy food. - General stores have lower odds of stocking all healthy items in a food basket, followed by independent supermarkets, compared with chain supermarkets, irrespective of location.
[63]	Characterization of the local food environment in New York City’s Washington Heights and Inwood community and to examine its influence on Hispanics’ perceptions of healthy food access.	- Survey via face-to-face interview in the participant’s language of choice. - Data from indtsutry data base, information extracted was company name, address, location type (single location or branch), franchise description, employee size, location square footage, and North American Industry Classification System (NAICS) codes and descriptions.	- The majority of the urban Hispanic participants have access to fruit/vegetable markets and smallsize and medium-/large-size supermarkets/groceries in their respective 400-m and 800-m residential radii. - The presence of medium-/large-size supermarkets/groceries within 400-m radius buffer significantly increased participants’ odds of perceiving that the fresh fruits and vegetables in the neighborhood are of high quality. - Presence of medium-/largesize supermarkets/groceries in both the 400-m and 800-m residential radii significantly increased participants’ odds of

		- Additional view of the locations on the web and site visits to establish “ground truth” of the retail food outlets. - Modelling of person-level local food environment, by calculating the 400-m and 800-m distances from the center of the participant’s geocoded residential address to the center of the food retailer’s geocoded location address. - Geocoding and spatial modeling were performed using ArcGIS 10.1 (ESRI, Redlands, CA).	perceiving that a large selection of low-fat products is available in the neighborhood. - The presence of small-size supermarkets/groceries, which accounted for 71% of the food environment landscape assessed in our study, did not have much influence on the participants’ perception of the availability and selection of fresh fruits and vegetables or low-fat products in the neighborhood.
[64]	Investigation of the association between neighborhood-level economic hardship, the retail food environment, fast food consumption, and obesity prevalence.	Linking data from the population-based Survey of the Health of Wisconsin and a commercially available business database.	This study indicates that neighborhood-level economic hardship is associated with an unfavorable retail food environment.
[65]	- Relationship between the population-weighted mean distances to supermarket - Associations of obesity and fruit and vegetable consumption with distance to supermarket in metropolitan and nonmetropolitan areas.	- 2006 Census Zip Code Business Patterns data to compute population-weighted mean distance to supermarket at the county level for different sizes of supermarket. - GIS for the calculation of distance and creation of the maps	- Distance to supermarket was greater in nonmetropolitan than in metropolitan areas. - The odds of obesity increased and odds of consuming fruit and vegetables (F/V) five times or more per day decreased as distance to supermarket increased in metropolitan areas for most store size categories. - In nonmetropolitan areas, distance to supermarket had no associations with obesity or F/V consumption for all supermarket size categories. - Obesity prevalence increased and F/V consumption decreased with increasing distance to supermarket in metropolitan areas, but not in nonmetropolitan areas. - Obesity and food environments in nonmetropolitan areas are likely driven by a more complex set of social, cultural, and physical factors than a single measure of supermarket accessibility.
[66]	Measure of food environment quality that characterizes urban neighborhoods by the relative amounts of healthy (e.g. fruits and vegetables) to	- Data from 307 food stores and 1243 telephone interviews. - Multilevel modeling to calculate the associations between individual, household and neighborhood food environment characteristics and obesity prevalence.	- Higher quality food environments – but not food store types – decrease the risk of obesity and overweight. - Need to move beyond a sole consideration of food store types to a more nuanced view of the food environment when planning for change.

	unhealthy foods (e.g. energy-dense snacks).		
[67]	Examine the association and variation of school neighborhood food environment and obesity across gender and urbanicity at multiple geographic scales.	- US nationally representative Early Childhood Longitudinal Study - Census, road network, and Dun and Bradstreet commercial datasets were used to construct time-varying measurements of 11 types of food outlet within 800-m straight-line and road-network buffer zones of schools and school ZIP codes, including supermarket, convenience store, full-service restaurant, fast-food restaurant, retail bakery, dairy product store, health/dietetic food store, candy store, fruit/vegetable market, meat/fish market, and beverage store. - Two-level mixed-effect and clusterrobust logistic regression models were performed to examine the association.	- A higher body mass index (BMI) in 2007 was observed among children experiencing an increase of convenience stores in school neighborhoods. - The higher obesity risk was associated with the increase of fast-food restaurants in urban schoolchildren and of convenience stores in girls and non-urban schoolchildren. - The increase of full-service restaurants was related to lower obesity risk in boys. - The decrease of dairy product stores was associated with the higher obesity risk, especially boys and urban schoolchildren. - The schoolchildren exposed to the decrease of meat/fish markets showed the lower obesity risk, especially urban schoolchildren. - Results from analyses within 800-m straight-line buffer zones of schools were more consistent with the theory-based hypotheses than those from analyses within 800-m road-network buffer zones of schools and school ZIP codes.
[68]	Relationship between community characteristics and household food security status among elementary school children in Wisconsin	- Self-administered survey of parents of elementary school children (8396 households). - Food security was measured with the standard 6-item Food Security Scale.	- Higher local housing costs, lack of access to public and private transportation, very low proximity to supermarkets and grocery stores, and living in a more urban area all significantly increased the risk of household food insecurity. - No significant relationship between median rent, access to public transportation, or proximity to supermarkets and the rate of food insecurity. - Significant differences by urbanicity, with the highest food insecurity in primarily urban areas. - The higher the median rent, the greater the risk of food insecurity, with a \$100 increase in median rent associated with a 21% increase in the odds of food insecurity. - Having access to public transportation reduces the odds of food insecurity by 32% ($P < .01$). Living more than 15 miles from a supermarket or grocery store increased the odds of food insecurity by 67% ($P < .01$), with no significant differences in food security at closer distances.
[69]	Influence of local food environments on the food provided in family child care homes and the impact on healthy food.	- Cross-sectional data from a mail survey of food environments around family child care homes (FCCHs) providers, InfoUSA.	- Rural FCCHs with higher counts of supermarkets, convenience stores, and produce stores had lower compliance with selected best practices (fried/prefried potatoes, high-sugar/high-fat foods). - Urban FCCHs with more supermarkets had higher compliance with fruit not canned in syrup; those with more small-medium grocery stores and

		- Logistic regression estimated associations between best-practice compliance and food environment. - Linear regression estimated associations between composite food healthfulness and food environment.	convenience stores had lower compliance with selected best practices (fried/prefried potatoes, vegetables, low-fat meats).
[70]	Neighborhood food environment and food acquisition behavior and the links to food pantry use.	- Survey and statistical data - Two models are use - Base model contained food and nutrition-related variables that had significant binary association with food pantry use. - Second model was a socioeconomic-adjusted model including additional variables for age, sex, race/ethnicity, marital status, the number of children at home, employment status, and education.	- Hispanic whites were the largest racial/ethnic group (47.3%), followed by non-Hispanic Blacks (26.6%). - 21.8% were food pantry users. - Significant ($p < .05$) differences in distributions of socioeconomic characteristics between food pantry users and non-users. - Food pantry users had higher proportions of those who were not working (71.9% vs 54.4%), not married (71.8% vs 67.1%), non-Hispanic Black (40.9% vs 22.6%), and having a minor child at home (41.3% vs 34.3%) compared with food pantry non-users. - Food pantry uses were younger compared with non-users (mean age: 44.5 years vs 46.1 years).
[71]	- Investigation of two diet related health programs. - Social practice theory (SPT) to investigate how the introduction of local food and slow cookers altered low-income individuals' food provisioning practices.	- Community-based participatory research (CBPR) method photovoice. - Photovoice is a qualitative research method that enables participants to document and investigate their experiences through photography, discussion, and storytelling.	- The programs built participants' food-related competences, cultivated relationships between fellow participants and farmers/ suppliers of local food, and increased consumption of healthy, locally produced foods. - Practitioners and policymakers should utilize the insights of SPT to design more effective nutrition programs that not only lower barriers of accessibility and affordability, and also address the "complex architecture of factors" (i.e., cultural norms and habits, social and economic policies, and systems of provisioning) that impede adopting healthier and more sustainable diets. - Offering useful cooking equipment, technologies, recipes, lessons, and other materials and competences helps facilitate the adoption of alternative food practices. - Without adequate financial resources to purchase more costly items, low-income carriers of alternative food practices may have no choice but to substitute cheaper foods into their diets, despite having acquired new food-related competences and meanings through their participation in communitybased nutrition programming.
[72]	Identification of the social missions of urban farms.	- Data collected from a 2012 national survey of urban farmers in the USA. - 35 questions, covering the 2012 farm year, targeted production and marketing practices,	- Food production is an essential part of the mission for all urban farms. - Some farms have social missions, as well, which the survey results indicate are related to food security, education, and community building.

		risks and challenges, information and technical assistance needs, farm size and location, age of primary farmer, and farm characteristics. - Multinomial logistic model to analyze the social missions of urban farms in the sample.	- All urban farms, regardless of their mission, are relatively small and face similar challenges in terms of providing the primary farmer with a living. - Farms with explicit social missions, relative to those with a strict market orientation, donate a higher share of food from their farm and are less likely to own farmland. - Urban farms located in with lower median income are more likely to have social goals related to building community or improving security food security.
[73]	- Explore food acquisition and shopping habits using multidimensional measures and examine its association with body mass index (BMI). - Identify distinct patterns in food acquisition and shopping habits in a nationally representative sample. - Examine whether socioeconomic status (SES), nutritional factors, and reasons underlying store choice were associated with the identified patterns. - Evaluate the association between the identified patterns and obesity.	- 4466 households from the US Food Acquisition and Purchase Survey during April 2012 to January 2013 were included in this analysis. - Latent class analysis was used to identify the latent profiles using travel distance and perceived travel time between residential location and primary store, store type, transportation mode, and farmers' market utilization. - Multivariable linear regression and multinomial logistic regression were used to assess the association between the identified patterns and continuous and categorical BMI.	- 65% (weighted percentage) of households were located in an urban tract. - 37% were categorized as Class 1 (households that shopped more proximally, used their own vehicle, and shopped at a farmers' market) - 50% as Class 2 (households that shopped more distally, used their own vehicle, and shopped at a farmers' market) - 14% as Class 3 (households that shopped proximally but perceived longer travel time, used someone else's vehicle, and did not shop at a farmers' market). - Among rural households, 54% were Class 1 and 46% were Class 2 (Class 3 was not identified) - Food shopping distance, perceived travel time to the primary store, and transportation mode to the primary store were the key factors that defined distinct acquisition and shopping patterns for both urban and rural populations. - No significant association was found between the identified patterns and BMI. - Food acquisition and shopping patterns were not associated with BMI in this national sample.
[74]	Analysis of use of supermarkets according to socioeconomic characteristic and diet quality index-international (DQI-I) according to supermarket use.	- 724 households were selected by a 2-stage clustered random sampling - Questionnaire to assess food retail habits - Socioeconomic data were collected at individual and household levels - Data analysis by regression or logistic regression models adjusted for energy intake and socioeconomic confounders when relevant	- 60% of the households used supermarkets - Most households still used the nearby grocer - Only 26% shopped at the market - Characteristics associated with supermarket use were urban milieu, small-sized households, greater educational attainment, higher economic level, steady income, or easy access.
[75]	- Examine the socio-economic characteristics and motivations of shoppers using different	- Cross-sectional survey (2006) - Clustered random sample of 724 households	Transition in food shopping practices in a south Mediterranean country; should be considered in the context of growing inequalities in health linked to the nutritional transition, as they differentiate use and motivations for the

	retail formats (large supermarkets (LSM), medium-sized supermarkets (MSM) or traditional outlets) in Tunisia. - Examine the socio-economic characteristics of shoppers using different retail formats in Tunisia, and their motivations for doing so.	- Socio-economic status, type of food retailer and motivations data were collected during house visits. - Associations between socio-economic factors and type of retailer were assessed by multinomial regression; correspondence analysis was used to analyse declared motivations.	choice of supermarkets v. traditional food retailers according to socio-economic status.
[76]	Examine the association between sociodemographic factors, Physical Activity (PA) engagement, and the selected Food Purchasing Practices (FPP) among people living in a low socioeconomic peri-urban and rural area of two provinces of South Africa.	- 400 participants were randomly selected from two communities, a township in Cape Town and a rural community in the Eastern Cape. - Data collected included socio-demographic characteristics, FPP and PA. - Logistic regressions were performed to identify the associations between sociodemographic factors, PA involvement and selected FPP, and Odds Ratios (OR) were calculated with 95% Confidence Intervals (CIs).	- Compared to participants aged ≥ 55 years, those within the age range of 25-54 years were more likely to travel with motorised transport compared to walking to grocery shop. - None-to-low education and with monthly income of $< R2000$ were more likely to purchase groceries at the supermarkets and compared to spaza or small informal food shop, respectively, while those who engage in PA were less likely to purchase groceries at the supermarkets. - Some demographic factors and PA have an influence on FPP among people living in a low socioeconomic peri-urban and rural area of two provinces of South Africa. - This might be an area to be focused on for public health interventions which could be directed at supporting adequate FPP among people, especially in low socio-economic areas.
[82]	Understanding of the diffusion dynamics of bottom-up innovations like “Foodsharing”	- Data of the development of “Foodsharing” registrations 2012–2016, data provided by the platform - Visualization of “Foodsharing” density and zip codes - Calculation on the correlation between “Foodsharing” rate and population density (2012–2016)	- The diffusion of “Foodsharing” shows spatial barriers between rural and urban areas, which can be interpreted as varied requirements of local supply chains. - The connection between “Foodsharing” quota and milieu-specific sociodemographic characteristics could be proven, and they seem to have a high explanation potential with regard to “Foodsharing” occurrence. - The results confirm the classification of “Foodsharing” as a niche innovation. - What until now has made the further development and diffusion of “Foodsharing” possible as a protective niche now seems to represent a barrier. - If “Foodsharing” is supported by certain milieus and their social networks, it is limiting its spatial distribution.

[81]	Ways to motivate farmers to participate in sustainable agriculture.	- Data from semi-structured interviews of 98 households using participatory rural appraisal methods. - Logistic regression models were used to explore factors that underlie farmers' attitudes towards agricultural production and their environmental awareness.	- Low agricultural economic efficiency could result in less enthusiasm for agriculture among local farmers. - This is a potential risk for China's food security and sustainable agricultural development. - Poor rural labour quality implied a lack of local participation in sustainable agriculture. - Suggestions for sustainable agricultural development include establishment of a reasonable market and agricultural subsidy mechanisms, basic and vocational education for young adults, effective agricultural instruction and environmental education agencies and two-way communication mechanisms.
[80]	- Trends in food markets - Coordinated supply chains - Incentives for investing in coordinated supply chains - Small-scale farmers and participation in coordinated supply chains - Possible policy interventions	No statement to the methods	- Important weaknesses of small-scale farmers are lack of knowledge about modern markets, modern technology and proper use of modern inputs. - Access to capital can be an obstacle for upgrading from production for direct consumption and local markets, rather than to more demanding markets. - Working with small-scale farmers is difficult for trading and processing companies. - Quantities of product are small and heterogeneous in quality, supply can be haphazard and bulking-up of volume into a steady stream of product of constant quality difficult to realize. - Benefits of working with small-scale producers in coordinated supply chains will be highest for labor-intensive products.
[79]	Documentary and empirical research addressing the main problems periurban farmers are facing in relation to local food distribution.	Questionnaire with a representative group of farmers from each region in three towns presenting different demographic sizes along with another questionnaire extended to the owners of small grocery stores, who play a vital role in the supply of fresh food in these municipalities.	- Among other factors, these refer to regulatory barriers, logistics, competition and dealing with consumers' preferences. - Most of the problems arising when dealing with short food supply chains (SFSCS) can be solved by introducing new forms of cooperation among the different agents of the food chain.
[78]	Acceptance of off-hour deliveries	Multi Actor Multi Criteria Analysis (MAMCA) as tool for measuring support for urban off-hour deliveries and describes the application of this methodology to a case study of a large food retailer in Brussels.	- A shift to off-hour deliveries to supermarkets should receive overall support because there are no scenarios that score very high for one stakeholder and very low for another and the scenarios that envision a high proportion of night deliveries receive a high score. - The retailer prefers a scenario with an even delivery distribution throughout the day, while the other two stakeholders prefer more morning deliveries.

[77]	- First-mile pickup and last-mile delivery logistics problem, where agro-food grains are available at multiple farmer's locations and are in demand by businesses like e-retailers, supermarkets, grocery shops, restaurants, hotels, etc. - Sustainable framework for agro-food grains supply chain (AFGSC) in urban and rural areas for e-commerce in developing countries.	- Optimisation model considers costs related to first-mile pickup, transportation with last-mile delivery, carbon emission tax, inventory holding, vehicle and food damage due to accidents, and penalties on late pickup and delivery. - The model also takes environmental and social (due to accidents) sustainability aspects into consideration, along with the economic aspects of sustainability.	- The most vital, but the most neglected part of delivery operations, is that accidents may occur to vehicles while delivering agro-food grains. - If computational time is considered there is a trade-off between computational time and the optimal cost. - Advanced particle swarmoptimisation always computes faster than any other algorithm.
------	--	---	---

Objective: Spatial system dynamics

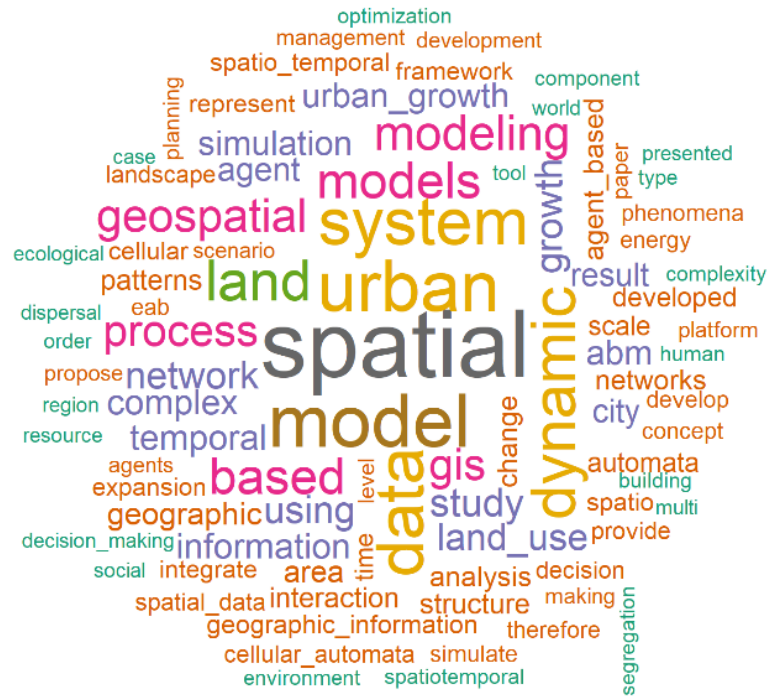


Figure A 6 Word cloud of the for the data set of 35 papers, min.freq = 10. objective: Spatial system dynamics

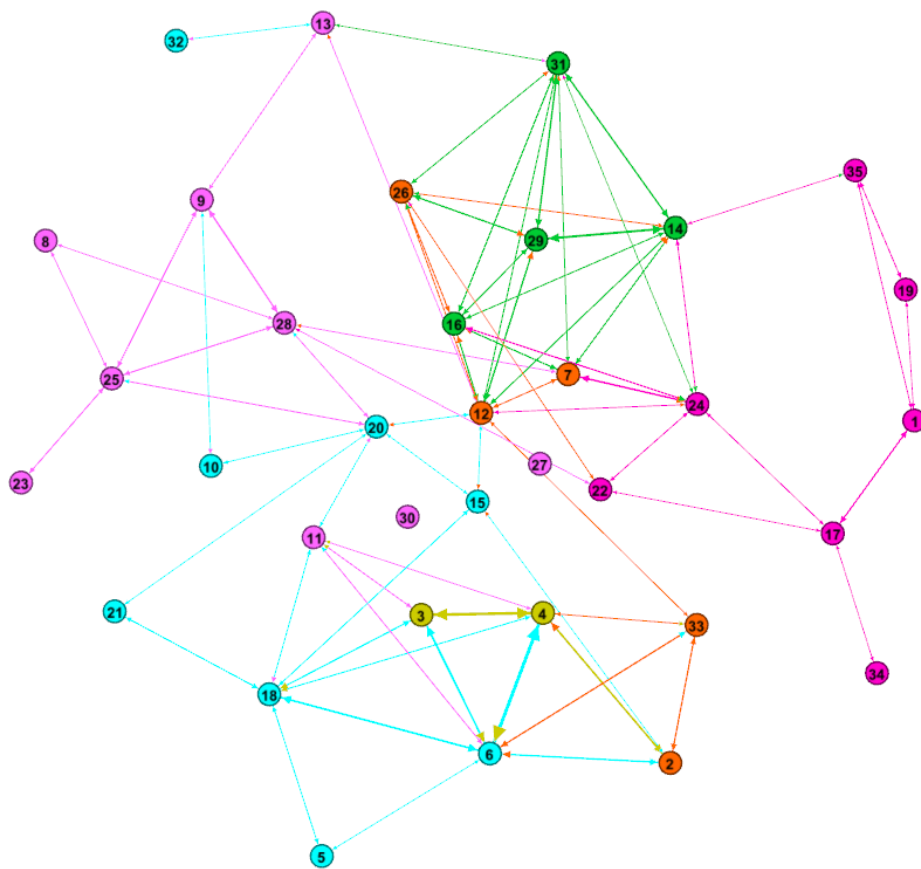


Figure A 7 Network graph of the selected papers for the objective: Spatial system dynamics, data set of 25s papers

Table A 6 Detailed overview of the publications studied for objective: Spatial system dynamics

Reference	Focus topics	Methods	Main Findings
[92]	Modeling framework of Geographic Network Automata (GNA)	- GIS, multi-criteria evaluation (MCE), and cellular automata (CA) are used to model emerald ash borer (EAB) spread across different hypothetical landscape types. - Proposed GNA modeling framework is implemented on the case study of the invasive bark beetle. - Use of iterative application of generative rules to represent the addition, loss, and rewiring of nodes over space and time as a function of the phenomena's dynamics.	The flexibility of the generative rules in the GNA approach facilitates the representation of long-distance connections or "hopping" over adjacent suitable nodes, useful for representing ecological species that exhibit this particular dispersal pattern.
[145]	Spatial modelling framework, Geographic Network Automata (GNA), to represent evolving spatial networks as a function of iteratively applied transition rules.	The explicitly spatial Game of Life phenomenon is used for the implementation of the GNA modeling framework.	- The model is highly sensitive to both the distance by which the neighborhood is defined and the values that were selected for each of the generative rules. - The GNA framework could be considered as a relaxed extension to the CA framework, equipped with a well-defined toolkit for model analysis. - GNA framework situates well within the larger framework of the geographic automata systems. - The GNA framework can also be considered as a simplified extension of a network-based agent-based model (ABM).
[146]	Network agent based modeling (N-ABM) that combines network and complex systems theory to simulate complex evolving spatial networks.	N-ABM approach is implemented on the case study of the emerald ash borer (EAB) bark beetle using geospatial datasets in Ontario, Canada. The N-ABM generates dynamic spatial network structures that emerge from interactions between the EAB and tree agents at the individual scale.	The N-ABM approach can be used to represent dynamic ecological networks and provides insight into how network structure emerges from EAB dispersal dynamics, useful for forest management.
[89]	- Develop a geosimulation approach to overcome the challenge of data scarcity and represent EAB infestation at a regional scale.	- Geographic information systems (GIS), multi-criteria evaluation (MCE), and cellular automata (CA) are used to model EAB spread across different hypothetical landscape types.	- The proposed EAB-CA model framework is useful by representing insect infestation from the bottom-up even in representing a phenomenon that lacks empirical data. - The model simulates local pest-host dynamics using readily available biological information obtained from field and lab

	- Explore the use of cellular automata to develop a geosimulation modeling framework capable of capturing complex emergent spatiotemporal behavior of EAB spread at the regional scale with the challenge of data scarcity.	- Use of geospatial datasets to create hypothetical landscapes for Windsor, Ontario, Canada in the year 2002.	studies that determine which factors influence ash tree susceptibility.
[147]	Develop and implement a validation approach called the NEtworks for ABM Testing (NEAT) that integrates geographic information science, ABM approaches, and spatial network representations to simulate complex systems as measurable and dynamic spatial networks.	Simulated spatial network structures are measured using graph theory and compared with empirical regularities of observed real networks.	-The NEAT approach can validate whether the internal model processes are represented realistically, thus better enabling the use of ABMs in decision-making processes. - The NEAT approach is a good fit for testing ABMs that contain internal processes that are based on interactions, relationships, dynamics, and flows between sets of system components. - The study of spatial and non-spatial social relationships between individuals is also an ideal application for the NEAT approach.
[93]	Implement a spatially-explicit ABM that simulates the dynamics of residential segregation of incoming immigrant populations.	Use of actual geospatial and demographic data in order to represent the socio-demographic profiles and the urban features of each study area realistically.	The research has the potential to contribute to policy-planning and decision-making by assisting city planners and policymakers in mitigating persistent residential segregation.
[90]	Develop a hybrid model that combines swarm intelligence (SI), agent-based modeling (ABM) and cellular automata (CA) with geographic information systems (GIS) for simulating tree mortality patterns introduced by insect infestations at a landscape spatial scale.	GIS serves as a tool to store, process and display the geographic environment as well as to visualize the dynamic changes of the forest environment over time.	- Coupling the outcomes of the Forest-SimMPB model at a tree scale with the GIS-based CA model to simulate the forest disturbance phenomenon at a landscape scale made it possible to address the problems of computation time when simulating larger geographic areas. - The model is sensitive to the changes in the neighborhood size, while no significant changes were observed from changes in the CA transition function weights.
[148]	A software systems approach to scale-free, multi-format, integrated modelling of evolving cross-domain utility infrastructure network topologies, and the analysis of the spatiotemporal dynamics of their resource flows. GIS-BIM integration.	- The system uses a graph database to integrate the topology of utility network components represented in the CityGML UtilityNetwork Application Domain Extension (ADE), Industry Foundation Classes (IFC) and JavaScript Object Notation (JSON) real-time streaming messages.	- A graph representation enables a more flexible approach to integrating the topologies derived from diverse datasets, without reliance on existing schemas and their overlapping concepts, and which is able to represent dynamics such as resource flows. - Continuation research should focus on associating data feeds with entities that are derived from other data streams and model instances, scaling the capability to multiple buildings

		- A message broker is used to disseminate the changing state of the integrated topology and the dynamic resource flows derived from the streaming data.	and distributions networks, applying the approach to other types of utility resources and their interdependencies, devising a spatial method for matching entities across data sources, and testing the operational robustness of the approach to a range of use cases.
[94]	- Spatial explicit epidemiologic model of flu to understand the disease's spatial diffusion through a network of human contacts. - Agent-based modeling (ABM) approach that integrates geographic information system (GIS) to simulate the spread of influenza in an urban environment, as a result of individuals' interactions in a geospatial context.	- Geo-referenced GIS layers of an urban area as the environment where typical agents' contact takes place. - Road network layer, block layer and urban boundary layer. - ArcGIS 9.2 was used to vector quantize the map and extract the road layer, the block layer and the boundary layer.	- The results of disease propagation simulation indicate that the model is very successfully able to generate various scenarios of an outbreak in realistic geographic urban settings by incorporating movement in the agent entities. - The model presented is a prototype that can be used as a laboratory to test possible outcomes under an infectious disease outbreak at city-scale and with different model parameter setup. - The outcomes of the model simulations allow stating the importance of achieving sufficient knowledge about the spatial interactions of individuals and their contact networks.
[98]	Validation techniques and challenges of Agent-based modeling (ABM) validation.	Description of the following validation methods: - Structural validation: shows the way that a system works to generate and regenerate the observed system behaviour. - Predictive validation: relating to ability of a model to forecast a behaviour that it has not observed before. - Replicative validation: based on the comparison between the outputs of model and data obtained from the real world. Focus on the structural validation method.	Structural validation involves four main processes: - Face Validation: it is performed in the initial step of a simulation process under supervision of conceptual validation. This method consist of three components: a) output assessment, b) immersive assessment, c) animation assessment - Calibration: a process that determines the domain of values for the parameters and fit the model with real data. - Sensitivity Analysis: considering the effects of various parameters on specific behaviour or model outcomes. - Output Validation: matching statistically and spatially the forecast of model's versus real data. There are two methods in face validation step that experts can judge the accuracy of a model: - Animation: It is a graphical view of the model behaviour during the run-time model. This feature is supported by some simulation software and while the simulation is running, they show the general performance of simulation or even a specific trait in simulation. Swarm and Repast are the examples of this type of software.

			- Graphical representation: shows the statistical variables of model outputs by some graphs.
[95]	Explore the integration Agent-based modeling (ABM) into GIS and its application in urban dynamic simulation.	Using a GIS tool of ArcGIS and a specified tool software of AutoCAD, included coordinates transformation, spatial scope unification and the spatial data structure transformation.	- It shows the ability to facilitate spatio-temporal inquiry into processes at the level of agents or individuals and data about specific cases and places. - The tight coupling of agent-based modeling and geographic information systems might be suggested, especially an integrated approach that uses middleware to link existing GIS and ABM software systems.
[96]	Coupling GIS with agent-based modeling (ABM) to assist with more dynamic explorations of past uses of space and geospatial phenomena.	NetLogo modeling software was chosen because it (a) has a built-in GIS extension; (b) can handle common spatial data types used by archaeologists (e.g., shapefiles and ASCII rasters); (c) is one of the easier ABM software packages to learn; (d) has good documentation and an active user community; (e) is a stand-alone platform requiring no additional software or system configurations to operate; and (f) is free to download.	No specific mentioned
[100]	This work expands the hypermap concept to overcome its limitations and harmonise it with geospatial resource oriented architecture (ROA), connecting it to the semantic web and generalising it to the World Wide Hypermap (WWH) as a tool for building a single 'Digital Earth'.	- Implemented in an extended version of the MiraMon software. - MiraMon is a GIS and Remote Sensing software that allows visualisation, query, edition and analysis of raster (remote sensing images, orthophotos, digital terrain models, conventional thematic maps with raster structure, etc.) and vector (topographic and thematic maps that contain points, lines or polygons) data-sets, and also connects to OGC services (e.g. WMS and WMTS).	- RESTful architecture can reproduce the hypermap concept defined two decades ago and overcome its original limitations. - The ROA hides the complexity of the web services and unifies data, metadata and services, reusing simple principles that have been used in the web from the beginning. - A network of dynamic hyperlinked geospatial resources is accessed using global URIs in a distributed environment that defines a single huge hypermap. - The proposed system combines common metadata catalogues with current search engine tools and makes cataloguing data access services unnecessary, as it provides an implicit way to access data.
[105]	Dynamic simulations of building energy consumption and building information from a geographic	- Integration of different types of data on estimating building energy consumption	No specific mentioned

	information system were used to develop urban energy use maps with high spatial resolutions for two urban areas in southern Taiwan.	- Approach using GIS data and dynamic building energy simulation to construct a prediction model for buildings energy use intensity. - Urban energy use maps with high spatial resolution were generated and illustrated for Kaohsiung and Tainan.	
[149]	Provide a guideline to orient the design of future generations of GIS data models, enabling them to achieve a better representation of available spatio-temporal data.	Provide a pyramidal framework composed of six ordered levels. 1-Temporal snapshots, 2-Object change, 3-Event and Process, 4-Identity, 5-Causality and 6-Interpretation.	The first three levels of the pyramid correspond to the three main stages through which the development of spatio-temporal modeling has evolved, namely the implicit representation of changes, the explicit representation of changes, and the explicit representation of phenomena leading to changes. The pyramid is then completed by three new levels of functionality, namely the explicit representation of identity, the explicit representation of causality, and allowing for multiple interpretations.
[150]	Develop and apply the spatiotemporal queries in order to analyze and explore the evolution of the 4D geospatial process.	- Using the geo-atom data model in the management of the spatiotemporal data for a simulated phenomenon. - The changes in the attribute values of the phenomenon along with the time values corresponding to the time-steps of the voxel automata simulation are all stored in the data structure.	For very large voxel datasets a storage mechanism would be required that uses an efficient compression algorithm such as one provided by zlib library that is implemented in MySQL databases.
[151]	Modeling space-varying, time-varying, and space-time-varying events in dynamic segmentation by using an object database approach that is in line with the Object Database Management Group standard.	A mechanism called parametric polymorphism is used to lift conventional data types to spatial, temporal, and spatio-temporal types for maintaining knowledge about events that could change spatially, temporally, and spatio-temporally along linear features.	While the object model developed here represents the events that change over both space and time naturally and elegantly, like the models in other object-oriented systems, it does not necessarily indicate that it can also improve segmentation efficiency.
[152]	Conceptual overview and architecture for the development of high-level semantic and qualitative analytical capabilities for dynamic geospatial domains.	The paper presented an overarching framework for narrative-centered high-level modeling and explanatory analyses in the geospatial domain and have provides a unified view of a consolidated architecture in the backdrop of an illustrated	- Researchers in GIS and spatial information theory have investigated several fundamental ontological aspects concerning the modeling of events, processes, the practical development of taxonomies of events relevant to a geospatial context and the construction of formal methods in qualitative spatial information theory.

		application scenario from the domain of urban dynamics.	- Event- and object-based explanatory analysis is especially important (e.g., in the context of a query-based GIS system), where the available data needs to be analyzed for various purposes, such as managerial decision making, policy formation and so forth.
[101]	A new model with characteristics of new generation's GIS platform, that is, Feature-Oriented Massive Spatio-temporal Object Tree (FOMSOT) with four-tier architectures.	Redhat Linux is chosen as the operating system environment for the prototype system with Oracle 9i for Linux as database management platform and FOMSOT model is built in the system. The developing language is C/C++, PL/SQL, integrated developing environment is Kylix, configuration management tool is CVS, OCI mode is adopted for database access and BSD Socket is set up for distributing computation environment.	The massive spatial table is optimized via index partitioning, spatial clustering and spatial indexing modes, realizing the fast processing of massive spatial data. The whole system is based on Linux environment and Oracle database, and both client and database server can do the trans-platform operation.
[109]	Describes a new approach to combine an system dynamics (SD) model with a semantic 3D city model.	- The SD model implemented uses the software package Vensim - In order to establish the bidirectional data exchange between the system dynamics model and the semantic 3D city model, the platform independent UML model has been translated manually into ETL processes based on the spatial ETL software package FME. - The SD use the data extracted from CityGML and then after one step of simulation the CityGML model gets updated.	- The approach shows that a bidirectional data exchange between semantic city models and SD models improves the predictions generated by the SD models. - Automatic modification of the semantic city model by the output of the SD model allows for 3D visualization and further analysis of future scenarios.
[97]	Multi-agent systems to model the mutual interactions between city residents as well as interactions between residents and spatial objects.	Test implementation for an agent-based system was done in the GAMA: agent-based, spatially explicit, modeling and simulation platform, and was tested on both model and real data.	- It is a useful tool not only for conducting urban big data analyses in urban studies spatial science or applied social science but also for shaping the smart cities of the future. - As future work, it is worth considering to supplement the proposed multi-agent, agent-based model with a game theoretical treatment.

			- The developed model is universal; it can be easily parameterized on the basis of any input data, e.g., social, sociological, or economic.
[91]	Fuzzy Cellular Automata and agent base model in Geospatial Information System and remote Sensing to simulated and predicted urban expansion pattern.	Data / software used: - Satellite data: LANDSAT Enhanced Thematic Mapper (ETM) - Software: For geo – referencing and general image processing we must work with ENVI 4.8. We work with ERDAS 10 for visual analysis and interpretation IDRISI for operating CA Modeling and ArcGIS 9.3 for GIS data acquisition, analysis and presentation.	- Fuzzy logic with CA could design a useful framework for modeling and simulate the urban growth dynamics. - Fuzzy Cellular Automata Urban Growth Model (FCAUGM) is generally capable of simulating and predicting the complexities of urban growth.
[86] Urban growth	Use the Artificial Neural Network (ANN) to make a powerful tool for simulating urban growth patterns.	- Methodology for urban growth modelling using satellite remotely sensed data. - Artificial Neural network (ANN) models - Data: Landsat imageries acquired at 2000 and 2006.	- Integration of GIS, remote sensing data and ANN as a computational method, provides a strong method in environmental modelling such as urban growth modelling. - ANN structure and advantages enable this method to perceive complex and nonlinear pattern between data.
[85] Urban growth	Urban expansion model of different urban growth pattern (SMDUGP), which can work well in both adjacent (i.e., infilling and edge expansion) and outlying growth patterns.	- Temporal set of cloud-free Landsat images taken in 1994, 2004, and 2014. - Buffer zone analyses to characterize the urban expansion pattern. - Logistic regression analysis for determining candidate regions. - Simulating urban expansion.	- Traditional CA models deemed that newly built-up areas occurred only around existing urban areas, that is, most neighborhood grids of a non-urban cell must be an urban land. - Traditional CA model lack the capacity to simulate outlying urban expansion. - The proposed SMDUGP could work well in both adjacent (i.e., infilling and edge expansion) and outlying growth patterns, and had better simulation accuracy than the traditional CA.
[86] Urban growth	Parcel-based cellular automata (ParCA) model for simulating urban growth under planning policies.	- Using an irregular vector format for displaying space and coincidence of parcelbased structure with spatial entities and creating parcel-based development areas automatically. - Presenting neighborhood effect as a radial structure that is based on a weighted function of distance, area, land-use types and service levels (local, district and regional) of cadastral parcels.	In contrast most urban CA models that assume the historical trend will continue into the future, this study proposes development alternatives according to different urban planning policies.

		- Defining neighborhood effect based on three components of compactness, dependency and compatibility.	
[87] Urban growth	Geographical and computational modelling approach to explore the nonlinear relationship between land use types and geospatial driving factors.	- It focuses on the dynamism of land use characteristics in a cross-border region. - The developed model is based on fully integrated Cellular Automata (CA), Geographic Information System (GIS) and Decision Learning Tree (DLT) model, which is used to define the CA transition rules.	- Land use dynamics in a cross-border region can be modelled adequately by combining GIS, CA and DLT methods, particularly when spatial and explicit variables are mobilised. - The model is able to predict correctly the changes in land use characteristics through the change-set-results validation process. - The use of CART implementation of a decision tree with a GINI index is able to test all probabilities in cell state transition.
[84] Coastal urban growth	Analyze spatiotemporal changes (2010–2020) and simulate future dynamics (2030 to 2050) of land use/land cover (LULC) in Alexandria Governorate, Egypt.	- Artificial Neural Network–Multiple Layer Perceptron (ANN-MLP) and Markov Chain techniques were employed within the GIS platform to assess processes of land transitions and predict urban growth trends, patterns and dimensions. - The forecasting process was based on three maps of LULC derived from classified Landsat images of 2000, 2010 and 2020. - In addition, topographical, demographic, accessibility, proximity factors were generated and developed in the form of raster spatial parameters of urbanization driving forces.	- Incorporating several driving forces, the model successfully projected the LULC changes up to 2050; throughout that period the topographical variables were identified as the most influential driving forces. - This study represents a significant contribution to the simulation and forecast of urban changes and the variability of urban growth patterns across the coastal city of Alexandria. - The robustness of the implemented ANN-MLP model and the remotely sensed data within advanced GIS platforms has produced reliable and accurate spatiotemporal prediction of urban development.
[88] Urban growth	Analyze the behaviour of a GIS-based CA urban growth model using sensitivity analysis (SA).	- The GIS-based urban CA simulations were produced for temporal intervals of 10-years using a one-year time step. - The results were obtained by varying the neighbourhood type and size at different spatial resolutions and the outcomes were compared using the integrated multi-method sensitivity analysis approach. - The cross-tabulation maps were generated at all spatial resolutions.	- Cellular automata models have inherent challenges associated with the use of different model elements and their impact on the model outcomes. - Determining the level of sensitivity of model parameters is important since uncertainties embedded in the model outcomes are often either ignored or not adequately addressed. - This study provides insights about the limitations of CA model behaviour and contributes to enhancing existing spatial urban growth modelling procedures.

[102] Land use optimum allocation	Development of a land-use optimum allocation model, the so-called “multi-agent shuffled frog leaping algorithm” (MASFLA).	This study coupled the multi-agent system (MAS) that contains land-use planning knowledge with the search iteration mechanism in the shuffled frog leaping algorithm (SFLA) and rebuilt the local optimization behavior of the SFLA.	(1) The MASFLA had remarkable optimization effects on land resource use, and the optimized values of ecosystem services, regional economic output, and land-use intensive degree increased by 18.6, 51.1, and 30.3%, respectively. (2) The MASFLA had better optimization effects than a single algorithm, and its comprehensive fitness value was 2.1 and 4.1% higher than that of the SFLA and the particle swarm optimization (PSO), respectively, under the same convergence conditions. (3) The MASFLA model could relieve the land-use conflicts between different decision-making agents and realize the optimum allocation of regional land-use in terms of both spatial structure and quantity under multiple optimization goals and restrictions.
[99] Urban growth / Simulation architecture	Utilize the GPU/CPU heterogeneous architecture to enable complex CA simulations for urban growth simulation over massive datasets.	Hybrid parallelism that combines processes with discrete memory and threads with global memory, for the development of a parallel geospatial CA model for urban growth simulation over the heterogeneous computer architecture composed of multiple central processing units (CPUs) and graphics processing units (GPUs).	- Experiments with the datasets of California showed that the overall computing time for a 50-year simulation dropped from 13,647 seconds on a single CPU to 32 seconds using 64 GPU/CPU nodes. - Hybrid parallelism of geospatial CA over the emerging heterogeneous computer architectures provides scalable solutions to enabling complex simulations and optimizations with massive amount of data that were previously infeasible, sometimes impossible, using individual computing approaches.
[106] Modelling architecture / infrastructure	Development of a novel cyberinfrastructure portal called GeoGames to model and understand coupled human and natural systems.	This computing environment integrates and leverages web-GIS and multiplayer online game technology to enable simulations of real-world scenarios of coupled human and natural systems applicable to anything from cities, urban regions to other human settlements.	- Mining data from game play in the manner illustrated here can also provide a companion to other modeling and calibration activities when creating agent based models and simulations. - Using an online GeoGame approach, large amounts of behavioral data from actual users can be gathered. - GeoGame analytics offers a new data- and computational-intensive approach to understand coupled human and natural systems.
[103] GIS Web / infrastructure	Review of the range of delivery platforms that have been developed for the PySAL open source Python library for spatial analysis.	Test of the software and demonstrate its functionality.	- The flexible delivery of open geospatial visual analytics in different desktop and web-based applications leverages the initial investment in developing the PySAL library for multiple purposes and audiences.

			- Especially the web-based applications contribute to a technological infrastructure that promises to improve the continuous monitoring of desired outcomes through the near real-time analysis of different data sources (including open, administrative and crowd sourced data).
[107] GIS Web / infrastructure / Gaming	Development of a generic framework for integrating Geographic Information Systems (GIS) with Massive Multi-player Online Gaming (MMOG) technology to support the integrated modeling of human-environment resource management and decision-making.	Review Web 2.0 concepts, online maps, and games as key technologies to realize a participatory construction of spatial simulation and decision making practices.	- The game metaphor is a viable framework for learning and collaborative modeling. - Massive multi-user participation in the GeoGame-framework has a potential to address the complex dynamics of human-environmental systems that require a simultaneous reconciliation of both top-down and bottom-up decision making where stakeholders are an integral part of a modeling environment.
[104] Simulation integration into QGIS	Open source GIS platform for water resource modelling.	- Demonstration of FREEWAT to the Lugano Lake basin case study, Switzerland and Italy. - Two specific modules of the platform were used to execute data integration and analyses: - The Observation Analysis Tool: integration of time-series observations into modelling by enabling pre- and post-processing in the model environment. - The Lake Package: an existing MODFLOW package allowing dynamic evaluation of groundwater/lakes interaction.	- The modeling process has led to various insights into the data needed for improving WRM, from novel uses of available data to important missing data. - This result may be then additionally used by the local stakeholders in the administration services to inform future data collection policies.
[108] Geospatial Participatory Modeling	Geospatial participatory modeling (GPM) to show benefits over non-spatial approaches for participatory research processes.	- Personalizing connections to problems and their solutions through visualizations of place. - Resolving abstract notions of landscape connectivity. - Clarifying the spatial scales of drivers, data, and decision-making authority. - Illustrate through a case study how GPM is bringing stakeholders together to balance population growth and	- An advantage of using geospatial models during participatory research is the immediate personalization of dynamic processes when they can be visualized in the locations where stakeholders live and work. - By making connections spatially explicit, participatory geospatial modeling makes the identification of pressing challenges and key solutions less abstract. - Connections between communities and ecosystems—whether physical, political, social, or economic—can be fully

		conservation in a coastal region facing dramatic landscape change due to urbanization and sea level rise.	understood only when the spatial scales of drivers, data, and decisionmaking are defined. - Geospatial models are essential complex sustainability problems because they intrinsically raise awareness of place and codify the cross-scale interactions inherent in complex systems.
--	--	---	--

Appendix C. System dynamics model documentation

1. Purpose and scope of the model

The purpose of the Spatial Food Systems Model is to represent the key mechanisms that shape household food security and to explore how policy interventions may change the system over time. The model focuses on three policy-relevant key performance indicators (KPIs) - accessibility, availability, and affordability of healthy food - and examines how these outcomes emerge from interactions between the built environment, household resources, and behavioral responses.

To support spatial analysis, the model operationalizes stocks as countable elements of the built environment (e.g., supermarkets, healthy food stores, fast-food outlets, public transport stations, and urban farms) that can be parameterized with GIS and datasets at the neighborhood or district scale. These spatial stocks connect the system dynamics structure to observed local conditions and enable comparisons between urban areas.

The model is structured into interconnected subsystems for geographical accessibility, household finances, and household circumstances. Reinforcing feedbacks primarily arise from parameters that change physical stocks (e.g., supermarket and healthy food store development, urban food production expansion), while balancing feedbacks capture stabilizing responses such as public-transport policies and household coping strategies under budget stress. The model is designed for scenario and strategy testing, i.e., to compare alternative policy packages and identify leverage points, rather than to produce precise forecasts for individual households.

2. Limitations

- The model boundary is the local urban food environment. Upstream processes such as global food trade, national price formation, and supply-chain disruptions are not modelled explicitly; their effects can only be represented indirectly through parameter changes or scenarios.
- The spatial scope is limited to the urban system represented in the GIS layers. Connections to suburban and rural production areas, commuter-based food purchases outside the study region, and cross-border retail competition are simplified, which may lead to an under- or overestimation of substitution effects over longer distances.
- Where no empirical evidence or basic data was available, assumptions had to be made. The results are therefore sensitive to parameter uncertainties and to the quality and temporal alignment of the input data sets.
- Macroeconomic dynamics such as inflation, wage growth, and broader demographic change are not endogenous in the current version of the model. In addition, the model

captures the effects of the food system on households (via purchasing power and access), but it does not represent downstream health outcomes or feedback from health status to behaviour and income.

3. Model Description

The system dynamics model is implemented in Vensim (PLE Plus) and follows the conceptual structure: three balancing loops (B1-B3) and two reinforcing loops (R1-R2) are translated into a modular stock-and-flow simulation.

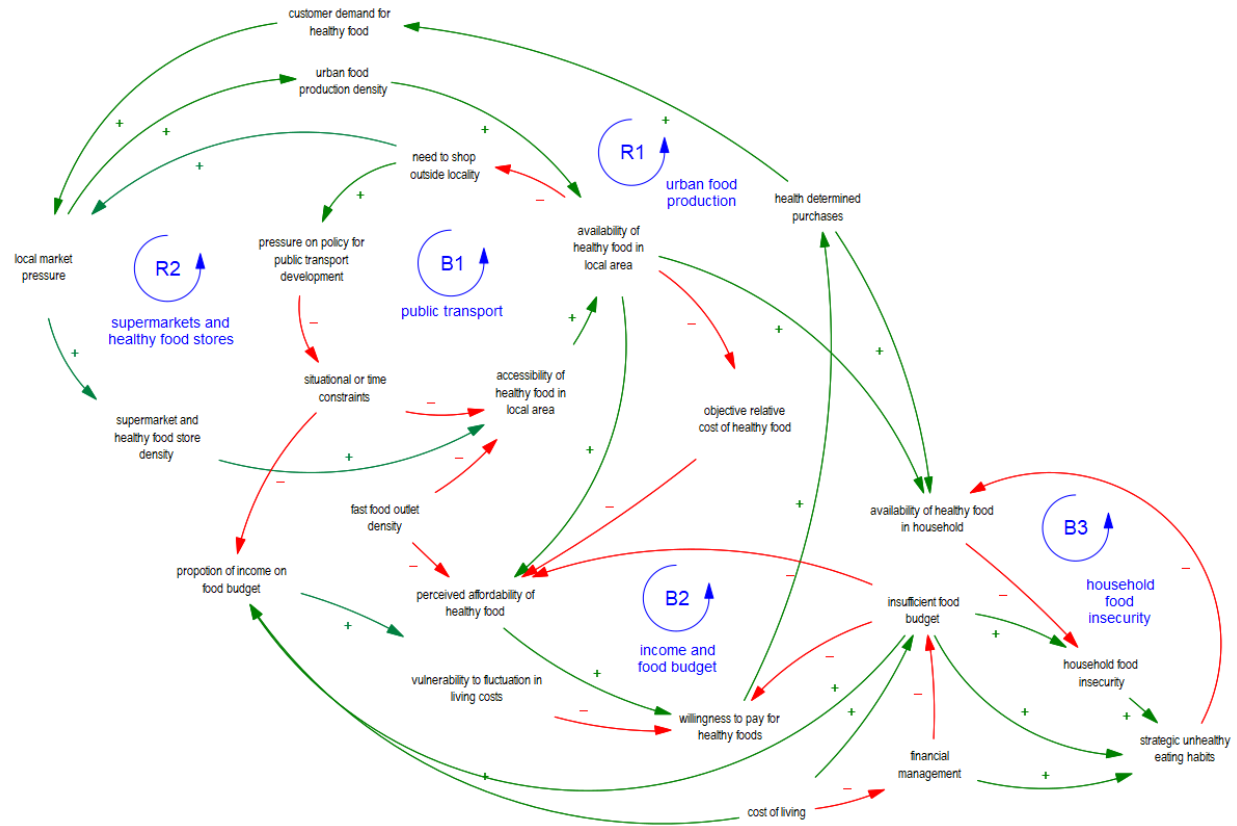


Figure A 8 High-level Causal Loop Diagram (CLD) of the developed Spatial Food Systems Model

The geographical accessibility subsystem contains the spatially explicit stocks (built-environment entities) and their development flows, while the household finances and household circumstances

subsystems translate cost-of-living pressures and structural vulnerability into purchasing behaviour and household food insecurity. Coupling variables (notably availability of healthy food in the local area and fast-food outlet density) link spatial interventions to household-level outcomes. The model is simulated with a monthly time step over a 10-year horizon to evaluate medium-term policy dynamics; parameters and initial values can be imported from GIS, census, and business datasets to apply the model to different neighborhoods or cities.

Vensim was selected to support transparent visual documentation of feedback structures, equations, and units.

An executable version of the model can be found on GitHub: <https://github.com/reiner-os4os/ssd-dss>. The repository includes a parameterized configuration for Ville-Marie and for the entire Island of Montréal, which serves as a reference implementation to illustrate the system's dynamics. Beyond the core model, the supplementary code and the linked datasets support independent installation and operation of the complete decision support system. Detailed documentation is provided for each dataset and its preprocessing, enabling the approach to be applied and recalibrated for other cities.

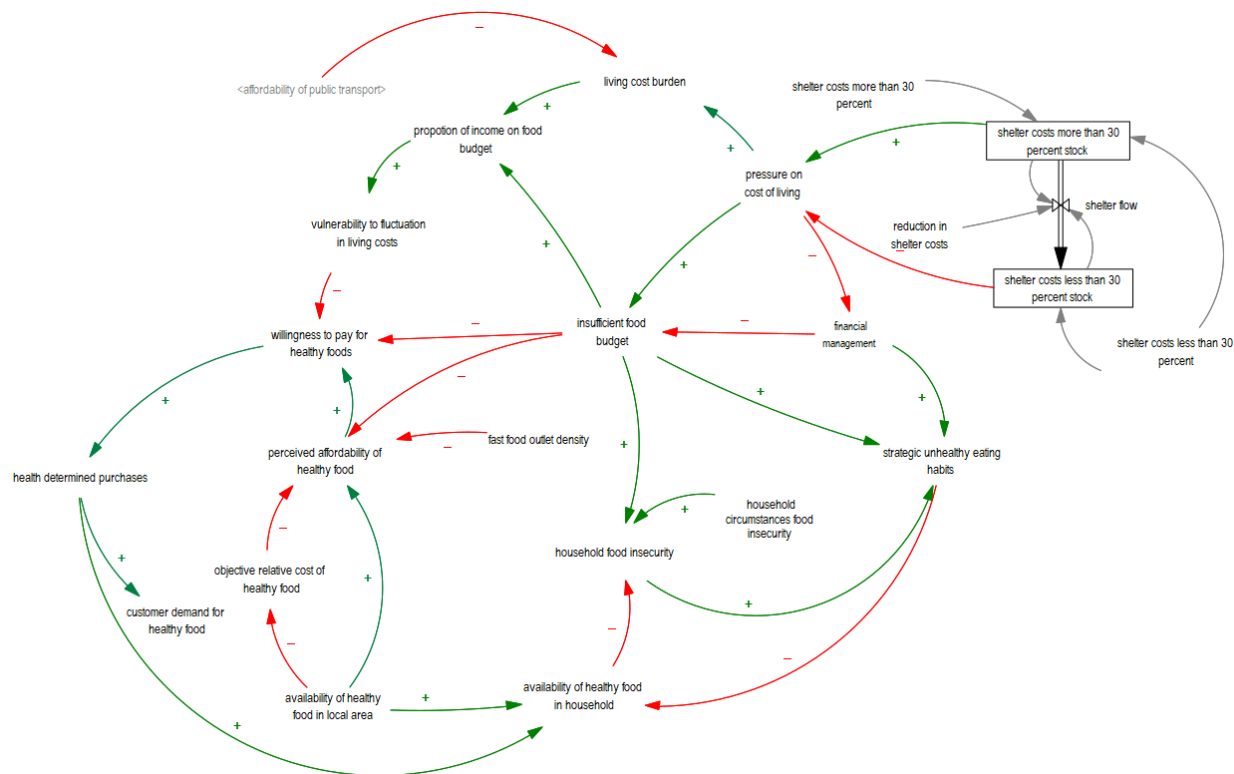


Figure A 9 Subsystem household finances

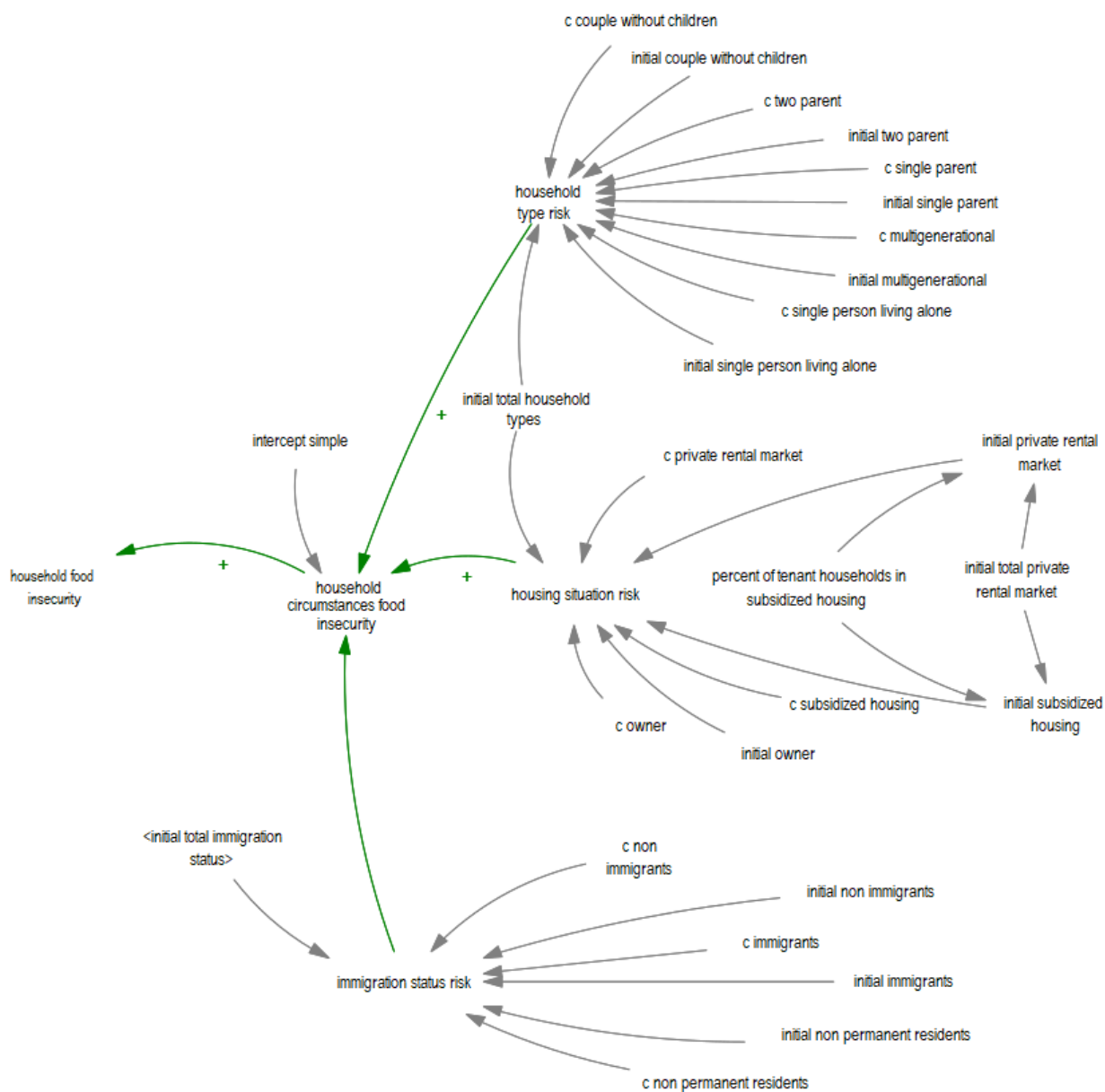


Figure 59 Subsystem household circumstances

Table A 7 Model information

Total number of variables	69
Total number of constants	40
Total number of auxillary	24
Total number of stocks	5
Time unit	month
Simulation horizon	10 years (120 months)
Time step	1

4. Constants in the model

Constants (C) are used to represent parameters that are assumed or parameterized by data and are fixed over the simulation horizon and therefore do not change as part of the system feedback structure. They capture relatively stable characteristics of the study context or simplify processes for which dynamic representation would not be justified by the available evidence.

4.1 Assumptions for constants

It is essential to note that several assumptions had to be made during the modeling process, as data from the literature or ground truth data were not available for all model variables. It is evident that the more realistic the assumptions are, the more precise the model outputs will be.

Table A 8 Assumptions made for constants in the model

Type	Variable Name	Value	Units	Description
Sub-system geographical access				
C	new build rate of public transport stations		<i>Number/ (Month *km2)</i>	The number of public transport stops, e.g., bus stops or subway stations, that can be newly constructed in the area concerned. This variable depends on several factors, such as the financial capacity of companies or the skills of their employees in relation to working on construction sites. This figure represents the maximum potential number of stops that can be newly constructed or dismantled.
C	new build rate urban farms CG		<i>Number/ (Month *km2)</i>	The number of urban farms, community gardens and other food production areas in the focus area.
C	costs individual vehicle use	0.66 - 0.72	<i>CAD/km</i>	For Quebec, a value of 0.625 CAD/km is compensated for employees, see: Directive on Travel: Appendix A – CRA Kilometric Rates. Government of Canada
C	costs public transport use	0.874	<i>CAD/km</i>	The following assumption is made: A monthly ticket costs CAD 104, the average distance to the nearest shopping facility is 2 km, and shopping is done every day. (CAD 104.5/(30 days*4 km)).

C	opening hours of supermarkets daily stores	0.5	-	Represents temporal availability, acknowledging that accessibility is not purely spatial but also constrained by operational time windows. A value of 0.5 means that stores are open for 12 hours a day.
C	negative perceptions of local area	0.5	-	The negative perception of a neighborhood or district in a city is the result of a complex interplay of various causes. Factors such as the physical and ecological environment (built environment), social/demographic factors, and economic factors such as limited employment opportunities or declining economic activity play a role in how people perceive the area. A value of 0.5 means that there is no impact on the overall behavior of the system, a value of 0 means that the perception is maximally positive, and a value of 1 means that the perception is maximally negative.
C	residential or geographical segregation	0.5	-	The residential or geographical segregation is representing the spatial separation of social groups within a city, it is a complex phenomenon and influenced by factors such as historical, economic, social and processes. A value of 0.5 means that there is no impact on the overall behavior of the system, a value of 0 means that the segregation is maximally positive, and a value of 1 means that the segregation is maximally negative.
C	reduction in shelter costs		<i>Percent/Month</i>	Target percent of reduction or increase from the stock “shelter costs more than 30 percent”

4.2 Constants parameterized by using data

Another approach to parametrizing the model constants is to use data from scientific literature, reports, or databases. The following table details the constants that can be parametrized using available information.

Table A 9 Constants parameterized using data

Type	Variable Name	Value	Units	Description
Sub-system geographical access				
C	optimal transport density	8	<i>Number / km²</i>	The optimal transport station density can be derived from the 15 minutes concept.
C	optimal production density	8	<i>Number / km²</i>	The optimal transport station density can be derived from the 15 minutes concept.
C	initial number of public transport station	-	<i>Number</i>	The value will be imported from the data base and depends on the area of interest. 538 Ville Marie and 9374 for Montréal Island.
C	initial number of healthy food store	-	<i>Number</i>	The value will be imported from the data base and depends on the area of interest. 35 Ville Marie and 568 for Montréal Island.
C	initial number of supermarkets	-	<i>Number</i>	The value will be imported from the data base and depends on the area of interest. 313 for Ville Marie and 2682 for Montréal Island.
C	new build rate supermarket and healthy food store	-0.0269 - 0.112	<i>Number / (Month * km²)</i>	Closing and opening of supermarkets ranges observed in the business dataset: -0.0269 - 0.112 Number / (month * km ²), per residential area. As the activity of supermarkets did not change much (no increase or decrease) over the last three years, a value of 0 is used to initialize the model. Values determined from the Montréal business dataset for the period 2016-2024.
C	new build rate fast food outlet	-0.0493 – 0.0359	<i>Number / (Month * km²)</i>	Closing and opening of new fast food outlets ranges observed in the business dataset: -0.0493 – 0.0359 Number / (month * km ²), per residential area. As the activity of fast food businesses has declined over the last three

				years, a value of -0.0179 is used to initialize the model.
C	initial shelter costs more than 30 percent	Imported from GIS database	<i>Number</i>	Number of households (owner and tenant) spending 30% or more of income on shelter costs.
C	initial shelter costs less than 30 percent	Database – Census data	<i>Number</i>	Number of households (owner and tenant) spending less than 30% of household income on shelter costs.
C	initial couple without children	Database – Census data	<i>Number</i>	Total number of couples without children CHARACTERISTIC_ID = 104 in the census data set.
C	c couple without children	0.006736	-	Determined using regression analysis, specific value for Montréal.
C	initial two parent	dynamic	<i>Number</i>	Total number of couples with children CHARACTERISTIC_ID = 103 in the census data set
C	c two parent	0.034904	-	Determined using regression analysis, specific value for Montréal.
C	initial single parent	Dynamic	<i>Number</i>	Total number of one-parent family households CHARACTERISTIC_ID = 105 in the census data set.
C	c single parent	0.012655	-	Determined using regression analysis, specific value for Montréal.
C	initial multigenerational	Dynamic	<i>Number</i>	Total number of multigenerational households CHARACTERISTIC_ID = 106 in the census data set.
C	c multigenerational	0.004491	-	Determined using regression analysis, specific value for Montréal.
C	initial single person living alone	Dynamic	<i>Number</i>	Total number of one-person households CHARACTERISTIC_ID = 110 in the census data set.
C	c single person living alone	0.006736	-	Determined using regression analysis, specific value for Montréal.
C	initial private rental market	Dynamic	<i>Number</i>	Total - Tenant households in non-farm, non-reserve private dwellings - 25% sample data CHARACTERISTIC_ID = 1490 in the census data set.
C	c private rental market	0.073278	-	Determined using regression analysis, specific value for Montréal.

C	initial total private rental market	Dynamic	<i>Number</i>	Total - Owner households in non-farm, non-reserve private dwellings - 25% sample data CHARACTERISTIC_ID = 1482 in the census data set.
C	initial subsidized housing	Dynamic	<i>Number</i>	Total number of tenant households in subsidized housing CHARACTERISTIC_ID = 1491 in the census data set.
C	c subsidized housing	0.015717	-	Determined using regression analysis, specific value for Montréal.
C	initial owner	Dynamic	<i>Number</i>	Total number of owner households in non-farm, non-reserve private dwellings - 25% sample data CHARACTERISTIC_ID = 1482 in the census data set.
C	c owner	0.002041	-	Determined using regression analysis, specific value for Montréal.
C	percent of tenant households in subsidized housing	Dynamic	<i>Number</i>	% of tenant households in subsidized housing CHARACTERISTIC_ID = 1491 in the census data set.
C	initial non immigrants	Dynamic	<i>Number</i>	Total number of non-immigrants CHARACTERISTIC_ID = 1528 in the census data set.
C	c non immigrants	0.031434	-	Determined using regression analysis, specific value for Montréal.
C	initial immigrants	Dynamic	<i>Number</i>	Total number of immigrants CHARACTERISTIC_ID = 1529 in the census data set.
C	c immigrants	0.035312	-	Determined using regression analysis, specific value for Montréal.
C	initial non permanent residents	Dynamic	<i>Number</i>	Total number of non-permanent residents CHARACTERISTIC_ID = 1537 in the census data set.
C	c non permanent residents	0.033475	-	Determined using regression analysis, specific value for Montréal.

5. Model Equations

Several variables in the model are implemented as fixed indices (dimensionless and interpreted on a 0–1 scale), such as insufficient food budget, living cost burden or need to shop outside locality. For these relationships, the model avoids linear mappings because linear functions can easily produce unrealistic values (below 0 or above 1) and can over-amplify effects at the extremes. Instead, smooth, bounded functional forms are used to keep outputs interpretable, numerically stable, and consistent across sub-systems.

Cosine (COS) is mainly used as a smooth re-scaling function that maps a normalized input $x \in [0,1]$ into a bounded output $[0 \rightarrow 1]$ using:

$$\frac{\cos(x\pi)}{2} + 0.5$$

Across $x \in [0,1]$, this creates a smooth transition between high and low influence while guaranteeing the result stays between 0 and 1. In several equations, a phase shift of $+\pi$ is added:

$$\frac{\cos(x\pi + \pi)}{2} + 0.5$$

This phase shift inverts the direction of the effect without changing the scaling logic.

EXP is used primarily inside logistic (sigmoid) terms to represent threshold and saturation behavior in a continuous form. In the model, this appears as:

$$\frac{A}{1 + \exp(-k(x - x_0))}$$

This produces an S-shaped response bounded in $[0, 1]$: small changes far from the threshold have limited effect, changes near the threshold matter more, and the effect saturates at high values.

Using COS-based shaping and sigmoid/logistic functions supports the model's purpose as a policy and scenario tool: it keeps key drivers bounded, allows nonlinear but interpretable responses (thresholds and diminishing returns), and prevents the simulation from producing extreme values when multiple pressures are combined. It also makes the model structure consistent across dimensions (accessibility, availability, affordability), because the same normalization logic can be reused even when the causal direction differs (handled cleanly via the $+\pi$ phase shift or sign).

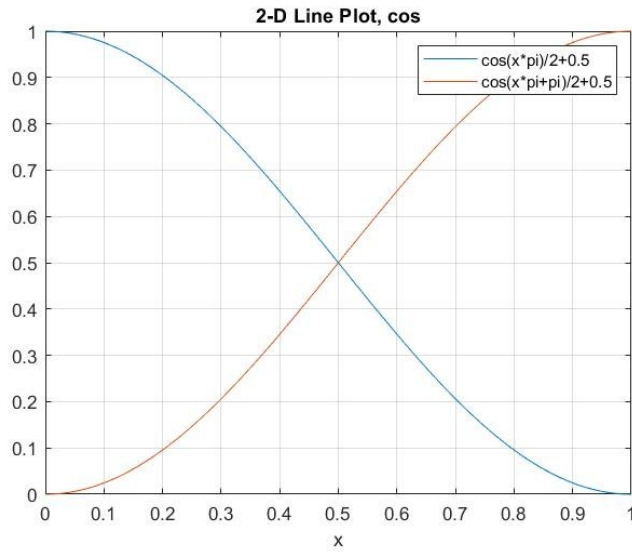


Figure A 11 Cosine rescaling, maps values smoothly between 0 and 1, with a phase shift used to reverse direction while keeping the same normalized logic

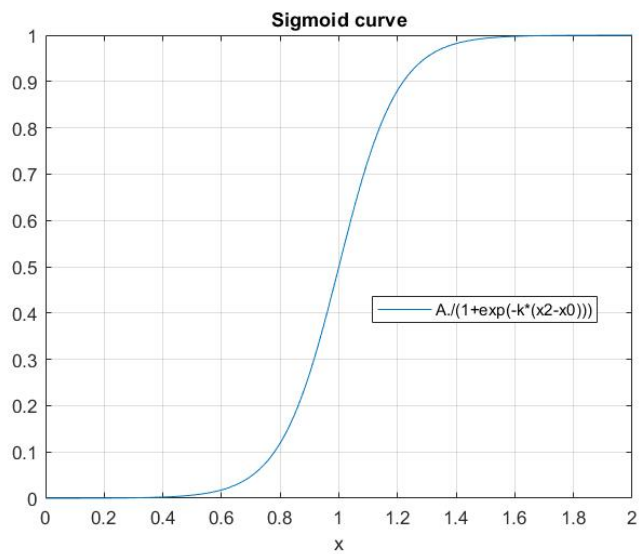


Figure A 12 Sigmoid thresholding represents threshold and saturation behavior in a continuous form. S-shaped response bounded between 0 and 1

Table A 10 Model equations

Type	Variable Name	Function and unit	Units	Description
Sub-system geographical access				
A	affordability of public transport	$1/(1+\text{EXP}(-10 * (\text{costs public transport use} / \text{costs individual vehicle use}) - 1))$	<i>Dmnl</i>	Costs for public transport compared to individual means of transport, e.g., using a car. If more is invested in public transport, the costs of operating the system increase, leading to higher costs for bus and subway tickets and thus reducing relative affordability. If gasoline or diesel prices rise, the costs of individual transport increase, thereby increasing the relative affordability of public transport. This is modeled using a sigmoid function: when the ratio of price per km by car to price per km by public transport is equal to 1, the function should yield a value of 0.5. Note: An increase in annual prices due to inflation or other conditions is not taken into account here.
A	accessibility and affordability of public transport	$(1/(1+\text{EXP}(-10 * ((\text{public transport station density} / \text{optimal public transport station density} - 0.5)))) + (\text{COS}(\text{affordability of public transport} * 3.14159 + 3.14159) / 2 + 0.5)) / 2$	<i>Dmnl</i>	In areas characterised by inadequate transport infrastructure, public transportation systems may incur significant costs and are often unreliable. Nevertheless, these systems persist in functioning as the sole viable mode of transportation. The accessibility and affordability of public transport are key factors in reducing pressure on politicians to invest in infrastructure. The increasing costs of public

				transport have a negative impact on affordability.
A	pressure on policy for public transport development	$(1 * (\text{COS}(\text{need to shop outside locality} * 3.14159 + 3.14159) / 2 + 0.5) + (\text{COS}(\text{accessibility and affordability of public transport} * 3.14159) / 2 + 0.5)) / 2$	<i>Dmnl</i>	The pressure on policy to invest in public transport infrastructure is influenced by accessibility and affordability, as well as the need for people to shop outside their locality. It is important to acknowledge that there are a multitude of factors that exert influence on this variable. This is a limitation of the model.
F	public transport station development	new build rate of public transport stations * $\text{COS}(\text{pressure on policy for public transport development} * 3.14159 + 3.14159)$	<i>Number/Month</i>	This flow is used to determine the number of public transport stations. It can take positive or negative values, which means that if the pressure on policy is 0.5, there will be no increase or decrease in the number of stations. The presence of high pressure results in an expansion of the infrastructure, while low pressure leads to a reduction in infrastructure.
S	number of public transport stations	Inflow equation: public transport station development Initial Value: initial number of public transport station + 0.001	<i>Number</i>	The following transport links are included: bus station, metro. In the event that no public transport stations are present within the area of interest at the initiation of the simulation, the model will be unable to function. Consequently, a constant of 0.001 is employed.
A	need to shop outside locality	$\text{COS}(\text{availability of healthy food in local area} * 3.14159) / 2 + 0.5$	<i>Dmnl</i>	There is evidence that residents in low-income neighborhoods are more likely to shop outside their neighborhood but have limited access to private vehicles and are heavily reliant on public transportation. This parameter describes the pressure residents feel to leave their neighborhood in order to obtain healthy and affordable food. A value of 0 means that people can do their

				shopping within the neighborhood, while a value of 1 means that they have to leave the neighborhood.
A	local market pressure	$((\text{COS}(\text{need to shop outside locality} * 3.14159 + 3.14159)/2 + 0.5) + (\text{COS}(\text{customer demand for healthy food} * 3.14159 + 3.14159)/2 + 0.5)) / 2$	<i>Dmnl</i>	Customer demand for healthy food and the need to shop outside the locality due to insufficient public transport are factors influencing the pressure on retailers to build new shops. If market pressure is low, the development of new supermarkets will also be low.
A	situational or time constraints	$(\text{COS}(\text{opening hours of supermarkets daily stores} * 3.14159)/2 + 0.5 + \text{COS}(\text{accessibility and affordability of public transport} * 3.14159)/2 + 0.5) / 2$	<i>Dmnl</i>	"situational or time constraints (including public transport and child care)" Opening hours of supermarkets, daily stores, restaurants, etc.. If people can't buy the food at the time they have time to shop, the time constraint is increasing.
A	customer demand for healthy food	$\text{COS}(\text{health determined purchases} * 3.14159 + 3.14159) / 2 + 0.5$	<i>Dmnl</i>	Customer demand for healthy food links the geographic access subsystem with the household finances subsystem. Consequently, it is the link between the socioeconomic status of people living in an area and the built environment, thereby shaping the development of grocery stores.
A	availability of healthy food in local area	$((\text{COS}(\text{accessibility of healthy food in local area} * 3.14159 + 3.14159)/2 + 0.5) + (1/(1+\text{EXP}(-10*((\text{production density} / \text{optimal production density})-0.5))))) / 3$	<i>Dmnl</i>	Imports and local production of healthy foods, outlets that sell healthy foods. Availability: addresses whether or not food is actually or potentially physically present, including aspects of production, food reserves, markets and transportation, and wild foods.
Household finances				
A	availability of healthy food in household	$((\text{COS}(\text{availability of healthy food in local area} * 3.14159 + 3.14159)/2 + 0.5) +$	<i>Dmnl</i>	The availability of healthy foods in a household is influenced by various factors, including the availability of healthy foods in

		$\frac{(\text{COS}(\text{strategic unhealthy eating habits} * 3.14159)/2 + 0.5) + (\text{COS}(\text{health determined purchases} * 3.14159 + 3.14159)/2 + 0.5))}{3}$		the area studied and health and cost-determined purchases. These factors are taken into account in the model, but factors caused by family circumstances, such as whether food is distributed evenly within the family, are not taken into account.
A	household food insecurity	$\frac{((\text{COS}(\text{insufficient food budget} * 3.14159 + 3.14159)/2 + 0.5) + (\text{COS}(\text{availability of healthy food in household} * 3.14159)/2 + 0.5) + (\text{COS}(\text{household food insecurity simple} * 3.14159 + 3.14159)/2 + 0.5))}{3}$	<i>Dmnl</i>	Household food insecurity represents the predicted proportion of households living in food insecurity in the area. This is determined by the physical infrastructure in which people live, their financial resources, and their household circumstances, such as whether they live in a single-family household or are a single parent.
A	strategic unhealthy eating habits	$\frac{((\text{COS}(\text{financial management} * 3.14159 + 3.14159)/2 + 0.5) + (\text{COS}(\text{insufficient food budget} * 3.14159 + 3.14159)/2 + 0.5))}{2}$	<i>Dmnl</i>	There can be several reasons for strategic unhealthy eating habits. In contexts of food insecurity, people often adopt different strategies to cope with the situation. They prioritise quantity over nutrition, skip meals to stretch their food supply or overeat when food is available.
A	financial management	$(\text{COS}(\text{cost of living} * 3.14159)/2 + 0.5)$	<i>Dmnl</i>	The financial management of a household is contingent on the cost of living incurred through housing.
A	pressure on cost of living	shelter costs more than 30 percent / (shelter costs more than 30 percent + shelter costs less than 30 percent)	<i>Dmnl</i>	Households that are able to maintain a financially stable situation are advised to allocate no more than 30% of their income toward shelter costs. This variable indicates the number of households that expend more than 30% of their income on shelter expenses. An increasing value of this variable suggests that the population in the

				specified area is experiencing a critical situation.
A	living cost burden	$((\text{COS}(\text{pressure on cost of living} * 3.14159 + 3.14159)/2 + 0.5) + (\text{COS}(\text{affordability of public transport} * 3.14159)/2 + 0.5)) / 2$	<i>Dmnl</i>	Living cost burden refers to the proportion of a household's income spent on essential expenses like housing, food, utilities, and transportation. A high burden indicates limited financial flexibility and increased economic vulnerability.
A	proportion of income on food budget	$((\text{COS}(\text{situational or time constraints} * 3.14159)/2 + 0.5) + (\text{COS}(\text{insufficient food budget} * 3.14159 + 3.14159)/2 + 0.5) + (\text{COS}(\text{living cost burden} * 3.14159 + 3.14159)/2 + 0.5))/3$	<i>Dmnl</i>	This value represents the overall tendency for a household to spend a larger share of its income on food under combined time, budget, and cost pressures. In this way, the indicator does not assume that one factor alone determines the food budget share; instead, it reflects the joint influence of multiple constraints.
A	vulnerability to fluctuation in living costs	$(\text{COS}(\text{proportion of income on food budget} * 3.14159 + 3.14159)/2 + 0.5)$	<i>Dmnl</i>	Vulnerability to fluctuation in living costs refers to how sensitive a household is to changes in essential expenses—like rent, food, or energy. Households with low incomes or tight budgets face higher risk of hardship when costs rise unexpectedly.
A	insufficient food budget	$((\text{COS}(\text{pressure on cost of living} * 3.14159 + 3.14159)/2 + 0.5) + (\text{COS}(\text{financial management} * 3.14159)/2 + 0.5)) / 2$	<i>Dmnl</i>	Insufficient food budget refers to a situation where a household's available money for food is not enough to consistently afford adequate, nutritious meals. This can lead to food insecurity, poor diet quality, and negative health outcomes.
A	willingness to pay for healthy foods	$((\text{COS}(\text{perceived affordability of healthy food} * 3.14159 + 3.14159)/2 + 0.5) + (\text{COS}(\text{vulnerability to fluctuation in living costs} * 3.14159)/2 + 0.5) + (\text{COS}(\text{insufficient food}$	<i>Dmnl</i>	Willingness to pay for healthy foods refers to the proportion of a household's food budget or income they are prepared to allocate toward purchasing nutritious food options, reflecting both value and affordability.

		$\text{budget} * 3.14159 / 2 + 0.5) / 3$		
A	perceived affordability of healthy food	$((\text{COS}(\text{availability of healthy food in local area} * 3.14159 + 3.14159 / 2 + 0.5) + (\text{COS}(\text{objective relative cost of healthy food} * 3.14159 / 2 + 0.5) + (1 / (1 + \text{EXP}(-10 * ((\text{fast food outlet density} - 0.5)))) + (\text{COS}(\text{insufficient food budget} * 3.14159 / 2 + 0.5)) / 4$	<i>Dmnl</i>	Perceived affordability of healthy food is influenced by a household's limited food budget, the availability of healthy options in the local area, and the proximity of fast food outlets. When nutritious foods are scarce or more expensive locally, and fast food is abundant and cheap, households are more likely to view healthy eating as unaffordable—even if they value it.
A	objective relative cost of healthy food	$\text{COS}(\text{availability of healthy food in local area} * 3.14159) / 2 + 0.5$	<i>Dmnl</i>	Low availability of healthy food in a local area increases its objective relative cost, making nutritious options more expensive compared to less healthy, more accessible alternatives.
A	health determined purchases	$\text{COS}(\text{willingness to pay for healthy foods} * 3.14159 + 3.14159) / 2 + 0.5$	<i>Dmnl</i>	Health-determined purchases are shaped by a household's willingness to pay for healthy foods, moderated by factors like income, food availability, and perceived affordability. A higher willingness to pay for healthy foods increases the likelihood of making health-driven food choices.
A	customer demand for healthy food	$\text{COS}(\text{health determined purchases} * 3.14159 + 3.14159) / 2 + 0.5$	<i>Dmnl</i>	Health-determined purchases can drive customer demand for healthy food by signaling to retailers and producers that there is a market for nutritious options. As more people buy healthy foods, these products become more visible, accessible, and socially accepted—reinforcing broader demand.
A	controlled purchases	$\text{COS}(\text{household food insecurity} * 3.14159 + 3.14159) / 2 + 0.5$	<i>Dmnl</i>	Controlled purchases are a financial survival strategy in food-insecure households, reflecting limited flexibility and

				reinforcing poor diet quality over time.
A	household circumstances food insecurity	household type risk + housing situation risk + immigration status risk + intercept simple	<i>Dmnl</i>	Household circumstances food insecurity arises when structural and demographic risk factors—such as household type, housing burden, and immigration status—combine to reduce a household’s ability to access or afford adequate, nutritious food.
S	shelter costs more than 30 percent	IF THEN ELSE(shelter costs more than 30 percent < (initial shelter costs less than 30 percent + initial shelter costs more than 30 percent), -shelter flow , 0)	<i>Number</i>	Stock of households (owner and tentant) spending 30% or more of income on shelter costs.
S	shelter costs less than 30 percent	shelter flow	<i>Number</i>	Stock of households (owner and tentant) spending less than 30% of household income on shelter costs.
F	shelter flow	IF THEN ELSE(shelter costs less than 30 percent > 0, reduction in shelter costs * shelter costs more than 30 percent , 0)	<i>Number/Month</i>	Flow of number of households between the two stocks “shelter costs more than 30 percent” and “shelter costs less than 30 percent”

Appendix D. Data set, description, and source

Food Establishments: “This set locates establishments under the responsibility of the Food Inspection Division of the City of Montréal. It should be noted that the City is mandated by the Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec (MAPAQ) with respect to inspections on its territory.”

Source: City of Montréal - <https://donnees.Montreal.ca/dataset/etablissements-alimentaires> (accessed: 12.11.2023)

Table A 11 Mapping of Food Establishments categories with SD model classes

French	English	Healthy food store	Supermarket	Fast food outlet	Restaurant	Out of home catering	Other
Distributrice automatique	Automatic vending machine						1
Épicerie avec préparation	Grocery with preparation		1				
Restaurant	Restaurant				1		
Brasserie	Brasserie				1		
Bar salon, taverne	Lounge bar, tavern				1		
Restaurant service rapide	Quick service restaurant			1			
Supermarché	Supermarket		1				
Garderie	Daycare					1	
Magasin à rayons	Department store						1
Centre d'accueil	Reception and Orientation Center						1
Épicerie	Grocery store		1				
Cafétéria institution d'enseignement	Educational institution cafeteria					1	
Boucherie-épicerie	Butchery and grocery	1					
Cafétéria	Cafeteria					1	
Casse-croûte	Snack bar			1			
Résidence de personnes âgées	Seniors' residence					1	
Boulangerie	Bakery	1					

Organisme d'aide alimentaire	Food aid organization						1
Restaurant mets pour emporter	Take-out restaurant				1		
École/mesures alimentaires	School/food service					1	
Bar laitier saisonnier	Seasonal dairy bar						1
Poissonnerie	Fishmonger	1					
Charcuterie/fromage	Delicatessen/cheese	1					
Pâtisserie	Patisserie						1
Confiserie/chocolaterie	Confectionery/chocolate shop						1
Boucherie	Butchers	1					
Aliments naturels	Natural foods						1
Traiteur	Catering						1
Autres	Other						1
Entrepôt	Warehouse						1
Kiosque	Kiosk						1
Hôpital	Hospital					1	
Événements spéciaux	Special events						1
Charcuterie	Delicatessen	1					
Pâtisserie-dépôt	Pastry shop						1
Bar laitier	Dairy bar						1
Cuisine domestique	Domestic kitchen						1
Local de préparation	Preparation room						1
Usine produit autre	Other product plant						1
Usine de produits marins	Seafood factory						1
Marché public	Public market						1
Distributeur en gros de produits mixtes	Wholesale distributor of mixed products						1
Vendeur itinérant	Traveling salesperson						1
Entrepôt de produits mixtes	Mixed products warehouse						1

Entrepôt de produits végétaux	Plant products warehouse						1
Distributeur en gros de produits laitiers	Wholesale distributor of dairy products						1
Camp de vacances / Auberge jeunesse / Gîte	Vacation camp / Youth hostel / Gîte					1	
Fruits et légumes prêts à l'emploi	Ready-to-use fruit and vegetables						1
Usine de produits laitiers	Dairy products plant						1
Distributeur en gros de fruits et légumes frais	Wholesale distributor of fresh fruit and vegetables						1
Entrepôt de produits laitiers	Dairy warehouse						1
Distributeur en gros de succédanés de produits laitiers	Wholesale distributor of dairy substitutes						1
Ramasseur de lait' 'Noix et arachides	Milk picker' 'Nuts and peanuts						1
Entrepôt d'eau	Water warehouse						1
Distributeur en gros de produits de la pêche	Wholesale distributor of fish products						1
Distributeur en gros de produits carnés	Wholesale distributor of meat products						1
Distributeur en gros d'eau	Wholesale water distributor						1
Cantine mobile	Mobile canteen					1	
Produits à base de protéines végétales	Vegetable protein products						1
Fabrique de boissons gazeuses	Soft drinks factory						1
Café, thé, infusion, tisane	Coffee, tea, herbal tea						1
Véhicule livraison	Delivery vehicle						1
Usine d'embouteillage d'eau	Water bottling plant						1
Pâtes alimentaires	Pasta products						1

Camion de distribution de produits carnés	Meat products distribution truck						1
Usine d'emballage de glace	Ice packing plant						1
Découpe à forfait	Contract cutting						1
Atelier de conditionnement de produits de la pêche	Seafood packaging plant						1
Camion-cuisine	Kitchen truck					1	
Camion de distribution de produits laitiers	Dairy distribution truck						1
Site d'eau vendue au volume	Water site sold by volume						1
Cabane à sucre	Sugar shack						1
Camion de distribution de produits de la pêche	Seafood distribution truck						1

Follow-up of food aid requests to 211: “The dataset presents all the requests (phone, chat and email) made to 211 Greater Montréal that relate to food in 2021 and 2022 as part of the food insecurity project funded by the City of Montréal.”

Source: City of Montréal - <https://donnees.Montreal.ca/dataset/demandes-aide-alimentaire> (accessed: 12.11.2023)

Community Gardens: “Location of community gardens on the territory of the City of Montréal.

A community garden is a vegetable garden made up of several gardens, each of which is allocated and cultivated by a citizen or family.”

Source: City of Montréal - <https://donnees.Montreal.ca/dataset/jardins-communautaires> (accessed: 12.11.2023)

3D Buildings 2016 (LOD2 model with textures): “Digital model of 3D LOD2 buildings with textures in CityGML, 3DM and GDB format and in DWG format without textures of some Montréal boroughs.”

Source: City of Montréal - <https://donnees.Montreal.ca/dataset/batiment-3d-2016-maquette-citygml-lod2-avec-textures2> (accessed: 12.11.2023)

Other sources: Administrative boundaries of the agglomeration of Montréal (boroughs and related cities) - <https://donnees.Montreal.ca/dataset/limites-administratives-agglomeration>

YELP: The website offers specialized search functions and provides information about stores in a specific area specified by address or zip code. Each paid store listing includes a filtered 5-point rating, filtered reviews from other site visitors, and details such as address, hours, handicapped access, and parking. Listings include retail stores, service providers, cultural venues, public places, and more.

Source: www.yelp.com

Appendix E. Mapping Tables of 211 Montréal Food Aid Request to the Census 2021

This appendix provides the detailed mapping tables that support Section 6.2.4 Mapping of Food Aid Request Data to the Census Data.

The tables document how categories from the Montréal Follow-up on Requests for Food Aid at 211 dataset were aligned with equivalent variables in the Statistics Canada 2021 Census data used in the Spatial System Dynamics (SSD) Simulation.

Each table presents:

- The 211 Montréal category as reported by respondents,
- The corresponding Census category and its CHARACTERISTIC_ID,
- And the number of recorded cases in the 211 dataset.

Categories for which no Census equivalent could be found—such as Homeless, Private residence for seniors, or Cooperative housing—are explicitly noted.

In addition, the appendix includes cases labeled “No information” and “Do not wish to answer”, which represent respondents who either declined to specify their situation or whose data were incomplete. These entries are retained to illustrate the limits of available information and highlight potential data gaps in representing food insecurity across all population segments.

The appendix is organized into three mapping domains corresponding to the main variables used in the model:

1. Housing situation
2. Citizenship and immigration status
3. Household type and composition

These mapping tables enable transparency in the data harmonization process and provide a clear reference for future updates or replication of the SSD model.

Table A 12 Mapping of housing situation from the food aid request data to the census data

Category in the follow-up on requests for food aid at 211	Category in the census data	Number of counts in the 211
Private rental market	Total - Tenant households in non-farm, non-reserve private dwellings - 25% sample data CHARACTERISTIC_ID = 1490	359
Subsidized housing	% of tenant households in subsidized housing CHARACTERISTIC_ID = 1491	77
Homeless	Not available for extraction from the Census data directly.	15
Owner	Total number of owner households in non-farm, non-reserve private dwellings - 25% sample data CHARACTERISTIC_ID = 1482	10
Private residence for seniors	Not available for extraction from the Census data directly.	4
Cooperative	Not available for extraction from the Census data directly.	2
No information	Not available for extraction from the Census data directly.	97
Do not wish to answer	Not available for extraction from the Census data directly.	8

Additional notes for the mapping of the housing situation:

The model does not capture food insecurity of homeless people, more studies and data is needed to get better insights into this area. Food banks and other initiatives can collect this kind of data and should report it.

Table A 13 Mapping of citizenship immigration status from the food aid request data to the census data

Category in the follow-up on requests for food aid at 211	Category in the census data	Number of counts in the 211
	Total - Immigrant status and period of immigration for the population in private households - 25% sample data	
Canadian citizenship at birth	Total number of non-immigrants CHARACTERISTIC_ID = 1528 ²	154
Canadian citizenship acquired	Total number of immigrants CHARACTERISTIC_ID = 1529 ³	87

² Individuals born in Canada are automatically Canadian citizens and are counted as non-immigrants

³ Those who were born outside Canada but later became Canadian citizens (by naturalization) are categorized as immigrants.

Permanent residence	Total number of immigrants CHARACTERISTIC_ID = 1529 ⁴	50
Refugee	Total number of immigrants CHARACTERISTIC_ID = 1529 ⁵	36
Temporary visa	Total number of non-permanent residents CHARACTERISTIC_ID = 1537 ⁶	32
Application form	Total number of non-permanent residents CHARACTERISTIC_ID = 1537 ⁷	132
No information	Not available for extraction from the Census data directly.	77
Do not wish to answer	Not available for extraction from the Census data directly.	4

Additional notes for the mapping of citizenship immigration status:

- Broad Categories: The census does not break down the immigrant category into subgroups (such as by immigration pathway or legal status beyond the permanent/temporary distinction). That means details like refugees versus other immigrants or naturalized versus non-naturalized (permanent residents) are subsumed under the broader Immigrants category.
- Implications for Analysis: If you need to analyze subgroups (e.g., to isolate refugees from other immigrants), you might have to supplement the census data with specialized administrative data or additional surveys from Immigration, Refugees and Citizenship Canada (IRCC).

Table A 14 Mapping of household type risk from the food aid request data to the census data

Category in the follow-up on requests for food aid at 211	Category in the census data Total - Household type - 100% data	Number of counts in the 211
Common-law couples	Total number of couples without children CHARACTERISTIC_ID = 104	33
Two-parent	Total number of couples with children CHARACTERISTIC_ID = 103	171

⁴ People with permanent resident status who have not yet naturalized are grouped with immigrants because they entered Canada under immigration programs.

⁵ Refugee claimants who have been granted permanent residency (and eventually may naturalize) are included in the immigrant category.

⁶ Individuals in Canada on a temporary visa (such as work, study, or visitor permits) are categorized as non-permanent residents

⁷ Applicants—those who have submitted applications for refugee status or immigration but are not yet permanent residents—are generally grouped with non-permanent residents.

Single-parent	Total number of one-parent family households CHARACTERISTIC_ID = 105	62
Multigenerational	Total number of multigenerational households CHARACTERISTIC_ID = 106	22
Single person living alone	Total number of one-person households CHARACTERISTIC_ID = 110	161
Not applicable household	Not available for extraction from the Census data directly.	123

Appendix F. Review of Urban Agriculture Projects

Table A 15 Overview of urban agriculture projects reviewed

Name	Website	Start	In operation (2025)	Continent	Country	City
Sky Green Farm	www.skygreens.com	2012	Yes	Asia	Singapore	Singapore
Gotham Greens - Queens	www.gothamgreens.com	2016	Yes	North America	USA	Queens, NY
Gotham Greens - Chicago	www.gothamgreens.com	2015	Yes	North America	USA	Chicago, IL
Gotham Greens - Chicago 2	www.gothamgreens.com	2019	Yes	North America	USA	Chicago, IL
Gotham Greens - Rhode Island	www.gothamgreens.com	2019	Yes	North America	USA	Providence, RI
Gotham Greens - Maryland	www.gothamgreens.com	2019	Yes	North America	USA	Maryland Baltimore, MD
Gotham Greens - Virginia	www.gothamgreens.com	2022	Yes	North America	USA	Virginia Stevensburg, VA
Gotham Greens - Colorado	www.gothamgreens.com	2020	Yes	North America	USA	Colorado Aurora, CO
Gotham Greens - Colorado 2	www.gothamgreens.com	2023	Yes	North America	USA	Colorado Windsor, CO
Gotham Greens - California	www.gothamgreens.com	2021	Yes	North America	USA	California Davis, CA
Gotham Greens - Georgia	www.gothamgreens.com	2023	Yes	North America	USA	Georgia Atlanta Metro, GA
Gotham Greens - Texas	www.gothamgreens.com	2023	Yes	North America	USA	Texas Dallas County, TX
Vertical Harvest plans2	https://verticalharvestfarms.com/	2012	Yes	North America	USA	Jackson, Wyoming

Green Sense Farms 2	www.greensensefarms.com	2014	No	North America	USA	Portage, Indiana
Aero Farms	www.aerofarms.com	2012	Yes	North America	USA	Newark
Bright Farms	www.brightfarms.com	2011	Yes	North America	USA (Pennsylvania)	Selinsgrove
Bright Farms	www.brightfarms.com	2016	Yes	North America	USA (Illinois)	Rochelle
Bright Farms	www.brightfarms.com	2018	No	North America	USA (Ohio)	Wilmington
Bright Farms	www.brightfarms.com	2016	Yes	North America	USA (Virginia)	Culperer
Bright Farms	www.brightfarms.com	2021	Yes	North America	USA (North Carolina)	Handersolville
Bright Farms	www.brightfarms.com	2017	Yes	North America	USA (New Hampshire)	Loudon
Thanet Earth Farm	www.thanetearth.com	2008	Yes	Europa	UK	Kent
Oko Farms	www.okofarms.org	2013	Yes	North America	USA	New York
Ouroboros Farms	www.ouroborosfarms.com	2013	No	North America	USA	Half Moon Bay, CA
Sustainable Harvesters	www.urbanharvest.org/vendors/sustainable-harvesters/	2012	Yes	North America	USA	Hockley, TX
Eco-ark greenhouse at Finn & Roots	https://finnandroots.com/the-eco-ark/	2014	Yes	North America	USA	Bakersfield, VT
Superior Fresh Farms	https://www.superiorfresh.com/	2015	Yes	North America	USA	Hixton, WI
Great Northern Hydroponics	https://www.greatnorthern.farm/	1998	Yes	North America	Canada	Quebec
IronOx	https://ironox.com/	2015	No	North America	USA	San Carlos - California

Spread Co (Kameoka Plant)	https://spread.co.jp/en/	2007	Yes	Asia	Japan	Kyoto
Orchidville	https://orchidville.com.sg/	No data	Yes	Asia	Singapore	Singapore
Edgemere Farm	http://www.edgemerefarm.org/	2012	Yes	North America	USA	New York
Intergrow (Sungrow farms)	https://intergrowgreenhouses.com/our-farm/	2018	Yes	North America	USA	Albion
The Edible Campus	https://www.mcgill.ca/mchg/files/mchg/MakingtheEdibleCampus.pdf	2007	Yes	North America	Canada	Montréal
Jones Food Company 1	www.jonesfoodcompany.co.uk	2018	No	Europa	UK	Scunthorpe
Josef Food Company 2	www.jonesfoodcompany.co.uk	2023	No	Europa	UK	Lydney
B-Four Agro	www.b4agro.nl	2006	Yes	Europa	Netherlands	Warmenhuizen
B4Hydrogrow - new project	http://www.hyperiongrowlights.com/b4hydrogrow/	2018	Yes	Europa	Netherlands	Warmenhuizen
Deliscious	https://deliscious.com/	2012	Yes	Europa	Netherlands	Beesel
Tuinderij Bevelander	www.tuinderijbevelander.nl	1970	Yes	Europa	Netherlands	Achthuizen
Mighty Vine	https://mightyvine.com/		Yes	North America	Illinois - USA	Rochelle

Appendix G. Glossary

This glossary summarizes key terms and acronyms appearing in the thesis architecture.

Table A 16 Glossary summarizes key terms

Term	Definition	Chapter Context
Chapter 4		
Anaconda	A Python distribution that bundles package and environment management; used on the User PC to run notebooks and the SSD library.	Deployment Architecture – User PC (Anaconda component)
API Endpoint	A specific REST URL that exposes a function of the DSS (e.g., /scenarios, /write_scenario) for clients to interact with the system.	Service Communication Standards – RESTful APIs; Example requests
Area of Interest (AOI)	The spatial domain selected for analysis; drives data extraction and model initialization for SSD simulations.	Deployment Architecture – Jupyter notebook for AOI selection; Component Interactions
BPTK-Py (Business Prototyping Toolkit for Python)	A toolkit that converts XMILE models into executable Python code, enabling SD models to run within the DSS.	Integration of Simulation Models Workflow; Pipeline for Creating XMILE Models
CLD (Causal Loop Diagram)	A qualitative SD diagram showing feedback loops (reinforcing and balancing) that guide model structure.	Referenced via SD methodology (details in Chapter 3); foundations section
Containerization	Packaging code, dependencies, and runtime configuration into isolated units (containers) for consistent deployment.	Infrastructure – Docker on Linux; Advantages & Challenges
Coupling (Embedded)	A strategy where one tool is fully integrated into another's environment (e.g., embedding SD in GIS), maximizing integration but reducing modularity.	Coupling Strategies – Embedded approach
Coupling (Loose)	An integration strategy that exchanges data via files (e.g., CSV), simple to implement but not suited for real-time or repeated operations.	Coupling Strategies – Loose coupling

Coupling (Moderate)	An integration approach where components share a common database (e.g., PostGIS) for reading/writing inputs and outputs, balancing flexibility and performance.	Coupling Strategies – Adopted for the DSS; System Architecture
Coupling (Tight)	Run-time integration of components through shared standards/interfaces, enabling high performance but at higher complexity and lower flexibility. <i>“Tight coupling indicates strong dependency between software components. The dependency is strong in the sense that two or more components have multiple and complex dependencies between internal states, data and functions of the components.” [119]</i>	Coupling Strategies – Tight coupling
Data Governance / Metadata / Versioning	Practices ensuring data quality and traceability (origin, versions) across ETL and simulations.	Data Ingestion and Preparation; Advantages & Challenges
Docker	A platform to build and run containers, supporting portable, reproducible microservice deployments.	Infrastructure – Containerized microservices on Linux
DSRM (Design Science Research Methodology)	A research framework that produces and evaluates artifacts (models, methods, instantiations) with rigor and relevance.	Theoretical & Methodological Foundations – DSRM guidelines
DSS (Decision Support System)	The central artifact: a microservices-based platform that integrates SD and GIS to support spatially explicit decision-making.	Chapter 4 overview; System Architecture and Technical Design
ETL (Extract–Transform–Load)	A pipeline that retrieves, cleans/transforms, and loads datasets into PostGIS for use by the DSS.	Data Ingestion and Preparation; Workflow figure
Flask	A lightweight Python web framework used to implement the DSS REST API web server.	Deployment Architecture – REST API Web Server
GeoPandas	A Python library that extends pandas with geospatial operations for data analysis and visualization.	Tools for visualization; Standards and Interoperability

GIS (Geographic Information System)	Software and methods for capturing, storing, analyzing, and visualizing spatial data.	Foundations and motivation for SSD integration
Interoperability	The ability of services and tools to work together through open standards and APIs.	Standards and Interoperability; Advantages & Challenges
JSON	A lightweight data format used for request/response payloads in the DSS REST API.	Service Communication Standards – REST examples
Jupyter Notebook	An interactive environment for parameterizing scenarios and AOI selection; also used for ETL notebooks.	Deployment Architecture – User PC; Data Ingestion and Preparation
Linux-based Infrastructure	The operating environment for deploying containerized microservices in the DSS.	Infrastructure – Linux and Docker
Microservices Architecture	A system design pattern decomposing the DSS into independent services that communicate via APIs, enabling scaling and fault isolation.	Principles of Microservices; System Architecture
OGC (Open Geospatial Consortium)	An international standards body specifying geospatial protocols like WMS and WFS for interoperability.	Geospatial Standards – OGC compliance
pgAdmin	A graphical administration tool for PostgreSQL/PostGIS used to test and manage SQL queries.	Geospatial Standards – pgAdmin example query
PostGIS	A spatial extension to PostgreSQL enabling geometry types and spatial queries (e.g., ST_Intersects).	Geospatial Standards; PostGIS Server in Deployment
PostgreSQL	An open-source relational database used as the shared store for moderate coupling and geospatial data via PostGIS.	Geospatial Standards; Shared database hub
PostgreSQL Wire Protocol (TCP/IP)	The low-level protocol by which clients (e.g., QGIS) connect directly to PostGIS for SQL operations.	Communication between QGIS ↔ PostGIS – Direct SQL protocol
QGIS	An open-source desktop GIS used for visualizing and analyzing spatial outputs from the DSS.	Deployment Architecture – User PC; Visualization

REST / RESTful API	A web architectural style using standard HTTP methods and stateless communication; adopted to expose DSS services.	Service Communication Standards – RESTful APIs
Scaling (Horizontal/Vertical)	Increasing resources (vertical) or instances (horizontal) to meet workload demands, especially for simulations.	Principles of Microservices; Infrastructure; Advantages & Challenges
SD (System Dynamics)	A modeling approach using stocks, flows, and feedback loops to simulate system behavior over time.	Foundations; Integration with GIS
Sensitivity Analysis	Testing how variations in parameters affect outputs to assess robustness and influential factors.	DSRM – Design rigor; Testing and validation in Vensim
Simulation Scenario	A specific configuration of model parameters and inputs used to explore system outcomes.	REST examples (/scenarios, /write_scenario); Business Layer
Spatial Heterogeneity	Variations across space that influence system behavior; a rationale for coupling SD and GIS.	Foundations; Motivation for SSD
SSD (Spatial System Dynamics)	An approach that integrates SD with spatial data so simulations can be location-specific.	Chapter 4 overview; Theoretical Foundations
ST_Intersects	A PostGIS spatial predicate that returns TRUE if two geometries intersect; used in spatial joins.	Geospatial Standards – pgAdmin example query
Three-Layer DSS Model	Conceptual structure comprising Business Layer; Software, Code & Infrastructure Layer; Data & Models Layer.	System Architecture and Technical Design
Unit Checks	Verification that model variables and equations are dimensionally consistent.	DSRM – Research rigor; Testing and validation
Vensim PLE Plus	A modeling tool used to build and validate SD models before exporting to XMILE.	Pipeline for Creating XMILE Models; Integration Workflow
WFS (Web Feature Service)	An OGC standard for querying and retrieving vector features over the web.	Geospatial Standards – OGC

WMS (Web Map Service)	An OGC standard that serves map images rendered on the server from spatial data.	Geospatial Standards – OGC
XMILE (XML Modeling Interchange Language)	An open XML standard for encoding and exchanging SD models; includes sim specs and model blocks.	System Dynamics Standards – XMILE; File structure description
Chapter 6		
211 Greater Montréal Dataset	Requests, Follow-ups, and Needs records on food aid inquiries (2021–2022) linked by ID Call.	Follow-up on requests for food aid at 211
Borough Boundaries	Administrative geometry used for aggregation and visualization.	Open Data Montréal; Framework
BPTK-Py	Toolkit to compile XMILE SD models into Python for execution.	Model pipeline and storage in SD library
Building-Level Matching	Associating food establishments to CERC building centroids and attributes.	Mapping Food Establishment Data with Building Data
Census Tract (CT)	Standard statistical geographic unit used for aggregation and spatial alignment in the DSS.	Statistics Canada 2021 Census
Census_analysis.ipynb	Notebook extracting and processing Statistics Canada variables for Montréal CTs.	Statistics Canada 2021 Census
census_select.py / select_data()	Script/function to filter Census tables by CHARACTERISTIC_ID.	Statistics Canada variable selection
CERC Buildings Dataset	Building inventory used for building-level matching of establishments and accessibility analysis.	Overview of Data Flow; Mapping with building data
CHARACTERISTIC_ID	Census identifier used to select specific indicators programmatically.	census_select.py; Table of thematic categories
Data Flow Diagram (DFD)	Diagram that shows sources, processes, data stores, and flows used to integrate datasets into the DSS.	Data Integration and Flow within the DSS
Data Governance & Archiving	Policies to preserve originals, translations, and processing metadata for reproducibility.	Governance; Bilingual data
Food Establishments Dataset	Daily-updated list of businesses selling/serving food; 73 original categories mapped to six classes.	Food Establishments; Mapping and categorization

GeoJSON	Interchange format for exporting processed spatial layers to the DSS.	Statistics Canada outputs; Integration
Jupyter Notebook	Executable document capturing dataset provenance, processing, and adjustments.	Technical Implementation and Reproducibility
Linguistic Standardization	Translation of FR-only fields to EN; archiving both versions for reproducibility.	Bilingual data availability; Governance
Mapping Tables (211 ↔ Census)	Crosswalk aligning 211 categories to Census variables by CHARACTERISTIC_ID.	Mapping of food aid request data to the Census
Open Data Portal Montréal	Municipal open-data platform providing Food Establishments, Food Aid 211, and Borough Boundaries datasets.	Overview of Data Flow; Key datasets
OpenStreetMap (OSM)	Crowd-sourced geospatial data used for public transport stations and public/community places.	Overview of Data Flow
Population-Weighted Aggregation	PostGIS SQL approach using geometric intersections to weight counts within boroughs/areas.	Mapping implementation in PostGIS
PostGIS DSS Database	Spatially enabled PostgreSQL instance hosting inputs and simulation outputs.	Central repository for integration and queries
Primary Data	Data collected directly in this work to fill gaps or complement secondary data (e.g., food consumption places).	Primary and secondary data; motivation for collection
Reverse Geocoding	Transforming coordinates to addresses to re-locate points precisely to buildings.	Mapping Food Establishment Data with Building Data
Secondary Data	Existing datasets from official and open sources (e.g., Open Data Montréal, Statistics Canada, OSM).	Primary and secondary data; sources overview
Six Analytical Classes	Healthy food store, supermarket, fast food outlet, restaurant, out-of-home catering, other.	Food establishment categorization and mapping table
ST_Union / ST_Intersection / ST_Area	PostGIS functions used to merge geometries, compute overlaps, and area-based weights.	SQL example for immigrants by borough

Statistics Canada 2021 Census	Boundary and profile datasets at census-tract level for demographics and socio-economics.	Statistics Canada 2021 Census; calibration and context
System Dynamics Model Library	Repository of compiled Python SD models (from XMILE via BPTK-Py).	Overview of Data Flow; Reuse
UML Elements (E, P, D, F)	External Entities (E), Processes (P), Data Stores (D), and Data Flows (F) used to structure the DFD.	Technical Implementation and Reproducibility
Reverse Geocoding	Transforming coordinates to addresses to re-locate points precisely to buildings.	Mapping Food Establishment Data with Building Data