PAPER NAME

jurnal_developing CLD.docx

AUTHOR

Ari Arsianti

WORD COUNT

4574 Words

CHARACTER COUNT

26241 Characters

PAGE COUNT

10 Pages

FILE SIZE

714.1KB

SUBMISSION DATE

Aug 24, 2024 11:38 AM GMT+7

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Regional Case Study

Developing Causal Loop Diagram for Urban Development and Land Carrying Capacity in Surakarta

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Abstract

Surakarta covers an area of 46.72 km² with a population of 583,961 people. The density figure for the city of Surakarta reaches 12,499 people per km². Land use has 62% for residential purposes. Green open space is currently only 9.82% of area of Surakarta. Meanwhile, the economic growth in Surakarta is always experiencing an upward trend, it is recorded that in 2022 investment growth has exceeded the target of reaching 243.46%. City development can affect the quantity and quality of natural resources as well as the carrying capacity of the environment. The aim of this research is to describe the general picture through the cause-and-effect relationship between urban development components and land carrying capacity in Surakarta. Identifying all variables were then arranged dynamically using the Causal Loop Diagram (CLD) techniques which were processed with vensim software. The CLD model shows that the land carrying capacity is influenced by supply and demand with the limitation that the supply model is influenced by built-up land and green open space and the demand model is influenced by population, investment and gross domestic product (GDP). There are 2 balancing loops that have negative feedback and 1 reinforcing loop that has positive feedback.

Keywords: Land Carrying Capacity, Supply, Demand, Causal Loop Diagram, Vensim

1. Introduction

Cities play a very important role in national economic development, but due to the high population and resource consumption, urban environmental degradation is a serious problem. It is generally believed that urban development and human activities will affect the ecological environment (Fang et al, 2017). Cities, as centers of human activity, can create environmental challenges such as greenhouse gas emissions and environmental degradation. The relationship between urban environments and human activities is a global research focus that focusing on urban ecosystem structure (including the impact of green spaces, water bodies, and air quality on residents' health), human activity patterns (traffic flow, land use changes, and their impact on environmental quality), the role of socioeconomic factors and the environment, and effectiveness policies and management (Zhou et al, 2024). In some developing countries, intense urbanization process accompanied by climate change has made cities more vulnerable when coping with the disturbances such as natural disasters, resources crises, political instability and financial crises (Li et al, 2020). It is estimated that almost half of humanity lives in cities. The world of the 21st century will be a largely urbanised world. This suggests that developing countries must be able to increase their capacity in the management of urban infrastructure, services and shelter in order to maintain urban capacity (Pertiwi, 2017).

Surakarta, also known as Solo, is a city located in Central Java, Indonesia. Surakarta has been a hub of cultural and economic activity in the region. The city has experienced rapid urban development, leading to a growing population and increasing demands for infrastructure and services. Mardiansjah (2018) stated that the city of Surakarta has fast and complex growth dynamics. The region experienced rapid urban population growth that tripled in size over the thirty years between 1980 and 2010. Furthermore, it is explained that the pattern of urbanisation and population growth shows a widening pattern to the periphery, with urban population growth in the periphery occurring faster than the stagnant growth in Surakarta. It is estimated that the stagnation in Surakarta is due to the limited potential land for urban development within its administrative area, which is also combined with the wide availability of potential land for urban development in the peripheral areas supported by the availability of regional road networks that connect the peripheral areas with activity centres in Surakarta. Based on Surakarta City Regional Regulation Number 6 of 2021 concerning the Regional Medium-Term Development Plan for 2021 - 2026, land utilisation in the Surakarta City area is mostly for settlements, with an area reaching 2889.8 ha while the rest is for economic activities and public facilities. There was an increase in residential land use from 2876.7 ha (2014) to 2889.9 ha (2018). This increase is caused by land conversion in Surakarta City which was originally for agricultural productive land turned into housing/settlement and also services.

Based on data from the Population Administration and Civil Registry Service of Surakarta, in 2022, it is stated that Surakarta has an area of 46.72 km² with a population of 583,961 people, the density figure for the City of Surakarta reached 12,499 people per km². The population growth rate in the period 2016 – 2022 is 0.81. Based on the data Surakarta Regional Environmental Management Performance Information 2022, land conversion is one of the environmental priority issues related to the availability of Green Open Space. Green Open Space in Surakarta has not yet reached the 30% target. The condition of green open space in Surakarta from 2018 - 2022 shows that the area of public green open space does not meet the requirement of 20 percent of the city area.

It was recorded that from 2018 – 2022 the area of Public Green Open Space was respectively 427.88 Ha (9.16 %), 357.92 Ha (7.66 %), 486.60 Ha (10.42 %), 355.23 Ha (7.6 %), and 458.71 Ha (9.82 %). It was further explained that the city of Surakarta is dominated by increasingly dense built-up land. It is difficult to find green open space in the city. There are concerns about land use irregularities triggered by several factors, including: The increase in population and spatial structure development policies. Meanwhile, the economic growth of the City of Surakarta from 2016 to 2019 always experienced an increasing trend, except in 2020 which experienced a decline due to the Covid-19 pandemic to -1.76% but then increased again to 4.01% in 2021 and will increase further in 2022 to 6.25 (BPS Surakarta City, 2023).

On the other hand, Surakarta Environmental Quality Index (EQI) 2022 shows value 59.42 which indicates a moderate condition (50 < EQI < 70). This value is derived from a combination of calculations from the Water Quality Index (50.98), Air Quality Index (80.06) and Land Quality Index (30.22). It can be seen that Land Quality Index indicates low range (25 < EQI < 50). It is found that the land quality index component is the most stressed and tends to be negatively impacted by the increase in population, gross income and per capita expenditure variables.

System dynamics modeling is one of the approaches in urban spatial planning. This modeling tries to offer a perspective that looks at the interactions between urban components (population and activity sectors in a city), which influence each other and produce certain dynamics. One of the hopes in developing this model is to support spatial planning activities, understand the city dynamically and city connection to other city systems. (Darmono, 2005). System dynamic is used as a method to make it easier to understand complex systems (Sterman, 2000). This model is an excellent method for understanding problems that arise in close loop systems where conditions are converted into observable information and carried out to change the initial conditions (Suryani, 2022). Developing causal loop diagrams (CLDs) involves identifying stakeholders and endogenous variables and formulating variable causal relationships (Dhirasana & Oz, 2019). Developing a causal loop diagram can help to identify the complex relationships and feedback loops that influence urban development. Based on this background, this research will analyze the variables, that

will be carried out on the land carrying capacity in Surakarta using a quantitative descriptive approach with a causal loop diagram which is part of the system dynamics model.

2. Methods

2.1 Research Site

Research activities will be conducted in Surakarta City, Central Java Province, Indonesia which is geographically located at 110˚45'15" -110˚45'35" East Longitude and 7˚36'-7˚56' South Latitude with a total area of 46.72 km² .

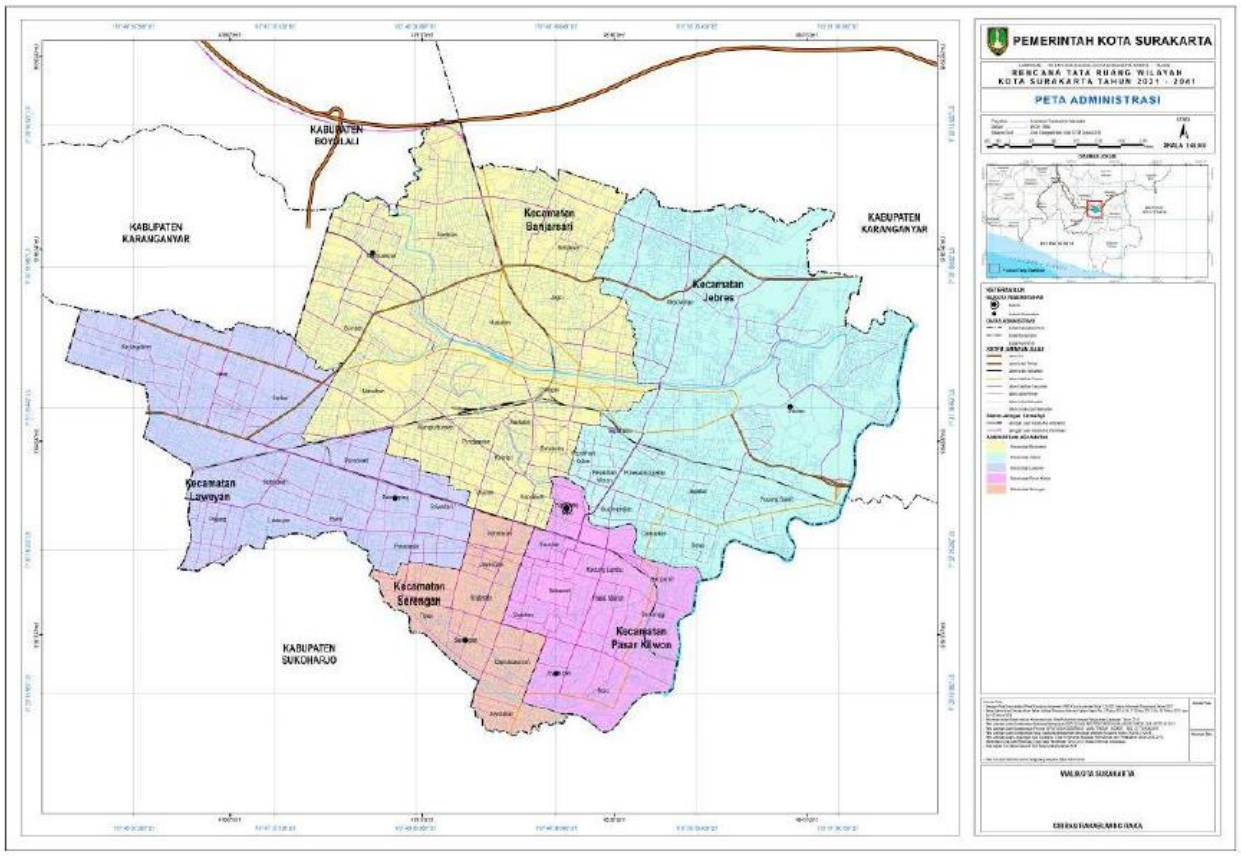

Figure 1. Administrative Map of Surakarta

2.2 Research methods

A quantitative descriptive approach with Causal Loop Diagram (CLD) analysis was used in this research. CLD is part of the dynamic system model. Modelling with system dynamics requires quantitative data for computer simulation. However, not all phenomena can be recognised through quantitative approaches. Wolstenholme (1990) in Rasyidi (2009) proposed to combine qualitative and quantitative approaches. These two approaches can be combined harmoniously and interrelate qualitative ideas with quantitative data so that information can be developed more broadly and comprehensively.

2.3 Research Steps

The research is divided into several steps according to system dynamics modeling using Vensim PLE v9.3.5 software. Vensim software can be used to conceptualise, simulate, analyse, and optimise dynamic system models starting from the creation of causal node diagrams or from the creation of stock and flow diagrams (Almamalik, 2021). There are two steps in developing the CLD, first step is problem articulation and second step is formulation of dynamic hypothesis (Sterman, 2000).

1. Problem Articulation

In problem articulation, modellers identify research problems and key variables or concepts. Problem articulation is also called 'conceptualisation', and 'problem identification and definition' (Dhirasana & Oz, 2019). In this step, the problem is determined, then identification and analysis of the problems to be studied are carried out. Data can be obtained from discussions with relevant parties, seeking additional research information that has been done before, collecting data, conducting interviews and direct observation. The process of articulating the problem can be done with reference mode and time horizon (Sterman, 2000).

a. Study of literature

Data was obtained through literature studies by studying the impact of urban development on land availability and studying models that have been used by previous researchers.

b. Data collection

At this steps is collecting secondary data. Data was taken from 2016 – 2022. The data required in the research is divided into availability (supply) variables and need (demand) variables.

2. Formulating a Dynamic Hypothesis

This step focuses on the formulation of dynamic hypothesis that can explain the feedback structure that is expected to have the ability to influence the problem behaviour . A frequently used structure development technique is the causal loop diagram (Sterman 2000, Rasyidi, 2009.)

a. Mapping

In the dynamic analysis method, the problem limitation is carried out by drawing a frame of mind, namely Big Picture Mapping (Thifalina, 2023).

b. Developing a causal loop diagram

Developing a causal loop diagram can help identify the complex relationships and feedback loops between different factors that influence sustainable urban development (Dhirasana & Oz, 2019). By visualizing these interactions, policymakers and urban planners can better understand the potential impacts of their decisions and interventions on the environment, economy, and society.

Causal loop diagrams are useful for, representing the conceptual model of the system designers (model), representing hypotheses regarding the causes of the dynamics (model) of the system, communicating important feedback aspects that are believed (to be) very important in a system (Prahasta, 2018).

c. Causal Loop Diagram Analysis

Positive sign (+) and negative sign (-) were given to indicate the relationship between one variable and another. A positive sign (+) can indicate a mutually reinforcing (R) relationship between variables. If the influencing variables or the cause increases, the affected variables or effect variables will also increase. Unlike the negative sign (-) which indicates an inverse relationship. If the influencing variables or the cause increases, the affected variables or effect variables will decrease. A negative sign indicates as balancing (B) (Prahasta, 2018).

3. Results and Discussion

Surakarta, as one of the big cities in Indonesia, is one of the most populous cities out of 35 districts/cities in Central Java Province, Indonesia. Surakarta devided into 5 district (Laweyan, Banjarsari, Serengan, Pasar Kliwon, Jebres) and 54 sub district. Based on data from Environmental Management Performance Information, 2022, Land use based on spatial patterns is dominated by cultivated areas (78.93%) mainly for residential purposes (61.53%) and trade and services (15.51%). The real pattern of conservation space is only 21.07%. Surakarta area has been affected by urban heat island (UHI) (a phenomenon or occurrence of an increase in air temperature in urban areas compared to neighbouring areas by up to 3-10°C) , which has a trend that continues to worsen from year to year (Putra et al, 2018). Data the development of Surakarta are presented in table 1.

Table 1. The Development of Surakarta City 2016 - 2022

	Unit	2016	2017	2018	2019	2020	2021	2022
Total population*	people	570,876	562,801	569,711	575,230	578,350	578,906	583,961
Built-up Land Area **	m^2	3,960.35	3,963.43	3,971.54	-	-	-	-
Public green open space ***	m^2	427.88	427.88	427.88	372.97	486.60	355.23	458.71
GDP****	Billions rupiah	29,975.87	31,685.48	33,509.9	35,441.11	34,815.97	36,211.25	38,475.98
Investment*****	Billion Rupiah	5,233.11	3,580.49	6,145.74	1,824.71	3,461.73	4,560.9	18,242.71

Source :
* Population Administration and Civil Registry Service Institution of Surakarta, 2016 – 2022
** BPS Surakarta City, 2016 – 2018
*** data.jatengprov.go.id/dataset/rasio-ruang-terbuka-hijau-publik-di-kota-surakarta
**** GDP Series 2010 Based on Constant Prices by Sectors, BPS Surakarta City, 2016 – 2022
***** Invesment and One Stop Integrated Service Institution of Surakarta, 2016 – 2022

Based on the Table 1, it can be seen that population development and built-up land area show an increasing trend. The development of green open spaces shows increase in 2020 but then decrease in 2021. Economic growth shows an increasing trend in GDP and a sharp increase in investment in 2022. In Surakarta, there is an increase in the area of settlements which indicates an increasing need for settlement land due to the higher population growth rate every year. It shows that there are 12 villages that have increased population density. The villages include Pajang, Kerten, Karangasem, Semanggi, Sangkrah, Pucang Sawit, Jebres, Mojosongo, Kadipiro, Manahan, Sumber and Banyuanyar. This is due to the increasing number of residents in limited settlement areas (Koesuma et al, 2022). related to the existence of public green open space, Surakarta has not reached 20% public green open space as required by the Ministry of Agrarian Affairs and Spatial Planning Regulation. The area of green open space will affect the value of the Surakarta Land Quality Index, where the Land Quality Index value in 2022 is in the low category. On the other hand, GDP growth is getting higher and investment growth has exceeded the target of reaching 243.46%. Economic development is the primary driver of a country's prosperity, but progress also poses significant challenges, especially the impact of economic activities on environmental quality (Febriana, 2019).

By literature study, it was found that the population increased in direct proportion to the consumption of natural resources. Increased consumption of natural resources, in a certain period, will exceed the carrying capacity of the environment. This condition is known as overshoot or exceeding the carrying capacity. (Fatimah et al, 2019). One approach to measuring environmental carrying capacity is the balance of Availability and Needs (Supply - Demand) approach. This approach is based on a balance between the availability or capacity of space/resources/territory and the needs of humans or other living creatures so that there is a threshold limit for adequacy or insufficiency of resources or space to support human life (Muta'ali, 2019). High population and economic density have brought water scarcity, land degradation, energy shortages, air pollution, and biodiversity loss, which have become key factors inhibiting social and economic development (Bao et al, 2022). The tendency of urban area development to be expansive and sprawling basically leads to the unsustainability of the urban environment, which is indicated by a decrease in environmental carrying capacity (Kustiwan & Ladimananda, 2012).

The results of analysis with basic data for 2022 using Minister of Environment Regulation Number 17 of 2009 concerning Guidelines for Determining the Carrying Capacity of the Environment in Regional Spatial Planning, the results obtained are that land availability (Supply) in Surakarta City is 2,440 Ha and

land requirements (Demand) in Surakarta City is 243,317.08 Ha. The value obtained for the Land Carrying Capacity Status in Surakarta City is Supply < Demand so that the land carrying capacity is declared a deficit or exceeded. Understanding land carrying capacity is essential for sustainable urban development in Surakarta. With the city's population continuing to grow and infrastructure expanding.

Based on literature and calculations of land carrying capacity in 2022, there are 5 key variables that influence land carrying capacity in the city of Surakarta. The variables that influence supply are the area of built-up land and the area of public green open space, while the variables that influence demand are population, investment value and gross domestic product (GDP). Variable identification is presented in table 2

Table 2.Variables that Influence Land Carrying Capacity in Surakarta City

No		Variable	
1	Green open space	• Public Green Space	
2	Built Up Land	• Housing / Settlements • Company • Service	• Industry • Etc • Land Conversion
3	Total population	• Birth • Death	• Inbound migration • Outbound migration
4	Gross Regional Domestic Product (GRDP)	• Construction • Wholesale and Retail Trade, Car & Motorcycle Repair • Information and Communication	• Processing industry • Provision of food and drink accommodation • Inflation
	Investment	• Micro business • Small business	• Medium business • Big business

Based on the formulation of relationships and interrelationships between city development variables and their relationship with land carrying capacity, it is presented picture mapping and a Causal Loop Diagram (CLD) with the Vensim PLE v9.3.5 application program. Ventana Simulation (Vensim) is a visual modelling tool that makes it easy to conceptualise, document, simulate, analyse and optimise dynamic system models (Suryani, 2022). In general, Vensim PLE (Personal Learning Edition) is a fully functional dynamical systems software that is free for personal and educational users, shareware for commercial users, and comes with model examples, help modules, and user manual documents (Almamalik, 2021). By mapping out these relationships, we can gain a deeper understanding of the complex dynamics at play and identify potential leverage points for intervention and improvement. The application of causal loop diagrams in scenario analysis for urban development in Surakarta offers a unique opportunity to explore the complex interconnections between various factors influencing the city's growth and sustainability.

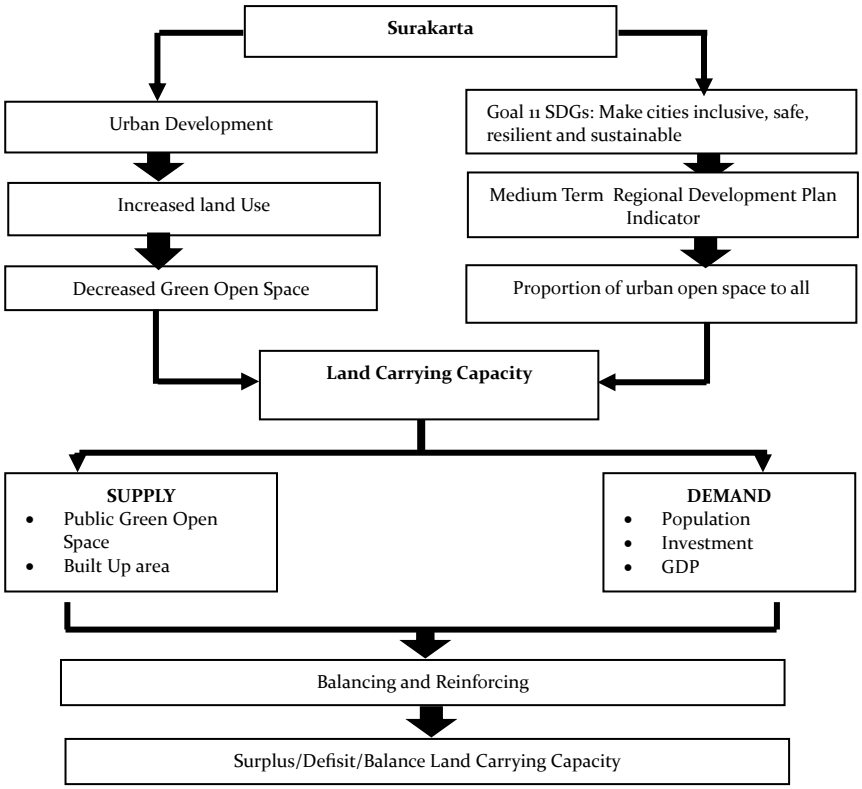

Figure 2. Picture Mapping

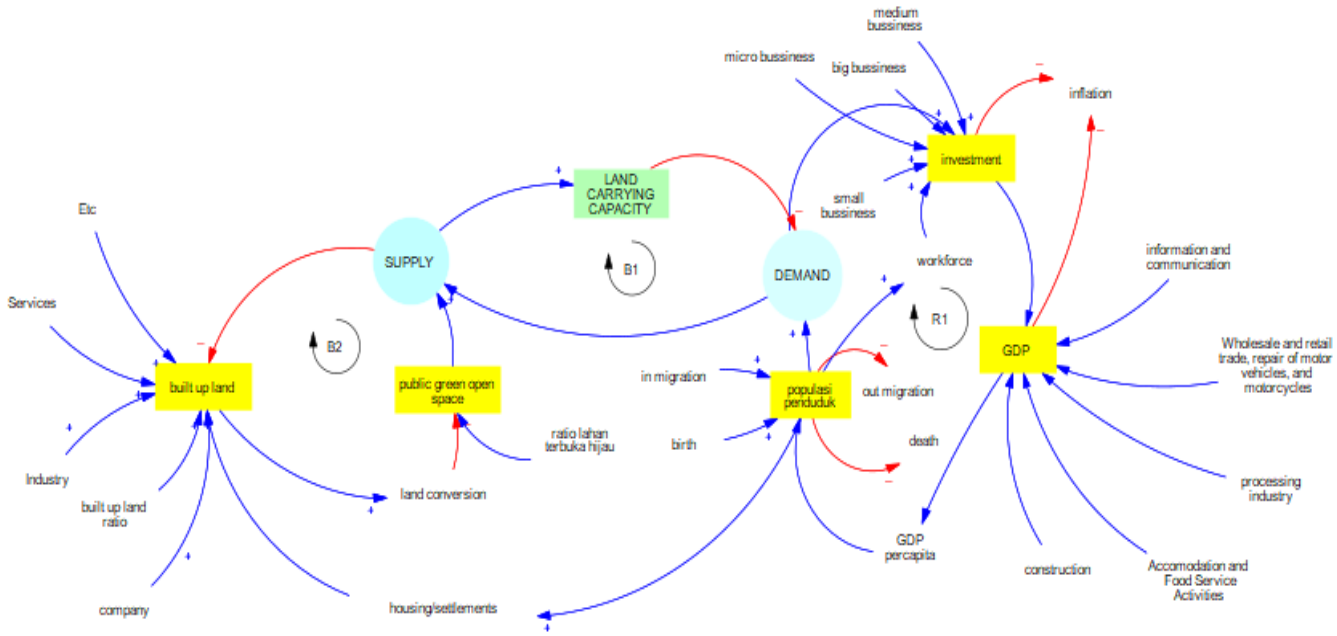

Figure 3. Causal Loop Diagram of City Development and Land Carrying Capacity in Surakarta City

The CLD diagram shows the interrelationship of variables that influence each other and illustrates cause and effect in the Land Carrying Capacity of Surakarta as follows:

a. Loop 1
   Land Carrying Capacity – Demand - Supply – Land Carrying Capacity – (B)
   Land Carrying Capacity is influenced by Land Availability (Supply) and Land Requirements (Demand). If supply increases, the land carrying capacity will be raised, while if demand increases, the land carrying capacity of will be decreased. This loop produces negative feedback /Balance (B).
b. Loop 2
   Supply – built-up land – land conversion – green open space – supply – (B)
   Built-up land will increase land conversion which will then reduce green open space, causing the supply/availability of land to decrease. This loop produces negative feedback/Balance.
c. Loop 3
   population – demand – investment – GDP – GDP per capita –– population – (R)
   The carrying capacity of cities are unable to support the scale of urban growth, posing great challenges to the sustainability of urban development. The increasing population will increase the need for land (demand), the population will also increase population consumption. Apart from that, population growth will also create a diversity of ideas and innovation, increase the workforce, and provide adequate infrastructure which will increase investment. This investment creates new jobs, increases productivity, and encourages consumption, all of which contribute to GDP growth. The business fields that are developing in Surakarta are Construction, Wholesale and Retail Trade, Car & Motorcycle Repair, Information and Communication, Processing Industry, Providing Food and Drink Accommodation. Increasing GDP in a sustainable manner increases per capita income and the quality of life of society as a whole. This loop produces positive feedback / Reinforce.

Land Carrying Capacity of Surakarta City is influenced by Supply and Demand (loop 1). To keep the Environment carrying capacity from being exceeded, two scenarios can be used. First, from the demand side, restraining the rate of increase in natural resource consumption by changing people's consumption patterns to be more efficient and wise and by utilizing technological interventions that can help support the availability of natural resources; Secend, from the supply side, restraining the rate of decline in carrying capacity to ensure the process, function and productivity of the environment runs well, among others, by improving the quality of services from the environment, utilizing resources in accordance with their capacity (Muta'ali,2019).

Supply is influenced by Built-up Land and Green Open Space (loop 2). Based on Prabowoningsih, 2018 , the main factor influencing the availability of green open space in residential and service trade areas is the allocation of green open space in spatial planning,. Changes in built-up land in Surakarta and reduction of open land have a high determination on temperature increase which leads to the Urban Heat Island (UHI) phenomenon (Putra et al, 2014).

Population growth, increasing GDP and investment are variable demand (loop 3). population and economic subsystems are sources of pressure throughout the urban ecosystem (Fang et al, 2017). Factors that cause a city to grow and expand in addition to urbanisation are the development of urban population activities in all aspects of life (especially economic aspects) and the process of concentrating population activities into the city concerned (agglomeration) (Ghalib , 2005). The increasing demands of urban populations create pressure on existing resources and lead to the fragmentation of green spaces. This trend is more common in developing countries and is especially prevalent in Asian cities (Siddique & Uddin, 2022). The factors that influence the lack of availability of green open space in Surakarta City are budget availability, green open space allocation in spatial planning, implementation of work plans related to green open space, awards in greening programmes, programme implementers, community participation, influence of community leaders, existence of green communities, absorption capacity of trees to CO_2, land availability, land value, and supervision of land use control (Prabowoningsih, 2018).

4. Conclusions

Urban development in Surakarta has been a key focus for policymakers and city planners in recent years. With rapid population growth and increasing urbanization, there is a growing need to understand the land carrying capacity of the city in order to ensure sustainable development. in Surakarta, ultimately guiding decision-making and planning efforts towards a more resilient and sustainable future. Based on the research results, a picture of the cause and effect relationship between variables is obtained which is presented in a causal loop diagram. There are 5 key variables that influence the carrying capacity of land in Surakarta City which are divided into supply and demand models. The supply model is influenced by the area of built-up land and the area of green open space, while the demand model is influenced by population, investment, and GDP. There are 2 loops with negative feed back (balancing) and 1 loop with positive feed back (reinforcing). These three loops must be managed well so that the land carrying capacity in Surakarta City does not become increasingly deficit. The causal loop diagram is then used as a basis for building a simulation model that can be used to develop and test alternative management policies. It is necessary to develop a simulation with a scenario to increase the demand for green open space so that the growth rate of green open space can reach at least 20% of Surakarta area. In addition, scenarios are also needed to increase supply so that the carrying capacity of land does not experience excessive deficits.

Acknowledgment

Thank you to all parties who have helped in collecting data and preparing this article. Especially for Environmental Office of Surakarta and Universitas Sebelas Maret Surakarta and also Surakarta City Government and other related agencies that have helped supporting data.

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