USING SYSTEMS DYNAMICS TO SUPPORT A CITY'S GROWTH AND DEVELOPMENT STRATEGY (GDS): A CITY OF JOHANNESBURG CASE STUDY

M RATHOGWA* and R MALOPE**

CSIR
Email: *MRathogwa@csir.co.za; **Rmalope@csir.co.za

ABSTRACT

The Growth and Development Strategy 2040 (GDS2040) envisions a transportation system that contributes to the resilience of the city and breaks the apartheid spatial form. The implementation of a cost-effective, dependable, safe, and efficient mass public transportation system is central to GDS2040. To this end, the GDS2040 states that "by the year 2040, the City will be pedestrian- and public transportation-oriented." According to GDS2040, this will manifest as reduced reliance on private automobile travel, decreased greenhouse gas emissions, and increased inclusiveness. The GDS2040 also acknowledges that transport solutions can only be effective if they are incorporated into a broader set of solutions that includes improved spatial planning, intergovernmental relations, and enhanced state capacity. This paper investigates the use of system dynamics to model the city's transportation system in support of GDS2040 to bring about a sustainable transport system.

1. INTRODUCTION

To resolve the increasing complexity of problems confronting society, Hjorth & Bagheri (2005) stresses the need to develop a systems thinking, "the ability to see the world as a complex system", in which we understand that 'you can't just do one thing' and that 'everything is connected to everything else'. There are various schools of thought and application fields for systems thinking, which include qualitative methods as well as formal system dynamics (SD) modeling (Rebs et al., 2018).

Using the system dynamics approach for the Growth and Development Strategy (GDS, 2040), the aim of this paper is to discuss a sustainable transport system. Adding to that, this paper gives an insight on how the model incorporates interconnected variables to secure a transport system that contributes to the capacity of the city. In essence, S.P. Shepherd (2014) stated that transportation systems are complex; they frequently involve multiple stakeholders or agents, resulting in feedback with varying time lags between responses from each type of user. However, system dynamics models provide a whole-system approach to transportation planning, demonstrating to policymakers the importance of these feedbacks and lagged responses.

2. PROBLEM STATEMENT

The Joburg 2040 GDS aims to respond to the city's numerous challenges and uncertain future. Up to date, sustainable transportation is still considered as a major challenge for the city (City of Johannesburg, 2017). To deal with change, the City of Johannesburg aims to strengthen the adaptive capacity of the city and its citizens, making them more resilient

to potential and unpredictable futures by putting in place a transportation system that contributes to the city's perseverance and breaks the apartheid spatial form (City of Johannesburg, 2017). To achieve this, a system dynamic approach is taken to ensure the sustainable transportation development of the transport system in the city.

3. LITERATURE REVIEW

3.1 Systems Dynamics

Forrester (1956) invented System Dynamics (SD) by merging applied control theory, information theory, decision theory, and other pertinent ideas and techniques. It allows for horizontal links across the scientific and social sciences by integrating structures, functions, materials, knowledge, and experiences (Zhihe & Shauai, 2013). SD is capable of addressing high-order, nonlinear, autofeedback, complex, and volatile system issues; it is an excellent method for studying the motion principles of complex systems, using the first-order differential equation with time to describe the dependence relationship between the rate of change of system state variables and such state variables or specific inputs (Coyle, 2017). The objective of system dynamics is to uncover the underlying structures and feedback processes that govern the behavior of a system, and to utilize this knowledge to forecast and affect future behaviour.

System dynamics is important because it allows for a better understanding of complex systems and their behaviour over time. This can lead to more effective decision-making and problem-solving in fields such as business, economics, and management. By identifying the underlying structures and feedback mechanisms that drive the behaviour of a system, system dynamics can help to identify key leverage points for intervention and can provide insights into the likely outcomes of different policy or management decisions. Additionally, system dynamics can help to highlight unintended consequences.

In interconnected systems, bad actions in all subsystems can affect others (Coyle, 2017). System dynamics is commonly used to conceptualize sustainability (Hjorth & Bagheri, 2005). This definition defines "sustainability" as a system state ideal and "sustainable development" as a means to achieve it, analogous to "survival" and "evolution" (Mirchi et al., 2012). Researchers say that, just as no one can forecast the future of evolution because it is so entangled with the species' interactions with its environment, considering sustainable development as a pathway with a known "end-state" is illogical.

Our values and system knowledge must constantly build it Coyle, 2017. However, Duran-Encalada & Paucar-Caceres (2008) stress that any sustainable scenario based on our values and system understanding must follow basic sustainability principles. System dynamics modeling can apply such ideas when relevant aspects are selected. With this in mind, we examine System Dynamics, one of several systems theory techniques, and how it may promote sustainable. System Dynamics can aid in understanding the dynamics of decision-making in complex situations, such as how policy objectives, strategies, incentives, or punishments in one part of the system influence other sub-systems and, ultimately, the behavior of the entire system (Rebs et al., 2018).

There are, nevertheless, a few existing studies that have used the System Dynamic to simulate and evaluate urban sustainability performance. Tan et al. (2018) stated that a dynamic system model which included six subsystems which are as follows: land use, population, transportation, water resource, solid waste and wastewater treatment, to evaluate the performance of the sustainability of the city of Taipei. According to Tan et al.

(2018) the model was never used for simulating the model outcomes in the cities in China directly because China has different characteristics of sustainable development.

There was a model based on integrated system dynamics and cellular automata for assessing the rate of urban growth. The study chose Shanghai, China, as a case study, which is not conducive to sustainable urbanization. Mavrommati et al. (2013) investigated a system dynamic approach for ecological sustainable development in coastal systems. The model was primarily concerned with the relationship between environmental and economic dimensions, with no consideration given to social dimensions. However, few studies have been conducted on the application of System Dynamics to sustainable development (Forrester, 2017).

In South Africa, SD has been used in *Sustainable Urban Development in Cape Town. Planning for Natural Resource based Service Provision with a Systems Dynamics Model* and research on obtaining *An easy-to-use spatial simulation for urban planning in smaller municipalities* (Systems Dynamics Society, 2021). SD has also been used in *Participatory systems approaches for urban and peri-urban agriculture planning: The role of system dynamics and spatial group model building* and *in Integrated spatial planning support systems for managing urban sprawl* (Systems Dynamics Society, 2021). Applications can also be found in greenhouse gases, freight, United Nations 2030 goals, the 2030 Agenda and Covid-19 (Systems Dynamics Society, 2021).

3.2 GDS2040

The GDS2040 includes a comprehensive plan for the future development of the city in areas such as infrastructure, economy, transportation, housing, and social services. It also addresses issues such as sustainability, resilience, and equity, and involves input from community members, business leaders, and other stakeholders. The strategy considers the city's current strengths and weaknesses and outlines specific goals and objectives for the future. To achieve this, the strategy includes a set of policies, programs, and projects that are designed to address the most pressing issues facing the city and to promote long-term growth and development.

The GDS2040 report has more sustainable outcomes, specifically to avoid activities and actions that may jeopardize societies and the environment's capacity to meet their needs over time. In this sense, 'sustainable development' necessitates an action plan or 'road map' for moving towards the ideal of sustainability; an ideal that must occur concurrently across the spheres of the environment, society, and economy. This is true regardless of how these spheres are defined or conceptualized to interact, or which values underpin these decisions.

3.3 Status Quo of Transportation in Johannesburg

The unusually low population densities in South African cities, relative to the rest of the globe, have a severe impact on the feasibility of public transportation, notably train and bus services (City of Johannesburg, 2017). Travel distance is much longer than in more densely populated cities elsewhere in the world. Car ownership is rising with most new growth being new entrants from smaller urban regions and rural areas. The city suffers numerous transport difficulties (City of Johannesburg, 2017).

According to the 2017/18 Quality of Life Survey conducted by the GCRO, the majority of Johannesburg residents (45%) commute via minibus taxi. This is followed by 28% who use

private automobiles, with only 4% using Rea Vaya/Metrobus and 0.4% using the Gautrain (City of Johannesburg, 2017). The rising usage of private automobiles and taxis has resulted in increased traffic congestions and the city's transport sector continues to be the greatest (38%) carbon emitter when compared to other sectors such as the industrial (28%) and the residential (26%) sectors (GRCO, 2017). In addition, a significant amount of working time is lost owing to traffic congestion (City of Johannesburg, 2017). Although the exact productivity cost of commuting has not been quantified, the accessibility of a city may influence investment decisions in the future (GRCO, 2017).

4. METHODOLOGY

The methodology used in this work is the high-level modelling procedure that is generally used when constructing a system dynamics model. The table below summarises the modelling process as described by the Eskom Research, Testing, and Development Centre at a high level.

4.1 High Level Modelling Process

Problem Articulation	• Focusing Question • Modelling time frame • Reference Modes • Literature Review
Problem Contextualisation	• Causal Loop Diagram • Model boundary chart • Behaviour over time
Systems Analysis	• Data mining • Preliminary calculations
Model Development	• Model Structure
Validation	• Scenario and sensitivity analysis • Work group meetings with subject matter experts • Theoretical and empirical consistency
Insights	• Policy design and evaluation • Recommendations

Source: Eskom Research, Testing and Development (2019)

5. RESULTS AND DISCUSSION

Strategies in the GDS2040 includes a comprehensive plan for the city's future development in areas such as infrastructure, economy, transportation, housing, and social services. In addition to addressing issues like sustainability, resilience, and equity, it solicits input from community members, business leaders, and other stakeholders. Indicators and their measures of success are indicated in the table below.

Table 1: Indicators of success from the GDS2040 (City of Johannesburg, 2017)

Indicators for Success from IDP	Model Variable
Outcome 1: Improved quality of life and development-driven resilience for all	• Average salary • Public transport safety • Population dynamics • Number of households • Transport Demand
Outcome 2: Provide a resilient, livable, sustainable urban environment – underpinned by infrastructure supportive of a low-carbon economy	• Energy consumption • Universal access • Road safety • Congestion • Spatial analysis • Fare management • Customer perceptions / service • Waiting time and queue length • Vehicle operating cost • Vehicle condition assessment
Outcome 3: An inclusive, job-intensive, resilient, and competitive economy that harnesses the potential of citizens	• Infrastructure condition • Travel time • Cost of travel • Employment rate
Outcome 4: A high performing metropolitan government that pro-actively contributes to and builds a sustainable, socially inclusive, locally integrated, and globally competitive Gauteng City Region	• Customer safety and security • Pax volume • Capability of department • Agility of department • Budget implementation department • Political will • Data Management

The Gautrain (provincially led) and Rea Vaya Bus Rapid Transport (BRT) system (city-driven) have ushered in a new era of mass public transport, but their use is still low compared to other modes. To address growing petrol prices, road infrastructure costs, and air pollution, Johannesburg should switch to public transit (City of Johannesburg, 2017). 55% of households utilize public transport weekly. Trains, taxis, and buses are included. By 2030, the City wants commuters to use public transport 20% more (City of Johannesburg, 2017).

Modal shifts offer economic and urban growth opportunities. As mentioned, a public transport agenda must also include campaigning for metro-rail safety and reliability (City of Johannesburg, 2017). This is not a City obligation, although it is essential to the BRT,

Metrobus, and Gautrain transport network. Transportation and civic initiatives including inclusive economic growth and development must be stressed (City of Johannesburg, 2017).

Large-scale transportation enhancement plans are ideal for creating jobs, developing scarce skills, and training young engineers. They empower women and youth by participating in transport value chain operations (City of Johannesburg, 2017). The design process must optimise these potential to create an enhanced transport system that fits our 2040 vision for the city. To accommodate transit changes, municipalities must make infrastructural and land use decisions (City of Johannesburg, 2017).

Towns must prioritise passenger transit. This requires fixing municipal workforce productivity, maintenance, congestion, and delays. Consumer appeal and efficiency will boost passenger transit (City of Johannesburg, 2017). Adding articulated or double-decker buses to popular routes, eliminating or downsizing less-used itineraries, or giving priority to higher-occupancy vehicles through dedicated bus lanes or high-occupancy/toll lanes (HOT lanes) can help the government better direct supply to where it is needed most. To lessen peak-hour traffic and spread out commuting hours, travel behaviours must be changed. Staggered workdays and flexible hours should be supported by employers. The City's 300,000-person structures may hasten this change by implementing these concepts (GRCO, 2017).

Real-time monitoring of driving conditions, intelligent traffic patterns that use data analytics to predict backups and redirect drivers to alternate routes, dynamic tolls that increase during peak hours (or differentiate between lanes), and other measures can also reduce congestion (GRCO, 2017). Simple electronic signs on vital arteries can warn vehicles of approaching traffic bottlenecks and suggest less congested routes.

Focus group discussions suggested creating successful venues to engage multiple stakeholders, including individuals, the private sector, and others, to promote road safety and cultural change. The city's economy and population depend on transport (City of Johannesburg, 2017). Public transportation reduces carbon emissions, improves socioeconomic performance, and expands citywide participation. The City is dedicated to improving its transport infrastructure to reduce congestion, lower its carbon footprint, minimise transit costs for the poor, and build an efficient and linked transport network (GRCO, 2017).

There are several ways that government transport departments in South Africa can be improved, as per insights from the model. These are listed below.

- Investing in infrastructure: The government can invest in the development and maintenance of transportation infrastructure, such as roads, public transport systems, and airports, to improve the efficiency and reliability of the transportation system.
- Reducing corruption: The government can take steps to reduce corruption in the transportation sector, such as implementing transparency and accountability measures, and strengthening oversight and enforcement mechanisms.
- Improving public transportation: Government can invest in the improvement of public transport system, such as providing more efficient, affordable, and safe services, and making them accessible to all people.
- Encouraging the use of alternative fuels: The government can encourage the use of alternative fuels, such as electric vehicles, and invest in the development of renewable energy sources to reduce the ecological footprint of transportation.

- Improving coordination and collaboration: The government can improve coordination and collaboration between different government departments and levels of government to ensure that transportation policies and programs are implemented effectively.
- Developing sustainable transportation policies: The government can develop sustainable transportation policies that promote the use of public transport, walking and cycling, and reduce the use of private cars.
- Investing in technology: The government can invest in new technologies to improve the efficiency, safety and security of the transportation system.
- Building capacity: The government can invest in training and development opportunities for transportation sector employees to build their capacity and improve their skills.
- Improving monitoring and evaluation: The government can improve monitoring and evaluation systems to track the progress of transportation policies and programs and identify areas for improvement.

The factors speak to the critical variables of the model, that mainly focus on the agility, capability, and the budget implementation of the government department as it gears and prepares to meet the 2040 goals successfully.

The figures below show the outcomes from the model. The GDS2040 sustainability index helps us track how the city would perform over the next 17 years as it continues working towards addressing the transport sustainability backlog.

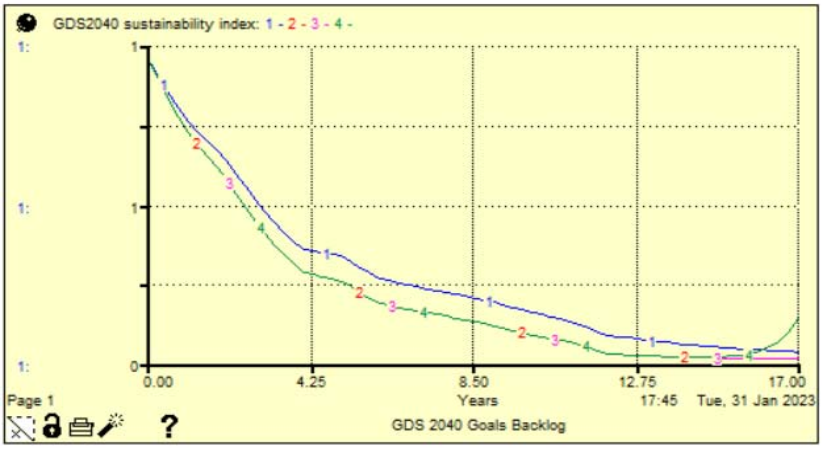

Figure 1: GDS2040 Index over time

Figure 2: Variable highlighted from the model

The five variables highlighted from Figure 1 above are ***Energy consumption per capita, Fare Revenue, Rate of addressing public transport backlog, Rate of traffic congestion and Public Transport Trip Length.*** The figure above shows how the variables that are highlighted as the key action variables behave overtime.

The development of a systems dynamics model is primarily the product of discussions among important role players. As a result, a systems dynamics approach tends to promote role players' active participation. In a systems dynamics model, both quantitative and qualitative variables of interest can be included. Feedback loops guarantee that the modelling process accounts for unforeseen consequences.

The ability to simulate the system in the past provides for better model validation. Causal loop diagrams and the associated models can be difficult to represent to the point where others who did not engage in the model development process may perceive them as confusing. In many cases, the lack of empirical evidence to describe reference behaviour outcomes may result in too many scenario variables within the model, making it vulnerable to many unknowns.

There are several factors that can affect the city’s ability to reach their GDS2040 goals as highlighted in the results from the model. Some of the most important ones include:

1. Political instability: South Africa's political landscape is complex, and changes in government can lead to changes in policy and personnel, which can disrupt the functioning of government departments.
2. Corruption: Corruption can undermine the effectiveness of government departments by diverting resources away from their intended uses, and by creating an environment in which officials are more concerned with lining their own pockets than with serving the public.
3. Bureaucratic inefficiencies: Government departments in South Africa are often plagued by bureaucratic inefficiencies, which can make it difficult for them to deliver services effectively.
4. Lack of capacity: Some government departments may lack the capacity to carry out their mandates effectively, which can be due to inadequate training, lack of resources, or poor management.
5. Limited accountability: The lack of transparency, lack of oversight and limited accountability mechanisms can make it difficult for government departments to be held accountable for their actions, which can lead to poor governance.
6. Socio-Economic challenges: poverty, unemployment and inequality are persistent challenges in South Africa that can affect the governance of government departments, especially those related to the provision of basic services. The high rate of service delivery protests in South Africa can indicate that citizens are not satisfied with the services provided by government departments, and this can be an indication of poor governance.
7. Race and Ethnicity: The legacy of Apartheid in South Africa has led to an unequal distribution of resources and opportunities which can affect the governance of government departments.
8. A lack of coordination and collaboration between different government departments and levels of government can also hinder the effective governance of government departments and encouraging public participation: The government can encourage public participation in the transportation sector by involving the community in the development and implementation of transportation policies and programs.

6. CONCLUSION

Multiple aspects determine the sustainability of transportation in a city, including air pollution, traffic congestion, the availability of public transport choices, the accessibility of transportation for all individuals, and the ecological footprint of the transportation sector. Transit sustainability can be achieved in numerous ways, including by investing in public transportation, supporting the use of non-motorized transport, such as walking and cycling, and encouraging the use of alternative fuels, such as electric automobiles.

It is possible and desirable to represent the behaviour of a city's transportation system using systems dynamics models. Systems dynamics is very useful for modelling complex phenomena like spatial transformation.

Turning around the transportation system and going toward the trajectory of the city reaching its GDS2040 goals, such that it contributes positively to sustainable outcomes is a task that needs cities to adopt various well-coordinated initiatives and to be vigilant about unintended impacts. Consequently, systems dynamics modelling should be an intrinsic aspect of urban development planning. However, deploying a systems dynamics model in a city necessitates a substantial investment in research to calibrate the model.

As opposed to being utilized as a forecasting tool, a model of system dynamics should be used to enable dialogues between key actors. In order to minimize alienation from what may be deemed complex model representations in the form of spider-web diagrams, role players who will use the findings should ideally be part in the model building process.

Consequences of actions and the ability to demonstrate how modest changes in one element of a system can have significant repercussions on the entire system. This can assist companies in recognizing and preventing possible problems before they develop.

7. REFERENCES

City of Johannesburg. 2017. *GDS2040,* Johannesburg: City of Johannesburg.

Coyle, RG. 2017. System Dynamics Modelling: A Practical Approach. *A Practical Approach, Journal of the Operational Research Society,* pp. 544-544.

Doolan, M & Featherston, C. 2012. *A Critical Review of the Criticisms of System Dynamics,* s.l.: System Dynamics Society.

Duran-Encalada, J & Paucar-Caceres, A. 2008. *System Dynamics Urban Sustainability Model for Puerto Aura in Puebla, Mexico,* puerto Aura: s.n.

Forrester, J & Emeritus, G. 1991. *System Dynamics and the Lessons of 35 Years,* s.l.: Massachusetts Institute of Technology.

Forrester, JW. 2017. Journal of the Operational Research Society: Industrial Dynamics. *Industrial Dynamics,* pp. 1037-1041.

GRCO. 2017. *2017/2018 Quality of Life Survey,* s.l.: GRCO.

Hjorth, P & Bagheri, A. 2005. *Navigating towards sustainable development: A system dynamics approach,* Lund: Lund University.

Mavrommati, G, Bithas, K & Panayiotidis, P. 2013. *Operationalizing sustainability in urban coastal systems: A system dynamics analysis,* s.l.: Panteion University.

Mirchi, A, Madani, K, David, W. & Sajjad, A. 2012. *Synthesis of System Dynamics Tools for Holistic Conceptualization of Water Resources Problems,* Florida: Water resource management.

Nabavi, E, Daniell, K & Husain, N. 2016. Boundary matters: The potential of system dynamics to support sustainability? *Journal of Cleaner Production.*

Pourbafrani, M, Van, ZS & Van Der, AW. 2020. *Scenario-Based Prediction of Business Processes Using System Dynamics,* s.l.: RWTH Aechen University and Fraunhofer Institute for Applied Information Technology.

Rebs, T, Brandeburg, M & Seuring, S. 2018. *System dynamics modeling for sustainable supply chain management: A literature review and systems thinking approach,* Karssel: University of Karssel.

Shepherd, SP. 2014. *A review of system dynamics models applied in transportation,* Leeds: Institute for Transport Studies, University of Leeds.

Systems Dynamics Society. 2021. *Prevoius Conferences.* s.l., International Systems Dynamics Society.

Tan, Y, Jiao, L, Shudai, C & Liyin, S. 2018. *A system dynamics model for simulating urban sustainability performance: A China case study,* Hong Hong: The Hong Kong Polythenic University.

Zhihe, C & Shauai, W. 2013. *Application of System Dynamics to Water Security Research,* Guangzhou: Department of Water Resources and Environment.