# USING SYSTEMS DYNAMICS MODELLING TO FACILITATE SUSTAINABLE DECISION MAKING AND IMPROVED PLANNING AND IMPLEMENTATION OF INTEGRATED PUBLIC TRANSPORT NETWORKS (IPTN) AS EFFECTIVE SPATIAL TRANSFORMATION INSTRUMENTS IN SOUTH AFRICAN CITIES

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Integrated Public Transport Networks (IPTNs) can contribute positively towards spatial transformation. The rate at which this is feasible is contingent upon the nature of decisions made by planning agencies, households, and businesses. The paper demonstrates the use of a systems dynamics modelling platform to simulate the dynamic fusion of decisions (and non-decisions) by the various role players who influence the performance of IPTNs, as well as the effect of their decisions on the performance trajectory of IPTNs as spatial transformation instruments in South African cities. The research demonstrates that underestimating and mismanaging the inherent interdependencies of the decisions made by the actors in the development and execution of IPTNs can have a substantial impact on the rate of spatial transformation. In order to turnaround the sustainability trajectory, a city will need to investigate various interventions while turning an eye out for any unintended consequences of decisions and the prospective repercussions of the interventions. In this sense, the model turns into a tool for facilitating discussions among stakeholders who are interested in the results.

## 1. Introduction

The chapter explores the use of systems dynamics framework for modelling the contribution of a city's transport system to spatial transformation. In accordance with a definition of a sustainable transport system presented by Holden et al. (2013), a spatially transformed city is considered a city advancing a sustainable transport agenda, which seeks to maximise, concurrently, inter-generation equity, intra-generational equity, long term ecological sustainability and also satisfies basic human basic needs. In addition to the definition advanced by Holden et al. (2013), which is essentially founded on the outcomes of the World Commission on Environment and Development (WCED, 1987), a spatially transformed city adopts financially viable transport solutions.

Systems dynamics modelling framework is considered appropriate because urban transport systems are complex (Rodrigue, 2020). In particular, overcoming the apartheid spatial planning legacy in South Africa will most certainly require the use of tools beyond those used in traditional transport planning. Observed by the authors suggests that transport planning in South African cities tends to be a secluded undertaking, with little functional interaction with other built environment disciplines, to the extent that transport planners rely on deterministic planning tools with little or no feedback mechanisms. Such a secluded approach limits the transport system capacity to meaningfully contribute to spatial transformation, which is inherently a multidisciplinary problem.

The chapter provides the approach process adopted to build a systems dynamics model to evaluate the transport system's capacity to transform spaces, and further discusses selected results for illustration purposes. Primarily, the chapter answers two questions: (1) To what extent does systems dynamics modelling platform offer a better alternative to established transport planning tools on the subject of spatial transformation, if any?, and (2) What methodological weaknesses should be overcome by systems dynamics framework for wider adoption in spatial transformation modelling?

## 2. Background

The preamble of the National Land Transport Act (Act 5 of 2009) (NLTA), which is cardinal legislation for land transport in South Africa, makes a political statement that the purpose of the Act is to: "*To provide further the process of transformation and restructuring the national land transport system initiated by the Land Transport Transition Act of 2000*". Implicitly, the statement requires land transport to be treated as a system, and further acknowledges that the necessary transformation and restructuring of the system are processes. Although the NLTA does not define transformation, in the context of this chapter spatial transformation is change necessary to give effect to the Constitution of Africa, including what the Constitution refers as freeing the potential every person, and having an environment that benefits present and future generations. It is imperative for transport planning authorities to demonstrate that that when plans are implemented they will free the potential of each person, and also create an environment that will benefit both the present and future generations.

The work draws from conversations between the authors and officials in five South African cities, namely Ekurhuleni, Johannesburg, Buffalo City, Nelson Mandela Bay, and Mangaung, which are among cities implementing integrated public transport networks (IPTNs). By definition, in terms of the National Land Transport Act (Act 5 of 2009), IPTNs promise to "*integrate public transport services between modes, with through-ticketing and other appropriate mechanisms to provide users of the system with the optimal solutions to be able to travel from their origins to destinations in a seamless manner".* Since 2007, the South African government has been investing several billions of Rand every year to implement IPTNs. Politically, questions about the scope for such an investment to transform urban spaces in order to dismantle the apartheid legacy remain largely unanswered by traditional transport planning methods which are mainly designed to guide budgeting for infrastructure delivery.

Through a bibliometric study of applications of systems dynamics, Shepherd (2014) shows that the modelling framework has been particularly useful for modelling holistic systems with feedbacks and delays between actors in the system, including studies commissioned by the European Commission. Areas of application in transport include dynamics on the take-up of alternate fuel vehicles, supply chain management affecting transport, infrastructure maintenance, and the business of airlines. Similarly, a bibliometric study by Torres (2019) shows a wide ranging application of systems dynamics modelling in areas that include the study of ecosystems, health care, waste management, climate change and energy. The chapter extends this wide range of applications by exploring the extent to which systems dynamics framework can be used for modelling the contribution of transport to spatial transformation.

## 3. Literature review

The use of traditionally fragmented and mechanistic science is not able to cope with complex, self-organising systems about sustainability which require non-linear and organic thinking of systems thinking (Hjortha and Bagheri, 2005). As a corollary, improved understanding of how different components of a system work together, is necessary for improved understanding of the system.

The emergence of systems thinking as a discipline since the late 1950s has gone through an evolution from basic mental models to the introduction of modelling software that is able to simulate system behaviour (Richardson, 1996). Nonetheless, simulation models are constructed on the basis of causal loop diagrams, which represent causal linkages between elements that make up a system. In essence, therefore, a causal loop diagram is a mental model representation of how elements of a system cause each other to change over time, and in that way represent system behaviour.

Torres (2019) provides an extensive bibliometric review of the application of systems dynamics in complex problems. Shepherd (2014) conducts a bibliometric review of system dynamics application in transport. In southern Africa, Rich et al. (2018) illustrates how systems dynamics can improve participatory approaches for stakeholder inclusion in urban and peri-urban agriculture planning. Mupfumira et al. (2015) present a model liberalisation impact of public transport in the city of Harare. Das (2020) models the possible trajectory of Bloemfontein as a smart city. Van de Merve et al. (2015) model opportunities for reducing greenhouse gas emissions as it relates to the shift of freight from road to rail. Jonker et al. (2017) used a systems dynamics to model the implications of biofuel production in the Western Cape Province.

The complexity of spatial transformation in South Africa lends itself to systems dynamics modelling. However, there is no case study to date, that has explored the use of systems dynamics for modelling spatial transformation, particularly as it relates to the contribution of transport and mobility. Using system dynamics modelling may be able to answer longstanding questions such as "*Are We Achieving Spatial Transformation in South Africa*?" (Maritz et al., 2016); and to complex interrelationships between state policies and practice identified by Todes and Harrison (2015).

## 4. Methodology

The work sought to create a systems dynamics model that is able to simulate the dynamic contribution of a city's transport system, in the form of an integrated public transport network, to spatial transformation. The contribution of the city's transport systems was considered highly correlated with a sustainable transport system as defined by Holden et al. (2013) which is captured in the form of Table 1. The metrics proposed Holden et al. (2013) for the transport system are equivalent to the United Nations' "Our Common Future" report (WCED, 1987) metrics. The year 2030 is selected for the purpose of reporting on Sustainable Development Goals. In addition to the metrics proposed by Holden et al. (2013), through conversations with officials from with South African cities, a further metric on the financial viability of the public transport solutions was added. Financial viability is defined as the extent to which a public transport is able to cover its operating costs from operational revenue, with a target of 100%. Furthermore, for South African cities, the requirement of satisfying basic human needs through provision of a minimum of 9.2 motorised kilometres per capita per day was considered unnecessary, since it is already met for South African cities. Public transport accessibility level is a composite measure comprising variable characterising quality and level of access to public transport (500m physical access to a service with 30 minute headways; fatal road crashes per 100 000 population; perception of security; public transport service speed; perception of quality of public transport service information; perception of quality of infrastructure for persons with disabilities; perception of quality of non-motorised transport infrastructure; and proportion of household income spent on public transport). Each of the constituent variables are normalised to system targets, such that they add to a maximum of 1.

**Table 1: Metrics for a sustainable transport system**

| Dimension | Overall indicator | Equivalent transport system indicator | Estimated 2030 threshold |
|---|---|---|---|
| Safeguarding long-term ecological sustainability | Yearly per capita ecological footprint | Daily per capita energy consumption for passenger transport | Maximum 5.6 kWh per capita per day |
| Satisfying basic human needs | Yearly per capita GDP purchasing power parity | Daily per capita travel distance by motorised transport | Minimum 9.2 km per capita per day |

| | | | |
|---|---|---|---|
| Promoting intra-generational equity | Gini coefficient | Public transport accessibility level | Public transport accessibility of 3 |
| Promoting inter-generational equity | The amount of renewable to total energy production | The amount of renewable to total energy used for transport | Minimum of 15% |

Source: Holden et al. (2013)

A composite index, referred to as an IPTN sustainability index is a weighted sum of four key variables, namely: (i) financial viability; (ii) daily per capita energy consumption for passenger transport; (iii) public transport accessibility and (iv) the amount of renewable to total energy used for transport level. Each of the variables are normalised to targets, such that they add up to a maximum of 4.

A systems dynamics model itself is a system of difference equations in which variables considered stocks (reservoirs) represent a cumulative state that is affected by inflow variables controlled by valves as well as outflow variables that are also controlled by valves. For each time step (one year in the context of the case study model) the state of each variable in the system is computed through numerical integration, on the basis of relationships that have been coded. STELLA systems dynamics software was used for the purpose.

Other variables of interest embedded in the model include household formation rate; trip length distribution; development density; energy intensity; agility of the city; capability of the city; unit transport cost; city's budget relative to need; and

Prior to model development, a series of technical workshops were held with officials from each city in order to construct causal loop diagrams representing the contribution of transport to spatial transformation. A version of one of the causal loop diagrams is depicted in Figure 1.

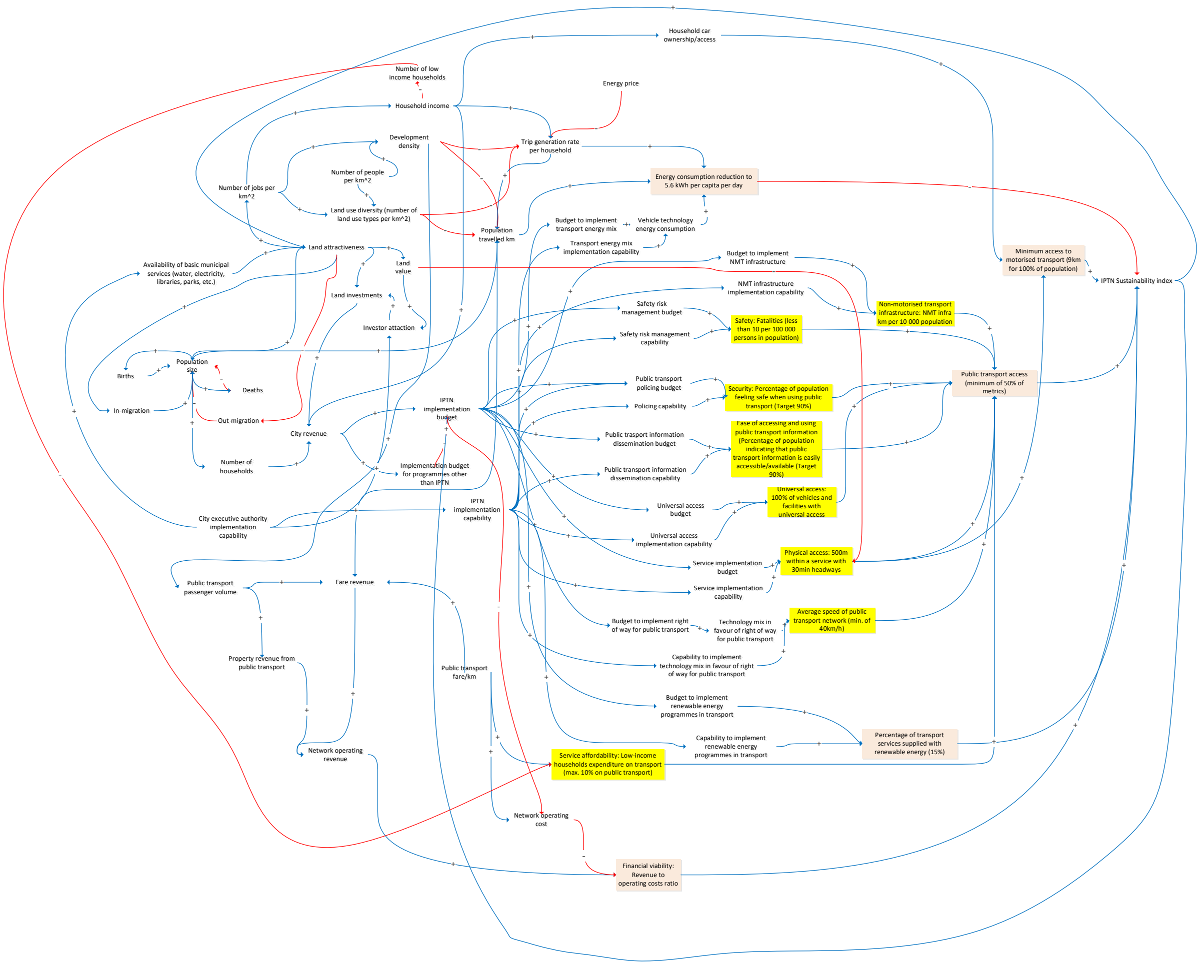


**Figure 1: A causal loop diagram from a technical session with city officials**

The causal loop diagram was translated to a systems dynamics model, whose structure is depicted in Figure 2. The model was calibrated using various datasets for each city, and well as relationships from literature or secondary datasets. Where relationships could not be established, such variables became scenario variables. The model is typically run for a 15-year period 2015/16 to 2030. Validation is achieved through retrospectively confirming the values of variables for time periods that have already passed.

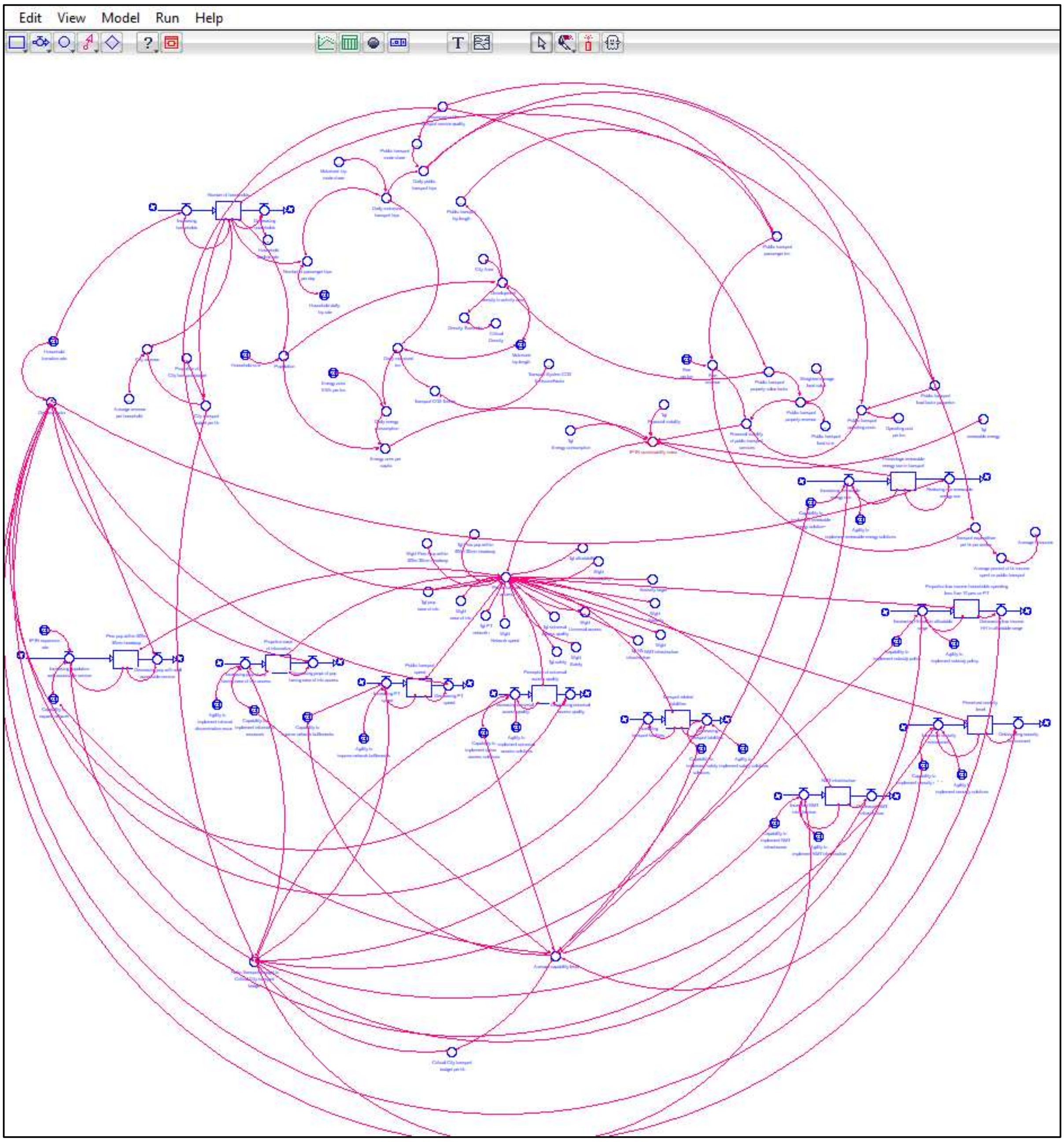


**Figure 2: Systems dynamics model**

## 5. Results

Figure 3 depicts selected baseline model outputs over a period of 15 years, showing on the one hand the individual variables forming part of the IPTN sustainability index, and on the other the actual IPTN sustainability index.

Indications are that the typical business as usual trajectory results in the transport system contributing lesser to sustainable outcomes. In another scenario evaluation, depicted in Figure 4, where the agility and capability to expand the IPTN for improved access, some marginal gain is realised. However, expanding the expanding the network in isolation of other interventions, which is typically what cities tend to do, while it does stabilise the system somewhat, does not result in a turnaround. Turning around the trajectory will require a city to explore multiple interventions, while observing potential effects of the interventions, and unintended consequences of choices, on the systems as a whole. In this way the model becomes a tool to facilitate conversations among stakeholders with interest in the outcomes.

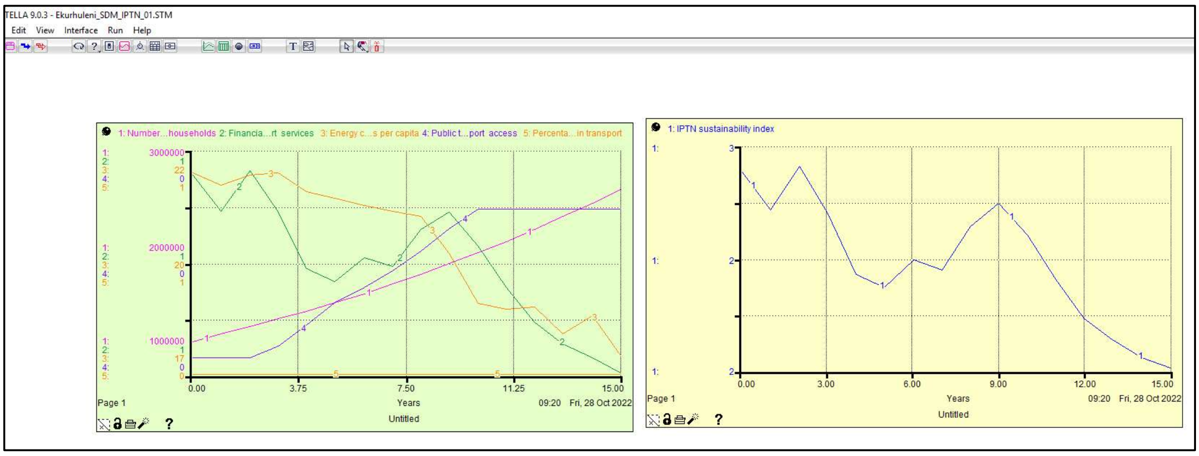


**Figure 3: Baseline model outputs**

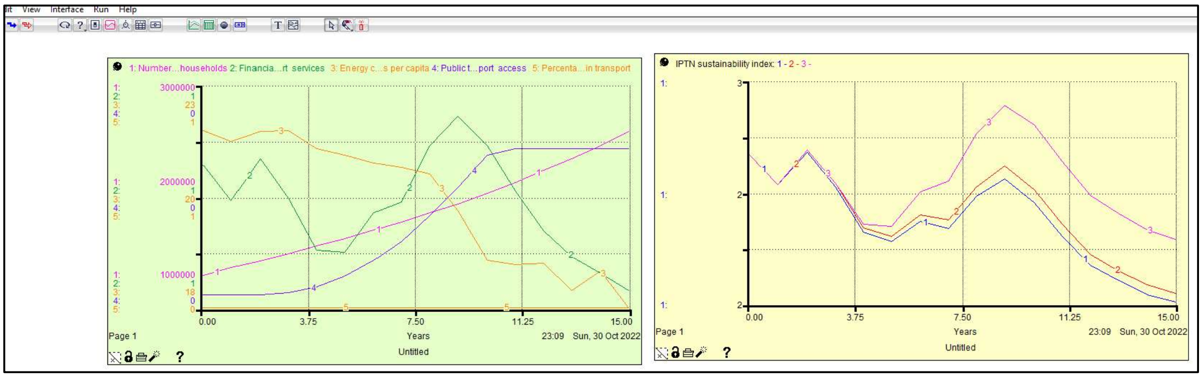


**Figure 4: Profile following changing of selected variables**

The two research questions are answered as follows:

(1) To what extent does systems dynamics modelling platform offer a better alternative to established transport planning tools on the subject of spatial transformation, if any?
  a. The building of a systems dynamics model is essentially a result of conversations among key role players. Therefore, a systems dynamics model tends to improve active participation of the role players.
  b. A systems dynamics modelling is able to take incorporate both quantitative and qualitative variables of interest in the model.
  c. Feedback loops ensure that unintended consequences are accounted for in the modelling process.
  d. The ability to model the system retrospectively allows for improved model validation.

(2) What methodological weaknesses should be overcome by systems dynamics framework for wider adoption in spatial transformation modelling?
  a. Causal loop diagrams and the resulting models can be cumbersome to represent, to the extent that they may be seen as complicated by those who did not participate in the model building process.
  b. In many instances, the absence of empirical evidence to depict reference behaviour results may result in too many scenario variables within the model, and in turn render the model susceptible to many unknowns.

**5. Conclusions**

It is possible and desirable to use systems dynamics modelling represent the behaviour of a city's transport system. Systems dynamics also lends itself well for modelling complex subject such as spatial transformation.

Turning around the transport system to contribute positively to sustainable outcomes is an undertaking that requires cities implement well-coordinated multiple interventions, and being actively conscious of unintended consequences. Therefore, systems dynamics modelling should form an integral part of development planning in cities. However, implementing a systems dynamics model in a city requires considerable investment in research to enable model calibration.

A systems dynamics model should be used to facilitate conversations among role players as opposed to being used as a predictive tool. Ideally, role players making use of the results should be involved in the model building process in order to minimise alienation from what could be considered complicated model representations in the form of spider-web type diagrams.

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