A SYSTEM DYNAMICS EXPLORATION OF PORT-CITY DEVELOPMENT

The Case of Tema, Ghana

MSc thesis

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EXECUTIVE SUMMARY

Research problem

Developing country cities are expected to expand rapidly over the coming decades, increasing pressures on their environment (United Nations, 2014). Because their expansion takes place in a more rapid and uncoordinated fashion, regions of ecological importance near cities experience more encroachment and haphazard development compared to countries that are already more developed (Cohen, 2006).

Large-scale infrastructure projects such as ports can have a significant impact on the development of nearby cities. While benefits generated by ports spill outside their immediate region, port cities experience negative externalities: congestion, pollution, land use issues and green space encroachment. This local-global mismatch of port infrastructure is becoming more important as containerization and increasing contestability of port hinterlands increases competition between ports, and increases the pressure for efficiency, port investments and the involvement of private parties (Rodrigue, Comtois, and Slack, 2017; Merk, 2013; Musso, Benacchio, Ferrari and Haralambides, 2000).

Social conflicts related to port development, involving port authorities, community groups, local business community, national and local government, are becoming increasingly relevant (Musso, Benacchio, Ferrari, and Haralambides, 2000). As such, port planning can no longer be based exclusively on the opinions of engineers, infrastructure specialists, transport economists or lawyers. Port planning needs to take into account the relationship between the port and the city, the economic and environmental impacts, and the stakeholders (Moglia and Sanguineri, 2003). As port communities provide ports with their social license to operate, port managing bodies have been pushed to adapt their strategies towards involving local community stakeholders in the port planning process and incorporating sustainability indicators in their reporting on port performance (Ircha, 2012; Adams, Quinonez, Pallis, and Wakeman, 2009; Dooms, 2014).

Traditional port impact studies are still of use in such an integrated port planning process, but they have two important drawbacks: firstly, they present only a static picture of expected port impacts, ignoring the effects of port development over time, changes in port operations (e.g. automation) and uncertainties influencing the port-city system. Secondly, while they can serve as an important tool to the community in understanding the structure of a port as well as its immediate economic effects, they tend to overestimate benefits while underestimating negative impacts (Musso, Benacchio, Ferrari, and Haralambides, 2000).

Rather than as static, separate entities, ports and their cities should be considered as single complex adaptive systems, characterized by mutual positive and negative interdependencies and with non-linear processes (Fusco Girard, 2010). However, empirical studies of ports systems and urban systems often study these systems separately. The current literature regarding the integrated sustainable development of port cities is rather limited (Merk, 2013; Xiao and Lam, 2017). There exists a need for research on port-city policy effectiveness that addresses the complexity of sustainable urban development in the long term (Merk and Dang, 2013). An ex-ante evaluation method is needed that takes into account the economic, environmental and social trade-offs that exist regarding sustainable port-city development, including metrics for both port performance and socio-economic impacts (Fusco Girard, 2010; Xiao and Lam, 2017; Musso, Benacchio, Ferrari, and Haralambides, 2000). This study aims to contribute to deepening understanding of sustainable port-city development.

Research approach

In this master thesis project, which is connected to the Integrated and Sustainable (Green) Ports in Africa study, the system dynamics modelling methodology is applied to model the impacts of port infrastructure investments on the development of the Ghanaian port city of Tema, where a 1.5 billion dollar port expansion is currently taking place. The following research question is used to guide the research effort:

"How can system dynamics modelling be used to represent the development of the city of Tema and its port and evaluate interventions for sustainable port-city development in an African context?"

Case study data and local stakeholder values are used to demarcate and guide the modelling effort. Factors of interest include road congestion, green space encroachment, and informal settlement resulting from port expansion and urban development. Explicit assumptions regarding urban and port development in a developing country context are made and both beneficial and detrimental aspects of port expansion are modelled.

Rather than developing an urban model from scratch, Forrester's Urban Dynamics model (1970) is selected as a base for the modelling effort given its ability to model urban development as a result of processes endogenous to the urban system, and its modest data needs. The latter factor is particularly advantageous when modelling in a developing country context, where data availability may be poor.

Modelling presents a threefold challenge: 1) adding model structures representing port infrastructure, road transport infrastructure, and green space encroachment, 2) adapting the model structure to represent the urban development of a developing country city (i.e. informal settlement, economy), and 3) adapting existing model parameters to local (Tema) conditions.

Model development, verification and validation

The model is adapted to explicitly model transportation infrastructure and congestion, green space encroachment, informal settlement and port infrastructure. Model parameters are adapted to local values based on literature or inferred or estimated from the available data. Model outcomes of interest are based on the principles of sustainable development (economy, social, environmental) and local stakeholder values.

The model has been specified in the simulation package Vensim, based on Forrester (1970) and estimations of causal relations drawn from literature. The final model contains 27 stocks and some 220 variables in total. Model verification tests have been performed based on the guidelines laid out by Sterman (2000), and model validation was done by performing a full sensitivity analysis, comparing model output with available historical data, and expert consultation. A scenario analysis was performed to assess the impacts of uncertainty related to the economic environment, port and industry automation and climate change on the simulated port-city.

The model verification and validation process showed that the model, despite some conceptual limitations owing to the lack of spatial disaggregation, adequately models the development of the city of Tema and the potential effects resulting from port infrastructure expansion.

Model use

The long-term impacts of different modes of port infrastructure investments on the port-city system are assessed, and potential development dynamics are explored. Potential interventions for sustainable development are generated in a systematic fashion based on model structure. Promising options are evaluated

for their effectiveness over time, using model simulations and a data analysis and visualization script designed for use with the model.

Conclusions

The analysis shows how the model may be used to simulate the effects of port expansion on the port-city system. The explicit causal structure of the model facilitates the identification of potential interventions for sustainable port-city development.

While the speed of urban development may vary, the port-city system follows a developmental pattern of logistic growth in a resource-constrained environment, with the urban land area being the limiting resource. While green space initially detracts from the available land area, it acts as a buffer for the city to expand into, postponing the actual constraining of the port-city system until green space is consumed as well, and growth stagnates. Simulation shows green space is completely encroached upon unless it is actively protected. Alternative approaches such as housing and industrial zoning policies are less effective, partly due to the possibility of informal settlement. Conservation of green space is shown to have limited consequences for the port-city socio-economic climate, but may be difficult to achieve due to resource constraints, the influence of traditional authorities and potential political interference.

Port infrastructure investments tend to trigger the system to behave more dynamically, attracting more industrial development and migration to the city based on increased employment opportunities. This accelerates the encroachment of Tema on its green space by ca. 10% in time. Following the proposed 2015 port expansion, port throughput may triple from 2015 values if it rises to the new port capacity. This will significantly add to the demand for urban road infrastructure: congestion levels are seen to rise dramatically, by up to 45%, if no measures are taken to divert cargo transportation away from the urban road system. However, this increase results both from port direct impacts, and from indirect effects of increased industry and population growth. The progressive throughput growth means that the simulated congestion increase lasts nearly a quarter of the model run time horizon of 100 years, despite increased investments in road infrastructure. The lack of spatial detail in the model however precludes the modelling of localized bottlenecks, which likely results in an underestimation of actual (local) congestion levels.

The possibility of informal settlement around the city renders policies that involve the demolition of (formal) slum estates ineffective, as evicted people settle informally. Refurbishment of slum estates, increasing their socio-economic status, would have a similar little impact, due to a 'waterbed effect': while the policy benefits labor-class families in the city, up to 20% increase of underemployed is observed. However, refurbishment of slum estates becomes more effective when land area is filled. Scenario analysis shows how the city of Tema might become 'locked' in a state of increased informal housing, for example triggered by port expansion. As informal housing rapidly claims available urban land, less is available for formal and industrial housing developments, stagnating urban growth.

Assessing different modes of port expansion reveals a key finding for port-city development patterns. The question of port-city development revolves around the notion who claims the most land the first: the port or the city. If port development holds back or takes a dosed approach, urban activities benefit and claim the available land. Subsequent port development is then met by serious constraints regarding transport infrastructure construction limitations, due to increased urban developments in the land.

From the perspective of a port it is better to expand dramatically and stifle urban development, claim infrastructure and port space before land is taken for other (urban) developmental needs and developments. From the perspective of the port-*city*, a less rapid port development is preferred, although negative externalities may be more pronounced on the long term as options to mitigate road congestion may be more (space-) constrained at that point.

These findings connect to theory on port-city evolution, which categorizes port-cities by respective urban and port prominence (Ducruet and Lee, 2006). The findings suggests that port-city evolution is not merely something that happens organically, but is actively decided by certain stakeholders in the port-city system. More concretely, port-city evolution may be (partly) the result of investment decisions by international shipping lines and terminal operators, who thereby increase port intermediacy and prominence which may in turn stifle urban development through externalities.

If port prominence in African port cities is claimed like it is right now in Tema, investments by private parties may dictate their evolution by constraining port-city urban development. Port authorities are in the middle of this, experiencing pressures from their local communities on the one side, and the commercial requirements of terminal operators regarding the exploitation of their port on the other. Active mitigation of port externalities with lastingly effective interventions may allow for sustainable African port-city development that benefits both sides.

The model has been proven useful in simulating developing country port-city development challenges and port infrastructure expansion impacts, and in the generation of high-leverage interventions. It shows how system dynamics was effectively used in a relatively data-poor environment, to model the development of the city of Tema and its port and evaluate interventions for sustainable port-city development in an African context. While its level of aggregation may preclude its use as an urban planning or prediction tool, it may be used as part of the port planning process to convey to key stakeholders a systems perspective and understanding of port-city development dynamics. The relative complexity and high level of aggregation of the model however suggest that a strategy needs to be designed for this.

Limitations and recommendations

Limitations of the model are discussed and the consequences for model use are explained. Recommendations for further research include the application of the model to other developing country port cities to evaluate external validity of model results and causal relations, and the applicability of the model to other port cities. Suggestions are made for model adaptations that could be relevant in other such port cities, such as port land use impacts, which were not a priority in Tema. Further research is proposed on the use of the model as a boundary object in strategic conversations on options amongst port stakeholders, combining principles from group model building and network management and process design. An alternative approach involves the conversion of the simulation model into a serious game of port city development, facilitating discussion and the evaluation of interventions for port-city sustainable development amongst stakeholders.

Reflection

The use of the system dynamics approach was appropriate, given the wide variety of factors involved in a developing country port-city. Model complexity and size presented a challenge especially in the (sensitivity)

testing of the model, and the analysis of model outcomes. The semi-automated data-interpretation and visualization script was a necessary aid in model outcome interpretation and presentation.

Tema has been a suitable case-study for this project. Its location in the Greater Accra metropolitan area meant that more data than expected was available on the port, the city and the lagoon, which aided the modelling effort. In applying the model to other African port-cities, more time and resources may be needed for the extraction of such data from local stakeholders and institutions.

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PART I: RESEARCH DEFINITION

1 INTRODUCTION

Urbanization is a worldwide trend. More than half of the Earth's population already lives in urban areas, and this number is expected to rise even further in the coming decades. Rapid growth of cities and urbanization is observed and expected to continue, most prominently in Africa and Asia (United Nations, 2014). However, cities worldwide face many challenges. How can they thrive economically and provide jobs and prosperity without placing strain on surrounding land and resources? Congestion, housing shortages and declining infrastructure are only some of the many problems facing cities (United Nations (UN), 2016).

As cities expand they put more pressure on their environment, both in the form of emissions and changes in land use and encroachment into green spaces. In developing countries this socio-ecological aspect of city development can be readily observed. Here urbanization generally occurs more rapidly and in an uncoordinated fashion. In addition, regions of ecological importance experience more haphazard development when compared to countries that are already more developed (Cohen, 2006).

Large-scale infrastructure projects such as ports can have a significant impact on the development of nearby cities. While ports provide jobs and stimulate the local economy, understanding is lacking of how such projects affect city composition and quality of life on the medium to long term, and what are effective port-city policies (Merk and Dang, 2013).

Social conflicts related to port development, involving port authorities, community groups, local business community, national and local government, are becoming increasingly relevant (Musso, Benacchio, Ferrari, and Haralambides, 2000). As such, port planning can no longer be based exclusively on the opinions of engineers, infrastructure specialists, transport economists or lawyers. Port planning needs to take into account the relationship between the port and the city, the economic and environmental impacts, and the stakeholders (Moglia and Sanguineri, 2003).

In this research, the choice is made to apply the system dynamics modelling approach in modelling the impacts of port infrastructure investments on the development of the Ghanaian port city of Tema. Explicit assumptions regarding urban and port development in a developing country context are made and both beneficial and detrimental aspects of port expansion are modelled.

The project forms a component of the Integrated and Sustainable (Green) Ports in Africa study carried out in response to a research call from the research and innovation programme 'Urbanising Deltas of the World' (Slinger, Taneja and Vellinga, 2017; Vellinga, Slinger, Taneja and Vreugdenhil, 2017; Slinger et al., 2017). It addresses a gap within the overarching research which is focused on integrated port design, by investigating and modelling the socio-economic impact of port infrastructure developments in developing countries.

The thesis report is structured as follows: first, the research problem is defined and demarcated, and knowledge gaps are identified, leading to the formulation of research questions (sections 2.1 through 2.11). Next, the research approach is discussed (Chapter 3). The second part of the thesis covers the design of the system dynamics model, including the theoretical framework (Chapter 4) model conceptualization and specification (Chapter 5), and verification and validation (Chapter 6). In the third part of the thesis, the model is used to

assess port development patterns and port investment impacts, and to generate and evaluate interventions for sustainable port-city development. Conclusions are drawn based on insights from the model and its use (Chapter 8), model limitations and recommendations for further research are discussed (Chapter 9). A brief reflection on the research effort marks the end of the main report (Chapter 10).

2 THESIS DEFINITION

In this chapter the research problem is defined and demarcated (section 2.1), knowledge gaps are identified (2.2), the problem statement and research questions are formulated (2.3 and 2.4), and the research structure and objectives are explained (2.5, 2.6).

2.1 PROBLEM DEFINITION AND DEMARCATION

Port investments are often cited as being beneficial to local and regional economic development (Musso, Benacchio, Ferrari and Haralambides, 2000). However, cities hosting these ports experience both beneficial and detrimental impacts from their ports. Generally speaking, the positive impacts are economic in nature, while the negative impacts take the form of externalities like environmental issues, land use and traffic congestion (Brunila, Kunnaala-Hyrkki, and Hämäläinen, 2015; Merk, 2013). Port cities experience what is deemed a local-global or port-city mismatch (Rodrigue, Comtois and Slack, 2017; Merk, 2013): benefits of the port spill over to other regions, often to internationally operating firms, while the negative externalities are experienced locally in the port-city.

These negative externalities become more important as a result of containerization and reduction of port hinterland captivity (the lands ports can exclusively claim to get their business from, see Cullinane, 2011). This increases competition between ports and increases the pressure for efficiency, investment in infrastructure and the involvement of private parties (Musso, Benacchio, Ferrari, and Haralambides, 2000).

The privatization of port activities in reaction to the increased pressure and vertical integration of international shipping companies has consequences for the balance of power in port governance. While historically ports could be considered more public institutions, and investments in port infrastructure were seen as social investments to benefit the region, the drive for increased efficiency and privatization changes port investments to principally economic ones (Musso, Benacchio, Ferrari, and Haralambides, 2000).

It is no surprise then that port impact studies mostly focus on the benefits of port infrastructure investments, and many studies have been done establishing the beneficial economic impacts of (individual) ports (e.g. Park and Seo, 2016; Eltalla, 2016; Bryan, Munday, Pickernell, Roberts, 2006). The notion is longstanding, that port impact studies seem to be primarily used as a way of justifying large-scale investments in port infrastructure and in public relations management, without adequately considering the costs for the local community (Musso, Benacchio, Ferrari, and Haralambides, 2000; Dooms, Haezendonck and Verbeke, 2015).

As the interests of ports and their cities are diverging (Merk and Dang, 2013), city budgets are constrained and negative externalities of port presence are experienced, cities and public institutions (as major shareholders in ports) put pressure on ports to engage in practices of economic development in the city (Pigna, 2014). Since the 1990's, environmental and spatial impacts of port development received increasing weight in the societal debate on port operations and development (Dooms, 2014). Social conflicts related to stakeholders of port development, involving port authorities, community groups, the local business community, and national and local government, are becoming increasingly important (Musso, Benacchio, Ferrari, and Haralambides, 2000). As such, port planning can no longer be exclusively based on the opinions of engineers, infrastructure

specialists, transport economists or lawyers. Port planning should take into account the relationship between the port and the city, both economic and environmental impacts, and stakeholders (Moglia and Sanguineri, 2003).

As port communities provide or withhold ports with their social license to operate, port managing bodies have been pushed to adapt their strategies towards local community stakeholders, involving local stakeholders in the port planning process, strengthening communication links with local communities and incorporating sustainability indicators in their reporting on port performance (Ircha, 2012; Adams, Quinonez, Pallis, and Wakeman, 2009; Dooms, 2014). Traditional port impact studies are still of use in an integrated port planning process, but they have two important drawbacks: firstly, they present only a static picture of expected port impacts, ignoring the effects of port development over time, changes in port operations (e.g. automation) and uncertainties influencing the port-city system. Secondly, while they can serve as an important tool to the community in understanding the structure of a port as well as its immediate economic effects, they tend to overestimate benefits while underestimating negative impacts (Musso, Benacchio, Ferrari, and Haralambides, 2000).

Sustainable port-city development entails the design and implementation of policies and interventions that reconcile these opposing values of ports and cities (Fusco Girard, 2010; Merk, 2013). This requires effective port-city governance and a process in which multi-criteria evaluation of possible interventions takes place, considering values from involved stakeholders and the distribution of net benefits and dis-benefits among all agents and groups. An ex-ante evaluation method is needed that takes into account the trade-offs that exist regarding sustainable port-city development, including metrics for both port performance and socio-economic impacts (Fusco Girard, 2010; Xiao and Lam, 2017; Musso, Benacchio, Ferrari, and Haralambides, 2000).

Rather than as static, separate entities, ports and their cities should be considered as single complex adaptive systems, characterized by mutual positive and negative interdependencies and with non-linear processes (Fusco Girard, 2010). However, empirical studies of ports systems and urban systems often study these systems separately. The current literature regarding the integrated sustainable development of port cities is rather limited (Merk, 2013; Xiao and Lam, 2017). This study aims to contribute to deepening understanding of sustainable port-city development.

2.2   RESEARCH CASE STUDY: THE PORT CITY OF TEMA, GHANA

The city of Tema is home to the largest port of Ghana. Situated near Accra on the Gulf of Guinea, Tema was developed specifically to support its port, which was opened in 1962. The presence of the port attracted industries dependent on the port, and the Port of Tema became a catalyst for urban development. Indeed, Tema was envisioned to become the industrial center of the country (Hoyle and Hilling, 1970). Tema's port is the biggest of the country, serving both Accra and the Volta Delta. The port is currently undergoing a 1.5 billion dollar expansion, more than tripling its container handling capacity from 1 million to 3.5 million TEU (APM Terminals, 2015).

The Port of Tema serves as a case study for the Integrated and Sustainable (Green) Ports in Africa research program, of which this research is a component. Tema serves as the case study for this thesis. A research mission was undertaken in February 2017 during which the port, the city and the adjacent Sakumo Lagoon were visited. A 50-strong stakeholder workshop was held on sustainable port development in which information on local stakeholder values, opinions and priorities regarding sustainability and port investments were gathered (Slinger et al., 2017).

These stakeholder values have been taken as a means of demarcating the research problem. Table 1 summarizes the priorities and concerns expressed by local stakeholders present at the workshop. Local concerns focus on the encroachment of the city on the adjacent Sakumo Lagoon, a coastal wetland of ecological importance with RAMSAR status (Appiah and Yankson, 2012), and the congestion of urban roads and pollution. These findings are used to demarcate the modelling effort.

Table 1. Port of Tema stakeholder values concerning sustainable port city development (Slinger et al., 2017).

Sustainable port city development in Tema					
More economic development		Less negative externalities			
More local employment [jobs/population]	Higher port throughput [mton/year]	Less congestion [infrastructure use/infrastructure capacity]	Less slum development [informal settlement]	Less pollution	Less green space encroachment [Ha green space]

From a port perspective, automation of operations and the presence of affordable housing for workers were mentioned as desirable. Relevant stakeholders to the port expansion project listed included the port authority, private sector, international organizations, environmental regulators, local, national and traditional governments, and interestingly, local politicians as a separate category. This last categorization may be related to the fact that instances of "political interference" in development by notables in Ghana are a common occurrence (see Appendix B. Actor analysis for a discussion on this).

Other concerns such as (renewable) energy, waste management, environmental biodiversity, the cultural link of the local community with the port, and tourism were also touched upon, but this research considers these topics out of its scope. Environmental and biodiversity impacts of port development are already covered by other research within the Sustainable Ports in Africa program, for instance by employing a ecosystems services approach. Additionally, Tema is unusual as there are relatively few environmental issues associated with its location. At another location these would have been more severe and would have had to receive more attention. Rather, this study focuses on socio-economic impacts and high level processes such as industrial and housing development, green space encroachment, informal settlement, and transport congestion, specifically connected to port-infrastructure development. These issues are explored more thoroughly in the coming chapters.

Figure 1 depicts a system diagram for the research problem as defined based on the discussed literature and case study local information. In the middle it depicts factors that are included in the modelled port-city system, such as housing, road transport, employment, land use and green space, and the port itself. Relevant

stakeholders, listed on top, can intervene in the system and influence its behavior (see Appendix B. Actor analysis, and chapter 7 Model simulation). Note that the list shown here is not exhaustive. External factors (depicted on the left) can influence the system exogenously, and introduce uncertainty into the modelling effort. A scenario analysis (Appendix D) is performed to explore the impacts of uncertainty on simulated port-city development. On the right a selection of model outcomes of interest are listed, based on stakeholder priorities and the problem demarcation.
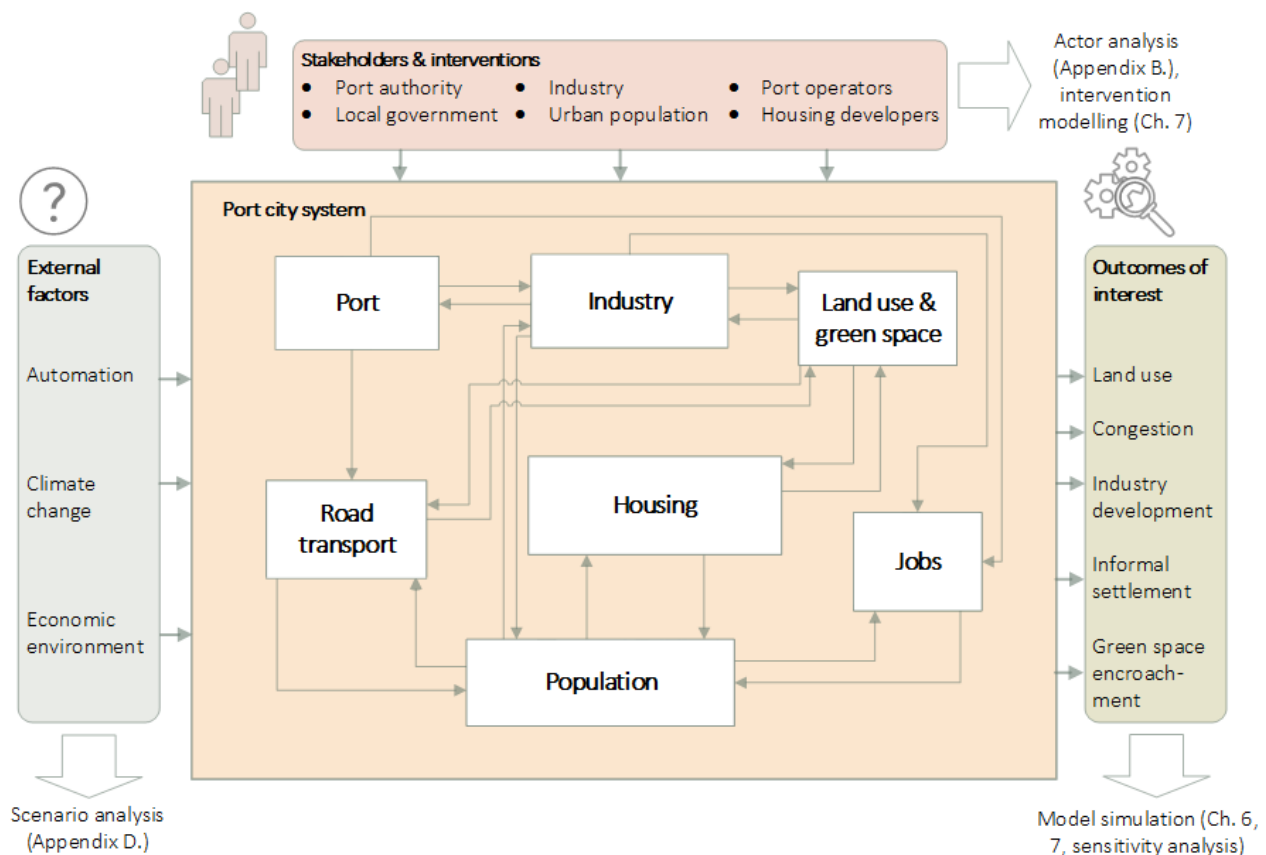
Figure 1. System diagram of the problem, showing the port-city system, relevant stakeholders, external factors and outcomes of interest.

Tema is adopted as a case study for several reasons. Firstly, being part of the Sustainable Ports in Africa program focusing on this port-city facilitated a research mission to the area, the visiting of the port, the city and the adjacent lagoon, and effective consultation of local stakeholders. Secondly, the proximity of Tema to Accra (the capital of Ghana and location of several universities) means that reliable data on relevant topics such as green space encroachment is more likely to be available.

The city is particular in that it was specifically developed to service its port. That means relatively detailed information on urban development and related policies is available. It also contributed to the city being very port oriented, featuring port dependent industries, which benefits the modelling effort. This peculiarity should be considered however, when interpreting and extrapolating modelling outcomes to other developing country port-cities.

2.3 MODELLING APPROACH SELECTION

Several modelling approaches could be used to fill the need for a dynamic ex-ante evaluation tool, and potentially facilitate strategic conversations amongst stakeholders on sustainable port-city development (Fusco Girard, 2010). Examples of such approaches are discrete event modelling, agent based modelling and system dynamics modelling. The modelling approach chosen for this research is system dynamics modelling. The reasons for this choice are explained below.

The choice for a modelling approach is determined by various factors: the desired level of aggregation, availability of data, tradeoffs concerning computational burden, the ability to carry out sensitivity analysis, understand and explain the behavior of the model, and communicate modeling outcomes to others (Rahmandad and Sterman, no date). Both system dynamics and agent based modelling could be used to model port-city development.

Some relative advantages and disadvantages of the system dynamics and agent based modelling approaches are summarized in Table 2. The following commentary is based on the comparison of the two modelling methods by Rahmandad and Sterman (2008).

An agent based model of port-city development could provide insight in the impacts of port infrastructure investments by modelling changes in urban land use by individual agents based on knowledge of the land and behavioral rules driving stakeholders in the port-city. An advantage of agent based modelling is that it could include spatial aspects of urban development and green space encroachment, and the heterogeneity of port-city agents. However, an agent based model of port city development would have considerable downsides: its granularity and complexity would significantly increase computational requirements, which would limit the ability to conduct sensitivity analysis. Additionally, linking model behavior to its structure would become more difficult with increasing model complexity, which would have consequences for communicating the reasons for model behavior to stakeholders, limiting its suitability for potential use in the port-city development process.

There exists a trade-off between model (dis-) aggregation and the breadth of the model boundary. Modelling at agent-level detail requires relatively detailed information on stakeholder heterogeneity and decision-making, which is less accessible in a developing country context, at least within the scope of this research.

Table 2. Advantages and disadvantages of system dynamics and agent based modelling (Rahmandad and Sterman, 2008)

	System dynamics modelling	Agent based modelling
Advantages:	- Can easily encompass a wide range of feedback effects - Lower computational requirements - Model behavior in complex models is easier to link to model structure, communicable to stakeholders	- Ability to incorporate spatial aspects - Can capture heterogeneity of actors and in the network of interactions among them.

Disadvantages:	• Aggregate agents into a relatively small number of states or groups, assume homogeneity • Not very suitable for modelling spatial aspects of urban development (e.g. Sanders and Sanders, 2004)	• Harder to link model behavior to structures in the model, and explain behavior to stakeholders • High computational requirements for complex models • Disaggregation increases model data-needs on agent behavioral rules

System dynamics modelling on the other hand offers a different approach to dynamically modelling complex systems. The approach stems from control theory and uses sets of non-linear differential equations and quantitative simulation to represent the behavior complex systems over time. It was first applied by Jay Forrester to represent complex problems involving social, economic and industrial elements (e.g. Forrester, 1961; Meadows and Wright, 2008). It is particularly suitable for the dynamic modelling of complex systems containing numerous interconnected subsystems and feedback loops, and can easily encompass a wide range of feedback effects, aggregating agents into a relatively small number of states. Its clear system structure facilitates the explanation of model behavior to stakeholders, and its low computational requirements make it suitable for sensitivity analysis and experimentation despite model complexity (Rahmandad and Sterman, 2008).

While the system dynamics approach is less suitable for explicitly modelling spatial aspects of development, it has been successfully applied to the modelling of ports and cities (e.g. Fu, 2016; Forrester, 1970; Duran-Encalada, and Paucar-Caceres, 2009). Forrester himself used the approach to model urban dynamics and socio-economic development as resulting from endogenous processes (Forrester, 1970). However, no integrated modelling study of port-city development has been undertaken. These considerations motivate a choice for system dynamics as a modelling approach in this research.

2.4 FORRESTER'S URBAN DYNAMICS

Rather than building a new model from scratch, Forrester's Urban Dynamics model (1970) is chosen as a base for the research effort. In Urban Dynamics, Jay Forrester applied the then just emerging system dynamics modelling approach to model the rise and decline of a generic American city. The innovative aspect of the model was that it dynamically described urban development as driven by endogenous processes, rather than by outside influences. The model contains both social and economic indicators of urban development Figure 2.

A drawback of the model is that it is not spatially explicit, which limits its use as an urban (spatial) planning tool (Lee Jr., 1973; Sudhira, Ramachandra and Subrahmanya, 2007). Its relative complexity and size are also cause for criticism (Stonebraker, 1972; Lee Jr., 1973). However, being a white-box model in which causal structures are clearly defined, it may be useful for tracing the consequences of different assumptions about the nature of urban development problems. Moreover, Forrester's Urban Dynamics was noted for its usefulness as a way of "teach[ing] lay decisionmakers and stakeholders about the structure of cities and possible sources of secondary effects" (Lee Jr., 1973 pp 174). This could facilitate the evaluation of interventions and uncertainties, and strategic conversations (Cunningham, Hermans, and Slinger, 2014) on options for the sustainable development of port cities with stakeholders.
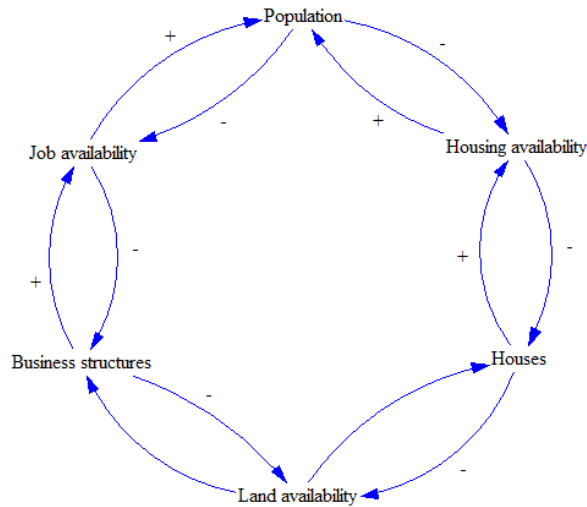
Figure 2. Urban Dynamics model structure conceptualization, incorporating economic and social indicators of urban development (Alfeld, 1995; Forrester, 1970).
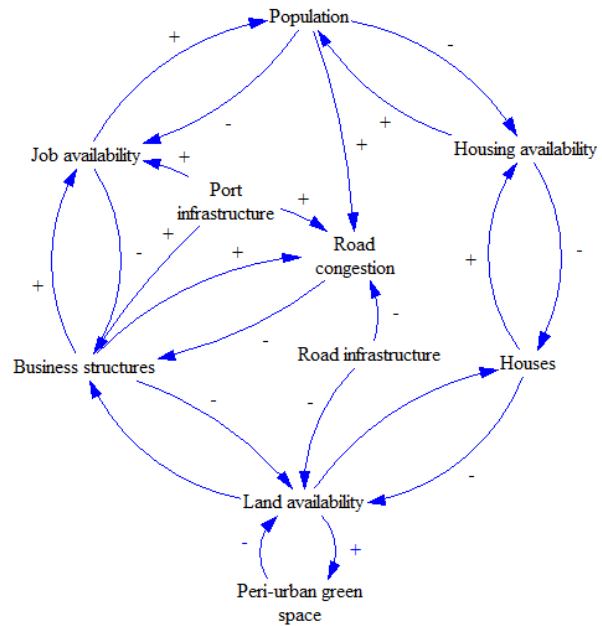
Figure 3. Additions to the Urban Dynamics model structure

While the model has been around for a relatively long time, its causal mechanisms and the challenges it describes are still relevant today. Describing a conceptual city, Forrester's model originally uses no real data, describing urban development as resulting from endogenous processes in the city. This expected low data need is an advantage when using the model to describe Tema. While the model has been criticized for its lack of empirical basis, research shows that it can be successfully adapted to represent particular cases, and that the behavior it produces does agree with developments observed in real world cities (Mass, 1974; Alfeld, 1995). Although it is originally specified to represent an American city, it could well be used to model the problems observed in a developing country city (Saeed, 2010).

For Urban Dynamics to be adapted to a port-city in a developing country however, Forrester's modelling assumptions have to be re-examined, and adapted where necessary. Model augmentations have to be implemented describing explicitly the impact of port infrastructure, and the evolution of green space encroachment and traffic congestion in the urban area (Figure 3). Forrester's model, the needed model augmentations, adaptions and outcomes of interest are discussed more thoroughly in chapter 5 Model conceptualization and specification.

2.5   KNOWLEDGE GAPS

As discussed in the previous sections, there is a lack of understanding concerning the sustainable development of port-cities. There exists a need for research on port-city policy effectiveness that addresses the complexity of sustainable urban development in the long term (Merk and Dang, 2013). An ex-ante evaluation method is needed that takes into account the economic, environmental and social trade-offs that exist regarding

sustainable port-city development, including metrics for both port performance and socio-economic impacts (Fusco Girard, 2010; Xiao and Lam, 2017; Musso, Benacchio, Ferrari, and Haralambides, 2000).

Existing dynamic studies on ports and cities have focused on the economic aspects of port-city development (Luan, Chen and Wang, 2010), the regional economic impacts of port infrastructure (Fu, 2016) or economic interactions influencing port investments and policies (Li and Wang, 2013). Other studies are not accessible in the English language (e.g. Liu, 2004 in: Luan, Chen and Wang, 2010; Ren and Ding, 1994).

Haase and Schwarz (2009) provide a comprehensive overview of dynamic studies of urban development. The examples are numerous and include system dynamics models of urban socio-economic development (e.g. Forrester, 1970), the impact of urban development on wetland biodiversity (Eppink, Van den Bergh and Rietveld, 2004), urban transport systems (Haghani, 2003; Raux, 2003; Wang Lu and Pen, 2008).

Other dynamic models offer a more comprehensive view of urban processes and land use change (e.g. Duran-Encalada, and Paucar-Caceres, 2009; Landis and Zhang, 1998), but require extensive and detailed data, which is unlikely to be available in developing country context. The dynamic models that address the issues specific to developing countries, such as informal housing, mostly focus exclusively on these issues (Shoko and Smit, 2013; Gutberlet et al., 2017).

In conclusion, no models exist that incorporate the impacts of port infrastructure development on urban development, urban transport and peri-urban green space in a single integrated model of port-city development. Moreover, research shows that Forrester's Urban Dynamics model can be successfully adapted to represent particular cases, but if this also holds for a developing country city is as of yet untested. This thesis addresses these knowledge gaps.

2.6   PROBLEM STATEMENT

The following problem statement has been formulated:

No comprehensive dynamic model of port-city development exists that incorporates the beneficial and negative externalities of port development on their cities and green space, facilitating and informing strategic discussions on sustainable development.

As discussed, the port-city of Tema and its adjacent estuary serve as the case study in this research. System dynamics modelling is taken as a main research approach for the reasons laid out in section 2.1, with Forrester's Urban Dynamics as a basis for the port-city model. As city development and dynamics can take many decades, a medium to long-term outlook is adopted.

2.7 RESEARCH QUESTIONS

The main research question follows from the problem statement. Applying the research to the port city of Tema, the following research question is formulated:

"How can system dynamics modelling be used to represent the development of the city of Tema and its port and evaluate interventions for sustainable port-city development in an African context?"

In order to answer this question and structure the research, several sub-questions are formulated:

1. What is an appropriate and useful model of port-city development in a developing country context?
2. What are potential development patterns of developing country port-cities? In particular, how does port expansion affect port-city evolution?
3. What are effective interventions for sustainable port-city development that mitigate the local-global mismatch in the benefits deriving from port expansion?
4. What do model outcomes mean, for the case study, and for the development of African port cities in general?

Research sub-question 1 is double-barreled: model appropriateness relates to model conceptualization and specification, and involves research of the literature on various relevant topics, actor and scenario analysis, stakeholder and expert consultation and system dynamics modelling activities (Table 3). Model appropriateness depends on its intended use and the concepts it aims to model. Model usefulness involves the determining whether the model accurately represents (Tema) port-city development. Various model verification and validation tests will be used to this end (Chapter 6 Model verification and validation), including expert consultation (Appendix E. Interview data).

Research sub-questions 2 and 3 are in fact modelling questions, used to further guide the conceptualization and use of the model. Answering research sub-question 2 involves the use of the designed system dynamics model and scenario analysis to explore potential development patterns (sections 7.1, 7.2). Research sub-question 3 is then addressed in section 7.3. Concrete answers to questions 2, 3 and 4 (the interpretation of modeling outcomes for the city of Tema and other African port-cities) are then presented in the Conclusions (Chapter 8).

Table 3. Relevant activities and research approaches for answering the research sub-questions.

Research question:	Relevant research activities/approaches:	Where answered:
1	Literature study, actor analysis, scenario analysis, system dynamics modelling, local stakeholder consultation, expert interview and consultation	Section 5.9 (appropriateness) Section 6.8 (usefulness)
2	System dynamics modelling, scenario analysis	Chapter 8. Conclusions
3	System dynamics modelling, actor analysis	Chapter 8. Conclusions
4	Research synthesis	Chapter 8. Conclusions

2.8   RESEARCH OBJECTIVES AND DELIVERABLES

The objective of the research is threefold:

(i)   To extend the application of system dynamics modelling in a data-poor environment in order to address the urban development dynamics of a port city in a developing country context

(ii)   Assess whether the model can be used to generate and evaluate interventions for sustainable port-city development

(iii)   Gain insights into sustainable port-city development patterns and intervention effectiveness

The project deliverables will include the written thesis with answers to the research and modelling questions, a system dynamics model representing a developing country port-city, namely Tema in Ghana, and a model databank containing a record of model verification and validation tests and testing outputs, including sensitivity analysis graphs and policy graphs and tables.

2.9   SCIENTIFIC RELEVANCE

The major scientific contribution lies in developing the knowledge gaps regarding the dynamic influence of port infrastructure and development on the quality of life and natural surroundings in a system dynamics model of urban development. The research will contribute knowledge on the influence of these factors on the sustainability of port development initiatives in the developing world.

Moreover, the project will explore how well the system dynamics modeling methodology performs when applied to an African city, a relatively data-poor environment.

2.10   SOCIETAL RELEVANCE

The research project aims to provide insight into the sustainable development of port cities in developing countries. Potential development of the city can be qualitatively explored under varying scenarios of external effects and policies. Moreover, by incorporating land use and sociological elements, it could help to protect ecosystems and natural areas of interest by identifying which policies have lasting benefits. Similarly, introducing infrastructural elements into the project might offer insight into pollution loads and health considerations and city-dweller well-being.

However, most importantly it could be used to inform policy and decision making by key stakeholders such as city planners and port developers. Rather than as a tool of prediction, the model can be used as a medium to convey to key stakeholders a systems perspective and understanding of port-city dynamics. By facilitating systems thinking it can foster sustainable choices and cooperative development.

2.11 RESEARCH STRUCTURE AND THESIS OUTLINE

The research is organized around the classic modelling cycle for system dynamics projects: problem definition, model conceptualization and specification in a simulation package, model verification and validation, and finally using the model to explore behavior and find policy options (Meyers et al., 2010).

The structure of the project is displayed in Figure 4. A comprehensive literature study is carried out focusing on the subjects of interest (e.g. impacts of port infrastructure expansions, urban development in developing countries, transport, green space encroachment). In addition, empirical data is gathered on the case study port-city of Tema, Ghana. The knowledge found in the first phase will inform model conceptualization, specification, verification and validation, and actor and scenario analyses. After the model is verified and validated, it is used to model the effects of port expansion on the city, and potential impacts of interventions and uncertainties. Thereafter, the outcomes of the modelling study are synthesized by drawing conclusions and recommendations for the case study, and generalizing as appropriate for port-cities.
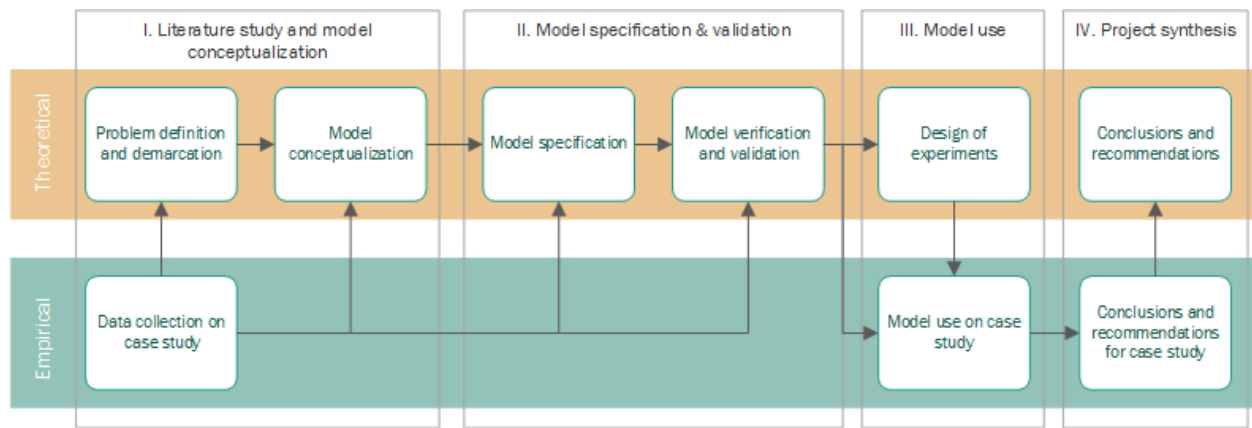
Figure 4. Thesis research flow diagram

3 RESEARCH APPROACH

Various research methodologies are applied in different phases of the research. These include the literature review, interviews and stakeholder consultation, and system dynamics modeling.

3.1 LITERATURE STUDY – DEVELOPING A THEORETICAL UNDERSTANDING OF THE PROBLEM

The literature review method is used to build a theoretical understanding of the problem, and to collect data that is relevant to or needed for the modelling effort. Topics of interest include urban dynamics modelling, urban development in African and developing country context, data on the (historical) development of the city of Tema and its port, and the (institutional) context of the problem.

Where available, scientific literature is used as the primary source of knowledge. The academic search engines used include Scopus, Google Scholar, and Web of Science. Where scientific research is lacking, academic literature is supplemented by other (local) sources that are deemed trustworthy (i.e. reports, news articles), in light of the relative data scarcity in the developing world. The information gathered is used to design and test the model and provide context to its use.

The literature will be drawn from the paradigms of social science, maritime science, governance, transport modelling, system dynamics modelling and urban ecology and ecosystems services where applicable.

3.2 GROUNDED AND PARTICIPATORY SYSTEM DYNAMICS MODELLING

System dynamics (SD) modeling is used to model port city development. As briefly discussed in section 2.3, the method of system dynamics modelling was first introduced by Forrester as a way of modelling the behavior over time of complex systems, containing feedback loops and non-linear structures (Forrester, 1961), and later applied by him to model the development of cities (Forrester, 1970).

The numerous examples (discussed in section 2.3) of system dynamics being used to model port impacts, green space, transportation and urban development issues separately, show that the method is appropriate for integrating these aspects in a single, integrated model of port-city dynamics. The SD modeling approach aims to capture the complexity of the urban system resulting from interactions between the port and the city, and the likely presence of feedback loops within the system.

The modelling of concepts as structures of stocks and flows (as system dynamics does) is appropriate considering the continuous and often gradual nature of changes in urban development, for instance regarding population growth and housing developments. The ability of system dynamics modelling to incorporate both technical, quantitative concepts and social, more qualitative concepts at a high level of aggregation is congruent with the expectation that port-city development involves both quantitative and qualitative aspects.

A dual approach is employed in informing the system dynamics model. Firstly, the model is grounded in existing theoretical knowledge on causal relations between the various factors that make up the port-city system story. Secondly, input from local stakeholders is added to scientific knowledge. This includes information on stakeholder values and their accounts of system stories, both from the stakeholder workshop as through local media and personal conversations (e.g. Slinger et al., 2017; Yeboah and Annancy, 1999; Zakaria, 2014; Agyemang, 2013).

Being a white-box modelling method with a clear model (causal) structure, using the system dynamics model will yield a model in which causal relations and assumptions are made explicit and clear. This facilitates the evaluation of the effects of different assumptions and interventions on model behavior, for instance in group model building sessions or strategic conversation (Cunningham, Hermans, and Slinger, 2014) with port-city stakeholders. This could allow port-city stakeholders to improve their mental models and develop collaborations in the planning for sustainable port-city development (Hovmand et al., 2012).
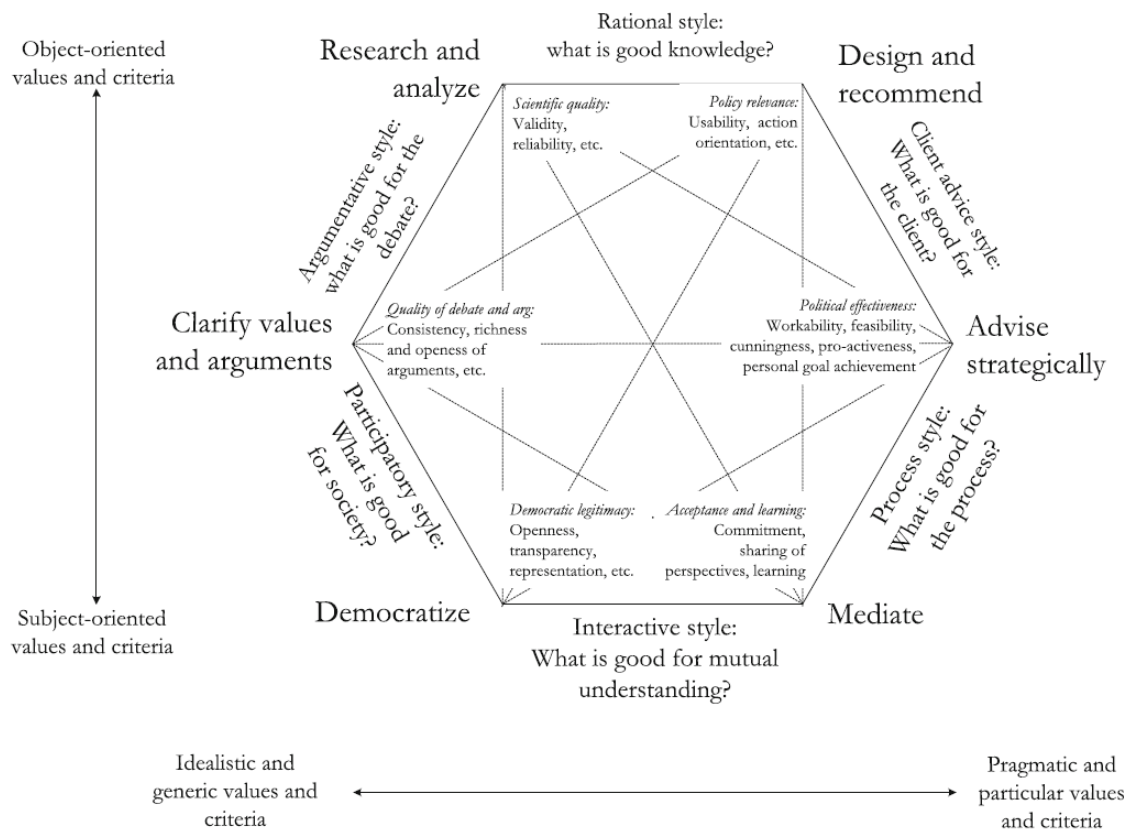
Using the model to that end, and in such a context, possibly as a boundary spanning object in strategic conversation with stakeholders (Star and Griesemer, 1989), corresponds to a participatory modelling style (lower side of the diagram in Figure 5), in which a model is used to capture and represent stakeholder values and facilitate system understanding (Mayer et al., 2004). With the model (or qualitative representations

thereof) as a basis, model assumptions can be discussed and scrutinized, and impacts of alternative assumptions and potential interventions can be explored interactively.

The method has some limitations. Due to the inclusion of qualitative concepts, non-linear relations and uncertainties regarding appropriate parameter values (for instance due to limited data availability), system dynamics modeling is not suitable for providing precise quantitative predictions of the future (Meadows and Wright, 2008). Therefore, model results will need to be interpreted more qualitatively. They can nonetheless provide insights into the magnitude of effects and overall system behavior with enough detail to answer the research questions.

A second limitation is that the model can never be comprehensive, and necessarily will provide a simplified or aggregated representation of the real world situation (Sterman, 2000). A trade-off exists between model comprehensiveness and detail of described behavior on the one hand, and model complexity and time and computational power spent on the other hand (e.g. Rahmandad and Sterman, 2008). While the system dynamics approach is appropriate for modelling complex systems covering a wide breadth of elements and interactions, which suits the modelling of the port-city system, this is at the expense of disaggregation and depth of system description (Kelly et al., 2013). Such aggregation may result in the loss of detail and validity of model inferences, and should be addressed in the model verification and validation process. Decisions regarding this trade-off will be guided by the requirements that are made of the model (section 5.1). Considering the model will be applied to a developing country city, a modelling stance is taken that favors (appropriate) aggregation, and limits model data needs.

Another shortcoming of system dynamics is that uncertainty regarding modeling parameters and input data is not explicitly considered in the model structure. That means that treatment of uncertainty requires extensive testing, for example using Monte-Carlo type simulations in sensitivity analysis or scenario based analysis (see Appendix D), which can be time-consuming especially in complex models (Kelly et al., 2013).

As discussed in the problem definition and demarcation section, the modeling approach taken is to base the port-city model on Forrester's Urban Dynamics model, rather than build a model from scratch (Forrester, 1970). Forrester specified his model to represent a generic, conceptual American city in decline. While it is based on existing system stories and plausible causal relations, most of the model's specifications of causal relations are not grounded on empirical data. Adapting Forrester's model to represent Tema and its development therefore presents a threefold challenge:

- Adapting existing model structure and parameter values to better represent the dynamics of a city in a developing country
- Augmenting the model to explicitly represent the port, informal settlement by migrants, green space encroachment and transport infrastructure,
- Adapting existing model parameters to available Tema empirical data

Forrester's original modelling assumptions are examined and adapted where necessary to better represent the situation in a developing country port city. The main modelling philosophy adhered to is to focus on modelling

the problem, rather than trying to recreate the complexities observed in the real world as accurately as possible (Meadows and Wright, 2008).

Considering that Urban Dynamics already is an extensive and complex model to begin with, containing 20 stocks and 150 model equations (Stonebraker, 1972), this paradigm serves to keep the modelling effort focused, and the size and complexity of the resulting model within acceptable limits. In applying the model to Tema, insights from Mass (1974) and Alfeld (1995) regarding the use of data are used.

3.3   INTERVIEWS AND EXPERT INTERACTION

Stakeholder and expert consultation and interviews are used to enhance the problem understanding and inform model conceptualization and validation. The research mission to Ghana offered opportunities to speak with local academics and stakeholders on a variety of subjects, including climate change impacts on urbanization.

The stakeholder workshop organized in February provided insight into local concerns and values regarding port sustainability and urban development issues (Slinger et al., 2017) and supported the modelling effort by providing guidance for the problem demarcation.

Expert consultation contributed to the verification and validation of the model. An informal, qualitative semi-structured interview method was used, guided by a presentation and documentation of the model. Questions used and interview data are included in Appendix E.

PART II: DESIGNING THE MODEL

In this chapter the theoretical understanding of the problem is deepened by providing an overview of the scientific literature on the various topics relevant to the research problem. Firstly, different ways of characterizing port-city relationships and the evolution of port-cities (Ducruet and Lee, 2006) is explored (section 4.1). Next, the manner in which ports impact nearby cities and regions (section 4.2) is discussed, and in what ways these impacts can be measured (4.3). Next, port governance is discussed, identifying the port authority as a nexus between port and city development (4.4). Section 4.5 moves the focus to urban development and addresses the challenges of development encountered in African context. Lastly, sustainable port-city development is defined based on prior research on the topic (section 4.6), and a summary is provided of the gained insights (4.7).

4.1   PORT CITY CHARACTERIZATION

Often situated at advantageous locations, historically the development of ports has coincided with the development of cities nearby (Merk, 2013). The coincidental development of ports and their cities is not surprising. Ports and cities are strongly linked, with ports providing employment opportunities and attracting business and trade, and the cities in return providing the ports with a labor force, infrastructures and facilities (Fusco Girard, 2010; Merk, 2013).

 However, a wide heterogeneity of port cities are found. One way of classifying port-cities was introduced by Ducruet, who developed a matrix of port-city relationships based on the concepts of (urban) centrality and (port) intermediacy (Fleming and Hayuth, 1994, in Ducruet and Lee, 2006). Centrality depends on whether the city is a local, regional, national or even continental center, from a geographical or economic perspective. The centrality of a city fundamentally affects its size and function (development), and traffic generating capacity as a port city (Fleming and Hayuth, 1994). Ducruet and Lee (2006) measure port-city centrality by the city's share of population among its region.

Figure 6. Matrix of port-city relations, (Ducruet and Lee, 2006)

Intermediacy is a measure of a city's importance or convenience as a distributional or connecting node in a transportation network. The city may serve as a point where local services connect with national and international services, or one mode of transportation connects with another (such as a port).

Port-city intermediacy may be determined by its closeness to established trade (shipping) routes, and may be artificial (i.e. the result of transport operator choices among competing alternatives). Ducruet and Lee (2006) measure intermediacy as the port-city's share of container traffic among its region.

The concepts of centrality and intermediacy overlap, as cities that are central to a (market) region can become important trade hubs in the region (Fleming and Hayuth, 1994).

These two measures allow for the classification of port cities as a function of their centrality and intermediacy. The matrix developed by Ducruet and Lee (2006), depicted in Figure 6, allows for the classification of port-cities based on the prominence of their urban and their port functions, discriminating between nine different types of ports, ranging from a coastal town (with low urban and port prominence) to the port metropolis (with both high urban and high port prominence, e.g. New York). Imbalanced combinations are also represented, in the General city (high urban, low port prominence, e.g. Stockholm) or hub port cities (low urban, high port prominence, e.g. Freetown).

The classification provides a measure of the dependence of a city on its port functions. It is important to note that port-city relationships can be dynamic and can evolve over time. For example, cities in which urban functions grow to be more prominent than their port functions can end up shifting from a hub port to a general city.

In his model of port-city evolution, Murphy (1989) suggests this is likely to happen as port cities move through successive stages of economic diversification, moving away from primary dependence on port maritime and port functions, through industrialization, and finally to the attraction of a service economy.
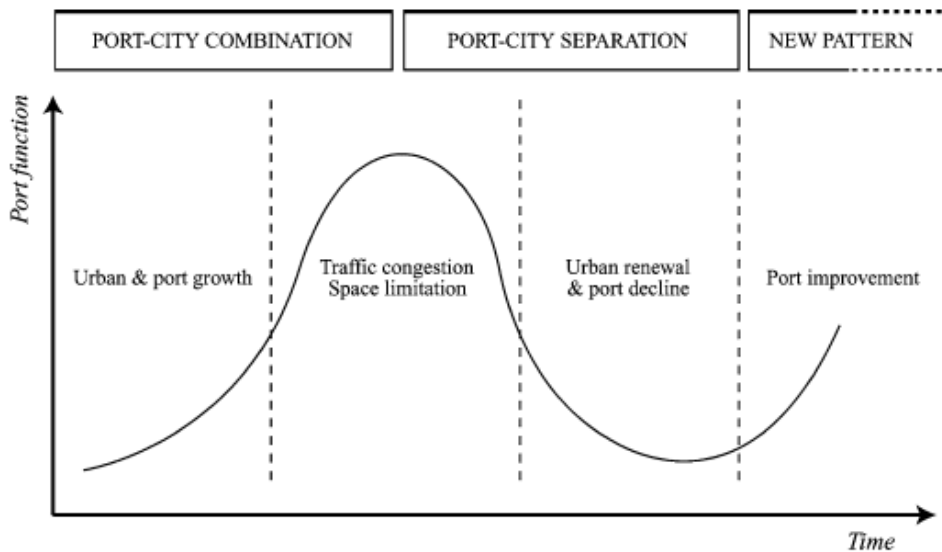
Figure 7. Logics of port-city spatial and functional evolution (Hoyle, 1989; Murphey, 1989; in: Ducruet and Lee, 2006)

Ducruet and Lee use their framework to typify port-cities and explain their development by the different kinds of problems encountered in port cities with different stages in their evolution (Figure 7). A common pathway is that of urban and port growth, leading to increasing congestion and spatial issues as port areas and throughputs expand, leading to pressure on the port to relocate away from urban centers unless those problems are dealt with effectively.

In the case of Tema, the port and the city both seem to be still growing and developing, in combination (Figure 7, Ghana Statistical Service, 2014b; Ghana Ports and Harbours Authority, 2016). The traffic congestion problem

that was discussed in the stakeholder consultation, and the choice for a port developing strategy involving the reclamation of land are indicative of this. The various different and sometimes particular evolutionary pathways that are found for port cities around the world however show that the future of Tema cannot be predicted solely based on this logic (Ducruet and Lee, 2006).

Another way of typifying port-cities is to use the type of cargo they handle primarily. Port traffic is very sensitive to the nature of the local economy of which the port is a component. More diversified port volumes, comprising high value added goods such as containers and consumer goods, indicate larger and richer regions with large tertiary sectors, whereas agricultural and industrial regions are usually more specialized in bulk traffic (Ducruet et al. forthcoming, in Merk, 2013).

These characterizations show how the port-city system may change over time and how different port-cities may experience a different class of problems (e.g. traffic congestions vs. port decline). As many developing country ports and cities are still in the growth stage, and containerization of ports in Sub-Saharan Africa is on the rise, it can be expected that the majority of these ports will start to experience or are already experiencing a phase of traffic congestion and space limitation, potentially resulting in the moving of port operations from the proximity to cities. Combined with the diversification of the port-city economies, these cities may evolve to general cities or urban ports, less dependent on port related operations. The trend of increasing container traffic in the Port of Tema (Ducruet and Lee, 2006) may be a sign of the diversification of the Ghanaian economy, and suggests a potential for Tema to evolve beyond primary port dependence.

4.2   PORT BENEFITS AND EXTERNALITIES

The body of literature on the nature of port-city relations and regional economic impact of ports is extensive. In general, ports are considered "funnels" to economic development as they act as a catalyst and incite development in specific economic sectors nearby ports (Rodrigue, Comtois and Slack, 2017). Port infrastructure investments are commonly characterized in literature as having a direct, indirect and induced economic impact (Figure 8).

Direct impact amounts to the employment within the port itself, both in the construction and operation of the port. Indirect impacts are economic activities of, and benefits for, users of port facilities, taking advantage of lower shipping costs and other cost savings. Lastly, induced effects are the effects generated through the increased potential for spending and production by direct and indirect beneficiaries, as more input factors are used by them.
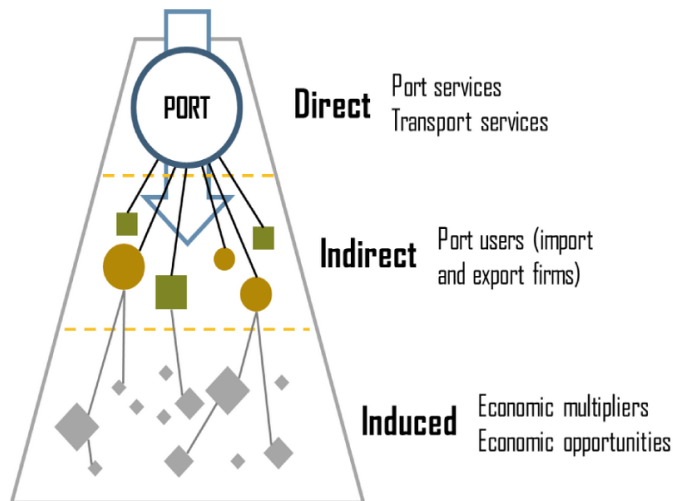
A slightly different typology is offered by Talley (2009), who also characterizes direct benefits to pertain solely to benefits and jobs related to port operation and construction. Secondary or indirect regional benefits of ports arise then when these direct benefits such as labor income, business revenues, and tax revenues are subsequently (at least partially) spent in the region, in turn generating additional income and business revenues; a multiplier effect.

Talley notes however that such secondary effects will be reduced if there are regional 'leakages', where labor or material from outside the region is used in port construction or operation, or conversely when direct benefits are (partly) spent outside the region. This will diminish the multiplier effect of port investment, at least for the region of influence of the port.

Talley also distinguishes tertiary and perpetuity benefits. Tertiary benefits relate to improvements in the region's transportation system as a result of the presence of the port, reducing transport costs and increasing market connectivity. Negative tertiary benefits (or dis-benefits) could ensue if port infrastructure use leads to congestion, affecting other stakeholders and sectors in the region.

Lastly, perpetuity benefits stem from the function of ports as a catalyst for greater economic growth in the region. This could be the attraction that their presence offers to industry or warehouses (Talley, 2009).

A third commonly used approach to the segmentation of the economic impact of ports is the "Dutch" functional method which recognizes direct economic effects and backward and forward linkages. Direct economic effects are similar to direct impacts and are related to the core operations of the port. Backward linkages involve goods and services used by stakeholders that are themselves part of the direct effect, e.g. subcontractors, who themselves need other subcontractors and so forth. Forward linkages are similar to induced impacts, and comprise activities that take place, or take place at lower operating costs, as a result of the port being present (Musso, Benacchio, Ferrari, and Haralambides, 2000).

However, besides the assumed beneficial economic effects of port presence, ports can have a negative economic influences as well. The presence of a port can expose local businesses to competition from cheap imports and foreign direct investment (FDI) by multinational firms (Talley, 2009; Oxford Business Group, 2013), and tax increases could occur as a result of public sector investments in the port. If these effects occur, port investment benefits have to be adjusted negatively to reflect this (Talley, 2009).

As discussed in the problem definition, besides the direct and indirect economic impacts, port-cities experience negative externalities from port activities: environmental issues, land use issues and traffic congestion (Brunila, Kunnaala-Hyrkki, and Hämäläinen, 2015; Merk, 2013). While a large part of the literature consists of studies of particular ports and their (beneficial) economic impacts (e.g. Park and Seo, 2016; Eltalla, 2016), fairly recently research has begun to focus more on these negative externalities of ports, and the policy challenges that these require.

Examples of environmental impacts of ports include those on maritime life and sediments (see Botwe et al, 2017 for an example of this for the Port of Tema), or on air quality through ship emissions (e.g. Lonati, Cernuschi, and Sidi, 2010). Alternatively, ports can have various soft values to the city, such as architectural or socio-cultural value, or the provision of a sense of identity to the city (Fusco Girard, 2010). Following the problem demarcation, these themes are considered to be outside of the research scope, and are therefore not addressed at length in this discussion.

Box 1. Benefits and externalities of the Port of Tema

The port of Tema, situated 28 kilometers east of Accra, was constructed to provide cargo handling services for the then rapidly developing eastern part of Ghana (Hilling, 1969). The area near the port was intended to become the industrial center of the country. The port of Tema was commissioned in 1962, and the Town of Tema was developed specifically to support the port and associated industrial activities.

While the benefits of the port of Tema on a national scale were somewhat relativized owing to the established presence of Takoradi port (servicing the western part of the country), indeed within ten years after commissioning, Tema had grown from a fishing village of 5000 to an industrial port city of 80.000 inhabitants, featuring leader industries dependent on port activities (Hoyle and Hilling, 1970).

Among other industries, Tema features an aluminum smelter and cement factory dependent on the port for the import of raw materials, and numerous manufacturing businesses (Hoyle and Hilling, 1970; Hilling, 1969; Apeaning and Thollander, 2013). The high concentration of port dependent industry, and the prominence of the port make Tema an appropriate case study for this research effort.

During the field visit to Tema and the stakeholder workshop organized by the Sustainable Ports in Africa project Slinger et al., 2017), it became apparent that Tema experiences some externalities from port presence. Most notably, local stakeholders dreaded increased congestion, increased informal settlement, ongoing pollution and green space encroachment as a result of port expansion.

4.3   MEASURING PORT INFRASTRUCTURE INVESTMENT IMPACT ON THE ECONOMY

There are three main methods used to assess port impacts on the economy. The first is a bottom-up approach, involving the use of surveys to assess the relationship between the port and related industries and actors. The aim of the studies often is to determine how much of the present employment is ascribable to the presence of the port. This is a contested way of assessing port economic impacts, as there is no way of assessing how the situation would have been without a port present (Musso, Benacchio, and Ferrari, 2000).

The second approach is a top-down methodology involving the use of economic input-output models. These studies are often done as case studies of specific ports. Their aim is to determine inter-sectoral multipliers, for

example between port transport and regional development. The coefficients found for multipliers vary significantly between studies and even between several ports within the same study and country (e.g. Park and Seo, 2016). For example, in his study on port-city competitiveness, Merk (2013) identified port multipliers varying between 1.13 and 2.47 for several European ports (Figure 9), and similar variation in impacts between different sectors within ports.

	Leontieff multiplier
Le Havre/Rouen	2.47
Marseille	2.01
Mersin	1.79
Hamburg	1.71
Antwerp	1.18
Rotterdam	1.13

Source: OECD Port-City case studies

Figure 9. Overview of port multipliers (backward linkages) for selected European ports (Merk, 2013).

A reason for this variety could be heterogeneity in the port-city characteristics and locational economy, as postulated by Ducruet using his matrix of port-city relationships (Ducruet and Lee, 2006). In areas where economic developments are highly dependent on port presence and capacity, investments in port infrastructure could have a more pronounced regional effect than in more diversified regions. Moreover, input-output studies provide a momentary picture, based on data from the past. Projection based on such multipliers will not take into account technological advances and future developments (Musso, Benacchio, Ferrari, and Haralambides, 2000). For instance, containerization of trade could mean a shift from labor-intensive port operations to more capital-intensive operations, reducing the direct benefits of ports to their communities over time (e.g. Talley, 2009; Rodrigue, Comtois and Slack, 2017).

A further method of assessing port economic impacts involves the comparative analysis of the port-city with another, comparable reference port-city. Economic developments that have happened to the reference city are compared and related to the port-city in which investments have yet to be made. Again, local heterogeneities between port-cities make the general applicability of this approach problematic. Musso, Benacchio, and Ferrari (2000) propose another, slightly different approach to comparative analysis with the aim of determining the impact of ports on their regional economy and employment. They propose a methodology in which a port city economy is compared to the economy of a very similar, but land-locked city (without a port). Any differences in employment and industry can then be attributed to the presence of the port, leading to a (highly) local multiplier coefficient for port economic benefits.

In addition to economic benefits and negative externalities, which represent values of socio-economic importance, ports influence values that are difficult to express economically, i.e. soft values. Soft values are non-socio economic, they include historical, archeological, architectural, landscape, recreational, sociological, and other cultural aspects (Van Hooydonk, 2007 in Fusco Girard, 2010). It is easy to focus on the quantifiable aspects of port-city performance, but although they are hard to monetize and measure, these soft values can contribute to the experienced value of the port and strengthen or weaken its relation with its city.

Box 2. Quantifying Port of Tema benefits

The highly localized nature of multiplier figures for port impacts complicates the quantification of the port impact on the local industry of Tema in the modelling study. The relatively high proportion of port related or dependent industries in Tema could lead to a significant impact.

On the other hand, the presence of the port may expose resident industry to competition from foreign investments and cheap imports, which could adversely affect it (cf. Oxford Business Group, 2013).

4.4   PORT GOVERNANCE

Changes regarding the governance of ports have been briefly mentioned in the problem definition as forming a driver of sustainable port(-city) design. Where ports and port authorities used to have a more public character, port investments have changed from purely social investments to increasingly economic investments (Musso, Benacchio, Ferrari, and Haralambides, 2000). This change is driven by public budget constraints, progressing containerization, increasing contestability of formerly captive port hinterlands and the resulting increasing competition between ports, and by the pressure placed on port authorities by vertically integrated shipping lines seeking to extend their business (see section 2.1,   Appendix B. Actor analysis).

Port governance is of relevance to sustainable port-city development. As ports and their cities' interest diverge, the question of how to influence each other's decisions becomes more important. The power relation between ports and their communities is in part determined by their level of privatization: the more privatized a port is, the less the direct influence that can be applied by the urban authorities.

Five types of port management models can be distinguished, based on the respective responsibility of the public and private sectors (World Bank 2007, in Rodrigue, Comtois and Slack, 2017):

- Public service ports (public asset ownership, public operation)
- Tool ports (public asset ownership, private cargo-handling)
- Landlord ports (public landownership and management, private superstructure assets, private operation)
- Corporatized ports (public majority ownership, private management, superstructure assets, cargo handling and operations)
- Private service ports (private ownership and operations)

The different port types vary with respect to the involvement of private parties in port asset ownership and port operations.

Public service ports represent the old port management model in which the port is publicly owned and operated. Inefficiencies, budget constraints and the aforementioned pressures drove ports away from this management model in favor of more privatized alternatives. The tool port can be regarded as a transitional form between public and landlord port models, in which all port assets are publicly owned and managed, but cargo handling is relegated to a private operator. The landlord port model gives more room (and therefore influence) to the private sector as not only port operations are privatized, but the port superstructure assets (such as terminals) are also privately owned and constructed, with the port authority retaining ownership of the land.

In the private service port the port is completely privately owned and operated, under the leadership of a fully privatized port authority. The port acts as a private enterprise, with the public sector maintaining a regulatory role. Corporatized ports are almost entirely privatized, with the exception that the majority of ownership remains public. The difference with landlord ports is that the port authority essentially behaves as a private enterprise, with ownership and control of the port separated. This means corporatized ports hold the middle ground between landlord ports and private ports in terms of experienced public socio-developmental pressures and private shareholder value pressures (Rodrigue, Comtois and Slack, 2017).

Despite privatization of ports, public entities can retain considerable influence on port strategies, for instance through the public port authority, or even as a majority shareholder in privatized ports. This influence can be used by local governments and port-city communities to pressure ports to adopt sustainable practices and strategies that are deemed to be in the public interest, even if they are not maritime activities (Pigna, 2014; Rodrigue, Comtois and Slack, 2017). Examples of this are the expectation that ports invest in urban infrastructure or local schools (Pigna, 2014).

These pressures place the port authorities in a difficult position between private actors that strive for maximized economic performance, and public entities that prescribe a more social role to the port (Moglia and Sanguineri, 2003). Due to this position, Musso et al. (2000) prescribe a more pro-active role for port authorities in port planning processes, in which they actively involve and cooperate with local stakeholders in order to address common interests and/or conflicts.

> **Box 3. Port of Tema: governance**
>
> The Port of Tema is characterized as a landlord port, under ownership of the Ghana Ports and Harbours Authority (GPHA) (Quansah, 2008; Chalfin, 2010). While the port has undergone a development of privatization in the past decades, the GPHA remains a state owned entity, tasked with the exploitation and development of the ports of Tema and Takoradi. Rather than executing all port operations themselves (like a public port), GPHA leases port assets to conglomerates of multinational firms and facilitates their operation of the port, while itself keeping a minority share in those same conglomerates.
>
> However, instead of fully privatizing port cargo handling operations as is typical of landlord ports, GPHA performs a portion of the cargo handling operations itself, competing with private parties in the port. Deemed a "hybrid" module of port operations, it attracted the interest of other port authorities on the Gulf of Guinee, as it allows GPHA to collect dividends with which it can develop the port further (Ghana Ports and Harbours Authority, 2015).
>
> Required to be financially self-sufficient, GPHA enjoys relative autonomy from other government agencies and relies more on own dividends and donor funds for the development of the port (Chalfin, 2010; Ghana Ports and Harbours Authority, 2015). This relative autonomy has resulted in the port becoming progressively more separate from and closed off from the city of Tema. Moreover, port development planning has been technocratic in nature, and executed with little public discussion concerning the interests or outcomes of the plan (Chalfin, 2010).
>
> This raises the question whether an autonomous authority such as the GPHA can be moved to acknowledge the need for (and benefits of) considering diverging local interests, with the aim of sustainable port-city development. For instance, there have already been protests against GPHA by local labourers because they have been laid off in favour of private parties from outside the city (Today, 2010).
>
> While the local stakeholder workshop organized at GPHA headquarters (Slinger et al., 2017) revealed a tendency of the port actors to focus on issues of port efficiency and development, it also showed a drive to be progressive and a willingness to consider other viewpoints.

4.5 URBAN DEVELOPMENT IN AFRICA

There are marked differences in urban environments between developed and developing countries. The latter are experiencing more rapid urbanization, a trend that is expected to continue in the coming decades (United Nations, 2014). In Sub-Saharan Africa, the trend of increasing rural-urban migration is driven by low agricultural productivity, exacerbated by population growth and in some instances by droughts, floods and other natural disasters (Hove, Ngwerume, and Muchemwa, 2013; Dr. Kenney, personal communication), as well as by war and conflict.

Moreover, urban development in developing countries is characterized by more uncontrolled, haphazard (informal) settlement (Cohen, 2006). Informal settlement is facilitated by shortcomings in effective land management and insecure land tenure, and usually occur in natural areas or public spaces near or within a city that are (or were) undesirable for alternative development, like peri-urban green spaces. They are characterized by a lack of basic infrastructures such as clean water provision and sewage facilities, paved road infrastructure and electricity provision (UNCHS (HABITAT), 2003; Mazeau, Scott, and Tuffuor, 2012). Shortages in available (or affordable) housing are also cited as a reason for informal settlement (Owusu, 1991).

Uncoordinated informal settlements can be detrimental to the maintenance of service infrastructures on which they are sometimes built, and are prone to flooding due to unwillingness of governments to provide proper

integrated drainage systems to these areas, which are often regarded as being outside accepted urban regulation and planning system. Changing rainfall patterns resulting from climate change are expected to make these problems worse (Douglas et al, 2008; Arup, 2016).

Informality, meaning "opposed to the laid down rules or the accepted norms", can be found in several aspects of urban life, not only in the way people obtain shelter (informal housing), but also in the way they earn a living (informal economy) (Obeng-Odoom, 2011 pp 357). As governmental welfare is lacking, a considerable fraction of developing country population receives their income from the informal sector (UNCHS (HABITAT), 2003).

Box 4. Urban development in Tema

Many of the urban challenges encountered in Sub-Saharan Africa are also present in Tema. Its status as a planned city sets Tema apart from other, organically developed cities. This can still be seen in the relatively high provision of infrastructures such as sewage and piped water in the city. However, the quality of service is decreasing due to overuse and lack of maintenance (Arup, 2006; Acquah, 2001). Moreover, the informal settlements like Ashaiman are still characterized by a lack of such facilities (Mazeau, Scott, and Tuffuor, 2012).

Squatter settlements such as Ashaiman have grown since the 1960's in reaction to a shortage of housing for migrant workers (Owusu, 1991). The Tema Development Corporation (TDC), tasked with providing affordable housing to workers employed in the industrial sector, struggled to provide adequate housing. Problems of housing shortage were exaggerated as local Chiefs, who traditionally hold the land in Ghana (Blocher, 2014) were in a dispute with the TDC, and started exploiting their land on their own, giving rise to increased informal settlement. During the 1980's and 90's, reductions in public funding of the TDC caused further stagnation in the development of affordable housing, as the government withdrew from actively funding housing developments, and private initiatives at providing affordable housing were not successful (Acquah, 2001; Appendix B. Actor analysis).

Meanwhile, industrial developments have led to the complete encroachment and environmental pollution of Chemu lagoon (Figure 11), leading to its biological decline, and threatening the health of nearby residents. Limited enforcement of environmental regulations result in companies not implementing wastewater treatment facilities (Tsetse, 2008).

Chemu Lagoon & Tema Oil Refinery
Tema Oil Refinery, located along the bank of the lagoon has been sited for illegal discharge direct into the lagoon. A massive oil spill in 2007 led to contamination spreading into the Gulf of Guinea affecting saltwater mangroves, fisheries, and bird habitat.

Sakumo Ramsar Site
The Sakumo Ramsar Site is a wetland of international importance covering an area of 1,340 ha situated between Accra and Tema. The area is under threat of encroaching urban development.

Tema Port
The harbour, managed by Ghana Ports and Harbours Authority handles 80% of Ghana's national exports and imports.

Figure 11. A map of Tema, indicating the Port, Sakumo Lagoon, Chemu Lagoon and part of the industrial area (Arup, 2016)

On the other side of town, Tema is slowly encroaching upon the Sakumo lagoon (Kufogbe and Amatekpor, 1997; Appiah and Yankson, 2012). As land becomes more scarce, the poorest residents of Tema are forced to settle the least attractive areas of land, which are unclaimed for development (UNHCS (HABITAT), 2003). These areas are vulnerable to flooding, for instance. However, more formal developments also take place, such as the construction of a church building observed on a field visit to the lagoon.

The impacts of climate change in Ghana may intensify rural-urban migration to Tema and its surrounding lands. This could put further pressure on the Sakumo lagoon and urban housing stock, and lead to increased informal settlement around the city in the coming decades.

4.6   DEFINING SUSTAINABLE PORT-CITY DEVELOPMENT

The United Nations use as the definition of sustainability the words of the World Commission on Environment and Development (1987): "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Sustainable development consists of three pillars: economic development, social development and environmental protection, which it seeks to achieve in a balanced manner (United Nations, 2017).

Xiao and Lam (2017) use this as a basis to define a framework for the assessment of port-city sustainable development. They incorporate factors from economic, social and environmental perspective for both the port and the city system, including GDP generation, tax generation, spatial impact on the community, employment impact, cultural impact and environmental impacts. They discuss operationalizing each category in separate factors measuring the performance of both the port and urban system. A drawback of their framework is that

while it acknowledges air pollution from port emissions, they do not regard transport congestion and the pollution load associated with it (Armah, Yawson, and Pappoe, 2010). Merk and Dang (2013) provide similar, more detailed outcomes of interest for their evaluation of port-city performance. The two frameworks are compared in Table 4.

Table 4. Port-city performance indicators in literature

	Xiao and Lam (2017)	Merk and Dang (2013)
Port development	Productivity [cargo handled per resource usage]	Port throughput [mton]
	Port operations [?]	Port throughput containers [m teu]
		Growth port throughput [mton and/or mteu]
	Trade facilitation [?]	Value added port area [mln USD]
		Efficiency index
Port-city development	GDP per capita	Metropolitan GDP per capita
	Income and profitability [household disposable income, gross savings]	GDP per capita growth
	-	Population
	-	Population growth
	GDP generation/value multiplier, commercial activities, employment multiplier	Port-related employment (direct, indirect)
	Unemployment rate	Unemployment rate
Transport	Transport spatial impact	Motorway network density [km/1000km^2]
		Railroad network density [km/1000km^2]
Research and innovation	-	I.e. total patent applications in region
Spatial development	Coastal land occupation	Land surface of port (km^2)
	Housing, shelter	Urbanized area (km^2)
Environment	Air quality & concentration of pollutants	CO_2 emissions per capita
		Population exposure to $PM_{2.5}$
	Water pollution by port activity	
	Waste generation and treatment	
Communication	-	Number of twitter followers
Heritage and cultural impact	(Maritime) heritage protection and culture preservation	Cultural projects related to port
Institutional	Regulatory framework of port industry	-
	Political stability	-

The indicators used by Xiao and Lam (2017) and Merk and Dang (2013) provide a starting point for the evaluation of port-city development over time. The prioritization as to what indicators are included in an analysis is determined by the problem demarcation, and local stakeholder values (cf. Slinger et al., 2017) on which the research questions are based.

As Merk and Dang (2013) note, the nature of actual impacts varies with the situation in specific port-cities. However, what is not considered is the relative importance of the identified factors, and how large scale port infrastructure projects and trade-offs between outcomes of interest should be evaluated. Such an evaluation is necessarily subjective and would involve the values and priorities of local stakeholders and decision makers, if sustainable port development is the objective.

> **Box 5. Operationalizing sustainable port-city development in Tema**
> While the considerations discussed in the problem demarcation guide what are considered model outcomes of interest for the study, the frameworks discussed above provide potential operationalizations of such model variables.
> It also shows the kind of aspects that, while outside of the scope of this modelling effort, may be considered in sustainable port-city development. This is importance to keep in mind when generalizing model outcomes to other developing country port-cities. For example, while port land use and coastal land occupation are not (indicated to be) issues of importance in Tema (yet) (Slinger et al, 2017), these may receive a high priority elsewhere. While Ghana is politically relatively stable (Fosu, 2013), this may be a factor influencing port-city development in other developing countries (see Appendix D Scenario analysis).

4.7   SUMMARIZING THEORETICAL INSIGHTS

Sections 4.1 through 4.6 each considered different aspects of port-city development based on the available literature, and connected theoretical understanding of the problem to the case study port-city of Tema.

Firstly, it was revealed how port-cities can be characterized by their intermediacy and centrality, and how those aspects could affect their evolution over time. Port cities can experience different kinds of challenges, depending on the evolutionary state that they are in. This provides clues of what might lie ahead for the port city of Tema, the subject of this research. Additionally, it was described how the type of port traffic (and operations) is linked to the (development of the) economy of its hinterland, with a high proportion of containers and high-value added cargo indicating growing diversification, away from primarily port-dependent industry, a process that seems to be taking place in Ghana.

Next, section 4.2 discussed how ports may offer benefits and dis-benefits to local and regional communities in its hinterland. Distinction is made between port direct impacts and indirect or induced impacts, affecting a wider region and group of stakeholders in the economy. This informs the conceptualization of the model, and suggests that both linkages should be included in it. Negative externalities are also touched upon, including traffic congestion and environmental impacts of port operations.

In section 4.3 common ways of measuring port benefits were discussed, and the challenges inherent to the use of these methods. Soft port values are mentioned as (potential) benefits of ports that are hard to quantify, but can have an influence on port-community relations.

The discussion on port governance (4.4) revealed the different ways in which port ownership, management and operation can be organized, and the implications of this for port-city development. The port authority was identified as positioned between local communities of which their ports are a component, and private parties such as shipping lines and terminal operators who drive port development. Tema was shown to be an exceptional case as having a landlord management model, but being capable of generating its own dividends, competing with private parties in the port, making it potentially less susceptible to pressures from the local community to contribute to its socio-economic development.

Section 4.5 addressed the characteristics and challenges associated with urban development in low income countries. Drivers for urbanization and rural-urban migration are described, and how this trend may intensify as the impacts of climate change become more apparent. The nature and drivers of informal settlement and economy are discussed as common components of developing country cities, and how these elements are present in Tema despite its background as a planned city.

Lastly, it was discussed what sustainable development may entail for port-city development based on available frameworks. These provide a basis for operationalizing model variables, and direct attention to the variables and aspects that are not considered within this study.

The discussions in this chapter increased understanding of the research problem and provided information for the design and use of the simulation model.

5 MODEL CONCEPTUALIZATION AND SPECIFICATION

In this chapter, the model is conceptualized based on the theoretical understanding of the problem and local case study data and stakeholder input. To guide the modelling effort, the requirements of the model are established (section 5.1). Second, the existing system dynamics model for urban development by Forrester is explained, which serves as a base for the port-city model (section 5.2). Next in sections 5.3 through 5.6 the conceptualization of the novel sub-models and concepts in the model is described. Lastly, sections 5.7 and 5.8 provide an example of the adapting of model parameters to the developing country context based on local data, and the specification of a novel model feature, respectively.

5.1 MODELLING REQUIREMENTS

In this section, the requirements for a model representing a developing country port city. First, model requirements that follow from the research questions are discussed (section 5.1.1). Next, the model outcomes of interest are defined (section 5.1.2), focusing on what needs to be modelled. Next, the impact of uncertainty on the model and model conceptualization is considered (5.1.3). Lastly, the necessity for the limiting of model data needs is considered briefly (5.1.4).

5.1.1 REQUIREMENTS FROM THE RESEARCH QUESTIONS

The research questions guide and focus the modelling effort. The following research questions were formulated, of which question 2 and 3 represent modelling questions.

1. What is an appropriate and useful model of port-city development in a developing country context?
2. What are potential development patterns of developing country port-cities? In particular, how does port expansion affect port-city evolution?
3. What are effective interventions for sustainable port-city development that mitigate the local-global mismatch in the benefits deriving from port expansion?
4. What do model outcomes mean, for the case study, and for the development of African port cities in general?

Research question 2 examines the reference model behavior with and without 2015 port infrastructure expansion, and evaluates negative externalities connected to port development. Moreover, different patterns of development are evaluated under various scenarios and port expansion options, and their effects on model outcomes of interest. Research question 3 addresses how negative externalities can be reduced without stifling port-city economic development.

In short, a model is needed that is flexible enough to allow experimentation and the analysis of potential interventions, potentially in the context of strategic conversations amongst stakeholders. Additionally, in line with the definition of sustainable development, the model should be able to dynamically describe urban development over the long term. On the other hand, the model must be general enough that model inferences may be generalized to other developing country port cities.

5.1.2 MODEL OUTCOMES OF INTEREST

Model outcomes of interest are based on the interests of local Tema port-city stakeholders (section 2.1), the definition of sustainable development (World Commission on Environment and Development, 1987) and the frameworks of Xiao and Lam (2017) and Merk and Dang (2013) (section 4.6). This means that indicators for both economic and social development, as well as environmental protection (United Nations, 2017) are required. As Forrester's original Urban Dynamics model contains several useful indicators, these are selected where appropriate. The selected model outcomes of interest are listed in Table 5.

Table 5. Model outcomes of interest. *=Indicators present in the original Urban Dynamics model.

Category	KPI	Unit
Economic indicators	Port throughput	kton/year
	Land fraction occupied*	-
	New enterprise*	Productive unit
	Road length	Km
	Road congestion	-
Social indicators	Population*	Persons
	Fraction underemployed of population	-
	Fraction informal of population (economic)	-
	Housing units total*	Housing units
	Informally housed	Persons
	Fraction informally housed of population	-
	Fraction underemployed housing of total housing	-
Environmental protection	Green space	Ha

The focus of the study lies on the impact that port infrastructure development could have on urban development, not on port operations and -competitiveness. However, the throughput of a port is an important determinant of the impacts it has on its surroundings. Moreover, it can serve as an indicator of the prominence of the port, which is useful in determining port-city evolutionary modes.

Given the complexity of the model and problem, the information these indicators provide can be supplemented by that of other variables in the model, should these provide better insights. An good example would be the *fraction of informally settled* to provide a better understanding of city social make-up than the absolute number of informally settled in some cases.

Care must be taken in choosing appropriate performance indicators and being transparent in choices regarding these constructs. Special attention must be paid to interpretation of constructs and modelling results when using the model or modelling concepts with stakeholders to avoid misinterpretation and confusion.

Alternatively, in such a context, active discussion on the terms could be encouraged to establish negotiated knowledge and uniform understanding (De Bruijn and Ten Heuvelhof, 2012).

5.1.3 MODELLING UNCERTAINTY

Uncertainty regarding model parameter values and model structure is not explicitly modeled in the system dynamics approach (Kelly et al., 2013). This necessitates the execution of a scenario and sensitivity analysis, to explore the impacts of uncertainties on model behavior and incorporate them in a policy (intervention) analysis (Sterman, 2000; Pruyt, 2007; Scenario analysis).

That means the model should be able to simulate the effects of uncertainties that are found to be important and relevant to the modelling effort.

5.1.4 MODEL DATA REQUIREMENTS

Modelling a developing country port city means that data availability may be a challenge. This could give rise to model inference validity issues, through uncertainty of parameter values and model causal relations.

In order to mitigate this, a modelling style that keeps the data needs of the model relatively low where possible, while preserving model usefulness and validity, is preferred.

Such an approach is beneficial to potential model use with port-city stakeholders in further research as well, as model inferences can be made based on relatively few data inputs.

5.2 FORRESTER'S URBAN DYNAMICS: THE STARTING POINT

Summarizing the points of the previous sections, the port-city model should:

1) include a range of economic, social and environmental indicators, guided by local input (Slinger et al., 2017),
2) be able to provide answers to the research questions and allow experimentation,
3) allow for the evaluation of relevant uncertainties, and
4) have limited data needs considering the expected scarcity of data.

Forrester's Urban Dynamics model fits these criteria. In the problem definition and demarcation, it was discussed how Forrester's generic model may be applied to a particular case study, and what its main advantages and limitations are. In the research approach section (3.2), the three steps involving the adaptation of the model were explained.

In this section, a brief conceptual overview of the Urban Dynamics model is provided as a starting point for the conceptualization of the port-city model.

5.2.1 CONCEPTUAL OVERVIEW

Forrester's Urban Dynamics model is essentially a land use model, defining a fixed area within which urban developments such as housing and industry can develop and decline. Forrester defined the model boundaries in such a way that the city can attract limitless numbers of immigrants and industries, depending on its attractiveness as a source of labor and housing. The city can also return migrants to its external environment if it becomes less attractive, and residents choose to emigrate. In other words, there is assumed to be no limit to the amount of migrants the environment can supply or absorb from the city.

Forrester's argues that the development of cities is driven by processes endogenous to the cities themselves. These processes, changing city socio-economic state and condition,

influence the attractiveness of the city relative to its environment, driving migration of the different social classes up or down.
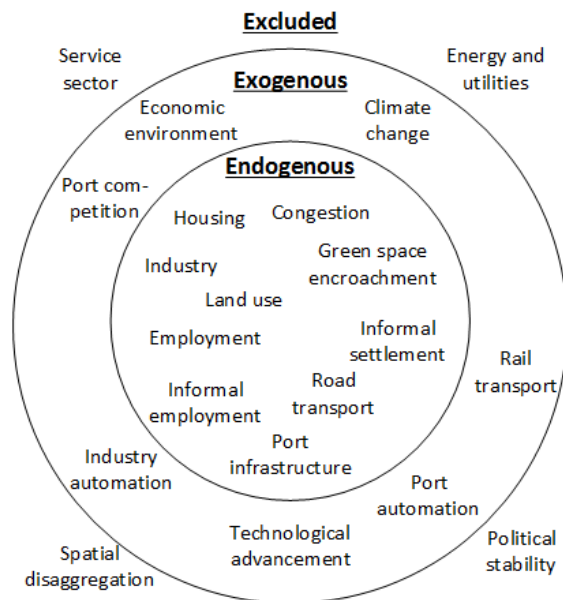
Figure 12. Boundary diagram of the port-city system, depicting endogenous, exogenous and excluded aspects.

This is in line with the traditional micro view on migration based on spatial disequilibria, which postulates that people migrate to places that increase their perceived utility (Waltert and Schläpfer, 2010). Forrester argues that the continued migration and urban growth lead to a reduced attractiveness of the city, reducing immigration.

This reduction of attraction can be due to economic stagnation, high unemployment and taxes, high land prices and rents, or low service provision and congestion. In that sense, planning for urban development essentially means choosing which downside or attractiveness-lowering complication is acceptable for a particular city (Alfeld, 1995), assuming that the land area that is available is (nearly) completely used. Naturally, a city can continue to grow if the land area within the allocated model boundary is large enough.

Figure 12 depicts the model boundary diagram for the port city model, based on the problem definition and demarcation. The diagram shows elements from the system diagram (Figure 1) and how they are conceptualized in the model. Endogenous concepts such as housing and green space encroachment are included in the model boundary and modeled to be driven by processes within the model. Exogenous factors such as climate change and port automation include external factors identified in the scenario analysis (Appendix D), or interventions into the model by stakeholders outside the port-city system from the perspective of the city (e.g. port automation). Lastly, excluded aspects are those aspects that are outside of the scope of this research (section 2.1 Problem definition and demarcation).

5.2.2 MODEL STRUCTURE

Forrester's original Urban Dynamics model consists of three main model structures describing industry and housing development, and population employment status respectively. These model structures are depicted in Figure 13. The boxes in this diagram represent the stock of each housing or industry type in the city. The arrows indicate the flow "material" between blocks. Industry and housing are modelled as aging chains, where newly constructed properties over time slowly decline to older, lower quality dwellings, housing more people. The average time it takes for housing to age depends among other things on the demand for that type of housing, with in turn is a result of the characteristics of the population in the city. The working population is disaggregated into managerial-professional class, a labor class and an underemployed class, each of which is "assigned" to its type of housing accordingly.
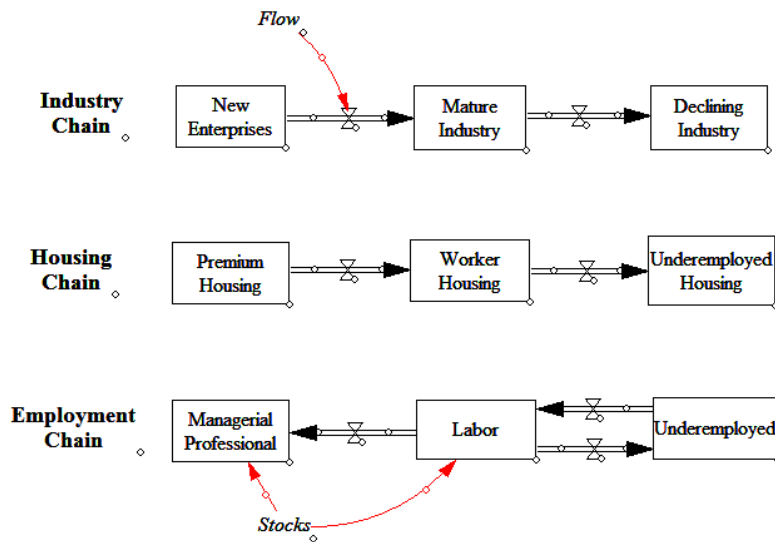
Figure 13. Three main structures of Forrester's Urban Dynamics model

In addition to these three main model structures, there are model subsections dedicated to determining the amount of jobs in the city from the knowledge of the different categories of industry and the type of labour they employ, the fraction of land use, and a computation of tax burdens in the city. All sub-models influence each other dynamically to determine among other things the amount of land area used, population in- and out-migration per class, industry development, and housing construction and destruction over time.

In the following sections the conceptualization of novel sub-models is discussed, including the port, transport and green space settlement. Additionally it is discussed how existing model parameters may be adjusted to reflect conditions in Tema, and an example is given of how the causal mechanisms in the model are specified.

5.3 MODELLING THE PORT

As discussed before, port infrastructure is not modelled in Forrester's original model. Based on what is known about port-city interactions, for example the distinction between port direct and indirect impacts on

employment (Rodrigue, Comtois and Slack, 2017), it does not suffice to simply model the port itself as a part of the local industry, for instance by adding to the stock of new enterprises. Hence, it must be modelled separately on a level that captures adequately the way in which the port impacts the city. This includes both benefits in the form of increased direct employment and added attraction to local industry, but also direct dis-benefits in the form of increased traffic congestion (Merck, 2013; Rodrigue, Comtois and Slack, 2017).

The qualitative diagram of the port infrastructure sub-model and its links to other parts of the model is shown in Figure 14. Variables and concepts that were present in Forrester's original model are depicted in blue.

The presence of port capacity stimulates the development of local industries because of the increased potential for import of resources and export of products. This is supported by both the literature (Merk, 2013; Rodrigue, Comtois and Slack, 2017) and observed empirically in Tema (e.g. Hoyle and Hilling, 1970).

Figure 14. Causal loop diagram of the port subsystem. Concepts that were in Forrester's model are depicted in blue. Note that the figure does not include all variables and causal links for clarity.

Empirical research on the developmental impact of port infrastructure suggests this impact varies with the developmental state of the regional economy (Song and Van Geenhuizen, 2014).

The positive impact of port infrastructure on economic development does not result directly from just its presence, but indirectly through increases in port demand and value added activities (Deng, Lu and Xiao 2013). Infrastructure is therefore modeled to increase the city's relative attractiveness to industry. Note that port congestion mediates benefits to local industries: when the port is heavily congested, transport costs increase and the benefit of its presence to local industry is reduced.

Considering the land area impact of port activities, Jansson and Shneerson (1982) note that the land area used per throughput of ports varies wildly per cargo type (bulk/container). To keep the complexity of the model within limits, and since port land area use is less of an issue in Tema (Slinger et al., 2017), it is chosen that a computation of this effect will not be included in this model. Inclusion of this effect might be an avenue for further research and possibly needed to model port expansion in cities where this is indeed an issue.

Modelling the GDP is done for port freight modelling purposes only. Although there is some discussion in the literature if GDP growth causes port freight increases or the other way around, a clear correlation exists between the two concepts (Figure 15). In this modelling effort the national GDP will be used as a basis for estimating port freight volume. To limit the model complexity, the influence of local port-city industry on GDP and port freight volumes is not modelled. The port of Tema serves a greater hinterland than just Tema itself, for instance including Accra and the Volta Delta region, extending to Northern Ghana and even neighbouring (landlocked) countries of Burkina Faso, Mali and Niger (Ghana Ports and Harbours Authority, 2016).
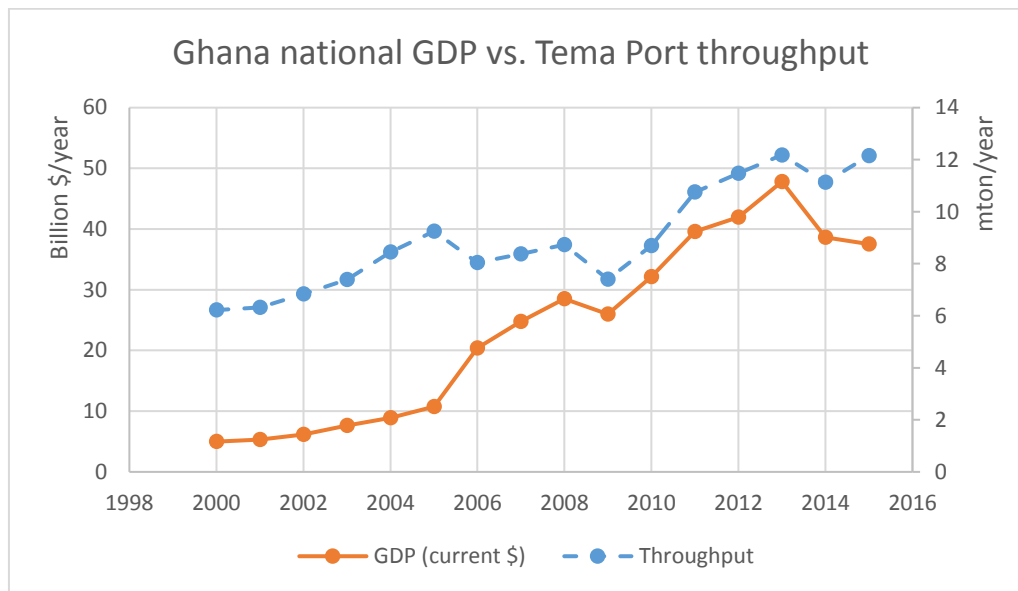
Figure 15. Ghana National GDP vs. Tema Port throughput (World Bank, 2017d; Ghana Ports and Harbours Authority, 2016)

5.4 MODELLING TRANSPORT INFRASTRUCTURE

Transport infrastructure is widely viewed as fostering economic development and productivity. Melo, Graham and Brage-Ardao, (2013) provide a meta-analysis of elasticities regarding the productivity of transport infrastructure investments. Their results show the highest impacts of investments are associated with investments in road capacity, and the effects are highest for primary industries and manufacturing (at an elasticity of ca 0.08). Estache, A. and Garsous (2012) suggest that due to their generally weaker infrastructural state, investments in (road) transport infrastructure have a greater impact in developing countries compared to more developed countries, where factors other than infrastructural capacities are limiting productivity.

A lack of transport infrastructures can act as constraining factor on development. Although transportation costs only account for a small share of the input cost of production, transportation can be seen as an economic factor of production: it is fundamental in its generation, economic activity cannot take place effectively without the transportation factor. This means that when infrastructure is insufficient, small investments can have large

impacts (Rodrigue, Comtois and Slack, 2017). This could be another reason for increased impact of infrastructure investments in developing countries.

However, infrastructural investments show declining marginal returns. At a certain point, benefits of further investments in infrastructure projects equal the costs of the investments themselves. After this point, infrastructure improvements cost more than they provide in benefits.
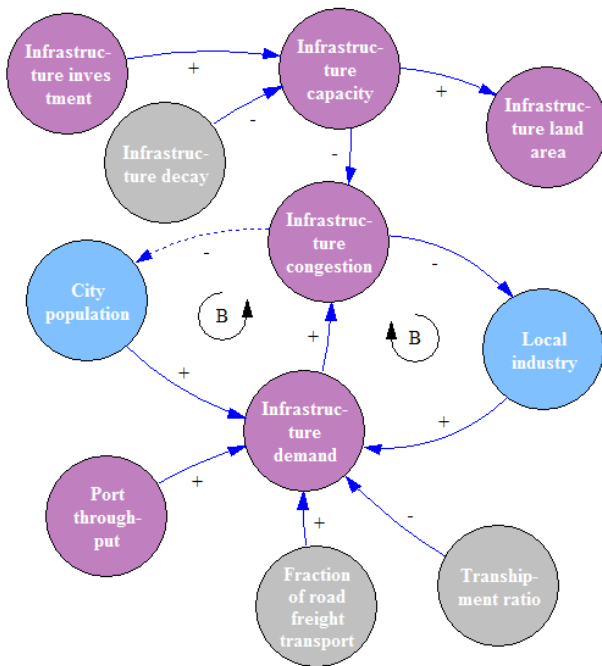
Figure 16. Qualitative flow diagram of the Transport sub-model and its influence.

Figure 16 depicts a causal loop diagram of the conceptual transport sub-model. Note that this does not represent the full model. Concepts represented in Forrester's original Urban Dynamics model are depicted in blue, newly added elements in purple or grey.

The sub-model structure is inspired by the macro capacity model of the urban road network (Shuo, 1999), modelling traffic as a function of infrastructure supply (road capacity) and demand (road use).

Local road infrastructure use is made up of use by population (e.g. commuting to work), use by industries (e.g. locally generated freight transport) and port freight transport. The amount of port freight is mediated by the transshipment ratio (freight unloaded in the port, but subsequently shipped again), and the ratio of road transportation of port freight, which is about 95% in Tema due to the poort state of the railway system. Investments in the road networks increase infrastructure capacity, while the decline and deterioration of road infrastructure over time and through use decrease it. Road infrastructure takes up space in the city and requires its share of the land area.

Congestion in the city has a negative effect on industry, as increased transport costs and reduced accessibility due to congestion make the city less attractive to new enterprises (Agyemang, 2013). The same does not apply in reverse: when transport infrastructure is sufficiently present, additional investments will not make the city more attractive to industry (Rodrigue, Comtois and Slack, 2017). These declining marginal returns of infrastructure investments should be represented in the model.

Effects of congestion on migration are assumed to be less strong. For instance, research on transport in Ghana shows that a major proportion of trips are made on foot, especially by the poorest population segment. Moreover, the economic opportunities of living in the city might overshadow the costs of longer travel times. Severely congested roads might deter high-income groups, who more often have cars themselves (Kwakye,

Fouracre and Ofosu-Dorte, 1997). The diagram in Figure 16 shows how port expansion could adversely affect port-city development, by causing congestion of the transport network.

5.5 MODELLING ENCROACHMENT IN PERI-URBAN GREEN SPACES

Massive urban encroachment on green space is a common issue in Africa (Darkwah and Cobbinah, 2014; Mensah, 2014). In order to simulate the impacts of port expansion on green space, it has to be explicitly represented in the port-city model.

In Forrester's original Urban Dynamics, the amount of land available for settlement is the constraining factor limiting the development of a city. A conceptual representation of Forrester's model is depicted in Figure 17.

Forrester defines the total area belonging to the city to be a fixed land area, a part of which is already occupied by existing developments such as housing and industries. Infrastructure is not explicitly modelled and is not assigned an area, but is assumed to be implicitly represented by the limited total land area, both regarding spatial and capacity limitations (Forrester, 1970).

Figure 17. Conceptual modelling of land area in Forrester's Urban Dynamics – conceptual representation, not necessarily the urban spatial distribution of the urban area

The undeveloped land is completely open to settlement. While there is some notion as to the attractiveness for development of the yet unsettled land, Forrester makes no distinction regarding the nature of the land.

Forrester's way of defining land area has been criticized in literature. For instance Sanders and Sanders (2004) expanded on the model to create several adjacent zones, each developing on their own and influencing each other, thereby aiming to provide a more geographically realistic model of urban expansion. However, it was not Forrester's intention to model urban expansion patterns spatially. In fact, it is not in line with system dynamics thinking, which is more concerned with the evolving dynamics over time of the specified stocks. Making the system dynamics model more spatially refined and complex reduces the transferability of model results to other port cities, and increases the need for more site-specific data which may not be available.

An alternative approach is chosen in which green space is introduced in the model and conceptually (albeit not spatially) defined. This contrasts with Forrester's assumption that all land surrounding the city is available for settlement.

Mass (in Mass, 1974) addressed a similar criticism on Forrester's conceptualization, that not all undeveloped land is available for settlement, but that urban expansion only takes place on the fringes of the developed land, thereby limiting the actually available land. He proposed making the available land a variable in the model, subject to a dynamic land pricing, which is in turn influenced by other factors such as land availability itself. The notion of defining the available land as a dynamic variable can be used to introduce green space encroachment in Forrester's model. In this new conceptualization, green space is given an explicit area within the urban system. This is depicted in Figure 18.

Figure 18. Explicit conceptual (not spatial) modelling of peri-urban green space
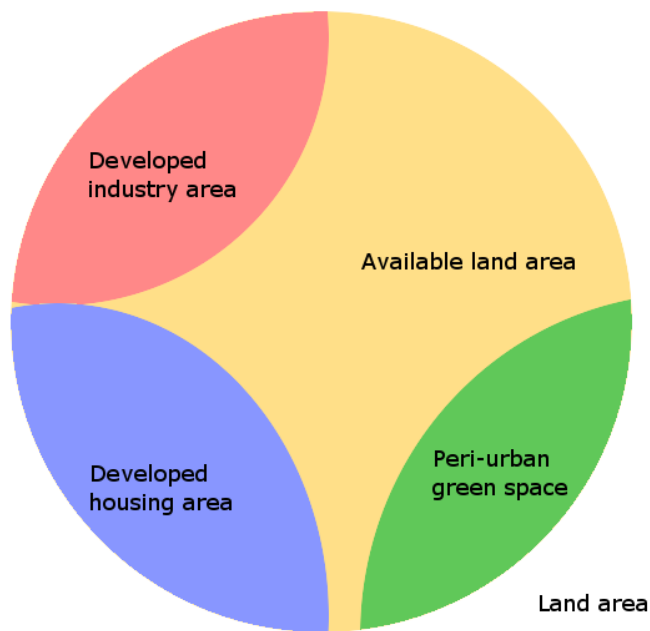
As green space is not readily available for settlement, it initially reduces the land area available for industry and housing. However, when the city expands enough, the pressure increases for the green space to be settled.

As the land around Tema is developed, available land becomes more scarce and therefore more expensive. Combined with a chronic shortage of housing in the city, this forces people to begin settling the less attractive (and therefore less expensive) areas around the city, such as the Sakumo lagoon (green space) (Mariwah, Osei and Amenyo-Xa, 2017).

In a system in which green space is not adequately protected from development, such settlement can take place both informally and formally. This has been observed in Tema. The Chemu lagoon has been encroached upon by both housing and industrial developments (Tsetse, 2008), and the Sakumo lagoon has been subject to settlement by informal housing, but also more formal developments such as the building of churches and lagoon-side villas for the rich in some places.

The dynamics of green space settlement in relation to urban development are visualized in Figure 19 below. Variables or concepts that were explicitly modelled by Forrester are colored blue, additions are given a different color (green and purple) and potential exogenous effects influencing model behavior are depicted in grey.

The two competing feedback loops at work in Forrester's original model can be readily identified. Although Forrester specified a single land multiplier lookup function influencing housing and industry, there are both a reinforcing and a balancing effect at work (R1 and B1 respectively in Figure 19. The reinforcing effect (R1)

models the synergistic effect of existing development attracting more development to the city. The balancing (B1) loop models the constraining effects of finite land area.

Adding green space as an explicit variable in the model identifies two new balancing loops.

- As land becomes scarce, green space settlement allows the city to continue to develop and acts as a buffer against limits to growth (B2 in Figure 19),
- Destruction of green space by urban development reducing the city attractiveness, in turn reducing migration and development (B3).

Figure 19. Causal loop diagram of urban development driving green space settlement. Concepts explicitly present in Forrester's original model are depicted in blue.

The former relationship (B2) reveals the nature of the green space encroachment problem. It is a finite resource (land area) exploited by urban residents until it is depleted, analogous to the extraction of resources from the lagoon (i.e. in the form of overfishing). This constitutes a tragedy of the commons archetype (Hardin, 1968; Ostrom, 1990; Meadows and Wright, 2008): it is in the interest of individuals to settle green space areas, but continued and complete settlement destroys the resource and its value.

The latter effect (B2) is based on this value and the benefits of the green space to the local community, increasing its attractiveness: urban green space provides opportunities for recreation and has beneficial impacts on resident health and wellbeing. In developed countries, landscape amenities are a determinant of urban

attractiveness and impact migration into the urban area. However, this effect is highly income elastic, and not observed in people migrating mostly for economic reasons (e.g. employment opportunity) (Waltert and Schläpfer, 2010; Douglas, 2012). Also in Ghana, high-income residents express such a preference for high-quality environment (White et al., 2007). In developing countries however, peri-urban green space is more strongly associated with dis-benefits such as flooding, disease vectors, pollution and associated health disservices. This reduces the valuation of green space by higher-income residents, and beneficial effects of green space presence on migration of high-income residents is reduced when quality is low (Douglas, 2012; Cilliers et al., 2013).

The urban poor in developing countries can value green space for the extraction of resources supporting their livelihoods (e.g. fishing, biomass for fuel, salt) (Cilliers et al., 2013; McHale et al, 2013). In Ghana, human uses of coastal lagoons comprise of various economic, recreational and even religious activities (Gbogbo, Oduro and Oppong, 2008).

In the case of Tema, there is evidence suggesting that the Sakumo lagoon has had a modest attractive effect on high-income residents. It is however likely that encroachment and decline of lagoon quality has reduced this effect (Van Stipthout, 2002). Sakumo lagoon supports fisheries by local urban residents either supplementing their income or gaining their livelihood from this activity entirely (Gbogbo, Oduro and Oppong, 2008; Pauly, 1976; Ntiamoa-Baidu, and Gordon, 1991). The presence of peri-urban green space is therefore modeled to have a weak effect on the underemployed as well.

5.6   ADAPTING FORRESTER TO AFRICAN CONTEXT

As discussed in the problem definition, urban development is markedly different for developed countries. The most prominent difference is the informality present in urban society (Obeng-Odoom, 2011), expressed both in housing and the economy. Where in Forrester's model underemployed people are relatively dependent on the decline of constructed worker housing and low cost housing programs, informal settlement and slum formation offers an alternative in a developing country. The developmental state is accompanied by a lack of societal welfare, which Forrester's model does include. This section deals with these differences.

5.6.1   INFORMALITY IN URBAN AREAS

Forrester tailored his model to represent an American city. In Urban Dynamics, Forrester defines three main aggregations of workers: a managerial-professional class, a labor class (holding formal jobs) and an underemployed class. The underemployed class is defined by Forrester as not holding formal jobs, but willing to work if a job opportunity presents itself. In the original model, generally they add to the tax burden of a city through a proportionally higher tax need than labor or managerial population (Forrester, 1970).

The definition of the underemployed in Forrester's model has been questioned in literature. On the appropriateness of its level of aggregation, Goodman (in Mass, 1974) asserts that the "level of aggregation within a model is appropriate when items or people grouped together share identical (or nearly identical)

characteristics and behave in similar ways" (p.63-64). For our purposes, defining a category of workers not holding formal jobs could be a measure of the proportion of the population working in the informal economy. Although in reality some employed in informal jobs have a higher income than those in low-paying formal labor jobs, most slum-dwellers are employed in the informal sector and vice versa (UNHCS (HABITAT), 2003). Thus, this conceptualization is compatible with Goodman's assertion.

Based on American culture in the 1970's, Forrester assumes that the working population is predominantly made up of men, by asserting that workers have families they provide for. In African society however women have a large role in generating income, especially in urban areas. As many are employed in the informal sector (Gomez et al., 2008), Forrester's way of conceptualizing the urban workforce might not seem adequate. The conceptualization might however be more appropriate when considering that the industrial sector still mainly employs men, while women are more prominent in the service and informal manufacturing.

The lack of a service industry in Forrester's model itself may reduce its realism. While port and transport infrastructure may have a relatively larger impact on industry and manufacturing than on services, especially in port cities that have not made the transition away from reliance on their port by diversifying their economy (Ducruet and Lee, 2006), it is important to keep these aspects in mind. Model outcomes might not generalize to cities that have a lower proportion of port dependent industry. The (informal) service sector is a substantial part of Tema's economy despite the industrial character of the city. The economic opportunities of earning a living in this sector is a driver for migration to the city Gomez et al., 2008). However, that effect would be present independent of the presence of a port infrastructure. As Forrester already included the effect of increasing urban development drawing more migration to the city in his original model, no model additions are made concerning this.

5.6.2 MODELLING INFORMAL SETTLEMENT

In Forrester's original model, attractiveness of the urban area for the underemployed is partly determined by the availability of low-cost housing and the fraction of underemployed living in the city. In general, the availability of housing attracts migrants. Likewise, a lack of housing deters them. Underemployed are dependent on the degradation of worker housing or targeted low-cost housing programs. Indeed, Tema features the development of slum estates, worker housing that has deteriorated due to lack of maintenance and informal housing extensions or additions (UNHSC (HABITAT), 2003).

Figure 20. Causal flow diagram of the housing sub-model, with informal settlement added. Forrester's original concepts are depicted in blue. Note that not all relations to the bigger model and not all variables are pictured for clarity.

However, the possibility of informally settling in the area could subvert this relationship. Where housing is limited, informal housing on the fringes of the city arises. In Forrester's model, pressure on the construction of housing is (among other factors) determined by the difference in the desired amount of people living in a house and the actual amount. Migration into the city leads to higher building occupancies. With informal settlement, houses are constructed informally in reaction to higher densities (a lack of housing), reducing densities by increasing the built-up area. Figure 20 depicts this conceptual modeling of informal settlement in an African city.

Forrester assumed in his model that each class lives in their own type of housing, e.g. managerial class lives in premium housing, labor class lives in worker housing, and underemployed are housed in low cost underemployed housing. In reality, this relation is not as strictly defined. In the context of Tema, the slum area of Ashaiman was initially formed by migrants who were employed in the various industries sprouting up around the city (Owusu, 1991). This is a limitation inherent to Forrester's way of conceptualizing the relationship between housing and socio-economic class. It is important to keep this in mind, as it can lead to reduced figures for worker migration and informal settlement compared to reality.

The possibility of upgrading Tema slum estates to worker housing status is added to the model, in order to investigate the effects of such interventions on the urban system. Such upgrades are modelled to detract from underemployed housing, and add to worker housing.

5.6.3 LACK OF SOCIAL WELFARE AND FAILING PROPERTY TAX COLLECTION

The informal nature of housing, combined with poor cadaster definition and data-keeping in Ghanaian cities results in poor property tax collection revenues, especially among informally constructed properties (Asare, 2015; Kuusaana, 2015). This situation is typical of developing countries worldwide (UNHCS (HABITAT), 2003).

Forrester assumes in his original model specification that the underemployed enjoy social welfare and subsidies, and 'cost' more to the tax payer than labor or the managerial class. In developing countries social welfare is much less extensive if present at all, and the difficulties with infrastructure provision in informal settlements means that the underemployed group generally enjoys less support from local government than the labor class (UNHCS (HABITAT), 2003). The assumption of shifts in political power in favor of the underemployed driving up local taxes, as modelled by Forrester, is therefore not likely to hold in a developing context.

5.7 ADAPTING EXISTING MODEL PARAMETERS TO TEMA

With the aforementioned adaptations, the model is conceptualized to adequately represent a generic African port city. In order for it to represent Tema, it has to be tailored (specified) to do so. This involves specifying model parameters and data to the situation in Tema. In this section, an example is given of such an adaptation. A complete overview of all model equations can be found in the model databank.

One of the model parameters that must be adapted to local conditions is the *underemployed housing population density*. This model variable represents the number of persons commonly housed in this type of housing. Forrester specifies this parameter as having a value of 12 persons per housing unit (which occupies 0.1 American acres in the original model). Local census data from Ashaiman (a large squatter settlement next to Tema) shows the actual population density and housing situation.

From these figures it can be derived that overall population densities are much higher in Ashaiman, but that Forrester's assumption on family size does not hold. In fact, average household size seems to increase with socio-economic status (compare with Acquah, 2001 who mentions middle income workers having larger family sizes). The average household size in Tema lies around 4 persons per household, compared with 3.7 for the total municipality of Ashaiman, which according to census data in actuality holds about 12.5% of managerial-professionally employed people. The limitations of the practice of modelling and averaging become apparent.

Table 6. Forrester model parameters vs. local data (Mazeau, Scott and Tuffuor, 2012). Additional calculations by author.

Variable	Ashaiman data	Forrester specification (1970)
Underemployed housing population density [persons/housing unit]	18	12
Underemployed family (household) size [persons]	Ca. 3	8
Area per housing unit [Hectare]	Ca. 0.03 – 0.05	0.0405 *(= 0.1 acre)*

An important note is made by Alfeld regarding the parametrization of the model. He stresses the importance of definitional consistency: "Census data or any other empirical groupings compiled on different principles cannot be imposed upon the model" (in Mass, 1974 p. 119). At the same time, he asserts that dynamic modelling is a broad-brush technique, which should not be expected to fill in the detail. Consequently, not too much focus should be placed on specifying parameter values precisely right, especially as they individually rarely have a significant impact on overall model behavior (Meadows and Wright, 2008).

Other parameter changes include settings for initial population, housing and industries, green space area, and city land area. An overview of the values and data compilations can be found in Appendix A. Tema Data, and the model databank.

5.8   MODEL SPECIFICATION

In order to attain a quantitative simulation model, the model relations identified and argued in the previous sections are translated into modeling equations by means of the modeling specification. This section provides an example of how this is done. The final model contains over 220 variables, of which 27 are stocks. The majority of the latter were present in the original Urban Dynamics model. A complete overview of model equations and argumentation is not included in this report for brevity, but is available in the model databank. To provide the reader with understanding of the model structure however, depictions of the specified model are included in Appendix C.

Figure 21 depicts a part of the final specified model, showing the link between the port capacity and the construction of new enterprises in the urban area. As literature showed, the presence of port infrastructure stimulates the development of industry by lowering transport costs, and the potential provision of raw material and export possibilities, opening up markets. This effect however was shown to exhibit diminishing returns; as soon as port capacity is sufficient for company operation, additional capacity will not have an additional impact.
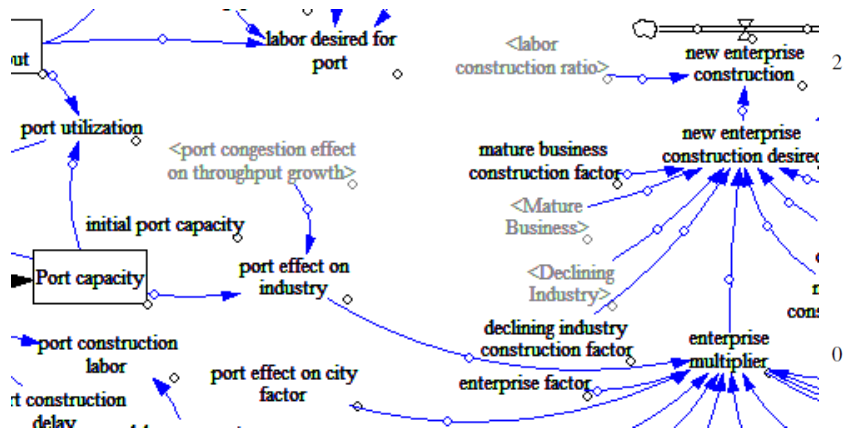
Figure 21. Part of the specified model, showing the link between port capacity and new industry construction
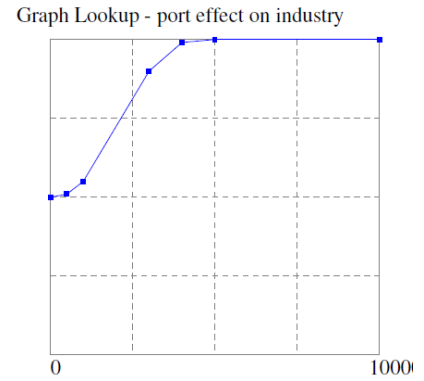
Figure 22. Port effect on industry multiplier, showing diminishing returns

The stimulating effect will not be present however if the port is severely congested. Increasing handling times and low efficiency drive up transport costs until the presence of the port offers no relative benefit. In order to model this multiplier effect, a variable *port effect on industry* is created. As Forrester makes ample use of multiplier effects in his Urban Dynamics model, the new multiplier will fit right in.

In order not to make the model more complex than necessary, the port effect multiplier must encompass both the effect of port capacity presence and congestion. A lookup function will relate the two concepts to a value between 1 and 2: a multiplier effect of 1 for no additional impact of port presence, and a value of 2 as the maximum positive impact of port presence on new enterprise construction. The latter value is arbitrarily chosen since no conclusive figures for this effect could be found in literature. However, on applying this way of specification himself, Forrester notes that the actual values of parameters matter less than the fact that the effect is modeled at all (Forrester, 1970).

The following formula is applied:

*Port capacity*port effects on city factor*port congestion effect on throughput growth*

With the following lookup function:

Port capacity [kton/year]	0	500	1000	3000	4000	5000	10000
Multiplier	1	1.02	1.1	1.8	1.98	2	2

The *Port capacity* is specified as the (maximum) throughput of cargo, in kiloton per year. As a reference, Tema's actual yearly throughput was 6219 kiloton in 2000, and 13415 kiloton in 2016.

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The variable *port effects on city factor* is added as a switch variable, that can be used to turn on and off the effects of the port infrastructure on the model. Additionally, this variable can be used to scale the effects of the port on the city, which is useful for sensitivity analysis.

The *port congestion effect on throughput growth* specified as having a value between 1 (no impact of port congestion on throughput growth) and 0 (port at maximum capacity, hence no further growth is possible). When the port is at capacity and severely congested, the stimulating effect on industry is lost (the multiplier falls to a value of 1).

Certain economies of scale with regard to the economic impacts of ports are described in the literature, more concretely that ports must have a certain size to have a real economic impact (e.g. Park and Seo, 2016). The lookup function reflects this by having a relatively modest effect at low available capacities. The diminishing returns are modeled by having the lookup level off at an (uncongested) capacity of 10000 kiloton per year, meaning that the value of the multiplier will not increase further than 2.

The value of two is an estimation of the beneficial effect of port capacity presence on industry. While infrastructure investments can have a significant effect on industry by facilitating transport of raw materials and providing export opportunities (Melo, Graham, and Brage-Ardao, 2013), it might also expose domestic industries to additional competition from foreign direct investment and cheap imports (Oxford Business Group, 2013). As the model makes no disaggregation between local and foreign industrial activity in terms of employment, a beneficial effect is assumed.

5.9   MODEL CONCEPTUALIZATION CONCLUSIONS

In the previous sections an answer was found to the question what constitutes an appropriate system dynamics model of port-city development in a developing country context. With this a part of the first research question is answered:

"What is an appropriate and useful model of port-city development in a developing country context?"

It was determined that an appropriate model of port-city development in a developing country context should be flexible enough to allow experimentation and the analysis of potential interventions, potentially in the context of strategic conversations amongst stakeholders. Additionally, the model should be able to dynamically describe urban development over the long term, in order to assess interventions of sustainable design. While specific enough to represent Tema, the model must be general enough that model inferences may be generalized to other developing country port cities.

Model outcomes of interest have been defined to include metrics describing social, economic, and environmental considerations, as well as indicators for explicitly modelling transport congestion. Additionally, the model should be able to simulate the effects of uncertainties that are found to be important and relevant to the modelling effort. Ideally, the model should have a modest need for data, as data availability may be an issue in applying the model to a developing country context.

Based on the problem definition and demarcation, the scenario analysis, and literature, it was determined that the model should include a port infrastructure sub-model, explicit modelling of the road transport network, green space encroachment, and should take into account characteristics found in developing country cities such as informal settlement, informal economy, and local data on key parameters to adapt the model to Tema. The conceptualization and specification of these elements has been grounded in the available knowledge and literature on the respective topics.

In the next sections the second part of this research question is addressed, by assessing model usefulness in modelling the development of Tema and developing country port cities in general.

6   MODEL VERIFICATION AND VALIDATION

In this chapter the specified model is verified and the validity of its inferences determined. The complete analysis with verification and validation tests for each sub-model are included in Appendix E. This chapter provides summaries of the relevant findings of these analyses.

The verification tests chosen are based on the guidelines of Sterman (2000) concerning model verification. Model validation approach is based on Sterman (2000), Meadows and Wright (2008), and Shadish, Cook and Campbell (2002).

6.1   MODEL VERIFICATION TEST RESULTS

In this section the results and points of interest of the model verification tests are summarized. A complete overview of performed verification tests can be found in the databank, but is not included in this report for brevity.

6.1.1   BOUNDARY ASSESSMENT

The model boundary delineates whether a variable in the model is endogenously driven, or assumed to be constant over the model run. Assessing model boundary adequacy then focuses on the choices and assumptions made regarding these exogenous constants. Defining a variable as constant over the model run might mean an important feedback loop is not considered, affecting model verification. Next follows a short overview of the most important omitted potential feedback loops.

The effect of local industry on port throughput is not modeled. This would require data that is difficult to come by, as the Port of Tema does not list the origins of its throughput in that level of detail. Modelling this feedback loop would necessitate broad, uninformed assumptions, and would introduce uncertainty that reduce model inference validity. Moreover, as discussed in section 5.3, the Port of Tema serves an area far larger than the city of Tema alone. The research effort maintains a focus on the impact of the port on the city, rather than the other way around.

The link between socio-economic city state and per capita transport demand is not made explicit, as this would increase model complexity and increase model data needs. An aggregate figure is taken instead, which is acknowledged as an uncertain factor. A potential link between road infrastructure decline and road use, road quality and weather/climate conditions is not modeled for similar reasons, but might be interesting to include in group modelling sessions or in further research.

A potential feedback loop concerning average *land per house* decreasing with rising land scarcity, for instance through high-rise buildings is not included in the model. That high-rise buildings are starting to be built in the Tema area (Zakaria, 2014) is an indication that this assumption is a potential vulnerability of the existing model.

Family size and net birth rates are assumed to be constant in the model, but could change over time due to economic and socio-cultural changes (see Appendix D. Scenario analysis). Such changes are partly incorporated however by assigning an appropriate family size and birth rates to the different socio-economic classes in the

model. It is assumed that these changes are not driven by processes endogenous to the model, so no important feedback loops are left out.

There could be a link established between city infrastructure investments and local taxes. In this study this is not done as the tax section has a very modest influence on urban development as modelled, but it is left as a possibility in using the model, for instance with stakeholders.

6.1.2 STRUCTURE ASSESSMENT

The assessment of model structure evaluates whether model structure is consistent with the relevant descriptive knowledge of the system, and if the level of aggregation is appropriate. Basic physical laws such as conservation laws should not be violated, and decision rules modeled should reflect the behavior of actors in the system.

As the model focusses on the impact of port infrastructure on the city and not on port performance or operations, the latter elements are not explicitly modeled. For instance, the implementation of effective port automation could greatly increase port capacity and throughput. Including such links would introduce complexity unnecessary for answering the modelling questions. However, care should be taken in using the model with port experts, who might want to focus on such details. Both automation and capacity increases are included as potential interventions, and can be modeled to apply in combination.

The lack of spatial detail reduces the modelling of transport to a very high level representation. Moreover, investments in transport are modeled as continuous and in reaction to congestion, rather than as discrete projects. While on the city scale this assumption might hold, the lack of spatial disaggregation may miss the locality of road works and the relative impact of the reduction of bottlenecks in a discrete projects. While basic causal mechanisms are valid, some detail and potential feedback loops (for instance between congestion and actual traffic demand itself) are not considered. This might reduce the usefulness of the model as a transport planning tool, but that was not the intended model use from the start.

The variable *societal willingness to settle green space* has been added to better reflect the impact of local informal institutions on local stakeholder decision making (Adegun, 2017; Tyroller, 2016).

Informal housing is assumed to be function of formal housing availability and urban population figures. The implication of this is that informal settlements can sprout up easily and instantly (which seems to be the case, World Bank, 2013), but also that they effectively vanish if population decreases. In reality, some informal settlements might have a certain level of permanence, but it is plausible that informal housing that is abandoned would be quickly torn down to make way for other developments.

The informal work section is limited by Forrester's assumption that every family can have only one formally employed member. That means that informal work is essentially a measure of un(der)employment and family size, which could limit validity of inferences based on this variable and therefore its use as a model KPI.

The modelling of housing as an aging chain, moderated by housing demand for each type, is in line with the observation that housing originally built as worker housing over time has degraded to slum status (UNHCS (HABITAT), 2003).

The lack of explicit modelling of a service industry might prove to be problematic if the model is applied to port-cities in which industry is less dominant and local economy is more diversified (e.g. more evolved port cities, Ducruet, 2006). This means the model cannot be used to simulate the development of such more general cities, limiting the evolutionary pathways it can model, and the generalizability of modeling outcomes.

6.1.3 DIMENSIONAL CONSISTENCY

The model makes extensive use of dimensionless multipliers, following Forrester's specification of the model. To be dimensionally consistent, lookup functions should all employ normalized variables. However, this is not implemented throughout as it would negatively affect model legibility and size.

The use of dimensionless factors means that these are automatically flagged as correct (or just missing) rather than wrong. This means that the automated units check is not as effective for checking model consistency, and more focus lies on manual evaluation.

Several unit errors arise from variables where 'unlimited' smoothing of model output is used as a way to obtain the initial (calculated) values of non-level variables (e.g. SMOOTH(population, 1e+009), this simply yields the initial value of the variable, which doesn't change over the model run). Examples include initial port throughput, initial population and initial . These are related to the way in which Vensim models smoothing, and do not point to a model inconsistency.

Note that in Forrester's model, the unit for managerial-professional, labor and underemployed is simply "men", with other factors derived from this. The term is changed to the more neutral "worker". Note that the implicit assumption that every family can have only one formally employed member is still in place, potentially skewing informal employment figures.

6.1.4 PARAMETER REALITY ASSESSMENT

A parameter reality assessment of the model finds two parameters of interest: *throughput growth factor*, and *transport investment factor*, as these parameters have limited real world meaning and can be interpreted in different ways. Care is to be taken in validating, implementing and explaining the use of these parameters.

The model includes various 'soft' parameters such as lookup functions driving migration and construction. While these effects are plausible and represent real-world effects, it is challenging to find evidence as to the magnitude of their impact especially in a data-poor developing country context. While the magnitude of impacts could be established (or negotiated) through local stakeholder input in group modelling sessions in further research, this limits the validity of current model inferences and of the model use as a forecasting tool.

6.1.5 EXTREME CONDITIONS

Extreme conditions testing uncovered a variety of inconsistencies and potential errors that have been corrected. A full description of model changes can be found in Appendix E.

Applying extreme conditions to the improved model yields plausible results. The model reacts well to policy shocks and changes in exogenous variables. Nevertheless, some care has to be taken when specifying (initial) conditions for the model. Inconsistent values of initial *Green space* and *max* or *min green space* can lead to anomalous model behavior, although model equations have been amended to react appropriately to certain misspecifications.

Extreme conditions testing revealed that the model cannot run with (initial) population levels of zero. This is a consequence of the way Forrester defined his model. The same applies to *Premium housing* and *Worker housing*. Also, care is to be taken with *demolition* and *training* programs, as specifying large values for these could lead to housing and employment stocks attaining negative values. Equations have temporarily been changed in sensitivity testing for this reason to avoid inconsistent results.

Forrester's definition of multiplier lookups did not take into account the full range that input values can attain. That means that lookup out of bounds errors are visible every time the model is run. A this does not affect model behavior, original multipliers are not changed for this reason.

6.2 INTEGRATION

The suitability of the integration method and time step is assessed by checking model behavior for integration errors. Numerical integration errors arise when (1) an inappropriate integration method is selected, or (2) the chosen time step is too large to adequately calculate model dynamics, resulting in averaging, overshoots and possibly oscillations.

The integration method selected is Euler, because potential intervention options involving STEP or PULSE functions may result in instances of non-differentiability resulting from such discontinuous events. This makes a Runge-Kutta 2 or 4 method less suitable for this model, as these methods may average out these discontinuous changes (Sterman, 2000).

Analysis prescribes the use of the finest time step, 0.0078125. As a result, model computing time is increased somewhat, especially in sensitivity testing, but not above acceptable limits on the computers used for modelling.

6.3 BEHAVIOR REPRODUCTION

Finally, the port-city behavior is simulated. Behavior reproduction shows that selected development dynamics are adequately modeled by the model. Figures 23 through 30 depict the behavior of the current model associated with the dynamic hypotheses listed in Table 7.

Hypothesis	Verdict	Comment
H1: urban development leads to green space encroachment	Success	Development of the city leads to reduction of green space (Figure 23)
H2: port expansion will lead to increased encroachment into green space	Success	Following expansion encroachment happens at a faster pace, arriving 10% sooner at full encroachment (Figure 24
H3: port expansion will lead to increased congestion	Success	Infrastructure utilization rises after port expansion, both due to freight and increased industry and migration (Figure 25), despite additional investments (Figure 26).
H4: port expansion will lead to increased informal settlement	Success	The model correctly reproduces the attractive effect of port expansion resulting in increased informal settlement (Figure **27**).
H5: port capacity expansion will stimulate local industry	Success	The stimulating effect of port presence is translated in the model as increased amount of new enterprises following the expansion (Figure 28).
H6: protecting green space will reduce urban development	Success	Protection of 1000Ha of green space has a slight adverse effect on industry and housing development (Figure 29 and 30).

Note that the below graphs are generated by the current model, including adjustments made to correct Forrester's assumptions on housing availability impacting migration, and the (weak) impact of green space on migration following expert consultation. The initial behavior resulted in significant (numerical) underestimation of informal settlement, which prompted a re-examination of Forrester's original assumptions on the mechanisms of migration (see 6.5. Internal validity, 5.5 Modelling Encroachment in Peri-Urban Green Spaces). The original graphs that were used in the interview with ms. d'Hont (Appendix E. Interview data) can be found in the model databank.

Land use (stacked)

Legend:
- housing area : reference run
- informal housing area : reference run
- industrial area : reference run
- infrastructure area : reference run
- available area : reference run
- Green space : reference run
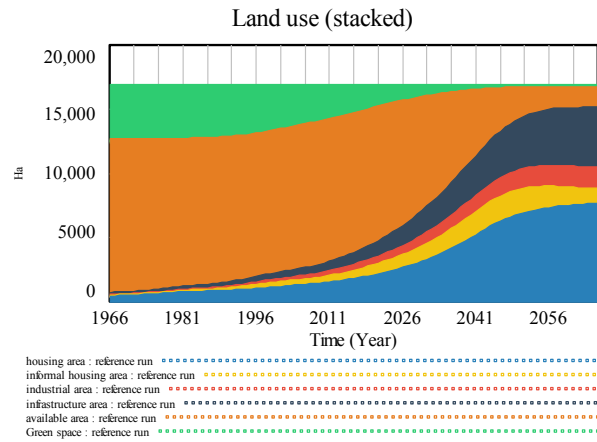
Figure 23. Urban land use distribution over time. Legend: Green space (green), available area (orange), road infrastructure (grey), industry (red), informal settlement (yellow), housing (blue)

Green space

- Green space : no 2015 port expansion
- Green space : 2015 port expansion

Figure 24. Accelerated green space encroachment following port expansion (red).

road congestion

- road congestion : no 2015 port expansion
- road congestion : 2015 port expansion

Figure 25. Increased congestion following port expansion, despite additional investments

infrastructure construction

- infrastructure construction : no 2015 port expansion
- infrastructure construction : 2015 port expansion
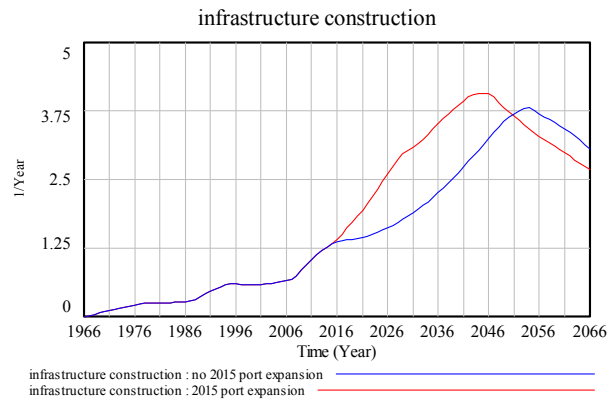
Figure 26. Increased infrastructure construction following port expansion

60
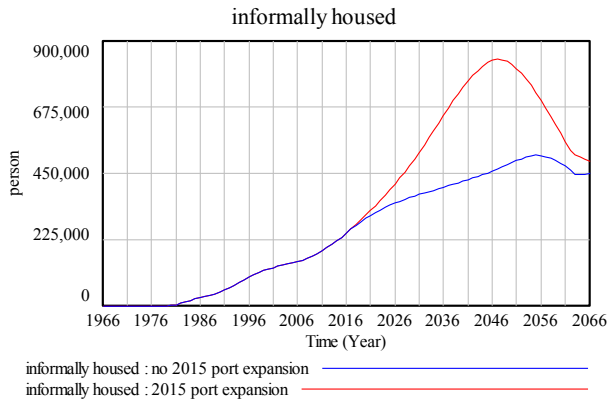
informally housed

Figure 27. Increase in informally housed after port expansion.
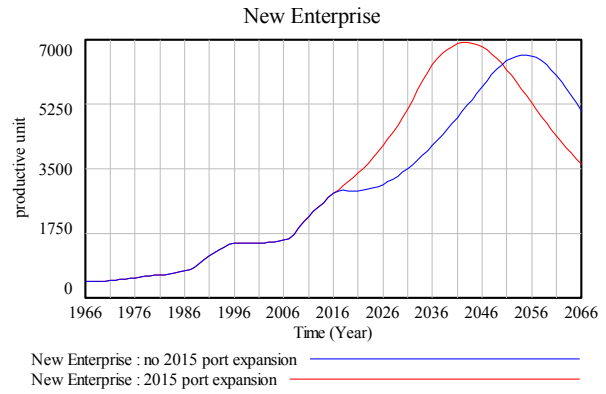
New Enterprise

Figure 28. New enterprises in the city increases due to increased port capacity supply.

New Enterprise
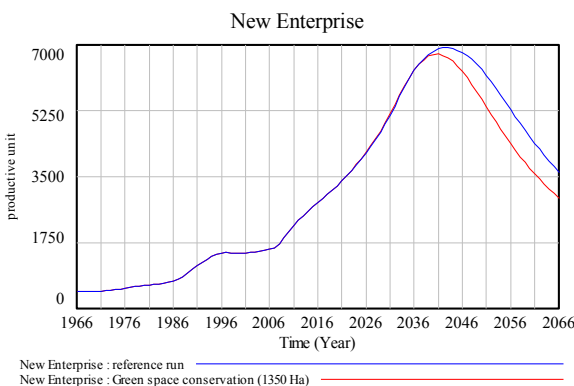
Figure 29. Protection of 1350 Ha of green space resulting in slight reduction of industrial development

housing units total
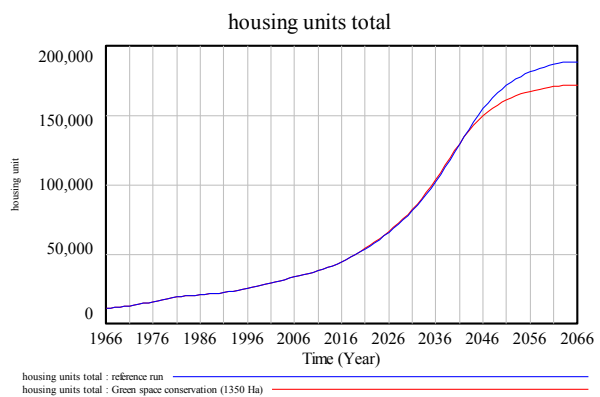
Figure 30. Reduction of housing stock in reaction to green space protection (1350 Ha).

6.4 SENSITIVITY ANALYSIS

A full-scale sensitivity analysis of the model has been performed, in which the effects of variations in some 220 parameters (including lookups) is evaluated.

The analysis reveals that the model is numerically sensitive to many parameters, especially late in model runs due to compounding effects (i.e. growth rates), despite being robust behaviorally. Figure 31 depicts model behavior sensitivity to multivariate variation (+/-10%) of housing sub-model parameters, which can lead to variations of up to 20% later in the model runs (95% of model runs). However, the analysis reveals that the type or pattern of behavior exhibited remains similar under a wide range of parameter values. Note that due its numerical sensitivity, the model should not be used to make precise numerical (quantitative) predictions regarding urban development, but results should be evaluated relative to the reference run.

Furthermore, the model shows a sensitivity to the specification of initial values of population, and to a lesser extent housing and industry. Another relatively influential variable is the *land area,* which greatly impacts the speed of urban development (Figure 32). Particular attention should be given to determining accurate and appropriate data for these parameters.
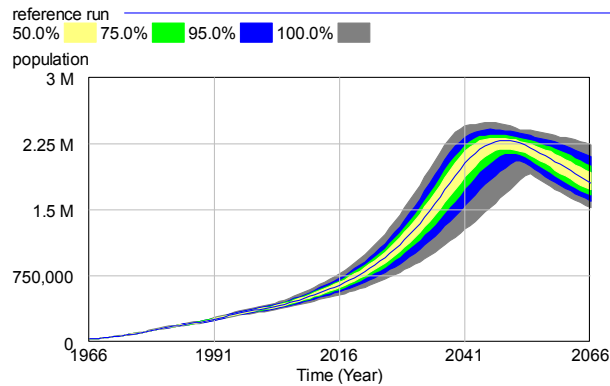
Figure 31. Population sensitivity to housing sector parameters and lookups (multivariate, +/-10%)
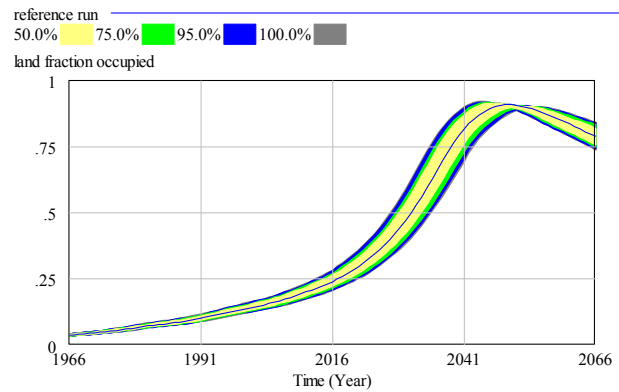
Figure 32. Land fraction occupied sensitivity to defined land area (+/-10%)

Another conclusion of the sensitivity analysis is that it provides plausible results for a range of parameter settings, which suggests the model can validly be used to model development of a wider range of port-cities and contextual scenarios.

There are many estimated parameters in the transport sub-model. However, the analysis shows that uncertainty regarding these parameters is not problematic, as their influence remains mostly numerical in nature. Care is to be taken interpreting model results especially later in model runs however. More influential is the factor *transport investment factor*, as this models endogenously the policy response to congestion, and its value is relatively arbitrarily defined due to lack of real world data on this aspect. The analysis reveals however little sensitivity to this variable: variation of 20% results in ca 10% numerical variation of main model KPI's, and 20% variation in congestion levels (cf. Figure 33 and 34).
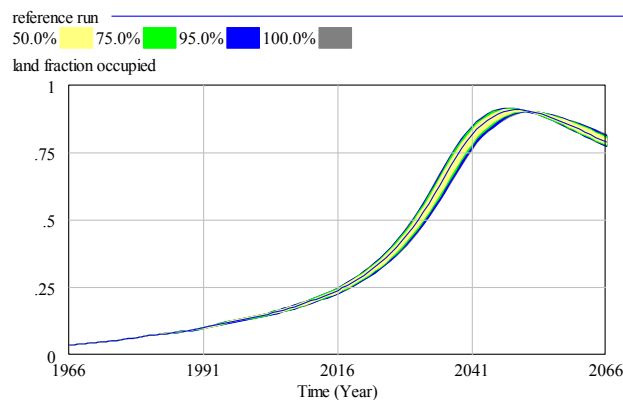
Figure 33. Land fraction occupied sensitivity to transport investment factor (+/-20%)
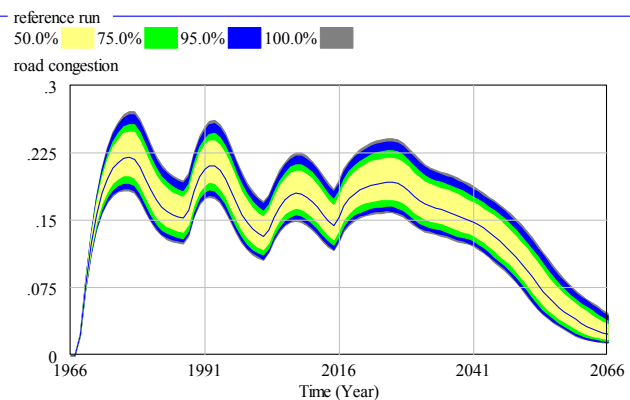
Figure 34. Congestion sensitivity to transport investment factor (+/-20%).

The model is relatively insensitive to many of the multiplier effects defined by Forrester. This corroborates the findings of Stonebraker (1972), and might warrant a significant simplification of the port-city model in further research. Alternatively, the impact of different specifications of multiplier effects and causal relations could be questioned and explored in model use with stakeholders.

A complete overview of model sensitivity graphs and more in-depth analysis is included in the model databank.

As Shadish, Cook and Campbell note (2002), validity is not a property of a design of a methodology (such as system dynamics modelling), but rather of inferences made from or using these approaches. Internal validity of model inference in essence translates to the validity of causal relations specified in the model. As discussed in more detail in the appendix, uncertainty regarding the strength of causal relations in the model can pose a challenge to the validity of model inferences. This is inherent to modelling in a data-poor environment.

In system dynamics modelling, causal relations are specified explicitly. The impact of uncertainties about these relations can be mitigated by evaluating their impact on model outcomes, and interpreting modelling results accordingly (Pruyt, 2007). Internal validity is therefore partly assessed in the sensitivity analysis, where the impacts of variations in model parameters are evaluated.

Another way of assessing internal validity is by comparing the results of model simulation with data on the actual historical development of the city of Tema. Modeling results are compared with historical data on population, port throughput, road length and informal housing and work. Graphs for population and port throughput are included below (figures 35 and 36).
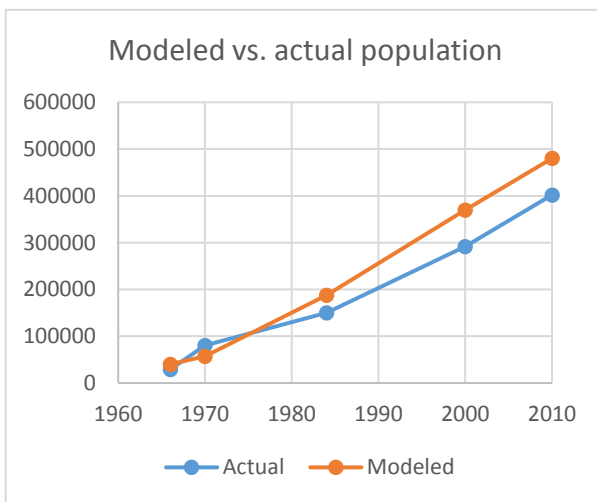
Figure 35. Actual vs. modeled population
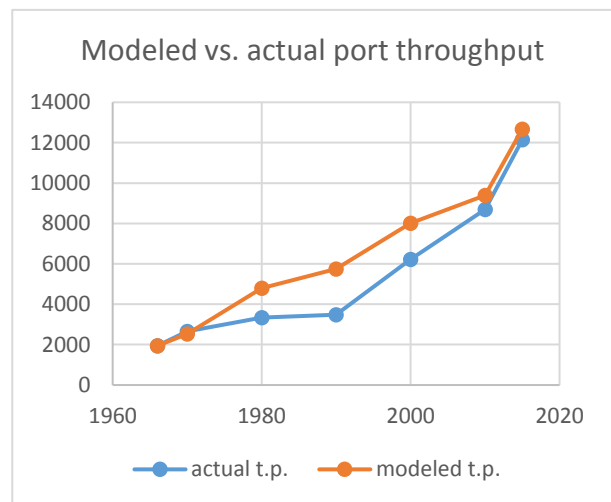
Figure 36. Modeled vs. actual port throughput, in kton/year

The model is seen to reflect actual development dynamics for these indicators. The somewhat lagging real world figures can be explained by the economic crisis stifling urban growth in Ghana in the 70' and 80's (Yankson and Bertrand, 2012), which is not included in the model. A tension is revealed between the model's foundation on the concept of relative attractiveness, and the real world situation of absolute growth figures being influenced by global developments.

Comparison with other indicators also reveal plausible results. A deviation of importance is the systematic underestimation of informal settlement in the model. The causal relations specified by Forrester governing this (that low housing availability stops migration) appear not to be valid in this developing context. While it is not

the objective of the model to recreate the complexities observed in the real world as accurately as possible (see section 3.2), model relations regarding formal housing construction, migration and informal housing have been adjusted to better reflect local system stories and causal mechanisms, and improve model appropriateness to the case study. The adjusted model shows a more realistic response of informal housing, without significantly (numerically and behaviorally) affecting other indicators. Note that the sensitivity analysis has been performed without this improvement, but subsequent testing revealed no large variations in overall model behavior.

Model results for land use show a value for *built-up area* that is significantly lower than real world estimations (including infrastructure area). This might be reflecting an oversimplification of the model (e.g. not modelling service industry, public spaces and market places, institutions such as schools etc.), or simply be a mismatch in the definition of what is considered built-up. Population densities associated with the land area and modeled population area show more plausible results.

Possibly as a result of the low *land fraction occupied*, modelled green space area remains somewhat high compared to the actual area. The earlier mentioned discrepancies with land use and the relative proximity of the lagoon to Tema communities and the coast might explain the increased settlement observed.

6.6   CONSTRUCT VALIDITY

Validity of model inferences can suffer when constructs (i.e. terms, variable names) used are ambiguously defined, or are not what is actually measured (or simulated). Using a particular construct (like *congestion*) can frame debate about results, raise expectations, increase relatability of outcomes, and facilitate making policy recommendations people and policy makers understand. Therefore, it is important to address the validity of constructs used in the model.

Most constructs used in the model reflect real-world concepts in the way they are used and defined. Notable exceptions is the *port capacity* concept, which is measured in kton cargo per year, but could be assumed to refer to a capacity to service a certain type of ship. Similarly, the concept of peri-urban green space can be defined to include varying land types. Ecological value could be a criteria for inclusion in the green space category.

Other concepts can simply be defined in multiple alternative ways. Road congestion is one such concept. Some other factors simply do not have tangible real world counterparts (e.g. transport investment factor), or vary to such a degree in reality that they are not useful as indicators of performance (what constitutes a productive unit for example). This is a result of the aggregating nature of the system dynamics modelling approach (Kelly et al., 2013).

Care must be taken in choosing appropriate performance indicators and being transparent in choices and assumptions regarding these concepts and what they constitute. Special attention must be paid to interpretation of model terms and modelling results when using the model or modelling concepts with stakeholders to avoid misinterpretation and confusion. Alternatively, active discussion on the terms could be

encouraged to establish negotiated knowledge and uniform understanding (De Bruijn and Ten Heuvelhof, 2012).

6.7 EXTERNAL VALIDITY

External validity of model inferences deals with the question whether model inferences from this study can be generalized to other developing country port cities, and different sets of contextual settings. Do model assumptions and modeled causal relations hold over variations of port cities studied, or under different circumstances?

Regarding this there exists a trade-off between local and general validity of modelling inferences. Tailoring the model to represent the conditions in Tema can increase the validity of modelling inferences for that city, but make modelling conclusions less generalizable to other cities.

The sensitivity and scenario analyses can help in this regard. It is established that the model generates plausible behavior over a wide range of parameter settings, and the influence of variations in contextual factors is evaluated. If modelling inferences are found to hold despite variations in external factors, they are considered robust and valid under the range of evaluated scenarios (Pruyt, 2007).

6.8 MODEL VERIFICATION AND VALIDATION CONCLUSIONS

The model verification and validation process provides an answer to the second aspect of research question 1: "What is an appropriate and useful model of port-city development in a developing country context?". The usefulness of the model depends on its ability to adequately model the development of developing country port-cities, and more particularly, the case study port-city of Tema, Ghana.

Verification and validation testing reveals that the model adequately simulates urban development processes at the required level, and is useful for the simulation of port-city development and the issues encountered in developing country port-cities.

Some model limitations have been identified. Firstly, care is to be taken in interpreting modeling results: the model should not be used to make precise quantitative predictions on port city development. Instead, it may be used to explore behavior responses to issues encountered in port city development.

Secondly, the validity of some constructs used in the model is limited, for example because they can be understood to mean or encompass different things (e.g. green space). Care is to be taken when explaining model outcomes or using the model with stakeholders.

Due to conceptual limitations, simulated model values regarding informal work and absolute levels of road congestion are not suitable for comparison with real world circumstances. They can however still be used to assess relative trends and impacts.

The biggest threat to model validity is the relatively low land fraction occupied for a certain size of urban population. Regardless of the reason for this, it has consequences for model behavior, as land scarcity is a main driver of urban development and determines for instance when growth stagnates.

Care must be taken in using the model with stakeholders, as the assessment of model construct validity indicated a risk of misinterpretation and discussion. It could be interesting to capitalize on this and foster such a discussion, in order to gain negotiated knowledge and a sense of commonality in group sessions and working with experts.

Sensitivity and scenario analysis provide optimistic indications for the generalizability of model inferences to other developing country port cities. Applying the model to another case should involve a critical assessment whether causal relations and parameter values apply in that particular city or should be adjusted. Applying the model to a different developing country port city could more strongly test external validity of the model inferences, but this is left as an opportunity for further research.

PART III: USING THE MODEL

In this chapter the verified and validated system dynamics model is used to answer the modelling questions. The modelling research questions were formulated as follows:

1. What are potential development patterns of developing country port-cities? In particular, how does port expansion affect port-city evolution?
2. What are effective interventions for sustainable port-city development that mitigate the local-global mismatch in the benefits deriving from port expansion?

Firstly, port-city development dynamics are analyzed based on the base run, and the impacts of port infrastructure development on the simulated port-city system are explored (section 7.1) Of particular interest are port expansion impacts on road congestion, informal settlement and green space. Then potential development patterns are discussed (section 7.2). Lastly, the model is used to generate and evaluate potential interventions for sustainable port-city development (7.3).

7.1   MODEL REFERENCE BEHAVIOR

The model reference run (including the proposed 2015 port expansion) shows the port-city system growing over time (Figure 37). The growth pattern is typical of growth in a resource constrained system: growth increases until the finite resource determining the system "carrying capacity" is fully used (Meadows and Wright, 2008; Ford, 2009). It is comparable to other system dynamics studies of urban development (e.g. Duran-Encalada & Paucar-Caceres, 2009).
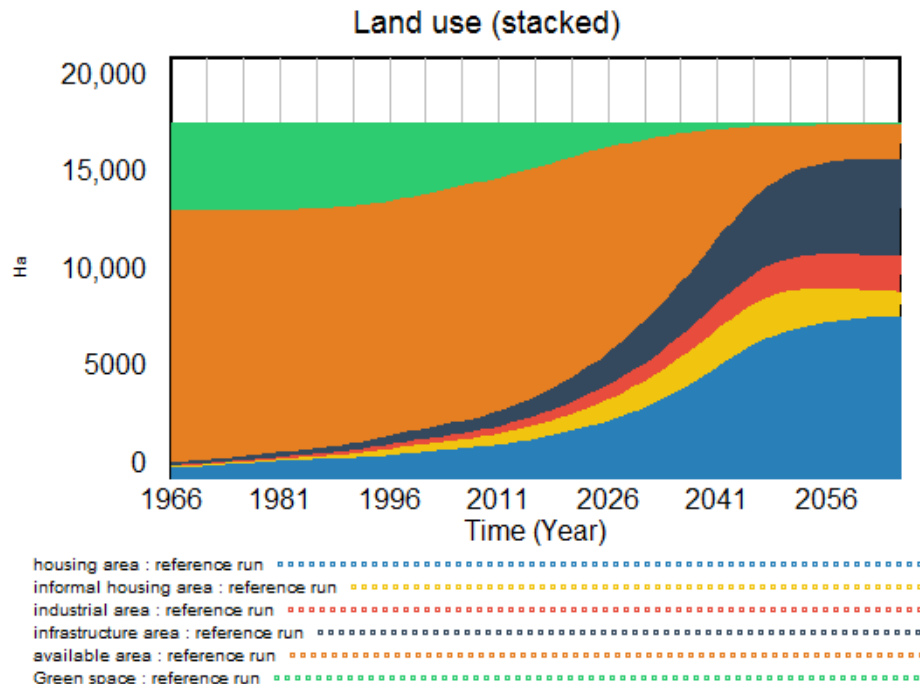
Figure 37. Land area distribution over time [Ha].Top to bottom: green space, available area, infrastructure, industry, informal settlement and housing area.

In this case the resource constraint is the total *land area* available to the system. As the city grows green space diminishes through the increased pressure for settlement (Figure 38). In that way green space land performs a buffering role: the effects of resource constraint are "delayed" by extension into the buffer until that too becomes depleted. Note that this behavior was qualitatively derived from the structure of the land area qualitative flow diagram in section 5.5.

As the land area fills completely, urban growth stagnates. Despite a growing number of underemployed in the system, informal housing diminishes as the city enters the stagnation phase. This is partly the result of the progressive aging and degradation of former worker housing in the city, offering a formal housing alternative to *underemployed* migrants and urban dwellers.
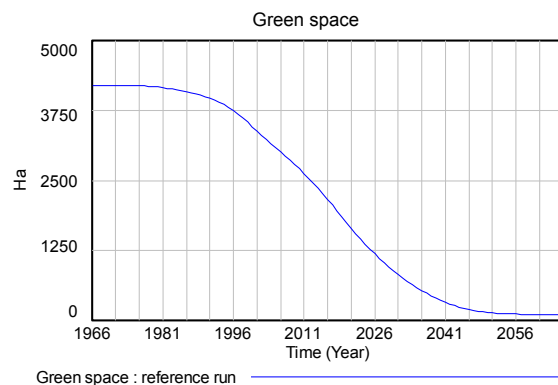
Figure 38. Green space area over time (reference run)
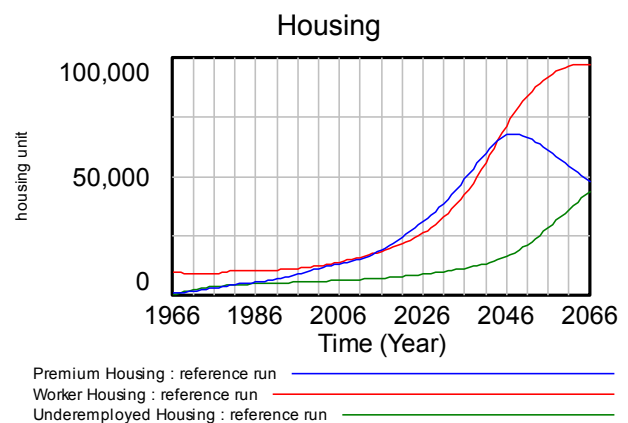
Figure 39. Premium (blue), worker (red) and underemployed (green) housing over time (reference run)
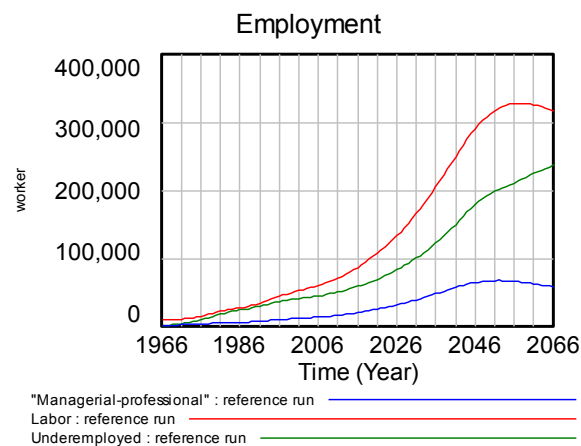
Figure 40. Managerial-professional (blue), labor (red) and underemployed (green) over time (reference run).
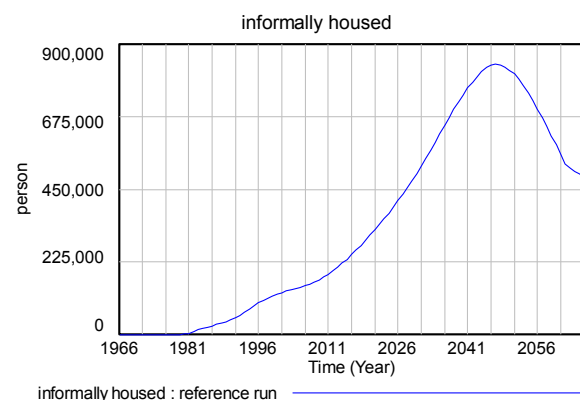
Figure 41. Informally housed [person] over time (reference run)

As industry growth stagnates, formal employment does so as well. The combined effect of lower employment opportunities and housing availability attracts underemployed to the city. This pattern of stagnation and decline is also observed in the original Forrester model (1970).
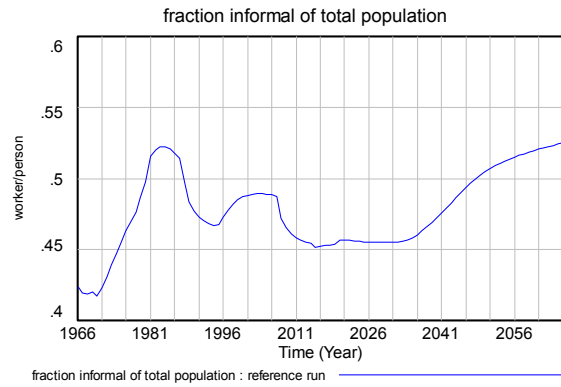
Figure 42. fraction of the urban workforce informally employed over time (reference run)
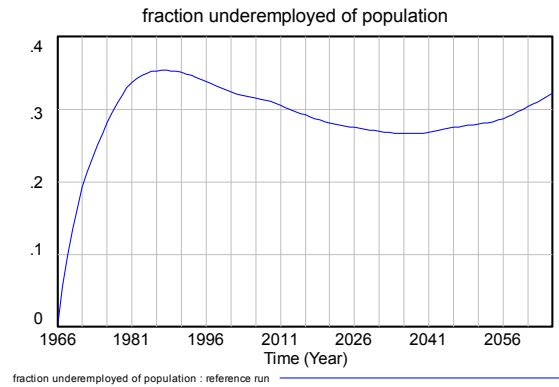
Figure 43. Fraction of the population in the underemployed social class over time (reference run)
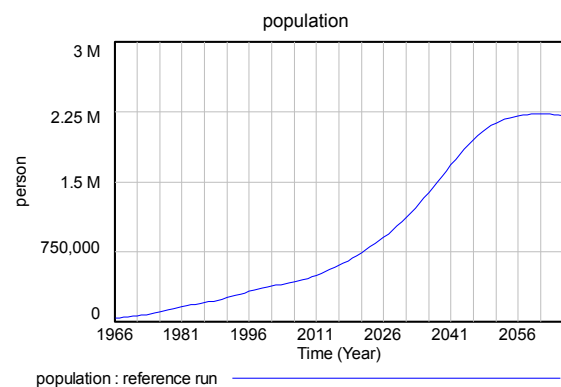
Figure 44. Tema population over time (reference run)
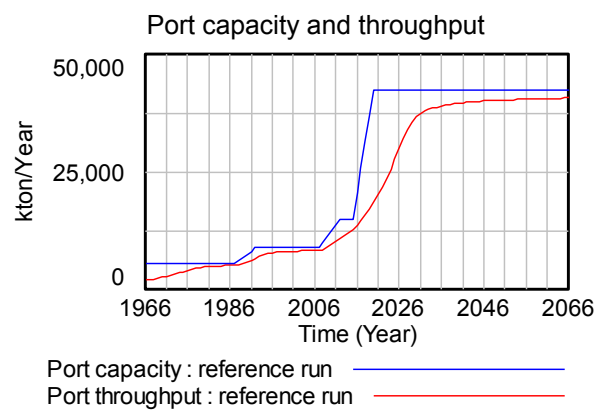
Figure 45. Port capacity and throughput over time (reference run)
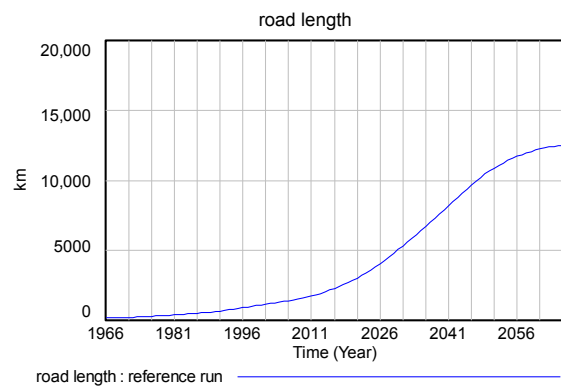
Figure 46. Urban road length over time (reference run)
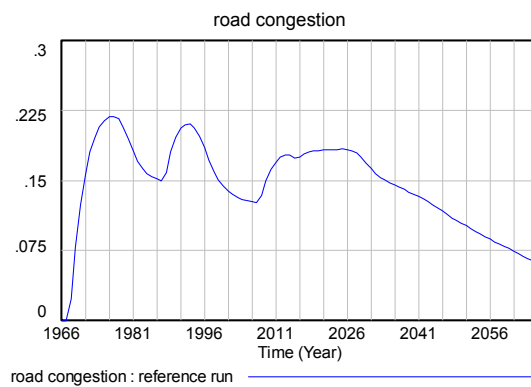
Figure 47. Road congestion over time (reference run)

Port throughput follows capacity increases over time, driven by national GDP growth rates. In this model run, which includes the 2015 port expansion, the local-global mismatch that Tema experiences is at its maximum, as the effects of rising port throughput affect the city. Road congestion rises in reaction to urban growth and the various modeled port expansion projects by as much as 45%, but as infrastructure expands with urban growth, congestion levels are seen to decline relatively soon (e.g. 2% of model run time).

Figures 48 through 59 show the impact of the 2015 port infrastructure development on selected port-city key performance indicators in the model. Model runs including and excluding the 2015 port expansion are compared and plotted in red and blue, respectively. Note that the *2015 port expansion* run is equal to the *reference run* in the previous discussion.
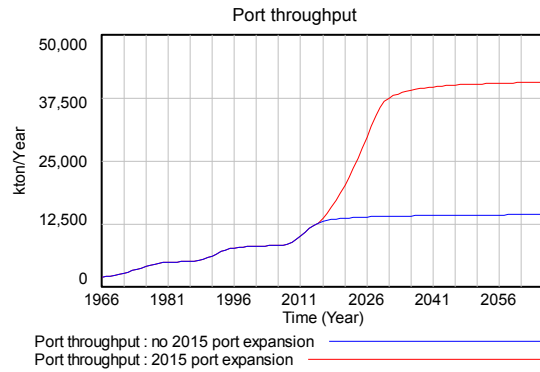
Figure 48. Port of Tema throughput over time, 2015 port expansion (red) vs. no 2015 port expansion (blue)
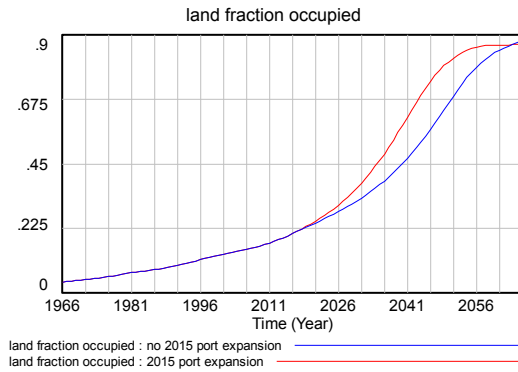
Figure 49. Land fraction occupied over time, 2015 port expansion (red) vs. no 2015 port expansion (blue)
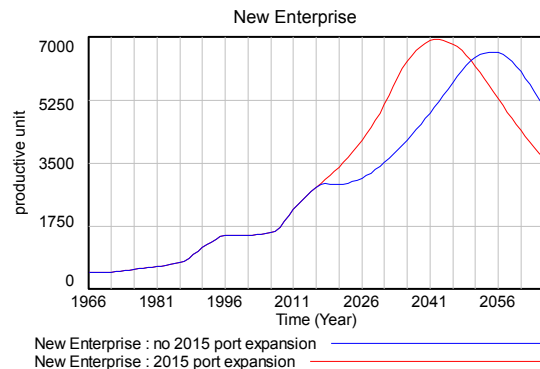
Figure 50. New enterprise stock over time, 2015 port expansion (red) vs. no 2015 port expansion (blue)
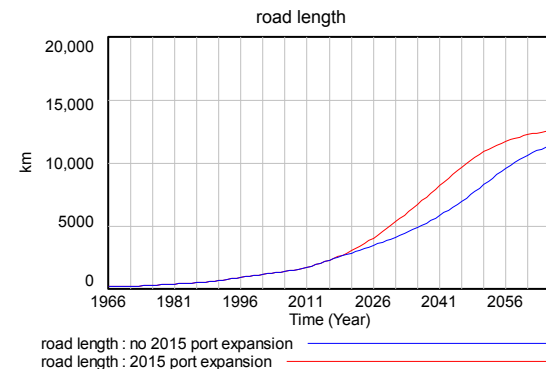
Figure 51. Road length over time, 2015 port expansion (red) vs. no 2015 port expansion (blue)
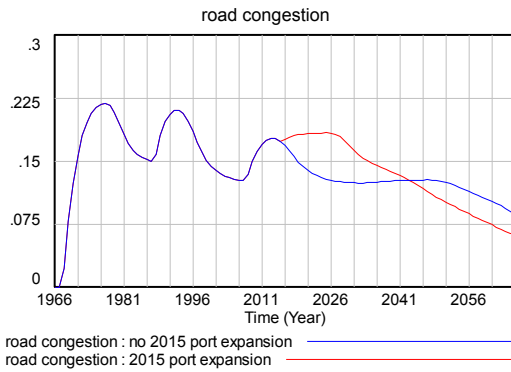
road congestion

Figure 52. Road congestion over time, 2015 port expansion (red) vs. no 2015 port expansion (blue)
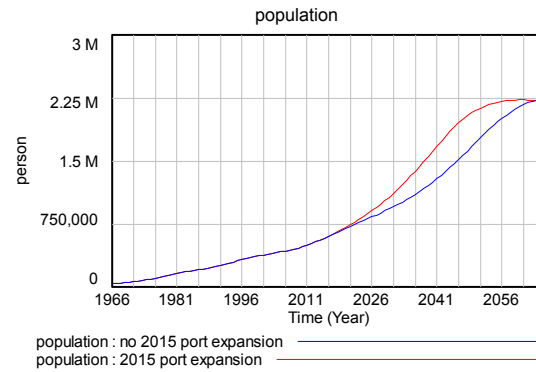
population

Figure 53. Tema population over time, 2015 port expansion (red) vs. no 2015 port expansion (blue)

fraction underemployed of population
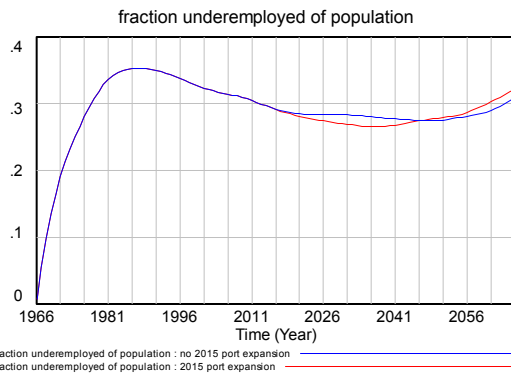
Figure 54. Fraction underemployed of population over time, 2015 port expansion (red) vs. no 2015 port expansion (blue)

housing units total
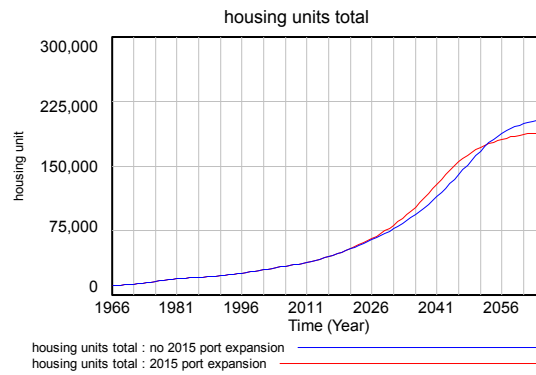
Figure 55. Total of (formal) housing units in Tema over time, 2015 port expansion (red) vs. no 2015 port expansion (blue)
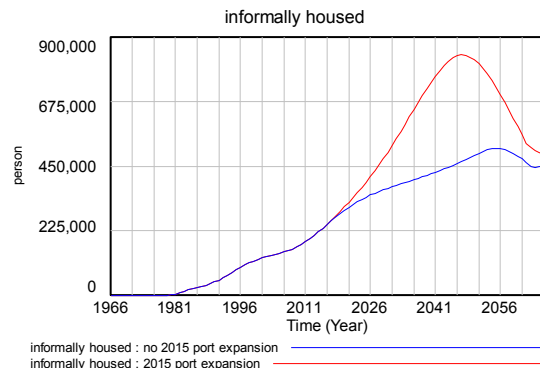
informally housed

Figure 56. Informally housed over time, 2015 port expansion (red) vs. no 2015 port expansion (blue)

informally settled/population ratio
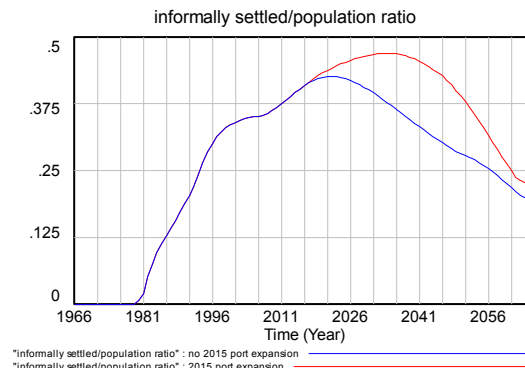
Figure 57. Fraction of Tema population that is informally housed over time, 2015 port expansion (red) vs. no 2015 port expansion (blue)

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fraction underemployed housing of total housing : no 2015 port expansion
fraction underemployed housing of total housing : 2015 port expansion
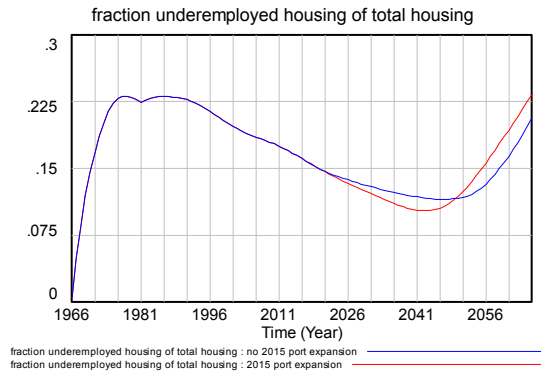
Figure 58. Fraction of Tema housing comprising of slum estates over time, 2015 port expansion (red) vs. no 2015 port expansion (blue)

Green space : no 2015 port expansion
Green space : 2015 port expansion
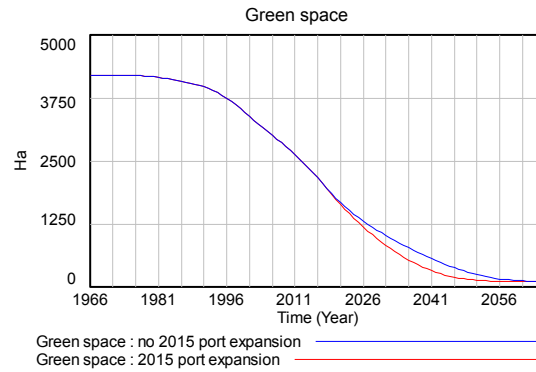
Figure 59. Tema green space area over time, 2015 port expansion (red) vs. no 2015 port expansion (blue)

The effects of port expansion on simulated urban development are profound. Indeed, local industry profits from the lower transport cost of the (less congested) port infrastructure. The increased direct and indirect employment opportunities generated from the increased port capacity and throughput accelerate urban development: industrial peaking is achieved 15% earlier in the model run, while land occupation peaks about 10% earlier than in the run without port development.

However, following the 2015 port expansion, port throughput may triple from 2015 values, if it rises to the new port capacity. This will significantly add to the demand for urban road infrastructure: congestion levels are seen to rise dramatically, up to 45%, if no measures are taken to divert cargo transportation away from the urban road system. However, this increase is only partly attributable to port direct impacts, as indirect effects of industry and population growth in reaction to (perceived) economic benefits of port expansion add to the strain on the urban road network.

The increased demand leads to a period of urban congestion lasting nearly a quarter of the model run time horizon of 100 years, despite increased investments. Only after a substantial time of extensive road investments is congestion consistently reduced.

Green space encroachment accelerates as a result of port capacity expansions: the same level of green space loss is observed 10% earlier in time. However, in both scenarios green space is encroached upon to the same extent towards the end of the model run, as no measures are taken to protect it.

Informal settlement is observed to increase dramatically, up to 80% around the time of stagnation of the city. This increase is both absolutely and relative to the total urban population. This indicates a housing shortage, driven by in-migration of managerial-professional and labor class, and to a lesser extent underemployed (note the temporarily lower fraction of underemployed housing and -population).
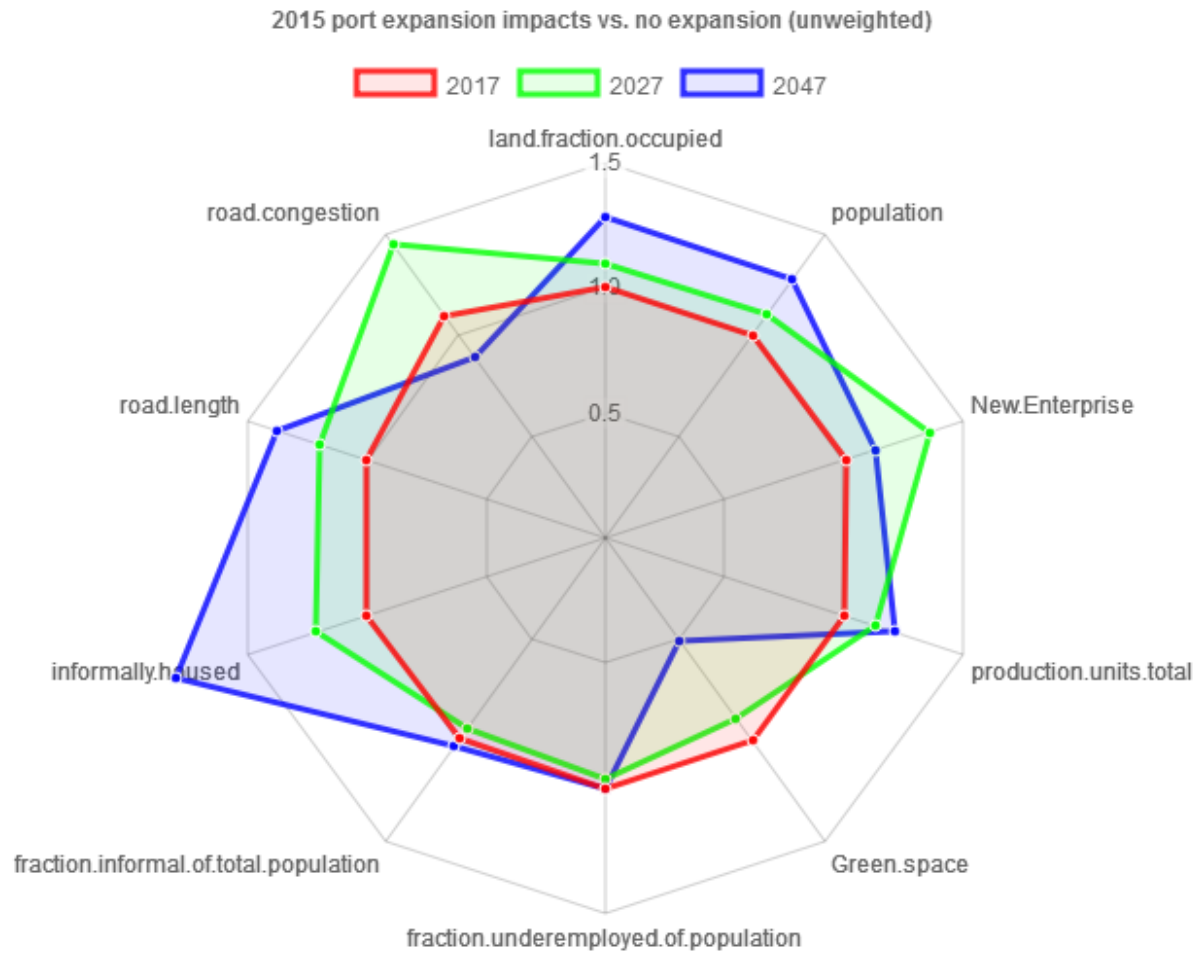
Figure 60. Radar chart of 2015 port expansion impacts for model KPI's compared to development without 2015 expansion (equal to value of 1).

The impacts of port expansion on the urban system are jointly visualized in the radar chart in Figure 60. The chart is generated using an automated R script written by the author to efficiently analyze and visualize the model outcomes of the port-city model (Appendix F). The script, reads and compares the model output of two simulation runs, at each year assessing the percentual differences for each performance indicator over a specified time horizon (in this case 2017 to 2057). The diagram in Figure 60 shows these relative differences at three snapshots in time: 2017, 2027 and 2047.

While precise model behavior between snapshots cannot be derived, this visualization provides a quick but complete overview of relative short and long term impacts without having to resolve to listing individual graphs for each indicator. The values in the chart reflect the change of the key performance indicator (in the policy run) as a factor of the original (base run) values at that time. Hence, a value of 1 would indicate no change or impact, a value of 1.2 represents a 20% increase of that variable compared to the reference run value at that time. Values below 1 indicate a lower value is attained.

The chart in Figure 60 reflects the local-global mismatch of port presence for the port-city in one diagram: while economic effects are enjoyed (e.g. a 25% increase of production units in 2047), negative externalities such as informal housing and congestion rise relatively dramatically. While congestion on the long term declines below levels without port expansion (note the below 1 value), this is only achieved through serious investments in road infrastructure (i.e. ca 35% increase in road length in 2047).

The beneficial impact on industry is not sustainable in the sense that New enterprise construction is not prevented from peaking and stagnating, as the effects of land scarcity and port congestion reduce the construction of New enterprise structures. The dramatic impacts on green space are partly caused by the limited amount of green space later in the model run, at which point a small decrease becomes a rather sizeable fraction of the original value.

Table 8. Scoring table showing mean impacts of 2015 port expansion between 2017 and 2057 for every KPI, weighed.

Model outcome of interest mean scores (2017-2057)	Weight	2015 port expansion (0% discount rate)	2015 port expansion (5% discount rate)
land.fraction.occupied	1	16.7%	5.3%
population	1	17.1%	5.5%
New.Enterprise	1	23.2%	11.1%
production.units.total	1	16.4%	5.8%
Green.space	1	-27.1%	-7.7%
fraction.underemployed.of.population	-1	2.0%	1.0%
fraction.informal.of.total.population	-1	1.6%	1.3%
informally.housed	-1	-46.0%	-14.0%
road.length	-1	-26.8%	-8.9%
road.congestion	-1	-10.7%	-8.9%
Total score	-	-33.6%	-9.5%

Table 8 contains overall scores of the port expansion intervention on model performance indicators. Using the same automated R-script, the yearly relative changes between the policy run and reference run for each KPI are averaged over the observed time horizon. These scores are then weighed to reflect a valuation, for instance by a problem owner or local stakeholders. For instance, as an increase of informal housing is rated negatively, a weighing factor of -1 is applied to positive (above zero) changes, in order to assign a negative score to this indicator in case of such an increase. Alternatively, weighing factors of varying strength and sign can be applied to indicators based on stakeholder preferences. Summing the indicator scores yields a total score for the

intervention on model outcomes, which provides a means of comparing different interventions. In keeping with the societal tendency to value short term impacts more than long term impacts, a discounting factor (e.g. Chichilnisky, 1999; Markandya, and Pearce, 1991) can be applied to the scores. Both negative and positive impacts will then be weighed less strongly in the total score the later they occur, reducing impacts on the scoring of intervention alternatives accordingly.

Table 8 presents a clear picture of the local-global mismatch of port infrastructure. Beneficial scores are achieved for most developmental indicators, including a modest effect on urban socio-economic climate. However, it becomes apparent that the negative externalities outweigh the benefits in Tema, at least in the reference scenario and using these weights. Applying a discount rate to the scores yields less extreme scores altogether (as can be expected), but certain shifts in the relative importance of effects can be observed: on the short term, the beneficial impact on New enterprise is now more pronounced than the negative effect on green space.

This means that when a short term view is taken, the benefits of port expansion on local industry outweigh the detrimental impacts on green space encroachment. Different weighing of performance indicator importance can also yield different outcomes. Moreover, note that in the demarcation of the problem some negative externalities such as pollution and greenhouse gas emissions were excluded from the analysis, based on local stakeholder values in Tema (Slinger et al., 2017) and the chosen modelling perspective. These considerations show that what is considered 'good' development is subjective and differs per port-city, stakeholder and the chosen time frame. In further analysis a broad timeframe, a low discount rate and an even weighing of port-city performance indicators are adopted.

A model is not just a set of equations, but necessarily incorporates assumptions on the nature of the problem and its causal mechanisms. A main assumption underlying the results discussed here is that the presence of the port will have a beneficial impact on local industry. As discussed in section 4.2, port infrastructure expansions can have negative economic impacts as well, for instance by exposing previously 'protected' local industries to foreign direct investment and competition from cheap imports. While this can provide a beneficial drive to industry to become more efficient and innovative, it may lead to a decline of employment in the port city. That means the 2015 port expansion project impacts may be even less beneficial than shown in this analysis, and there are signs that industry around Tema is (starting to be) affected this way (Oxford Business Group, 2013).

7.2   POTENTIAL DEVELOPMENT PATTERNS

Potential development patterns are evaluated based on insights gained from the model through the scenario and sensitivity analyses, and through systematically modelling the impacts of different modes of port development. Firstly, the impacts of port infrastructure are generalized and evaluated in combination with external factors influencing port-city behavior. Next, port impacts in the stagnation phase are examined more closely, and the developmental impacts of different modes of port expansion and retreat. The experiments are summarized in Table 9.

Experiment	Comment
Variation in model parameters	*Insights based on sensitivity analysis (model databank)*
Variation in external factors	*External factors impacts and 2015 port expansion impacts in scenarios (Appendix D)*
Stagnation phase port expansion	*Additional port expansion of 9167 kton/yr (33% of 2015 expansion), 2047 in model time, using the reference model with port automation applied*
Stagnation phase port retreat (2047, model time)	*Simulated move of port activities away from the port-city, 2047 in model time, decrease of port capacity to pre-2007 capacity*
Modular port expansion (2015, 2025, 2035)	*Alternative to 2015 port expansion scheme, where port expansion is increased in three steps rather than one (same final capacity)*

The sensitivity and scenario analysis revealed the potential development trajectories of port-cities. Despite the complexity of the system, its behavior is some variation of logistic growth, which can be accelerated or slowed down depending on city (initial) state, external factors or applied interventions (Figures 61, 62). Compared to developed country cities this growth can occur relatively fast due to the possibility of informal settlement for (potential) migrants, and the relatively large supply of rural residents that can potentially migrate to cities, compared to higher income countries (McHale et al., 2013).
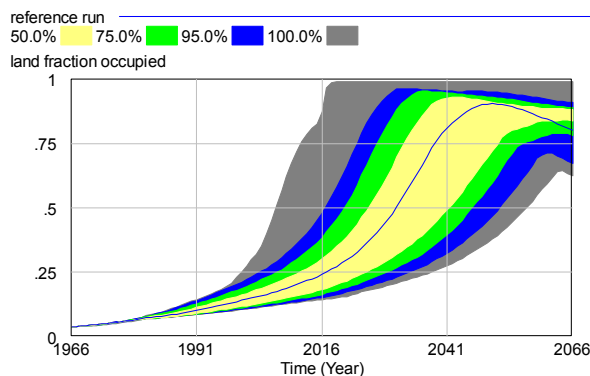
Figure 61. Land fraction occupied sensitivity, under all plausible values of port sub-model parameters
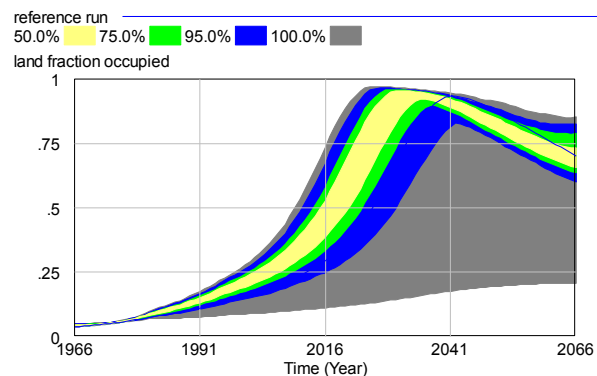
Figure 62. Land fraction occupied sensitivity, under all plausible values of industry-section

Port infrastructure investments tend to trigger the system to behave more dynamically, but on the whole the system is relatively stable. This can be attributed to the stabilizing effect of the many stocks in the system: while flows can (and do) vary wildly over the model run, their associated stocks vary more slowly over time.

In the stagnation phase the city tends to move speedily into a pattern of decline. This behavior is also the central outcome of Forrester's original model (1970). Formal housing ages and deteriorates, due to overcapacity of premium and worker housing and industrial decline. As this happens, the proportion of underemployed (slum) housing rises, attracting more underemployed to the city and stifling development unless urban renewal is stimulated. Port infrastructure (expansion) acts as such a source of urban renewal, when a beneficial effect on industry is assumed.

Interestingly however, while on the short term port infrastructure provides benefits, it causes this decline to be worse in the long term (after the equivalent of 25 years in modelled time): underemployed rates are higher, and the industry bust after the peak is more severe. This prominent effect is observed under all scenario's, which suggests it is a fundamental behavior for the port city as it is modelled: slow but steady growth for simulated cities is preferable to more dramatic development.

External factors driving port-city development

In addition to port infrastructure, there are external effects that may drive port-city development, or lead to interventions such as port infrastructure expansions having different impacts. The scenario analysis (Appendix D) evaluated the potential impact on the port-city system of the economic environment, climate change and technological advancement in the form of port and industry automation.
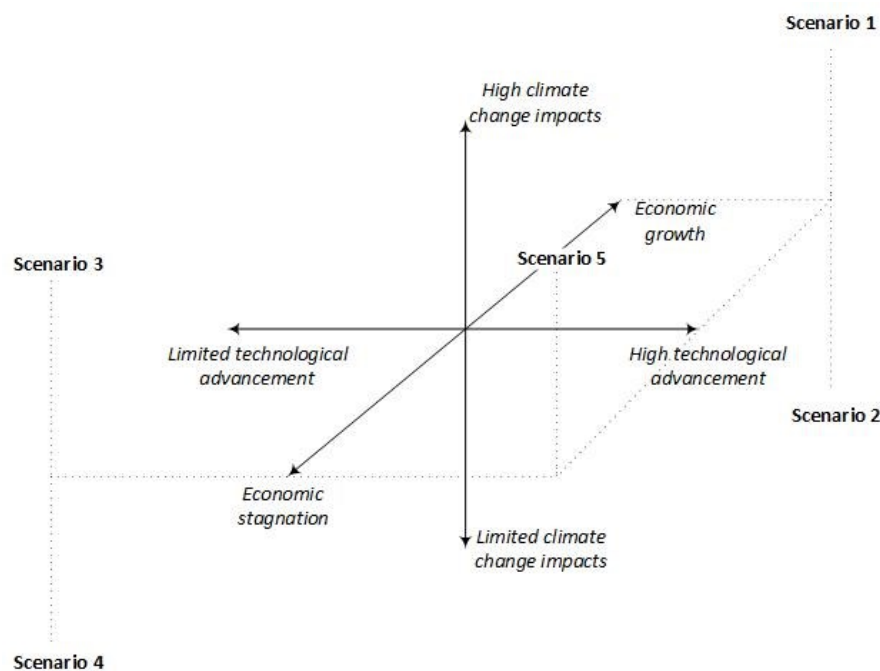
Figure 63. Specification of scenarios as a function of the driving forces

The main findings of the scenario analysis are that an economically beneficial environment may lead to increased industrial growth in the city, driving population growth despite the rise of industrial and port automation. Reduced labor needs and improved road infrastructure capacity mean industry can grow, but as less labor is employed the population of the city shifts to managerial-professional and underemployed, at the cost of the labor class. As a result, inequality in the port-city increases.

Unfavorable economic circumstances on the other hand reduce the speed of industrial development in the city compared to the reference scenario. However, interestingly this still leads to an increase of local industry in the long term, despite reduced road infrastructure construction. As port throughput also decreases due to slowed economic growth and competition from other ports, port negative externalities are reduced. As port capacity

is still readily available, and road transport is less congested, local industry has a relative benefit concerning these input factors. Moreover, as road infrastructure takes less land area, there is more left for the development of the city.

This is a prime example of the local-global mismatch of port development, where the port operations and resulting freight flows stifle the city development and keep it from flourishing, despite the stimulus to the local industry. This effect would become even more pronounced when port land use would rise as a result of increased container shipping and handling. Further research could expand the model to include port land use and the impacts of the shift to container transport.

Considering output as dependent on model assumptions, it must be noted that the modelling of automation assumes that human capital for such a development is present in the city or can be created, for example through limitless in-migration of managerial-professionals, or training of labor in the city. For Tema this assumption may in fact be valid, as the manufacturing industry in Ghana has a relatively high prevalence of in-house training of labor and a relatively well developed educational system.

Increased rural-urban immigration due to climate change can increase the immigration of underemployed into the city, but in the modeled scenarios this does not lead to increased informal settlement. This may be a result of the other drivers modeled in each scenario: either economic stagnation or technological advancement reduces employment opportunities in the modeled scenarios where climate change impacts are high (or both in case of scenario 5). Increased in-migration of underemployed by itself does have that effect by raising the demand for housing.

Table 10. Mean impacts of 2015 port expansion (vs. no 2015 port expansion) on model KPIs in scenarios (2017-2057).

2015 port expansion impacts (vs. no port expansion) in scenarios (2017-2057, discount factor: 0%)	Weight	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
land.fraction.occupied	1	12.4%	12.2%	25.0%	23.6%	29.9%
population	1	11.9%	11.4%	27.8%	25.8%	32.3%
New.Enterprise	1	12.8%	12.9%	55.0%	53.0%	54.8%
production.units.total	1	11.4%	11.3%	28.6%	27.8%	33.3%
Green.space	1	-21.1%	-21.8%	-29.4%	-29.7%	-32.8%
fraction.underemployed.of.population	-1	-0.5%	0.1%	2.3%	3.7%	3.7%
fraction.informal.of.total.population	-1	0.7%	0.8%	3.5%	3.4%	3.2%
informally.housed	-1	-28.7%	-30.1%	-84.6%	-86.8%	-255.1%
road.length	-1	-21.8%	-21.6%	-27.6%	-26.5%	-31.1%
road.congestion	-1	-3.1%	-3.8%	-25.9%	-24.9%	-29.1%
Total score	-	-26.0%	-28.6%	-25.3%	-30.6%	-190.9%

The expansion of port infrastructure has different mean net impacts in the modelled scenarios. Interesting is the increased beneficial impact of port infrastructure expansion in scenarios of economic stagnation. This reflects the relative benefits of a reduction of the local-global mismatch of port infrastructure: negative externalities are reduced, and in economically unfavourable time companies near ports have a relative advantage. Increased port and industry growth however does lead to dramatic increases of informal housing (on average 80% higher between 2017 and 2057).

The exceptional rise of informally housed in scenario 5 follows from the rather slow (population) development of the city in the absence of a port in that scenario. Formal housing construction is better able to keep up with reduced immigration. The expansion of the port changes this, despite progressing automation. A relative stimulus to local industry combined with reduced port negative externalities due to stifled throughput growth spur new enterprises: a maximum increase of 80% new enterprises is achieved a third of the model run after port implementation. Once automation progresses, immigration has led to a boost in informal housing. Formal housing at the point of urban stagnation cannot be built due to land scarcity, trapping the city in a state of informal housing until saturation of employment opportunities reduce housing demand in the city (Figure 64).
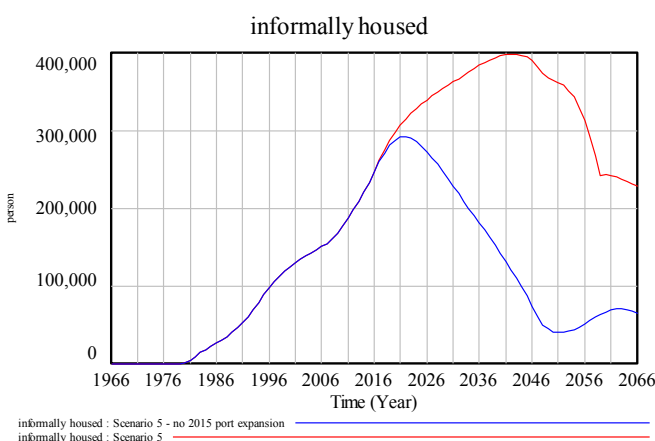
Figure 64. The effect of port expansion on informal settlement, in scenario 5.

A closer look at the stagnation phase

The impacts of a port expansion in the stagnation phase of the port-city are examined. A port expansion one third the size of the 2015 expansion is applied to the model as the urban development starts to slow down (around 2047 in model time). In this exploration it is assumed that (container terminal) expansions are accompanied by automation of port processes in order to avoid unrealistic port labor needs. The effects of a 2047 port expansion are then compared with a model run (including automation) without it. The automated scripts are adjusted to regard impacts from 2047 (in model time) to the end of the model run (2066) only.

Model output shows that the port can act as a source of urban renewal when development in the city has stagnated (Table 11, Figure 65). Industrial activity is stimulated, but port (infrastructural) externalities also increase. The beneficial effect is short-lived, however. Formal housing construction is reduced due to increasing

land pressures, driving informal settlement instead. These same land pressures quickly stifle additional industry growth as well (Figure 66). Unless slums are actively cleared, port expansion benefits quickly fade.

Stagnation phase expansion (9167 kton/yr, 2047) (2047-2066, discount factor: 0%)	Weight	Score
land.fraction.occupied	1	4.7%
population	1	8.4%
New.Enterprise	1	30.9%
production.units.total	1	7.7%
Green.space	1	-16.4%
fraction.underemployed.of.population	-1	-0.4%
fraction.informal.of.total.population	-1	2.0%
informally.housed	-1	-29.7%
road.length	-1	-6.3%
road.congestion	-1	-22.4%
Total score	**1**	**-21.4%**
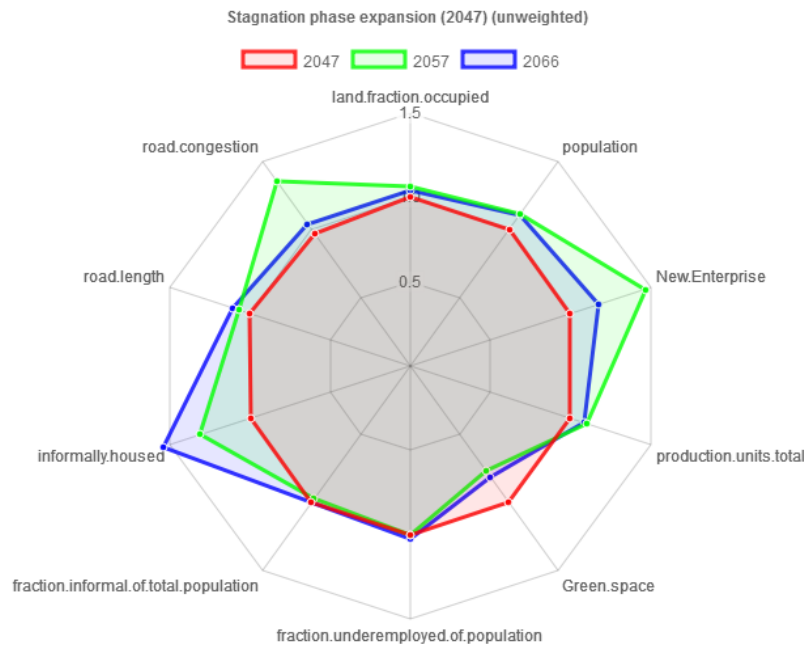
Figure 65. Stagnation phase port expansion impacts on the port-city system (2047-2066), unweighted.
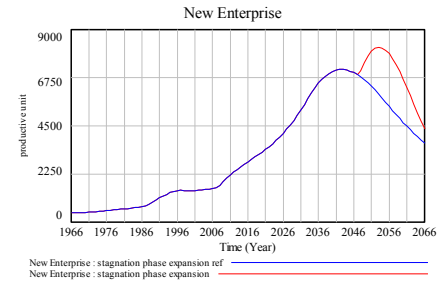
Figure 66. Stock of New enterprise in the city, 2047 port expansion (red) vs. reference run (blue) (port automation applied)

Stagnation phase port retreat

Port terminal superstructure assets do not have unlimited lifetime, but depreciate over time without refurbishment. An estimated depreciation time of 30 years has been estimated for terminal assets in developing countries (Novaes et al., 2012). Following port privatization and the trend of port investments to become capital-intensive rather than labor intensive, the power to decide in which port to invest of private parties such as shipping lines and terminal operators has increased (see problem definition and demarcation, and section 4.4 Port governance). It is therefore plausible that, in reaction to port-city land scarcity and congestion, port activities move away from the city (Ducruet and Lee, 2006; see section 4.1 Port city characterization).

Such a scenario is evaluated for Tema, in the model including the 2015 port expansion and with progressive port automation applied from 2017 (rate: 0.02). The automated model outcome evaluation script is again adapted to analyze impacts from the point of port retreat, some 30 years after commission of the new port terminals, to the end of the model run (2047-2066). The model is adjusted for this occasion to avoid negative port construction labor following capacity *decrease*.
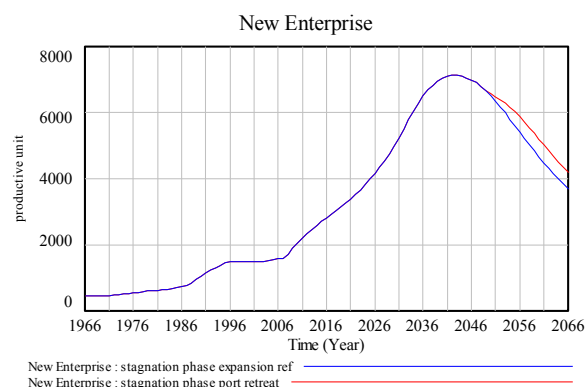
Figure 67. Stock of new enterprises in the city, following 2047 capacity reduction, compared to reference run including port automation effects).
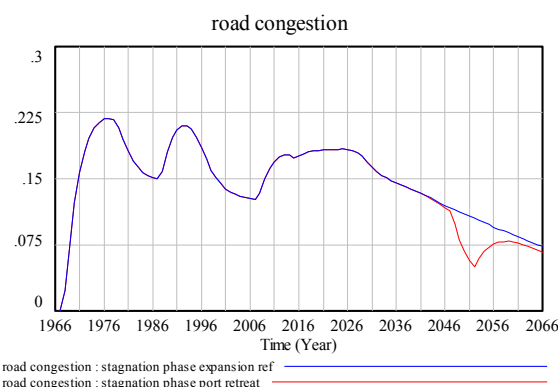
Figure 68. Temporary road congestion relief following 2047 port retreat.

Table 12. Stagnation phase (2047) port retreat (-33550 kton/yr) impacts on model (2047-2066, 0% discount rate).

Stagnation phase (2047) port retreat (-33550 ktn/yr)	Weight	Score
(2047-2066, discount rate: 0%)		
land.fraction.occupied	1	-0.5%
population	1	0.7%
New.Enterprise	1	7.6%
production.units.total	1	1.8%
Green.space	1	2.9%
fraction.underemployed.of.population	-1	0.6%
fraction.informal.of.total.population	-1	0.3%
informally.housed	-1	-2.3%
road.length	-1	5.0%
road.congestion	-1	20.1%
Total score	**1**	**36.2%**

Table 12 shows beneficial outcomes for Tema. Despite an initial reduction in port direct employment, the city benefits from reduced port externalities and infrastructure demands of port throughput. New enterprises and housing profit from this (+13%, max 2% respectively), attracting more migration and urban development. While informal housing drops initially through housing increases, subsequent migration due to reduced congestion and newly created employment opportunities cause it to remain slightly elevated, both in absolute and relative terms (2-5%).

A modular port expansion approach

It is investigated how different modes of port development can influence port-city development patterns. For instance, would it be beneficial to split up port development projects over time rather than implementing large capacity expansions all at once? A modular approach may be preferred, as impacts on the city, both positive and negative, are spread out over time.

The impacts of a modular port expansion approach are presented in Figure 69. Modular expansion has both beneficial and detrimental effects on the port-city compared to a single larger expansion. The stimulating effect on local industry is more spread out over time, leading to a longer lasting impulse for the local economy. However, congestion is increased dramatically even though the total expansion amount is ultimately the same for both situations. Green space is also adversely affected on the longer term, indicating increased land pressure arising from paced port development.
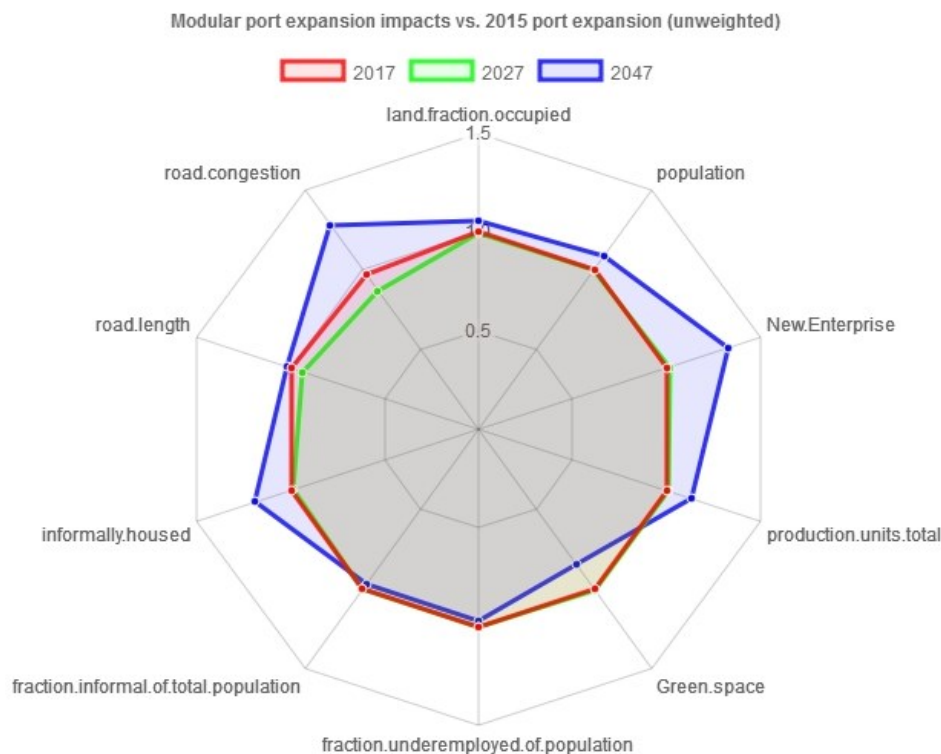
Figure 69. Modular port expansion impacts respective to 2015 port expansion

Table 13 shows the mean percentual changes for each KPI over time (2017-2057) of modular port expansion compared to the single expansion. Using the showed standard weighing factors, no significant improvement is discerned in the reference scenario. In scenarios with a good economic environment a significant negative net impact is even observed.

Table 13. Modular port expansion (2015-2045) mean impacts for KPI's vs. 2015 port expansion, in scenarios.

Modular port expansion (2015-2045) vs. 2015 port expansion *(2017-2057, discount factor: 0%)*	Weight	Refe-rence	S1	S2	S3	S4	S5
land.fraction.occupied	1	2.4%	2.2%	2.1%	0.0%	0.0%	0.0%
population	1	4.1%	5.1%	4.8%	0.1%	0.1%	0.2%
New.Enterprise	1	15.3%	12.0%	11.9%	1.0%	1.0%	0.8%
production.units.total	1	6.5%	7.0%	7.0%	0.7%	0.7%	0.6%
Green.space	1	-7.0%	-8.6%	-7.7%	0.1%	0.1%	0.1%
fraction.underemployed.of. population	-1	0.7%	-0.2%	0.4%	0.0%	0.0%	0.0%
fraction.informal.of.total. population	-1	1.2%	1.0%	1.0%	-0.0%	-0.0%	0.0%
informally.housed	-1	-10.8%	-16.6%	-18.0%	-0.1%	-0.1%	-0.2%
road.length	-1	1.2%	0.7%	0.9%	1.7%	1.7%	1.6%
road.congestion	-1	-13.3%	-19.3%	-18.6%	0.3%	0.3%	0.3%
Total score	**-**	**0.4%**	**-16.7%**	**-16.1%**	**3.7%**	**3.8%**	**3.4%**

As port throughput rises more slowly but continuously rather than suddenly, road congestion remains high over a longer period of time, as investments keep lagging behind road demand levels. Later in the model run, land scarcity constrains additional road infrastructure construction and the city is choked by ever more increasing port throughput. In scenario's in which port throughput does not increase after 2031 due to economic stagnation and port competition (Scenarios 3 through 5 in Table 13), additional capacity expansion impacts are very limited (although in reality it is questionable if further port expansions would take place at all in such a case).
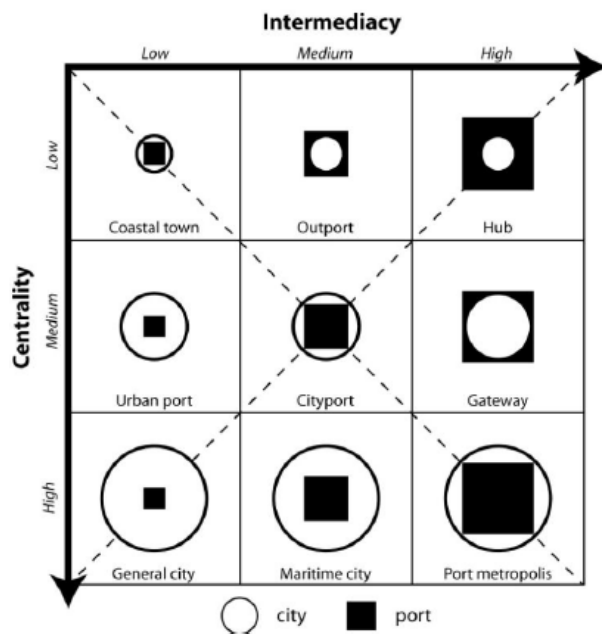
Intermediacy

Low   Medium   High

Centrality

Low

Coastal town   Outport   Hub

Medium

Urban port   Cityport   Gateway

High

General city   Maritime city   Port metropolis

○ city   ■ port

Here we arrive at a key finding for port-city evolution patterns. The question of port-city development revolves around the notion who claims the most land the first: the port or the city. If port development holds back or takes a dosed approach, urban activities benefit and claim the available land. Subsequent port development is then met by serious constraints regarding port land area expansions (not modelled in this project but an avenue for further research), and transport infrastructure construction limitations, due to increased urban developments in the land.

From the perspective of a port it is better to expand dramatically and stifle urban development, claim infrastructure and port space before land is taken for other (urban) developmental needs and developments. From the perspective of the port-*city*, a less rapid port development is preferred.

This relates back to the theory of port city evolution by Ducruet and Lee (2006), which sought to describe port city evolution patterns over time, based on port and city characteristics (Figure 70 and 71).

By expanding the port so dramatically at one time (2015), Port of Tema might have set out the path of development for the port-city of Tema. If port throughput indeed rises to port capacity, urban development may increasingly suffer from the negative externalities and developmental constraints. In that case the city might be 'doomed' to exist as a gateway (Figure 70) for Accra and the port hinterland, at the cost of its own socio-economic development. The port would 'use' the city for its labor and road infrastructure. This parasitic effect would be even greater if port operations are automated, reducing port employment of local workers. This might threaten the port's social license to operate (Ircha, 2012; Adams et al., 2009; Dooms, 2014) even more.
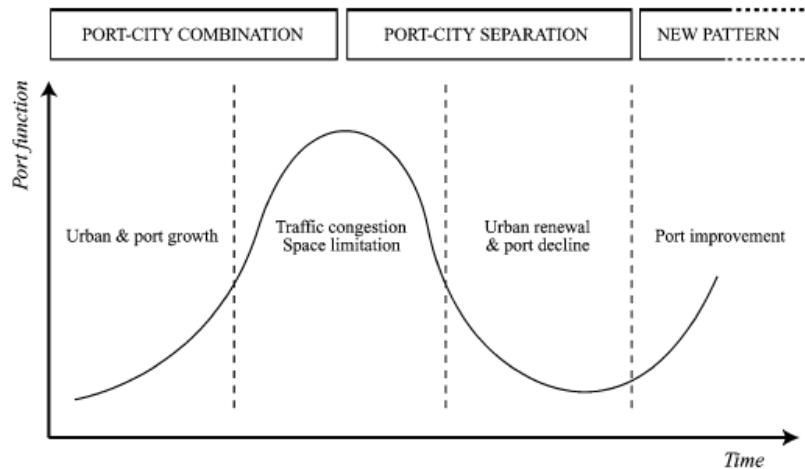
Figure 71. Logics of port-city spatial and functional evolution (Hoyle, 1989; Murphey, 1989; in: Ducruet and Lee, 2006), repeated here from section 4.1.
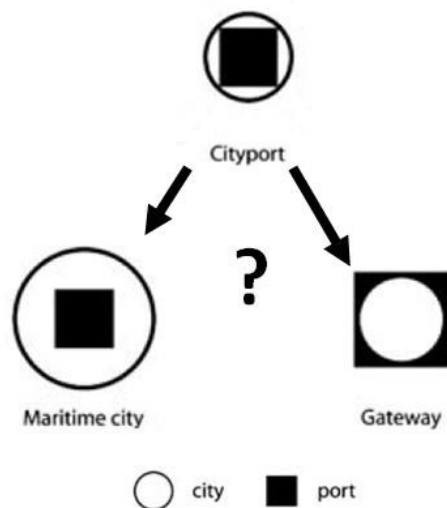
Figure 72. Port city evolution: a question of dominance. Adapted from Ducruet and Lee, 2006.

However, port development is not a matter of just investing in port infrastructure and automatically experiencing increasing port throughput. Many factors affect port competitiveness and throughput levels, for example port hinterland connections and captivity, and economic environment (Scenario analysis).

Competition by other ports in the Gulf of Guinee reducing port throughput, and/or the implementation of interventions aimed at the mitigation of port externalities might allow the city to profit from port presence, develop and gain prominence over port functions, like a dosed port development would have allowed. This in turn can however lead to port decline (Figure 71) if urban prominence reduces port competitiveness and throughput, for example due to land side congestion following land constraints.

Port-city evolution seems to be a balance between port development and city development (Figure 72). Different interventions might tip that balance in a more favourable direction, or avoid the balancing act at all, if port negative externalities can be mitigated effectively.

7.3 USING THE MODEL TO SYSTEMATICALLY GENERATE HIGH-LEVERAGE, SUSTAINABLE INTERVENTIONS

From a systems thinking perspective, the port city local-global mismatch represents a system consisting of sub-systems with respective goals which are not aligned (Meadow and Wright, 2008). Where the goal of the port is

to be as profitable and successful as possible, the city sub-system (itself comprising of multiple subsystems) has its own, diverging objectives (e.g. employment opportunities, high quality of living, low congestion, etc.).

Sustainable port-city development entails the design and implementation of policies and interventions that reconcile these opposing values of ports and cities (Fusco Girard, 2010; Merk, 2013). Using the model, the effectiveness of potential policies from a system perspective can be evaluated. Moreover, the model itself can be used as a sounding board for such policy design (Lee Jr., 1973; Alfeld, 1995).

Meadows and Wright (2008) provide guidelines for identifying (sub-) system archetypes and finding effective, potentially high leverage policies. This can provide clues about which policies might have a lasting benefit for the port-city system.

The model is used to perform a systematic brainstorm. Working backwards from the point in the system where negative externalities are experienced, concrete pathways and points of attack to change model outcomes can be identified. This process is illustrated below for the reduction of *road congestion* in the transport sub-system.
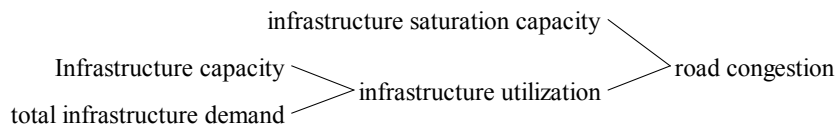
Figure 73. Factors influencing road congestion in the simulated city.
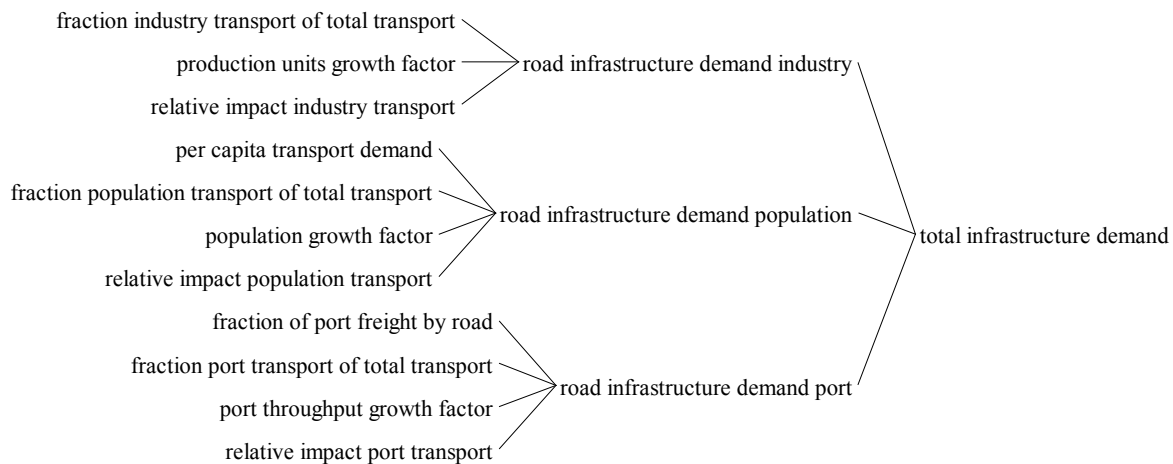
Figure 74. Factors determining total road infrastructure demand in the simulated city.

Figures 73 and 74 show the causal structure determining road congestion and total road infrastructure demand (generated by the Vensim modeling package). It follows from Figure 73 that there are three approaches to decrease congestion in the city: increasing road transport infrastructure capacity, decreasing the total road infrastructure demand, or increasing the infrastructure saturation capacity.

The information in Figures 73 and 74 is then used to systematically identify potential interventions in the city:

1. **Decrease demand (lower utilization)**
   a. Reduce *road infrastructure demand port*
      i. Reduce *port throughput*
         1. Use other ports: divert ships to Takoradi
      ii. Decrease *fraction of port freight by road* (e.g. rail investments)
      iii. Increase *transhipment ratio* to smaller ports (Volta river)

   b. Reduce *road infrastructure demand population*
      i. Reduce *population* growth
      ii. Reduce *per capita transport demand*
         1. Invest in public transportation services
      iii. Reduce *relative impact population transport*
         1. Stimulate the use of motorcycles

   c. Reduce *road infrastructure demand industry*
      i. Reduce *industry* (growth)
      ii. Reduce *industry transport relative impact*

2. **Increase supply (lower utilization)**
   a. Increase road infrastructure construction
      i. Attract more resources for investments
         1. Attract more FDI
         2. Increase tax revenues (from ports?)
   b. Decrease road decay
      i. Improve road quality
      ii. Improve road maintenance (also construction)

3. **Increase saturation capacity (reduce congestion @ same utilization)**
   a. Improve road (travel) efficiency (e.g. tunnels, fly-overs)

The road transport sub-system can be characterized as showing signs of the *addiction* systems archetype (Meadows and Wright, 2008). Users (population, port freight shippers, industry) depend on the road network (*Infrastructure capacity*) for their transportation needs (*total infrastructure demand*) until the resource is fully utilized and growth is stifled. Investing in additional road infrastructure capacity only provides a temporary fix, without addressing the harder to solve actual problem (Meadows and Wright, 2008). Such an easy, short term fix facilitates the addiction, inviting more road demand. While road infrastructure investments can help slow down congestion increases, a more sustainable alternative would be to find interventions that break the addiction, by reducing road transport demand permanently. A combination of the two approaches might prove effective and sustainable.

The results of the sensitivity analysis provide clues for high leverage interventions. Results for the most promising solutions are presented here.

Considering lowering transport demand; as lowering port throughput goes against the port's sub-goals, the focus shifts to high leverage urban solutions. Selected interventions are reducing the *fraction port freight by road*, by means of railroad investments, and reducing *per capita transport demand* (both growth rate and maximum demand are targeted).
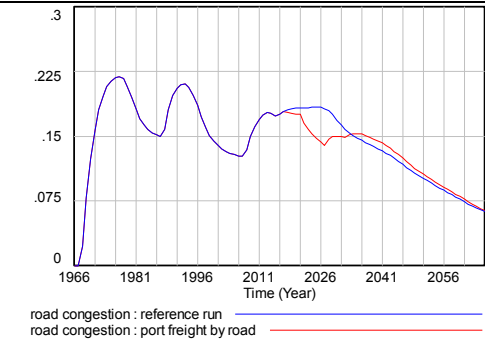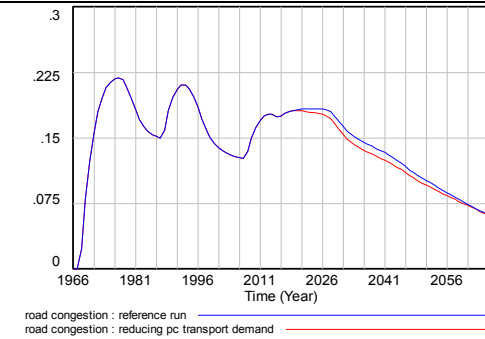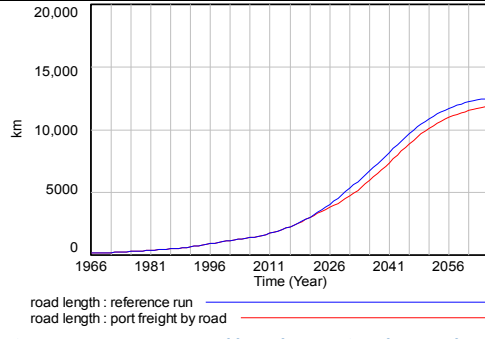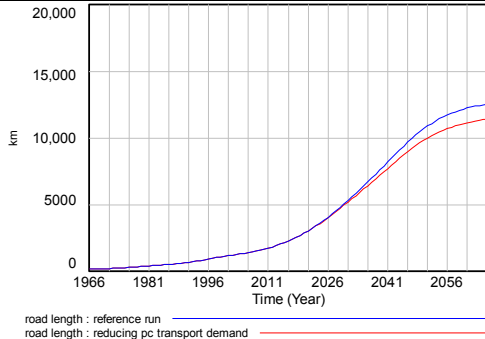
The stakeholders involved in railway investments include the Ghana Railway Development Authority. Stakeholders responsible for the planning of roads for bus transportation include the Ministry of Local Government and Rural Development (Department of Town and Country Planning) and the Ministry of Road Transport (Dept. of Urban Roads). The Metro Mass Transit Limited agency is incorporated to provide accessible public transport in metropolitan and urban areas (see Actor analysis). This means that the Tema Municipal Assembly would be dependent on these actors, and probably outside (foreign) investments for the implementation of these interventions. As the Ghana Ports and Harbours Authority is state-owned, it could be pressured by local government to invest in such measures (section Port governance) to mitigate port externalities.

The policy specifications that are used are listed in Table 14 below..

Table 14. Transport sub-model policy specification

Policy	Variable	Specification
Port freight by rail (60%)	*road transport change*	-0.50
	fraction of port freight by road	0.95+RAMP(road transport change/30, 2017 , 2032) + RAMP(road transport change/10, 2021 , 2027)
Reducing per capita road transport infrastructure demand	*pc transport demand growth rate*	0.05 - RAMP(0.01/10,2017,2027)
	max per capita transport demand	2-RAMP(0.4/10,2017,2027)

The results are less impressive than expected (Figure 75). Counterintuitively, while a short term reduction of congestion is achieved (a maximum of 20%), on the longer term congestion actually increases. This is another manifestation of the mechanism uncovered in the previous section: allowing the city to develop by reducing negative externalities will put more pressure on the system later as land pressures rise and further port expansions can no longer be mitigated effectively.

KPI	Port freight by rail *(Legend for all graphs: reference run: blue, policy run: red)*	Reducing per capita road transport infrastructure demand
Road congestion	 **Figure 75. Impact on road congestion over time by port by rail intervention, reference scenario**	 **Figure 76. Impact on road congestion over time by reducing pc transport demand intervention, reference scenario**
Road length	 **Figure 77. Impact on road length over time by port by rail intervention, reference scenario**	 **Figure 78. Impact on road length over time by reducing pc transport demand intervention, reference scenario**

Reducing per capita road transport infrastructure demand on the other hand does have a lasting effect on congestion (Figures 76, 78), albeit small (6% maximum). The intervention does not have the short-term impact that the port freight by rail intervention has, as population demand growth is only reduced rather than halted.

A combination of both interventions is evaluated to explore if short term and long term benefits can be combined in a single effective strategy (Figure 79).

port freight by road & reducing pc transport demand (unweighted)
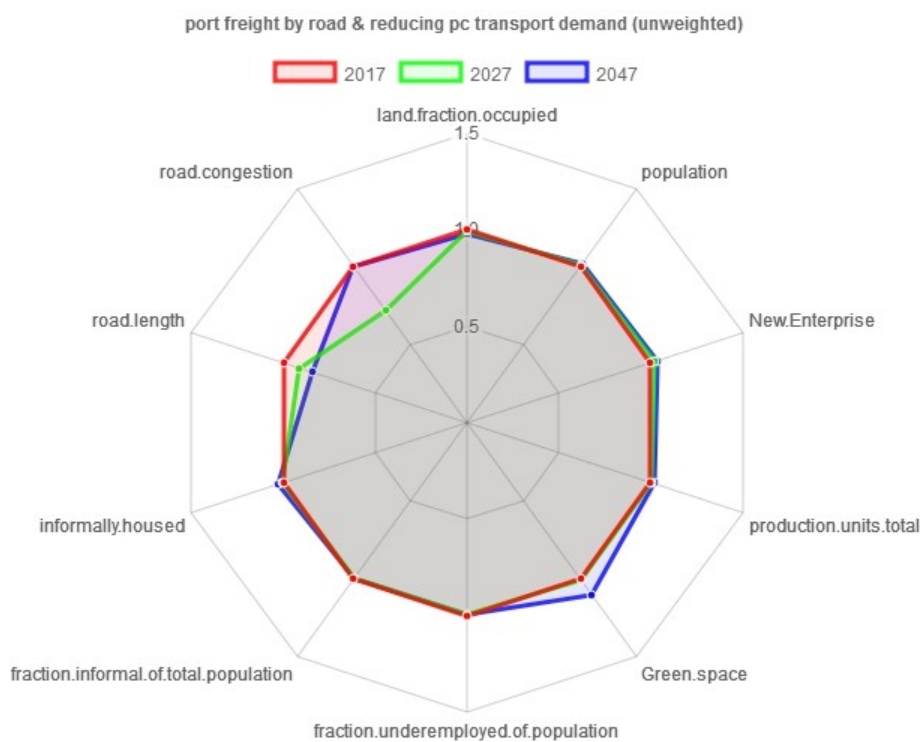
Figure 79. Radar chart, relative impacts of port freight by rail and reducing per capita transport demand interventions on simulated development in 2017, 2027 and 2047 (unweighted)

Table 15. Weighted KPI scores for selected transport policies

Weighted KPI scores *Discount: 0%*	Weight	Port freight by rail (60%)	Reducing p/ capita transport demand	Combined approach
land.fraction.occupied	1	-0.7%	-0.5%	-1.2%
population	1	0.7%	0.5%	1.2%
New.Enterprise	1	1.4%	1.5%	2.9%
production.units.total	1	0.7%	0.6%	1.3%
Green.space	1	2.7%	2.1%	4.9%
fraction.underemployed.of.population	-1	0.2%	0.1%	0.3%
fraction.informal.of.total.population	-1	0.1%	0.1%	0.2%
informally.housed	-1	-1.1%	-1.0%	-2.1%
road.length	-1	7.3%	4.4%	11.7%
road.congestion	-1	1.1%	4.6%	6.0%
Total score	-	12.4%	12.5%	25.3%

The result show that this is possible: the combined approach is more effective especially at reducing urban road demand; up to 15% reduction is achieved on the long term (+40% of total modeling time horizon after implementation) with the modelled policy, a decrease that is robust to uncertainties (the same but higher congestion peaks occur in scenarios without the policy (Figure 83). Congestion levels decline a little as well, but more importantly the increase in congestion due to port throughput growth later in the run (when space

constraints start playing a bigger role) is averted. Moreover, this effect is achieved despite an increase in population and industry.

Table 16. Total scores for selected transport policies, 5% discounting rate.

Weighted KPI scores *Discount rate: 5%*	Weight	Port freight by rail (60%)	Reducing p/ capita transport demand	Combined approach
Total score	**-**	**5.7%**	**3.5%**	**9.3%**

By comparison, taking a more short term perspective by introducing a yearly discounting of impacts of 5% makes the port freight by rail policy significantly better compared to reducing per capita transport demand (Table 16. Note that individual KPI scores are omitted for brevity). Rail freight is the better option to improve congestion and road length on the short term, but won't solve the transport crisis in Tema on the long term, unless port throughput impacts on the urban road system can be completely mitigated.

KPI	Reducing road freight & per capita transport demand *Graph legend: reference run: blue, policy run: red.*	Robustness *Graph legend: reference run: blue, scenario 1: red, 2: green, 3: grey, 4: black, 5: brown*
Road length	 **Figure 80. Impact of reducing freight transport by road and per capita transport infrastructure demand no road length over time.**	 **Figure 81. Impact of reducing freight transport by road and per capita transport infrastructure demand on road length over time, in scenarios**

Congestion		
	Figure 82. Impact of reducing freight transport by road and per capita transport infrastructure demand on road congestion over time	**Figure 83. Impact of reducing freight transport by road and per capita transport infrastructure demand on road congestion over time, in scenarios**

New Enterprise		
	Figure 84. Impact of reducing freight transport by road and per capita transport infrastructure demand on New enterprise over time	**Figure 85. Impact of reducing freight transport by road and per capita transport infrastructure demand on New enterprise over time, in scenarios**
Population		
	Figure 86. Impact of reducing freight transport by road and per capita transport infrastructure demand on population over time	**Figure 87. Impact of reducing freight transport by road and per capita transport infrastructure demand on population over time, in scenarios**

Green space encroachment

The sensitivity analysis shows the common trend that all green space is encroached upon, unless urban growth is halted before that time. In the modelled scenario's for Tema, such a premature end to growth does not occur, as there is still land area available for settlement. In practice this could mean densification of already built-up area, or the encroachment into areas that are used for (illegal) urban agriculture. The same brainstorming method as with the transport sub-system is used to generate potential interventions from the model.

Reduce green space encroachment:

1. **Reduce green space settlement**
   a. Reduce land fraction occupation
      i. Reduce housing area
         1. Housing zoning policy
         2. Reduce average *land per house*
            a. high-rise building construction
      ii. Reduce industrial area
         1. Industrial zoning policy
      iii. Reduce informal housing area
      iv. Reduce infrastructure area
         1. Reduce road infrastructure demand
   b. Reduce societal willingness to settle green space
      i. Advocate a return to traditional values and ecosystem valuation
      ii. Pressure Chiefs not to sell lagoon lands
   c. Increase the minimum green space area
      i. Protect and enforce
2. **Increase the return of land to green space**
   a. Decrease unused land to green space delay
      i. Active restoration of urbanized green space areas
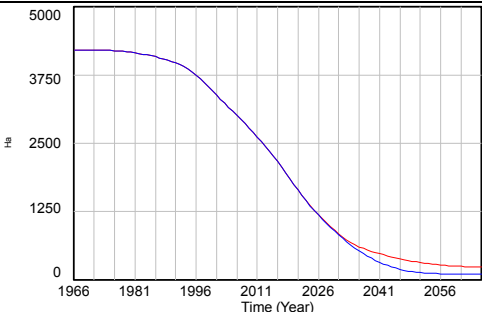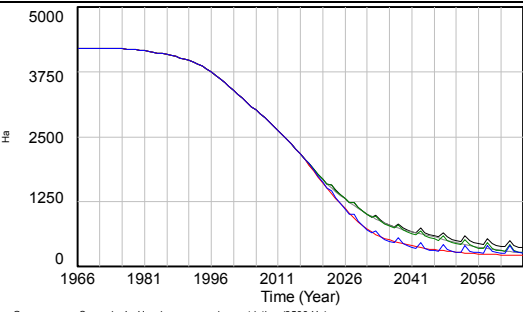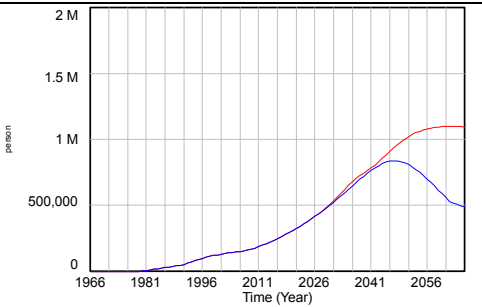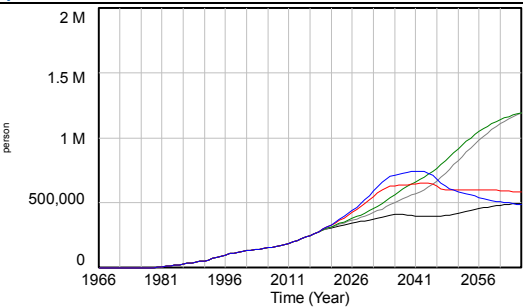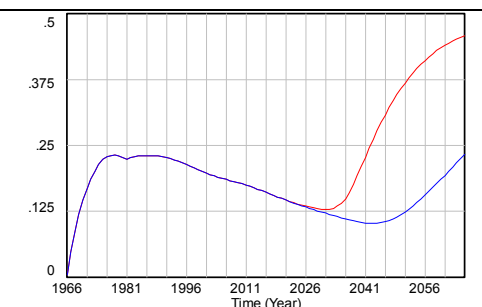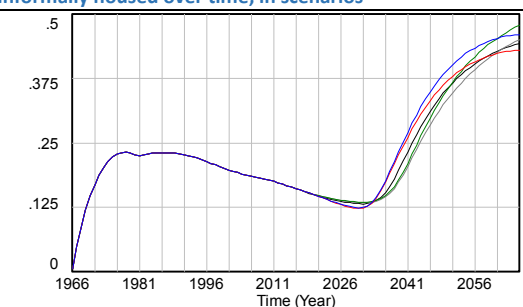
Firstly, the effects of a housing zoning policy are assessed. This is an intervention that the Tema Municipal Assembly could implement themselves. The sensitivity analysis (see databank) showed that this variable can influence simulated port-city development significantly.

A zoning area of 3500 Ha (of pure housing) is applied to the model. That amount is roughly 150% of the simulated housing area in 2017 in the reference run.

Figures 88 through 93 depict the impacts of a housing area zoning restriction on the model and policy robustness in different scenarios. It becomes clear that a housing zoning limiting formal housing developments has only limited effects on green space (Figure 88), while stifling urban development and stimulating informal settlement by urban residents (Figure 90).

KPI	Housing area zoning restriction (3500 Ha) *Graph legend: reference run: blue, policy run: red*	Robustness *Graph legend: scenario 1: blue, 2: red, 3: green, 4: grey, 5:black*
Green space	**Figure 88. Housing area zoning restriction impact on green space over time**	**Figure 89. Housing area zoning restrictions impact on green space over time, in scenarios**
Informally housed	**Figure 90. Housing area zoning restriction impact on informal settlement over time**	**Figure 91. Housing area zoning restrictions impact on informally housed over time, in scenarios**
Fraction underempl-oyed housing of total housing	**Figure 92. Housing area zoning restriction impact on housing type over time**	**Figure 93. Housing area zoning restrictions impact on housing type over time, in scenarios**
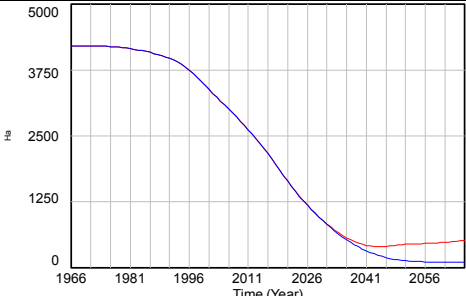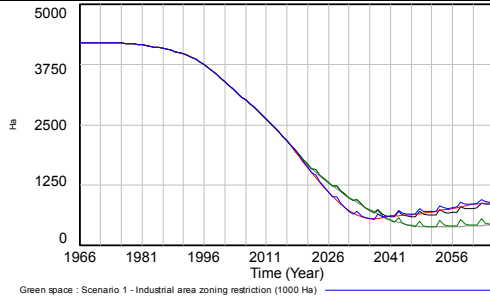
The zoning policy not only fails to protect green space in a significant way, other port-city performance indicators suffer as well. The possibility of informal housing means that a zoning policy restricting the building of housing effectively turns the city into a slum, with a larger proportion of both 'formal' slum estates and informally settled. This effect is especially observed in scenario's which yield increased climate-related migration from rural areas into the urban area. Robustness analysis shows that the housing area zoning

restriction policy does increase in effectiveness with respect to green space conservation in scenarios of high economic growth and industrial automation (Table 17. Note that only the most affected variables are included in the table, but the total score does contain all effects).

Table 17. Robustness of housing zoning area restriction impacts for selected model KPI's, in scenarios (S1 t/m S5) and the reference scenario.

Housing area zoning restriction (3500 Ha) *Discounting factor: 0%*	Weight	Refer-ence	S1	S2	S3	S4	S5
Green.space	1	50.7%	71.2%	78.1%	43.8%	50.3%	69.5%
fraction.underemployed. of.population	-1	-4.7%	-7.0%	-7.8%	-3.6%	-5.0%	-7.7%
informally.housed	-1	-10.7%	-11.7%	-21.0%	-6.3%	-10.9%	-7.7%
road.congestion	-1	4.4%	12.3%	10.8%	5.1%	5.1%	9.0%
Total score	-	29.1%	47.9%	45.3%	22.4%	22.0%	36.5%

An industrial zoning policy is more successful at containing urban growth and even informal settlement. The lack of employment opportunity makes the city less attractive for migrants, but at the cost of a higher unemployment. While easier to enforce (in theory), it is doubtful that city residents would understand the choice for limiting industrial activity. No politician would want to be responsible for actively keeping away jobs from his constituents. The effectiveness of this intervention is therefore vulnerable to political interference by politicians and notables (see Actor analysis). An upside of this approach is that it is a relatively low cost measure.

KPI	Industrial area zoning restriction (1000 Ha) *Graph legend: reference run: blue, policy run: red*	Robustness *Graph legend: scenario 1: blue, 2: red, 3: green, 4: grey, 5: black*
Green space	**Figure 94. Industrial area zoning restriction impact on green space over time**	**Figure 95. Industrial area zoning restrictions (1000 Ha) impacts on underemployed housing stock over time, in scenarios**

Land fraction occupied	**Figure 96. Industrial area zoning restriction impact on land fraction occupied over time**	**Figure 97. Industrial area zoning restrictions (1000 Ha) impacts on land fraction occupied over time, in scenarios**
Informally housed	**Figure 98. Industrial area zoning restriction impact on informally housed over time**	**Figure 99. . Industrial area zoning restrictions (1000 Ha) impacts on informally housed over time, in scenarios**
Fraction underemployed of population	**Figure 100. Industrial area zoning restriction impact on underemployed fraction over time**	**Figure 101. Industrial area zoning restrictions (1000 Ha) impacts on underemployed fraction over time, in scenarios**

Again, robustness analysis shows that a zoning policy is especially effective in scenarios of economic growth and automation, however at the cost of urban employment and socio-economic state (Table 18). Note that these negative impacts (scores) are additional to the adverse effects of the external factors in these scenarios.

Table 18. Robustness of industrial zoning area restriction impacts on selected model KPI's in scenarios (S1 t/m S5) and the reference scenario. Total score includes all KPI impacts

Industrial area zoning restriction (1000 Ha) *Discounting factor: 0%*	Weight	Refer-ence	S1	S2	S3	S4	S5
New.Enterprise	1	-40.4%	-54.7%	-54.7%	-27.5%	-27.5%	-39.9%
Green.space	1	76.5%	213.5%	238.0%	35.2%	36.2%	95.0%
fraction.underemployed. of.population	-1	-6.3%	-5.9%	-10.5%	-2.3%	-3.9%	-4.9%
fraction.informal.of. total.population	-1	-4.9%	-6.6%	-7.1%	-4.3%	-4.3%	-6.2%
informally.housed	-1	36.2%	53.2%	53.7%	25.7%	26.8%	43.8%
Total score	**-**	**54.5%**	**186.4%**	**206.6%**	**24.0%**	**24.6%**	**80.7%**

An interesting approach would be to change the public perspective on the green space area. In research on the littering of lagoons in Ghana it was revealed that such practices are mostly done by younger people; older individuals are more inclined to be respectful of the area (Tettey, 2015). However, the sensitivity analysis already revealed that even small fractions of *societal acceptance of green space settlement* lead to green space encroachment when land pressure rises. Moreover, this alternative would constitute the changing of informal institutions (i.e. norms), which are relatively slow to change according to Williamson (1998) (see Appendix B. Actor analysis).

High rise building could alleviate some of the land pressure for a time by effectively lowering the average *land per house* area. However, system structure prescribes that this will only postpone the inevitable, and not prevent total green space development.

Conserving the green space areas by protecting it actively from green space settlement is a challenge in a country that is resource-constrained and suffers from adverse effects of "political interference" (personal communication, Mr. Dickson during field visit; Appendix B. Actor analysis), as a change in formal laws could be ignored by influential individuals. Despite this, it is investigated what such a policy would mean for the port-city system.

Traditional Authorities play a role in the conservation of green space and the reduction of encroachment, as they can decide whether to keep green space land they own and conserve and exploit it for resources, or sell it to private parties for development (Appendix B. Actor analysis; Tyroller, 2016). An informal institutional approach for conservation would be to appeal to Chiefs traditional norms and religious beliefs on green space, and sensitize them to the importance of conservation. A neo-classical economic approach would be to influence

day to day decisions and economizing (the fourth layer in Williamsons framework (1998), see Actor analysis) by Chiefs by offering them a compensation for not selling their land and conserving green space. The ecosystem services valuation approach may be used to assess the intrinsic and (resource) use values of the lagoon, which may add to its protection (Van Stipthout, 2002; Koetse, Brouwer and Van Beukering, 2015).

KPI	Green space conservation (1350 Ha)	Robustness
	Graph legend: reference run: blue, policy run: red	*Graph legend: scenario 1: blue, 2: red, 3: green, 4: grey, 5: black*
Green space	**Figure 102. Green space conservation impact on green space over time**	**Figure 103. Impact of green space conservation on green space in scenarios**
New enterprise	**Figure 104. Green space conservation impact on New enterprise over time**	**Figure 105. Impact of green space conservation on New enterprise in scenarios**

The conservation of green space, while potentially difficult to achieve in practice, would not affect the urban system significantly in a negative way. Population reduction would be less than 5% and New enterprise stock reduction would be less than 6% averaged over the model run in all modelled scenarios. The city would be slightly smaller, with the stock of new enterprises peaking only 3% lower than in the reference scenario, and would only be marginally worse off socio-economically. This effect is robust to uncertainty regarding external factors.
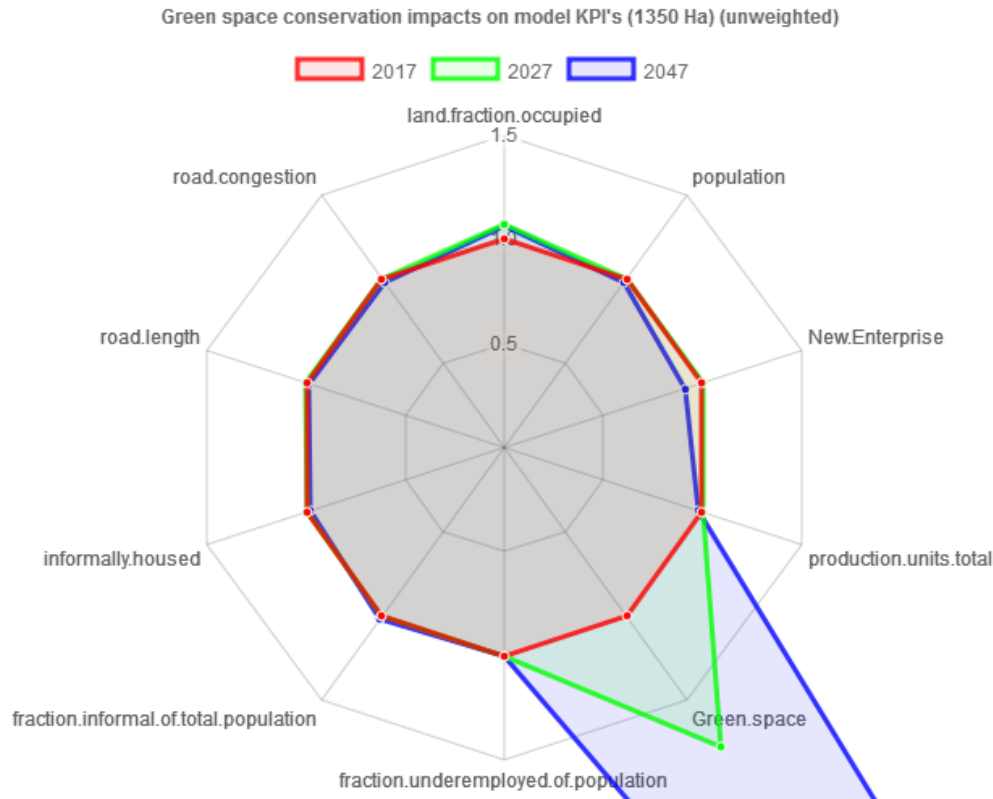
Figure 106. Green space conservation impacts on model KPI's (1350 Ha) (unweighted).

Green space conservation is significant especially in scenarios of economic growth: averaged over the model run green space area would increase at least 250%, with a maximum of 600% in scenarios with a favourable economic environment and automation. That means if the resource constraint could be solved, this would be very beneficial intervention on the port-city system.

Reducing informal settlement

The structure of the system indicates that there are two approaches to reducing the extent of informal housing in the city (Figure 107): either reduce the demand for housing units, or increase the supply of formal housing units in the city. Hence, factors that increase urban population of workers and underemployed will lead to increased informal settlement, and interventions stimulating formal housing construction would reduce it.
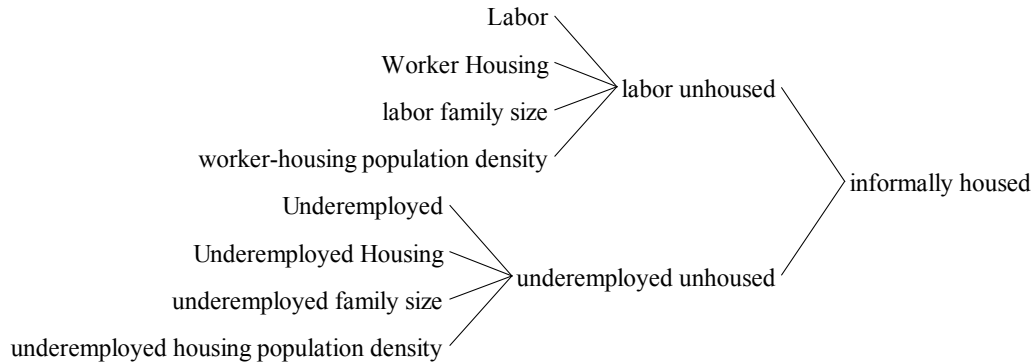
Figure 107. Part of the causal structure behind informal settlement in the model as generated by Vensim.

The model structure is used to systematically explore intervention alternatives. Unethical solutions for the reduction of labor and underemployed populations such as forced departures from the city are not considered.

Reduce informal settlement:
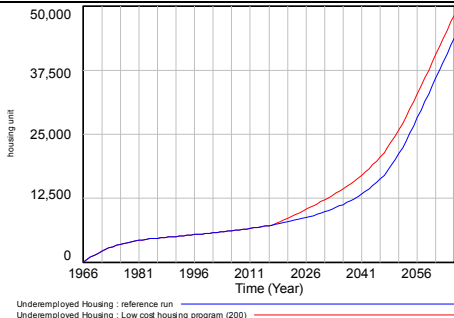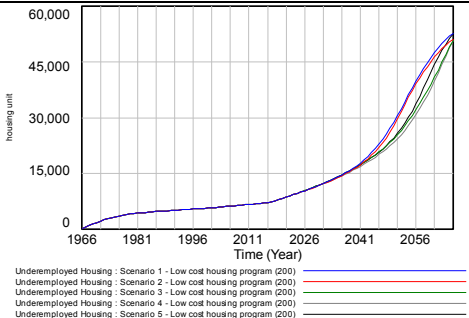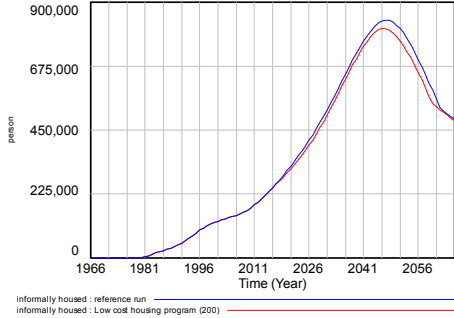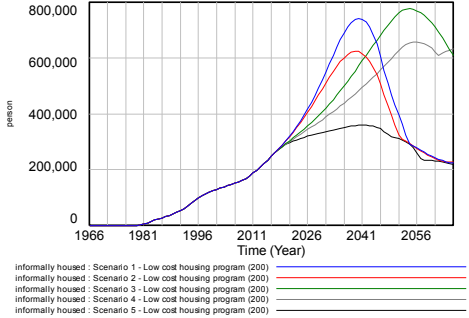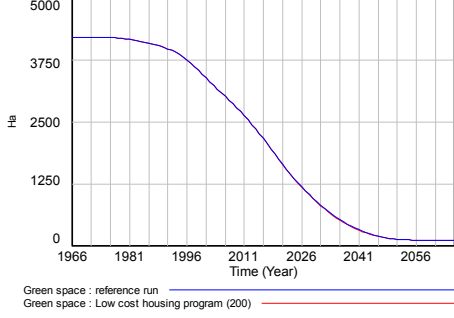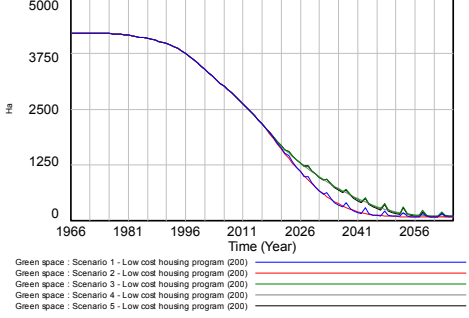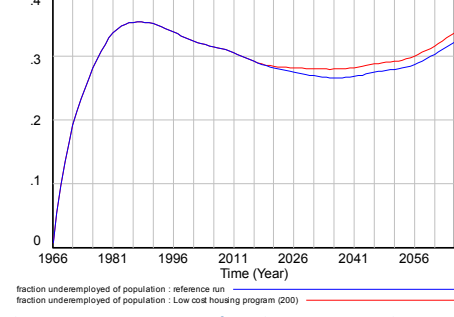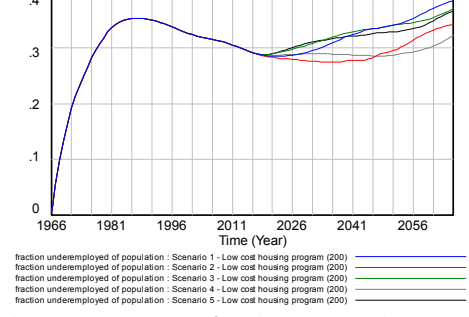
1. **Reduce demand for housing**
   a. Reduce labor unhoused
      i. Reduce labor population
         1. Reduce labor net migration to the city
            a. Increase attractiveness of rural areas
            b. Reduced employment opportunities
         2. Increase labor social status to managerial-professional
            a. Labor training programs
            b. Education availability
      ii. Reduce labor family size
         1. Increase birth control availability
      iii. Increase worker-housing population density
   b. Reduce underemployed unhoused
      i. Reduce underemployed population
         1. Reduce labor layoffs
            a. Stimulate employment in the city
         2. Reduce underemployed net migration to the city
            a. Increase attractiveness of rural areas
            b. Reduced employment opportunities
         3. Increase underemployed social status to labor
            a. Underemployed training program
            b. Underemployed job program
            c. Education availability
      ii. Reduce underemployed family size

                    1.   Increase birth control availability

        iii.   Increase underemployed housing population density

2. Increase supply of formal housing
       i.   Increase worker housing
            1.   Increase worker housing construction
                a.   Worker housing construction programs
                b.   Housing financing programs
                c.   Reduce land scarcity impact
                     i.   Reduce land per house
                         1.   High-rise building
            2.   Reduce worker housing dilapidation
                a.   Invest in housing maintenance
                b.   Slum refurbishment
       ii.   Increase underemployed housing
            1.   Increase worker housing dilapidation
            2.   Increase underemployed housing construction
                a.   Low-cost housing program
                b.   Reduce formal slum housing demolition
                     i.   Reduce land scarcity impact

Some of the identified interventions would result in a 'waterbed effect' analog to communicating vessels. For instance, policies that increase underemployed social status to labor status would lead to an increase of labor unhoused. However, a larger labor group might in turn result in increased upward mobility to managerial-professional status and improved ability to finance formal housing.

However, an obviously more direct way to combat informal settlement resulting from port expansion is the increase of 'formal' low cost housing in Tema through low cost housing programs. The impacts of such a program on the simulated port-city are displayed in Figures 108 through 115.
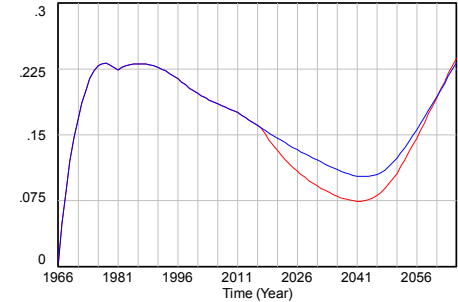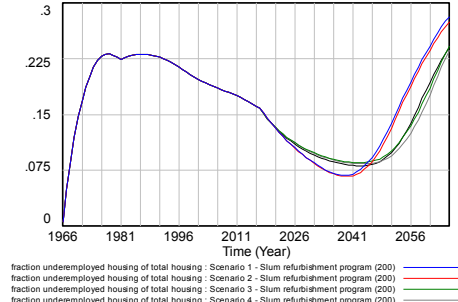
KPI	Low cost housing program (200/year) vs. reference run *Graph legend: reference run: blue, policy run: red*	Low cost housing program (200/year) in context scenarios *Graph legend: scenario 1: blue, 2: red, 3: green, 4: grey, 5: black*
Underemployed Housing	 **Figure 108. Impact on underemployed housing stock of a low cost housing program over time**	 **Figure 109. Low cost housing program impacts on underemployed housing stock over time, in scenarios**
Informally housed	 **Figure 110. Low cost housing program impact on informally housed over time**	 **Figure 111. Low cost housing program impacts on informally housed over time, in scenarios**
Green Space	 **Figure 112. Low cost housing program impact on green space over time**	 **Figure 113. Low cost housing program impacts on green space over time, in scenarios**
Fraction underemployed of total population	 **Figure 114. Low cost housing program impact on underemployed in the city over time**	 **Figure 115. Low cost housing program impacts on urban underemployed over time, in scenarios**

While low cost housing programs do reduce informal settlement, this improvement is offset by a higher in-migration of underemployed into the city. This lowers city socio-economic state just like it did in Forrester's model (Forrester, 1970). Low cost housing programs also compete with Worker housing for land area, leading to a slightly higher (max 2.4%) number of unhoused *labor*, that settle informally. Compared to a reduction of *underemployed unhoused* of 18%, this increase is not substantial enough to counteract the beneficial effects.

Although low cost housing is lumped in with degraded worker housing estates in the Underemployed housing stock in the model, a substantial improvement in living quality may be achieved compared to informal housing due to the increased potential to provide services and sanitation in these formal housing developments, an effect which is not explicitly modelled (cf. Mazeau, Scott, and Tuffuor, 2012). However, summarizing, informal settlement itself is not significantly reduced by this intervention.

An analysis of what best to do with the (formal) slum estates in Tema could shed light on what is the best approach to raising urban development standards. Two policy options are compared for effectiveness: a slum refurbishment program in which slum estates are upgraded to worker housing status, and slum housing demolition program, which is advocated by Forrester as a solution for urban decay (Forrester, 1970).

Slum refurbishment

KPI	Slum refurbishment program (200 housing units/year) vs. reference run *Graph legend: reference run: blue, policy run: red*	Slum refurbishment program (200 housing units/year) in scenarios *Graph legend: scenario 1: blue, 2: red, 3: green, 4: grey, 5: black*
Fraction underemployed housing of total housing	Figure 116. Slum refurbishment program impact on underemployed housing fraction over time	Figure 117. Slum refurbishment program (200 housing units/yr) impacts on underemployed housing fraction over time, in scenarios

Informally housed	 **Figure 118. Slum refurbishment program impact on informally housed over time**	 **Figure 119. Slum refurbishment program (200 housing units/yr) impacts on informally housed over time.**
Green space	 **Figure 120. Slum refurbishment program impact on green space over time**	 **Figure 121. Slum refurbishment program (200 housing units/yr) impacts on green space over time, in scenarios**
Fraction underemployed of population	 **Figure 122. Slum refurbishment program impact on underemployed fraction over time**	 **Figure 123. Slum refurbishment program (200 housing units/yr) impacts on underemployed fraction over time, in scenarios**

The upgrading of slums to worker housing has relatively little net impact on simulated urban development. This is due to a 'waterbed effect': while it benefits labor families in the city, the program as modeled leads to a 20% increase of underemployed settling informally. The program does little to combat informal settlement initially (an 0.8% mean decrease between 2017 and 2057) but becomes more effective in the stagnation phase of urban development when land area scarcity is maximum (close to 10% reduction of informal settlement compared to the reference scenario). All the while it has a modest beneficial impact on industrial development and city socio-economic climate, but this effect diminishes in the long term.

Slum demolition programs where advocated by Forrester in his study on Urban Dynamics (1970) as a solution to urban decay and stagnation. That warrants an evaluation of this intervention for slum estate management.

KPI weighted scores *Discount factor: 0%*	Weight	Low cost housing program (200 housing units/yr)	Slum refurbish-ment (200 housing units/yr)	Slum demolition program (200 housing units/yr)
land.fraction.occupied	1	0.6%	2.0%	-0.3%
population	1	1.5%	0.5%	-0.7%
New.Enterprise	1	-0.2%	0.1%	0.1%
production.units.total	1	0.1%	0.4%	-0.1%
Green.space	1	-1.2%	-4.6%	0.6%
fraction.underemployed.of.population	-1	-3.8%	2.1%	1.9%
fraction.informal.of.total.population	-1	-0.2%	-0.3%	0.1%
informally.housed	-1	3.7%	0.8%	-6.4%
road.length	-1	-0.8%	-0.3%	0.4%
road.congestion	-1	0.1%	-0.9%	0.1%
Total score	1	-0.2%	-0.2%	-4.3%

In developing country context, the demolition of slum housing estates will not have lasting benefits. Apart from the ethical considerations that were a critique on Forrester's suggesting the solution, in Tema the demolition of slum housing will lead to an increase of informal housing of more than a third of the amount of demolished housing.

Another approach to reducing informal settlement would be the increase of formal housing not through government building but by improving worker housing financing for residents and developers. It is assumed that improved financing possibilities will increase the normal construction rate of worker housing to eventually double (Table 20).

Table 20. Worker housing financing improvements intervention specification.

Policy	Variable	Specification
Worker housing financing improvements	*Worker housing construction normal*	0.01+RAMP(0.00025,2017,2027)

Increasing formal worker housing construction in the city dramatically reduces informal settlement. The policy as modeled increases worker housing by 20% both on the short and long term. It leads to a 20% reduction in informal settlement absolutely, and ca. 28% relatively to the (increased) population. The intervention has a double effect: worker housing shortages are reduced, and more formal housing becomes available for underemployed in the city. Informal housing declines up to between 17 and 30% in all modelled scenarios.
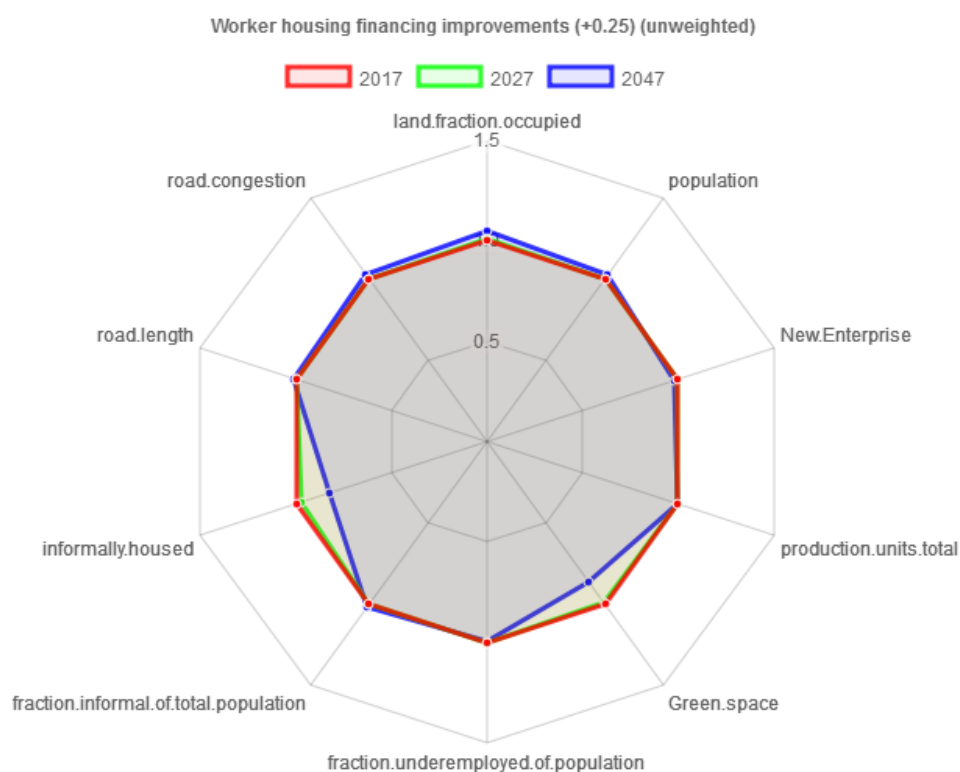
Figure 124. Relative impact scores for Worker housing financing improvements vs. reference run (2017, 2027, 2047) (unweighted)

However, the increased housing developments mainly impact green space encroachment. Combining this intervention with green space conservation may make it even more effective.

Combining promising interventions

With the effectiveness, sustainability and robustness of port-city interventions established, it is interesting to evaluate whether their beneficial effects persist when interventions are combined. As the port-city system is a complex system with many feedback and delayed effects, this cannot be stated with certainty without simulating the effects. The interventions jointly applied to the model are listed in Table 21. Due to time constraints, no in-depth analysis of robustness of these results in scenarios is performed within this project.

Table 21. Combined interventions applied to the model and their specifications.

Intervention	Model variable	Specification
Port freight by rail (60%)	*road transport change*	-0.50
	fraction of port freight by road	0.95+RAMP(road transport change/30, 2017 , 2032) + RAMP(road transport change/10, 2021 , 2027)
Reducing per capita road transport infrastructure demand	*pc transport demand growth rate*	0.05 - RAMP(0.01/10,2017,2027)
	max per capita transport demand	2-RAMP(0.4/10,2017,2027)

Worker housing financing improvements	*Worker housing construction normal*	0.01+RAMP(0.00025,2017,2027)
Green space conservation (1350 Ha)	*min green space*	50+STEP(1300, 2017)
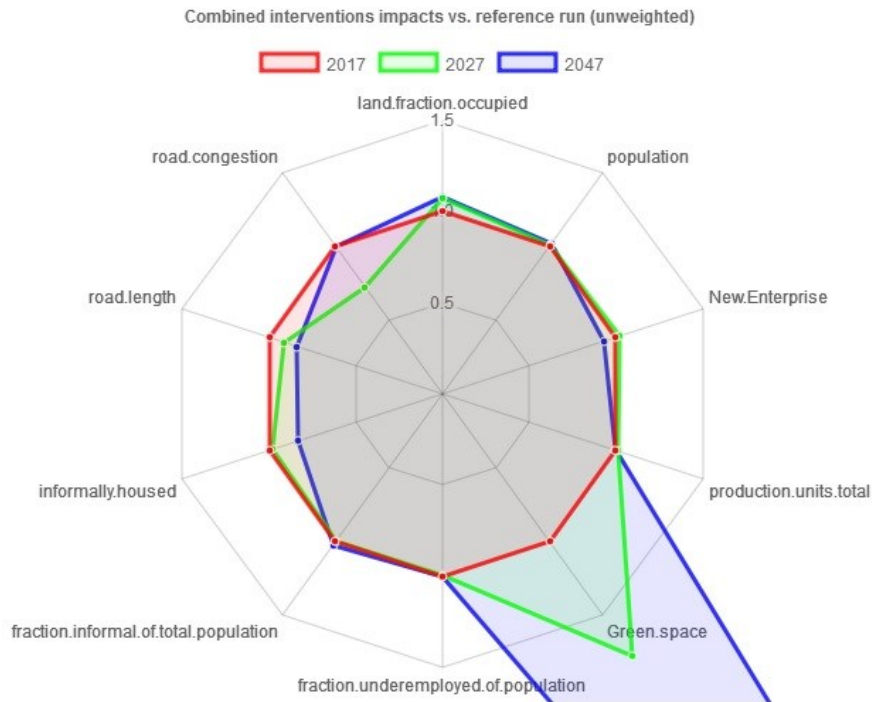
Figure 125. Impacts of combined interventions (2017, 2027, 2047)

The impacts of the combined interventions are shown in Figure 125. The port-city shows improvements almost across the board. Green space is conserved, informal housing reduced, road length and congestion are mostly reduced despite an increase in population. It shows how different interventions can reduce effectively the negative externalities of port and urban development.

8   CONCLUSIONS

The research question that guided this research was formulated as follows:

 "How can system dynamics modelling be used to represent the development of the city of Tema and its port and evaluate interventions for sustainable port-city development in an African context?"

This research question was operationalized in several sub-questions, each concerning a progressive step in the overall research process:

1. What is an appropriate and useful model of port-city development in a developing country context?
2. What are potential development patterns of developing country port-cities? In particular, how does port expansion affect port-city evolution?
3. What are effective interventions for sustainable port-city development that mitigate the local-global mismatch in the benefits deriving from port expansion?
4. What do model outcomes mean, for the case study, and for the development of African port cities in general?

The first research question concerned the requirements made of the model and its conceptualization on the one hand (appropriateness), and its ability to validly model Tema and developing country port-city development on the other (usefulness). This research question has been answered comprehensively in sections 5.9 (Model conceptualization conclusions) and 6.8 (Model verification and validation conclusions). The main findings are summarized here.

The research effort has shown how system dynamics modelling can be used to represent the development of the city of Tema and its port, and to evaluate interventions for sustainable port-city development in an African context.

To this end, firstly it was explored which additional elements a system dynamics model for sustainable port city development should contain. Based on literature and stakeholder input it was determined that the model should feature representations of informal housing, green space encroachment, traffic congestion, as well as the port infrastructure itself to correctly capture both benefits and negative externalities of port infrastructure investments that are relevant to the city of Tema. The literature used for this comprised both of theoretical literature and a considerable amount of research on Ghana, the port and the city of Tema, and on the Sakumo lagoon itself.

Next, causal relations between these system elements were determined or estimated based on known impacts in literature, facilitating the specification of the model in a simulation package. Providing a definitive figure for the strength of causal links like the impact of the port on local industry proved challenging because of the heterogeneity of such links between port cities. Besides beneficial economic impacts, claims in literature that port infrastructure presence could make the local industry vulnerable to foreign direct investment seem to apply to Tema. The extent to which this reduces employment in the city is however unclear.

Model verification, validation and policy analysis confirmed that the model adequately captures urban development issues in a developing country port city. While the model has some conceptual limitations (see chapter 9. Limitations and recommendations) which reduce the validity of model inferences on problems which have a highly localized, spatial dimension (such as flooding), the model adequately captures the local-global mismatch affecting port cities in developing countries.

Research question 2 has been addressed in sections 7.1 and 7.2, but will be answered at this point.

What are potential development patterns of developing country port-cities? In particular, how does port expansion affect port-city evolution?

A systematic exploration of potential port-city developmental patterns was conducted based on insights from the sensitivity and scenario analysis and through various experiments with alternative modes of port expansions (and retreat). A semi-automated data-analysis and visualization script was designed for use with the model, to facilitate the interpretation and presentation of model outcomes.

While the speed of urban development may vary, the port-city system follows a developmental pattern of logistic growth in a resource-constrained environment, with the urban land area being the limiting resource. While green space initially detracts from the available land area, it acts as a buffer for the city to expand into, postponing the actual constraining of the port-city system until green space is consumed as well, and growth stagnates. At the point of stagnation, urban industry and housing slowly age and deteriorate over time as land scarcity constrains new developments, attracting more underemployed to the city. This same behavior was observed in Forrester's original model, and is the result of the way the port-city system is conceptualized using aging chains.

On the whole the port-system is relatively stable. This can be attributed to the stabilizing effect of the many stocks in the system: while flows can (and do) vary wildly over the model run, their associated stocks vary more slowly over time. The possibility of informal housing however adds to developmental dynamics, as migrants moving to the city are less deterred by a lack of housing, compared to high-income country cities. Port infrastructure investments tend to trigger the system to behave more dynamically, attracting more industrial development and migration to the city based on increased employment opportunities. Following the proposed 2015 port expansion, port throughput may triple from 2015 values, if it rises to the new port capacity. This will significantly add to the demand for urban road infrastructure: congestion levels are seen to rise dramatically, up to 45%, if no measures are taken to divert cargo transportation away from the urban road system. However, this increase results both from port direct impacts, as from indirect effects of increased industry and population growth. The progressive throughput growth means that the simulated congestion increase lasts nearly a quarter of the model run time horizon of 100 years, despite increased investments. Only after a substantial time of extensive road investments is congestion consistently reduced. The lack of spatial detail of the model might however underestimate the actual impacts of the port on congestion, as the chosen modeling approach and aggregation level causes congestion to be modeled in an aggregated, averaged way. Space within the city may be more limited locally than modeled, constraining local road infrastructure expansion.

Green space encroachment accelerates as a result of port capacity expansions: the same level of green space loss is observed 10% earlier in time. However, green space is encroached upon to the same extent as the urban land area fills up, regardless of the port expansion, when no measures are taken to protect it. Informal settlement is also observed to increase dramatically in reaction to port expansion (up to 80% on the medium term), both absolutely and relative to the total urban population, indicating a housing shortage resulting from sudden population growth and increased land pressures (and potentially, prices).

The scenario analysis shows that automation and the economic environment can have significant impact on the urban population. Port and industrial automation decrease industry labor needs and facilitate industrial growth, but lead to socio-economic inequality in the city. It is revealed that port expansion in such a context could lead to Tema being trapped in a state of increased informal housing, as economic stagnation combined with more limited port negative externalities lead to a relative advantage for Tema's development, compared to its environment (e.g. other cities without port infrastructure). The sudden rise in informal housing captures the urban land area, precluding formal housing and industrial development in the city unless space is actively cleared.

Both port expansion and port retreat can be a source of urban renewal for a port-city which is stagnated. Port expansion can attract new industry to the city, but its beneficial effects (up to 14% increase from the peak achieved without additional expansion) are short-lived (10% of the model run), as congestion and land scarcity limit further urban developments.

Assessing different modes of port expansion reveals a key finding for port-city development patterns. The question of port-city development revolves around the notion who claims the most land the first: the port or the city. If port development holds back or takes a dosed approach, urban activities benefit and claim the available land. Subsequent port development is then met by serious constraints regarding transport infrastructure construction limitations, due to increased urban developments in the land.

From the perspective of a port it is better to expand dramatically and stifle urban development, claim infrastructure and port space before land is taken for other (urban) developmental needs and developments. From the perspective of the port-*city*, a less rapid port development is preferred, although negative externalities may be more pronounced on the long term as options to mitigate road congestion may be more (space-) constrained at that point.

These findings connect to theory on port-city evolution which categorizes port-cities by respective urban and port prominence. It suggests that port-city evolution is not merely something that happens organically, but is actively decided by certain stakeholders in the port-city system. More concretely, port-city evolution may be (partly) the result of investment decisions by international shipping lines and terminal operators, who thereby increase port intermediacy and prominence which may in turn stifle urban development through externalities.

Research question 3 was evaluated in section 7.3: *What are effective interventions for sustainable port-city development that mitigate the local-global mismatch in the benefits deriving from port expansion?*

The model has been used to generate potential interventions for sustainable development of the port-city system in a systematic way. Systems thinking insights and archetypes, and model simulation were then applied in order to assess the potential effectiveness and leverage of these interventions on the system. Different alternative interventions were evaluated and compared using the designed multi-criteria scoring script, calculating impact scores for the selected model key performance indicators over the model run.

Policy runs with selected variables yielded varying success. Interventions reducing congestion and infrastructure land use were offset by increased migration and industrial activity, as city attractiveness was raised by reducing congestion. The combination of rail transport of freight and the reduction of population *per capita transport demand* (i.e. by improved public transportation alternatives in the urban area) opened up the possibility of sustainable growth, with population figures rising without associated increases in congestion.

Outside active conservation, few interventions are effective against green space encroachment without harming the city socio-economic state. Modelling results suggest that actual conservation of an area the size of the Sakumo RAMSAR site would have little impact on Tema's development: a 6% mean reduction of the stock of New enterprises in the city over a period spanning 40% of the model runtime, and population mean decrease would be less than 5%. This effect is robust to uncertainty regarding the external factors modelled. Green space conservation would be significant especially in scenarios of economic growth, where land pressures rise the most. However, conserving green space areas by protecting it actively from green space settlement is a challenge in a country that is resource-constrained, and suffers from adverse effects of "political interference": formal institutions would be less effective as enforcement would be a challenge, and may be ignored by influential individuals. Alternative approaches would involve convincing traditional authorities in charge of the lands to not sell them for development, despite rising land pressures, either by appealing to their values or by monetary compensation.

The possibility of informal settlement around the city renders policies that involve the demolition of (formal) slum estates ineffective, as evicted people settle informally. Refurbishment of slum estates, increasing their socio-economic status, would have a similar little impact, due to a 'waterbed effect': while the policy benefits labor families in the city, up to 20% increase of underemployed is observed. However, refurbishment of slum estates becomes more effective when land area is filled, close to 10% reduction of informal settlement compared to the reference scenario at that time. Supplying low cost housing programs to Tema residents would lead to a modest decrease of informal settlement, up to a 5% reduction, both absolutely and relatively. The intervention would however lead to an increase (of about the same magnitude) of underemployed population in the city, lowering Tema's socio-economic state.

The model shows the best approach to lowering informal housing is by stimulating formal housing developments by improving financing options for residents. This strategy has a double effect: worker housing availability is increased (, and over time more lower-cost housing becomes available for underemployed in the city, reducing also their need to settle informally. The increased housing developments (+20%) do lead to accelerated green space encroachment (10% more reduction over the rest of the model run).

It is shown that a combination of the most effective interventions can jointly work to mitigate the negative externalities of port and urban development in Tema.

What do model outcomes mean, for the case study, and for the development of African port cities in general?

With their choice for Tema, the consortium of terminal operators responsible for the port expansion may have determined the course of the city's development. The modelling effort showed that the additional strain placed on Tema's road network by the port expansion that is currently taking place will be considerable. A 285%

increase of port throughput is theoretically possible. If nothing is done to divert such a cargo increase from moving through Tema using the road system, the resulting 40% increase in total city road infrastructure demand will likely lead to problems and stifle the development of Tema. Additional investments in road capacity will only be a temporary fix for this. Investing in rail infrastructure will be more beneficial on the short term, but unless the majority of cargo is taken off the road, congestion is not reduced on the long term. It should be noted that the lack of spatial detail in the port-city model may lead to an overestimation of the beneficial effects of cargo transport by rail on urban congestion, as increased freight trains through the city might in turn cause some congestion from closed railway crossings. This model limitation renders it ineffective as a transport planning tool.

Whether the port expansion will actually lead to such large increases of inland cargo remains to be seen however. With its ability to service larger ships, Tema's improved intermediacy may also result in increased transshipment of cargo to other nearby ports in the region that cannot host such ships, especially if Port of Tema's landside congestion will rise as dramatically as modeled.

The parasitic effect of the port on Tema is increased even further if port operations become progressively automated. When the port's direct benefits on employment to local residents declines and negative externalities increase, the port may come to lose its social license to operate in the city. Increased resistance from the community may pressure the port authority to invest in interventions that mitigate port negative externalities. With their own revenue streams from port cargo handling, the port is in the position to contribute to this, but may be harder to influence due to its relative autonomy.

Another cause for concern is the rising car ownership in Ghana. While the bad roads in Tema might deter some from driving in the city at the moment, efforts should be made to reduce per capita road demand if the city is to develop sustainably. This can take the form of improved public transportation, or stimulating the use of smaller vehicles like motorcycles and bicycles. Once an alternative for car or taxi transport is (more readily) available for traveling in the city, a reduction in dependence on the road network will relieve congestion on the long term and reduce the need for road investments.

Informal housing in the city may be reduced by improving the financing of formal housing developments for residents. Increasing employment opportunities in the city will likely do this, but increased attraction of rural migrants may offset any beneficial impacts. Model results show that the city can become locked in a state of elevated informal housing if the city land area is quickly captured by informal settlements following port expansion, preventing industrial and formal housing developments from taking place unless residents are actively evicted. Improving housing financing may address this problem.

Tema will have to actively protect its green space from settlement if it is to survive. Resource constraints will likely be a problem however. Local Chiefs may be too tempted by the short term monetary gains of selling their land to consider conservation as an option. Conservation efforts must also focus on eliminating the possibility of political interference circumventing formal institutions.

Whether the conclusions from the model apply to other African port cities depends on the whether the same causal mechanisms hold in those other port cities. The sensitivity analysis revealed that the model provides

stable and robust results under a wide range of port-city specifications and parameter settings, indicating its versatility. While the high level of aggregation in the model makes it less suitable as a spatial or transport planning tool for one specific city, it benefits the generalizability of modelling outcomes to other port-cities.

Model inferences are likely to apply to other developing country port cities, as long as the assumptions and causal relations in the model apply to that particular city. Issues such as informal settlement and green space encroachment are common throughout the developing world, meaning that model inferences regarding these challenges likely apply to other developing country port-cities as well. However, the impact of the port on local industry may vary significantly between port cities, and even over time. While a beneficial impact was seen in Tema, especially in the years after the port was commissioned, there are indications that competition from cheap imports through the port is starting to detrimentally affect some local industry, reducing indirect port benefits. As port impacts vary between port-cities due to differences in their local economy and the extent of protectionist policies, model inferences should be interpreted with that in mind. In addition, model limitations suggest caution in applying the model to cities with more diversified economies, as assumptions on industry land use and employment apply less. Indicators of port prominence, urban centrality and the type of cargo (container vs. break bulk) that the port handles could inform to what extent other port-cities resemble Tema.

Other assumptions made in the model should be evaluated as well. Like, port land impacts on urban developments are larger for other African port cities. Partly due to seaward port expansion, port land area impacts in Tema were not considered an issue, and therefore not explicitly modelled. While partly represented in the effects on road infrastructure, port land area impacts may be significant in other port-cities. This would effectively only strengthen the central argument of this research in those instances that port investments dictate urban development.

In general, both port expansion and port retreat can be a source for urban renewal for a African port cities that have reached a phase of stagnation. Port expansion could provide a stimulus to the local economy, increasing industrial developments, but land area scarcity and port negative externalities mean that such an economic improvement would be short-lived unless externalities are actively mitigated. Port retreat, while leading to short term loss of direct employment, may be a source of more lasting urban renewal when port negative externalities reduce their constraining effect on the city.

The research argues that the development of developing country port cities is in that way at least partly determined by the investment decisions by shipping lines and port terminal operators. If port prominence is claimed like it is right now in Tema, investments by private parties may dictate the development of the city by constraining the urban development. Port authorities are torn between a responsibility for and pressures from their local communities on the one side, and the commercial requirements of terminal operators regarding the exploitation of their port on the other. Active mitigation of port externalities with lastingly effective interventions may allow for sustainable African port-city development that benefits both parties.

The model has been proven useful in simulating developing country port-city development challenges and port infrastructure expansion impacts, and in the generation of high-leverage interventions. This research shows how system dynamics was effectively used in a relatively data-poor environment, to model the development of the city of Tema and its port and evaluate interventions for sustainable port-city development in an African

context. While its level of aggregation may preclude its use as an urban planning or prediction tool, it may be used as part of the port planning process to convey to key stakeholders a systems perspective and understanding of port-city development dynamics. The relative complexity and high level of aggregation of the model however suggest that a strategy needs to be designed for this.

9 LIMITATIONS AND RECOMMENDATIONS

Reflecting on the research carried out in this thesis project, several limitations and recommendations for further research have been identified. These pertain both to the modelling methodology used as to the model itself.

The simulation model is not perfect, nor can it be or was it intended to be (Coyle and Exelby, 2000). However, some fundamental conceptual properties of the model have significant consequences for intended model use. For instance, scenario testing revealed that due to its spatially aggregate nature, the model is not adequate when modelling highly localized problems such as flooding. Even when floods are modeled to last a year, no significant impacts on the port-city system are experienced unless a significant portion of the city is compromised.

Similarly, the construction of road infrastructure might be overestimated due to the lack of localized spatial constraints in the model (i.e. bottlenecks). However, the causal mechanisms governing congestion (e.g. the supply vs. demand of infrastructure) still apply.

The same but reverse limitation applies to the modelling of green space encroachment. Spatial aggregation results in an "average" encroachment, insensitive to spatial proximity of the green space to the urban core. While in the current model the settlement of green space can be adjusted to approximate such a spatial effect, it can be questioned if this solution is a good representation of the real world system. The value of coupling the system dynamics model with an agent based (cellular automata) model of (urban) land use could be explored in further research, although such a study would require detailed geospatial information (e.g. Mariwah, Osei, Amenyo-Xa, 2017) and knowledge regarding local settlement behavioral rules. Obtaining such information for developing country port cities might prove challenging, but would increase insights into port-city spatial development over time.

Although port spatial impacts on the city were not cited as a sustainability concern in Tema at the present time and therefore not included in the model, (Slinger et al., 2017) the port-city functional evolution model discussed in section 4.1 suggests that rapid containerization and port-city growth could lead to spatial constraints gaining more prominence in the future. In future applications where spatial issues are indeed given priority (for instance by some local port-city stakeholders), the model could be adapted for ports to have a spatial impact, similar to road infrastructure. Care then needs to be taken to differentiate between container and break-bulk cargo, as these have significantly different land use impacts (Jansson and Shneerson, 1982).

While utilities such as energy were left out of the analysis to limit its scope, they may have an influence on port-city development, for instance when unreliable energy supply limits industrial development. While Ghana's energy provision ranks among the best in the region (Gyamfi, Modjinou, and Djordjevic, 2015), there are indications that this has played a role in Tema in the past (e.g. Yeboah, and Annancy, 1999). Although energy scarcity may not have been explicitly modeled, its effects resemble that of an economically unfavorable environment, which has been addressed in the scenario analysis.

Other potential linkages could involve the impact of road infrastructure investments and port presence on urban tax needs and revenues, although sensitivity analysis showed a modest response to this section of the model. The prominence of agriculture in the Ghanaian economy might suggest the explicit modelling of peri-urban agricultural land use competing with the urban expansion, or the dependence of some urban poor on resources extracted from green space (Adegun, 2017). Lastly, the Tema model could be connected to a socio-economic model of the Volta delta, from which many migrants of the city originate.

What should be evaluated at all times however is whether such adaptations would serve modelling requirements and use. If anything, the present model already is quite large and complex, which could reduce its explanatory power and usefulness in participatory modelling contexts with stakeholders. However, the

sensitivity analysis showed that the model was relatively insensitive to a large number of variables in the original Forrester model. This corroborates the research of Stonebraker, and suggests that the present model, like Forrester's Urban Dynamics, could be significantly simplified without losing its functionality and behavioral characteristics (Stonebraker, 1972).

The lack of a service industry in the model is a potential problem for external validity of modeling conclusions. It was preferred to keep this modelling effort focused by not including it in the model just for it to resemble the real world system more. Tema, as a city with a prominent port and industrial sector, therefore was an appropriate case study for this modelling effort. However, it means that the modeling conclusions might not extrapolate to port-cities with more diversified economies. These would be port cities with a lower prominence of port and/or port related industries (section 4.1). Further research could be undertaken in which the service industry is more explicitly included in the port-city model (e.g. Sanders and Sanders, 2004).

That means model applicability should be established for each potential case study. While the use of a single case study for this project was a consequence of the resource- and time constraints of a master thesis graduation project, further research may establish the validity of model inferences and behavior for different developing country case studies.

The relative heterogeneity of port impacts on local economies (Merk, 2013) suggests that the validity of model performance can be improved if port impacts can be locally determined. Traditional port impact studies are expensive, require extensive surveys and do not necessarily provide an objective multiplier figure. An alternative method of estimating port impacts presented by Musso, Benacchio, and Ferrari (2000) could prove useful for future applications of the model. It involves comparing the port city (e.g. Tema) to one or more landlocked cities of similar size (e.g. Kumasi, Ho), and establishing the differences in industrial and economic activity. This could be done using aggregate, census data.

In addition to these model-related recommendations, there are some avenues for further research regarding model use in a multi-stakeholder port-city sustainable development process. Next steps could include the formulating of guidelines for effectively using the model or concepts thereof to impart a system thinking approach on port city stakeholders. Consultations with experts on ports and urban development suggested that the model could serve as a boundary object in strategic conversation on port-city option generation amongst port-city stakeholders (Appendix E. Interview data; Star and Griesemer, 1989; Cunningham, Hermans, and Slinger, 2014).

An interesting strategy for this model use would be an approach which combines principles of group model building and network (process) management: rather than confronting stakeholders with a complete model straight away, through a process of guided discussion participants could come to a consensus on how the port-city system functions, gaining negotiated knowledge, facilitating fruitful cooperation (Hovmand et al., 2012; de Bruijn, and Heuvelhof, 2012; d'Hont, personal communication (Appendix E)). Such group model building sessions could then add to the elicitation of stakeholder values and conferring the systems thinking approach to port development to port and city stakeholders, fostering active debate and win-win thinking. Another approach would involve the creation of a serious game of port-city development, in which participants get interactive feedback on the effects over time of port infrastructure and interventions on the port-city system.

10 REFLECTION

Reflecting on the research, it can be noted that the use of the system dynamics approach was appropriate, given the wide variety of factors involved in a developing country port-city. Despite rigorous demarcation, the relatively high level of model aggregation and active efforts to keep modelling detail and data needs in check, the resulting model has become quite comprehensive and complex. This presented a challenge especially in the (sensitivity) testing of the model (which took more resources and reporting space than anticipated), and the presentation and analysis of model outcomes. The semi-automated data-interpretation and visualization script was developed to mitigate this, and to aid in model outcome interpretation and keeping reporting within acceptable limits.

Tema has been a suitable case-study for this project. Its location in the Greater Accra metropolitan area meant that more data than expected was available on the port, the city and the lagoon, which aided the modelling effort. In applying the model to other African port-cities, more time and resources may be needed for the extraction of such data from local stakeholders and institutions.

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This appendix contains an overview of the data used to specify and apply the model to Tema. Parameter values have been compiled from multiple sources, or estimated based on the available data. This process of estimation or calculation is made explicit in order to aid reproducibility of the research and to explain the choices that have been made in the face of limited data availability.

The appendix has a dual function of serving as a precise manual on what data is needed to apply the model to a(n alternative) case study. This involves specification as well as validation purposes.

• City (potential) land area	• Migration rates
• Population size (over time)	• Industry (initial values)
• Net birth rates (disaggregated if possible)	• Port capacity (initial, expansions)
• Housing (initial, construction)	• Port throughput
• National GDP	• Initial green space area
• GDP growth	• Minimum possible green space area
• Aggregate housing and enterprise valuation figures	• Max pc (per capita) transport demand growth

CITY LAND AREA

Determining a suitable figure for the area of Tema is a challenge, as several definitions of the urban area exist. For instance:

565 km^2: Tema Metropolitan District, before the carving out of Ashaiman (2008) and Kpone-Katamanso (2012) as separate districts (Statoid, 2008). Ashaiman has a land area of 45 km^2 (Ghana Statistical Service, 2014a).

87.8 km^2: Tema Municipality area).

365.78 km^2: Tema Metropolis Area (without Ashaiman): (Mariwah, Osei and Amenyo-Xa, 2017). Adding Ashaiman area (45 km^2) yields 410.78 km^2 or 41078 hectare. But this still includes Kpone-Katamanso which is outside the port-city influence

The final value for Tema city land area is defined to be the area of the original Tema Acquisition Area (167 km2), the area designated for development by the Tema Development Corporation in 1952 (Clottey, 2015; Acquah, 2001). It includes Ashaiman (45 km2) (Ghana Statistical Service, 2014a), and is comparable in size to the city proper area of Accra (Statoid, 2008).

NET BIRTH RATE

The model requires net birth rates of the three population groups. Forrester's use of the word birth rate for this is not entirely correct, as death rates are implicitly included. The net population birthrate are calculated by subtracting the crude death rate (in deaths per thousand per year) from the crude birth rate (Table 22, Table 23 below).

Table 22. Calculation of net birth rate from crude birth, death rates.

District	Crude birth rate (live births per thousand)	Crude death rate (deaths per thousand)	Net birth rate (sic, Forrester), per 1000
Tema metropolitan	21	4.4	16.6
Ashaiman district	23.5	3.9	19.6
Kpone-Katamanso	24.4	4	20.4

GSS, 2014b

Translating this to the following net birth rates:

Table 23. Model values of (net) birth rates

Group	Net birth rate
Managerial-professional	0.017
Labor	0.017
Underemployed	0.02

INITIAL CONDITIONS OF THE MODEL

The Forrester model does not support jumpstarting from nothing (little population, no industry). This is partly the result of the way migration multipliers are specified, yielding little concentration until a critical mass is formed. Therefore, the start time of the simulation is set at 1966, the year the port was officially commissioned (Hilling, 1969).

The initial conditions of Tema at that time can be derived from Acquah (2012) and other sources. A compilation of population data from multiple sources is included below in Table 24. The data is contradictory, which might depend on varying definitions of what is considered Tema, for instance after the carving out of Ashaiman.

Table 24. Estimations of population for Tema and Ashaiman over time.

Year	Houses built	Population						
	Acquah (2012)	*Owusu (1991), GSS (2002)*	*Acquah (2012)*	*Hoyle and Hilling (1970)*	*Songsore (2009)*	*Hilling (1969)*	*GSS (2010)*	*World Bank (2015)*
1948		1,120						
1954				4,000		3,000		
1960		15,000 (2,624)	25,223		27,127			
1966	10,700 (TDC)		29,080 (calc.)					
1968				80,000				
1969						80,000		

1970	1,750 (TDC)	83,316* (22,549)	60,767		102,431			
1981	7,380 (TDC)		*Acute housing shortage*					
1984		150,970* (50,918)			190,917			
2000		291,791 (150,312)						447,472
2010							402,637 (190,972)	633,011

(*Numbers in brackets are population figures for Ashaiman, which are included in the calculated total).

Population numbers for the year 1966 have to interpolated from the available data. Following Acquah's figures and comments on population growth rate of 2.4 percent, yields the population in 1966: $(25{,}223 * 1.024^6)$ = 29,080 people.

Judging by the other population estimates around that time, and that Owusu's figures seem to be consistently on the low side, a higher figure of 40,000 is taken, which is somewhat more realistic compared to the cited 1968 figure of 80.000.

EMPLOYMENT

Following Forrester's model logic, it is assumed that out of a population of 40,000 about 10,000 are working (dividing by the average family size of 4). Assuming 10% of these 10,000 are managerial-professional, the figure for initial employment can be divided in roughly:

A + B = 100 -> A = 0.1* B 1.1 * B = 100 → B = 10,000/1.1 = 9,091 labor and 10,000-9,091=909 managerial-professional.

HOUSING UNITS

Taking Owusu's figure for housing units built at the end of 1966 as a base (10,700) and applying the same technique yields 10,700/1.1= 9727 worker housing and (10,700 – 9727) = 973 premium housing units. That leaves almost full occupancy of premium housing (0.934) and a housing surplus for workers (0.315), which is in line with Owusu's claim of an initial worker housing surplus.

INDUSTRY

Determining an initial condition for industry is harder, as there are no sources indicating actual amount of industry settled, and the limited comparability of the construct of *productive unit* used in the model. It can be derived however by assuming that all workers living in town are employed by industry. As new enterprises enroll on average 20 laborers, it can be inferred that the equivalent of 9,091/20 = 455 new enterprise productive units must be present in Tema at that stage (modeled units). As industry has just started, no mature or declining industries are assumed to exist yet.

PORT THROUGHPUT

Table 25. Yearly throughput of the Port of Tema, compiled by author from JICA, 2001; Pedersen, 2001; Hilling, 1969 and Ghana Ports and Harbours Authority, 2016.

Year	Throughput (kton/year)	Year	Throughput (kton/year)
1962	622,24	1990	3477,00
1963	1301,09	1991	3647,01
1964	2277,50	1992	3909,66
1965	2194,79	1993	4130,20
1966	1940,17	1994	4090,25
1967	1975,67	1995	4611,44
1968		1996	4879,93
1969		1997	5168,59
1970	2665,00	1998	5417,11
1971	2823,00	1999	6368,54
1972	2522,00	2000	6219,52
1973	2713,00	2001	6314,97
1974	2953,00	2002	6841,48
1975	3124,00	2003	7391,27
1976	3234,00	2004	8447,66
1977	4055,00	2005	9249,98
1978	3799,00	2006	8046,84
1979	3394,00	2007	8378,68
1980	3344,00	2008	8727,05
1981	3640,00	2009	7406,49
1982	3035,00	2010	8696,95
1983	1906,00	2011	10748,94
1984	1811,00	2012	11468,96
1985	2365,00	2013	12180,62
1986	2875,00	2014	11126,36
1987	2998,00	2015	12145,50
1988	3026,00	2016	13414,78
1989	3311,00		

Historical data regarding Tema port yearly throughput (Table 25) had to be compiled from various sources, as there was no single source that had all data available.

TEMA PORT CAPACITY AND CAPACITY INCREASES.

The same applies to estimations of the capacity of the port of Tema. The port was officially opened for operation in 1962. Precise port capacity was unknown but estimated to be well above it's cargo volumes in the early years of operation (Pedersen, 2001). Due to faltering efficiencies and congestion, investments in port infrastructure were carried out from 1987 and 1990, increasing port handling capacity by 1.6 times (which equates an increase

of 3286 ktons/year) (Coquart, 1998). It is possible to derive from these numbers an estimate for the initial handling capacity of 5476 kton/year.

Consequential investments in additional quays in 2007 led to theoretical increases of capacity of 550.000 TEU per year. Using an average weight of 11 tons per TEU (Alila, Khayesi, Odhiambo and Pedersen, 2005; Van Eeden, 2016), this amounts to an estimated increase in capacity of 6050 kton/year.

The current expansion project is estimated to increase the harbour's capacity with 2.5m TEU per year, or 27500 kton/year. (earlier estimated capacity: 11000 kton/year), again taking 11 tons as the average container weight. The project is expected to be completed in 2019 (APM Terminals, 2015).

Table 26. Overview of Tema port-city relevant actors' interests, objectives, percieved problems, causes, and possible solutions.

Actor	Interests	Desired situation/objectives	Existing or expected situation and gap	Causes	Possible solution
Ghana Ports and Harbours Authority (GPHA)[1]	Manage and operate the Port of Tema in cooperation with private parties. Continuity of business.	Efficient and viable port operations, port facilities - Ghanaian ports more competitive in the sub-region - Social and industrial stability - Good roads and trucks	Port efficiency and service delivery must be improved.	Low port efficiency and capacity, insufficient transport infrastructure	Modernization and development of the ports, increase private sector participation, investing in road transport infrastructure
Port operators and liner shipping companies[2]	Continuity of business, expansion of market	Development of competitive position in the market, increase market share, geographical coverage, cargo handling capacity	Port terminals must be developed in order to cope with increasing containerisation and globalisation of the market.	Globalisation, economies of scale and scope, labour regulations and global competition.	Upscaling and vertical integration of shipping and cargo handling activities. Increasing port container terminal capacity and efficiency.
Tema Metropolitan Assembly[3]	Providing effective and efficient Metropolitan services	Improved living standards of the people in the Metropolis, more employment opportunities	Inhabitant quality of life is too low. Industrial development must be improved. Traffic congestion is problematic	Low resources, informal settlement,	Attract foreign investment for infrastructure development; pressure GPHA to contribute
Tema Development Corporation (TDC)[4, 11]	Development of Tema (originally). Facilitation of development by other parties	Plan, layout and develop the land area of Tema (housing schemes, roads, industrial sites, public utilities).	State of the infrastructure (sewage, water, etc.) is deteriorating. Reduction of public funding for programs.	Lack of maintenance, lack of resources.	Allow private parties hustle-free access to land made ready through site and services schemes.
Industry[5, 6, 7, 8, 9]	Continuity of business, expansion of market	Ample provision of labor, good access to markets and resources (transport infrastructure)	Traffic congestion and bad roads may harm business. Lack of industrial development deters newcomers	Raw material burden, unfavourable competition from cheap imports and FDI, weak infrastructure, financial constraints	Privatization, foreign investments
Population of Tema[7, 10, 11]	Continuity of existence; income, shelter and safety	Attain a steady source of income (employment), affordable dwelling space	Low cost housing is not present. Living standards in slum are sub-par.	Lack of infrastructure (maintenance), lack of formal employment.	Informal economy, informal settlement (lowest cost of housing)

Traditional Chiefs[11, 12, 13, 14]	Employment opportunities for their respective peoples, benefits from selling their lands	Increase benefits from their land, local harbour and industry development.	Increasing potential to benefit from selling and developing their land, including formerly unattractive green space areas.	Rising land pressures from urbanization, encroachment. Lacking compensation for green space conservation (e.g. Ramsar)	Offer part of their land to the Tema Development Company (1950's), Selling their lands to residents or private parties to develop directly.
Home Finance Company (HFC)[11]	Development of the housing market in Tema	Enable residents to purchase or build houses or other projects	Most of the workers are low and middle-income earners and cannot meet the precondition terms for loans	Instability of housing policies and strategies in Tema, low resident incomes.	Offer more affordable mortgages and loans to local residents seeking to buy or develop a house.

Sources: 1) Ghana Ports and Harbours Authority, 2013; 2) Junior, Beresford and Pettit, 2003; 3) Tema Metropolitan Assembly, 2017; 4) Tema Development Corporation, 2017; 5) Agyemang, 2013; 6) Oxford Business Group, 2013; 7) World Bank, 2015; 8) Yeboah and Annancy, 1999; 9) Owusu, and Oteng-Ababio, 2015; 10) UNCHS (HABITAT), 2003, 11) Acquah, 2001, 12) Blocher, 2014; 13) Clottey, 2015; 14) Tyroller, 2016.

Table 26 presents an overview of the stakeholders that are most relevant to the port-city system in Tema. In addition to these actors there are national governmental institutions and non-governmental organizations with a variety of interests and goals. Table 27 summarizes the information on local stakeholder values regarding sustainable Tema port city development, gathered in the stakeholder workshop in February. This information is used to demarcate and focus the research problem (Chapter 2).

Table 27. Port of Tema stakeholder values concerning sustainable port city development (Slinger et al., 2017).

Sustainable port city development in Tema					
More economic development		Less negative externalities			
More local employment [jobs/population]	Higher port throughput [mton/year]	Less congestion [infrastructure use/infrastructure capacity]	Less slum development [informal settlement]	Less pollution	Less green space encroachment [Ha green space]

Institutional context

Williamsons four-level model of institutions (Figure 126) is used to guide a discussion of the institutional context of the port-city development problem. Williamson argues that there are four levels of institutions that govern and structure economic transactions. The first comprises of informal institutions that evolve slowly, such as customs, traditions, norms and religion. The second level contains the formal institutions that determine the rules of the game, such as property rights and laws. These are the product of politics. On the third level governance structures, such as contracts, markets, and organizational structure are studied. The fourth and last level discusses everyday decisions and resource allocations where prices and quantities are aligned, the terrain of neo-classical economics and agency theory.
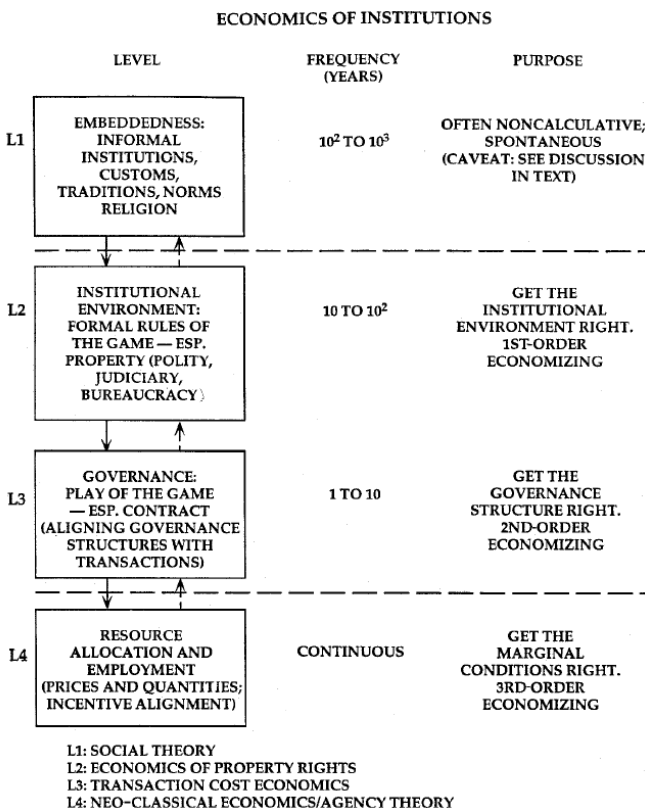

Figure 126. Four layers of institutions governing economic transactions (Williamson, 1998).

Ghana, like many other African countries has an extensive system of traditional authorities and institutions. Land in Ghana is often owned or bought from local Traditional Chiefs and their families, following local traditions. This informal system functions alongside formal (governmental) institutions regarding land rights, and can lead to friction between formal land tenure rules and actual land use (Blocher, 2014). In Tema, the land of the Tema Acquisition Area was bought by the government from local Chiefs, and allocated to the Tema Development Corporation for development (Acquah, 2001; Clottey, 2015). A dispute of local Chiefs with the TDC over compensation led to them selling land themselves, facilitating the formation of haphazard development and informal settlements around Tema (Acquah, 2001). The system of traditional authorities is common across sub-Saharan Africa, but political and economic changes, as well as migration have undercut their authority. It is however unclear if a general trend towards land privatisation is actually underway (Lawry, 1990; Boone, 2006).

Formal institutions in Ghana include the laws and regulations and formal mandates that are in place. Relevant laws for port city development for instance include environmental regulations (Halcrow Engineers PC, 2010), the mandate of the Tema Development Corporation to develop the Tema Acquisition Area (Acquah, 2001), governmental ministries and local municipal assemblies, and the Ghana Ports and Harbours Authority.

Governance structures in this case include for example Meridian Ports Services, the joint venture of the Ghana Ports and Harbours Authority (GPHA) with the Bolloré and APM terminal operator companies set up for

developing and exploiting the new Tema port expansion (Chalfin, 2010). They operate in this mutually beneficial governance structure within the frames set out by informal and formal institutions to optimize risk and benefits of port operations and asset ownership (see section 4.4 Port governance).

While Ghana is a politically relatively stable country (Fosu, 2013), informal authorities and political elites can still exercise considerable influence on day to day resource allocation decisions and even policy making when it is in their interest to do so, even violating formal institutions (Wong, 2010; Paller, 2012). This practise is not unique to Ghana but a common occurrence in developing countries that can hamper development (Owoye and Bissessar, 2014), and should be kept in mind when evaluating interventions.

Transport

Faah (2008) provides a comprehensive overview of the ministries, departments and agencies relevant for road transport planning and interventions. Examples include the Ministry of Local Government and Rural Development (Department of Town and Country Planning) and the Ministry of Road Transport (Dept. of Urban Roads). Other agencies include the Ghana Railway Development Authority, Metro Mass Transit Limited, incorporated to provide national railway services and affordable public transport in metropolitan and municipal areas, respectively (Republic of Ghana - Ministry of Transport, 2017).

Housing

In Ghana several institutions for housing development have been employed. After independence, the Tema Development Corporation (TDC) was established and tasked with the development of the city and port of Tema. In other parts of Ghana the State Housing Corporation (SHC) was mandated for housing development. Lack of resources led to the rise of informal settlements (Bank of Ghana, 2007). There have been several strategies formulated over the years for stimulating development (Bank of Ghana, 2007):

- National Shelter Strategy (1986). Aimed at providing adequate and decent housing units, improving quality of life of people in urban and rural areas.
- National housing policy and Action Plan (1987-1990).
- Ghana Vision 2020. (1997-2000). First Medium-Term Development Plan. Targeted provision of low-income housing units. Lack of funds, private sector participation and political will meant that none of the housing strategies so far were implemented.
- Ghana Poverty Reduction Strategy (GPRS I, 2001). Focus on the attraction of foreign capital to fund housing development.
- Highly Indebted Poor Country debt relief program – allocated some funds to the housing sector.
- GPRS II (2006-2009) – focused upgrading of slums.
- Ministry of Water Resources, Works and Housing, currently pursuing various affordable housing programmes through agencies such as the TDC and SHC. National Housing Programme is also building in Tema.

The Tema Development Corporation appears to be at odds with the Tema Municipal Assembly (TMA) over jurisdiction over city land and its development, as the TDC aims to expand its mandate in order to be allowed to develop lands outside the original Tema Acquisition Area it was assigned (Ghana News Agency, 2010).

This appendix is included to provide an overview of how the model is specified in Vensim. As modelling equations are not included in this report for brevity, these pictures are included to represent the structure of the final model.
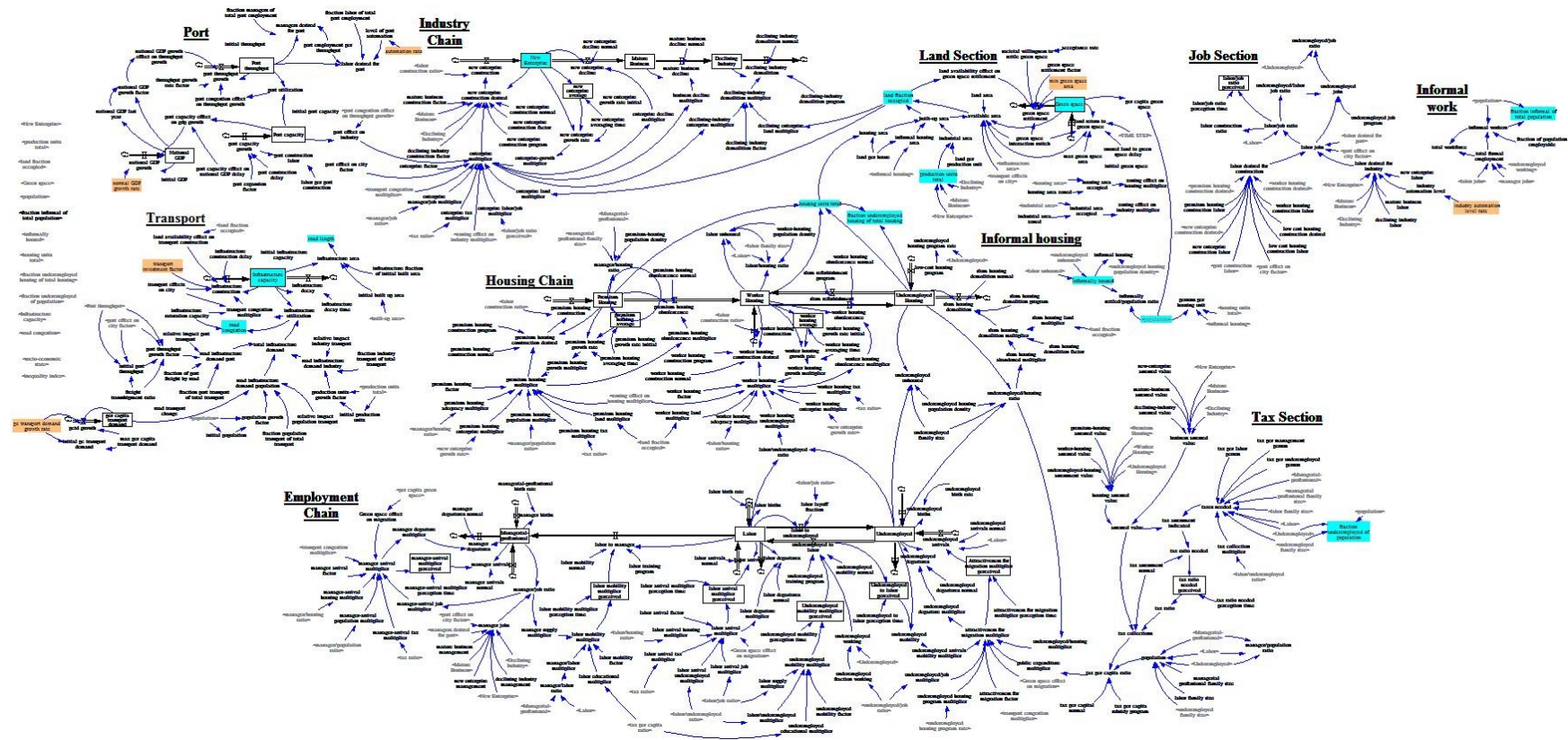
Figure 127. Overview of the complete model as specified in Vensim.
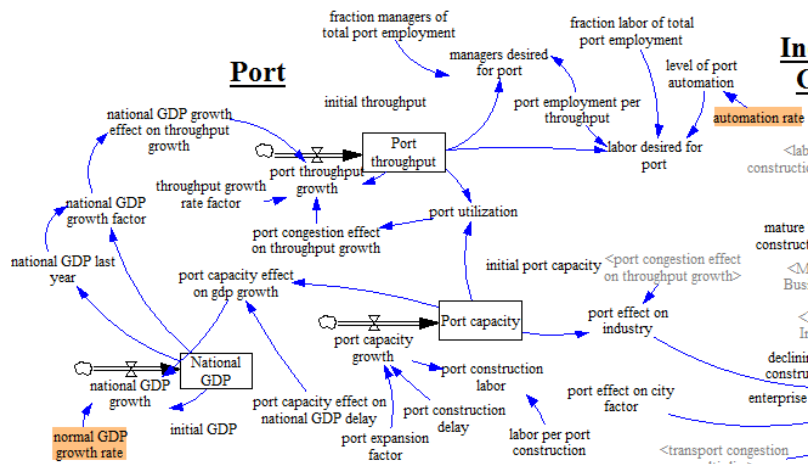
Figure 128. Port sub-model as specified in Vensim
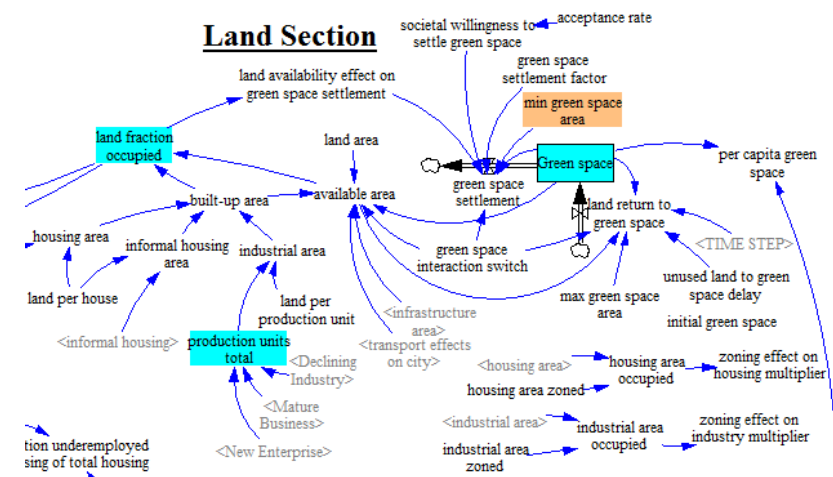
Figure 129. Land section as specified in Vensim

Figure 130. Transport sub-model, as specified in Vensim

146

Figure 131. Industry chains as specified in Vensim
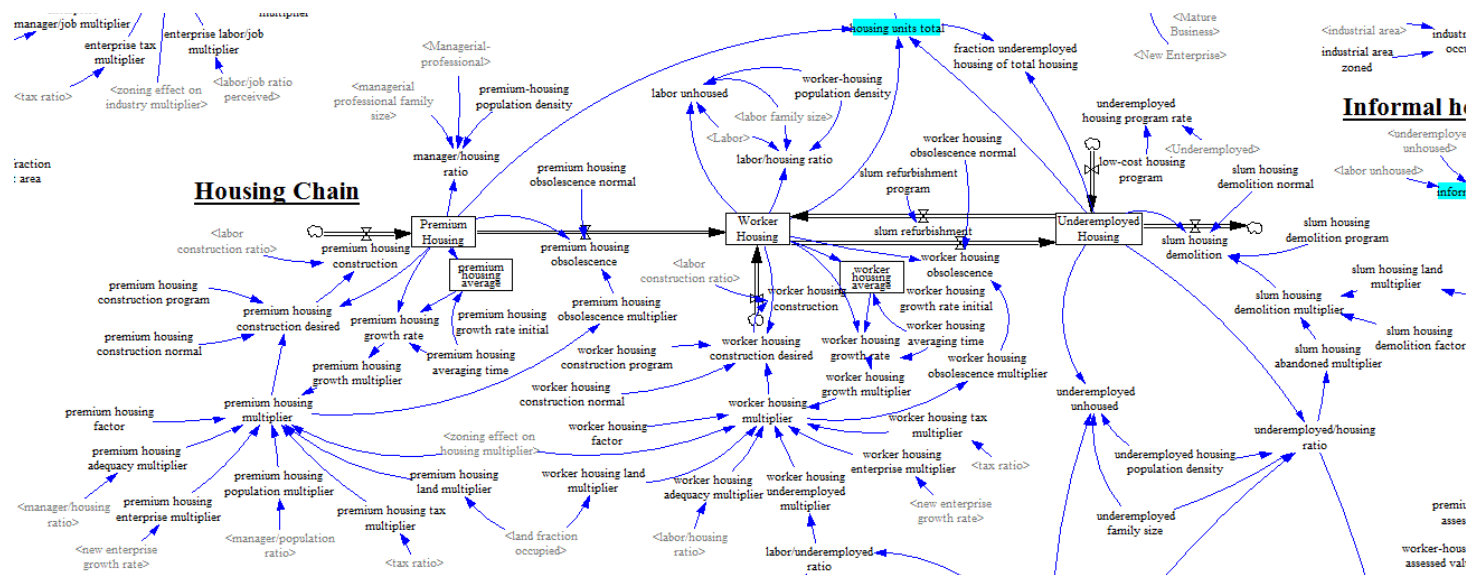
Figure 132. Housing chain as specified in Vensim

Figure 133. Employment chain as specified in Vensim.

Figure 134. Job and informal work section as specified in Vensim
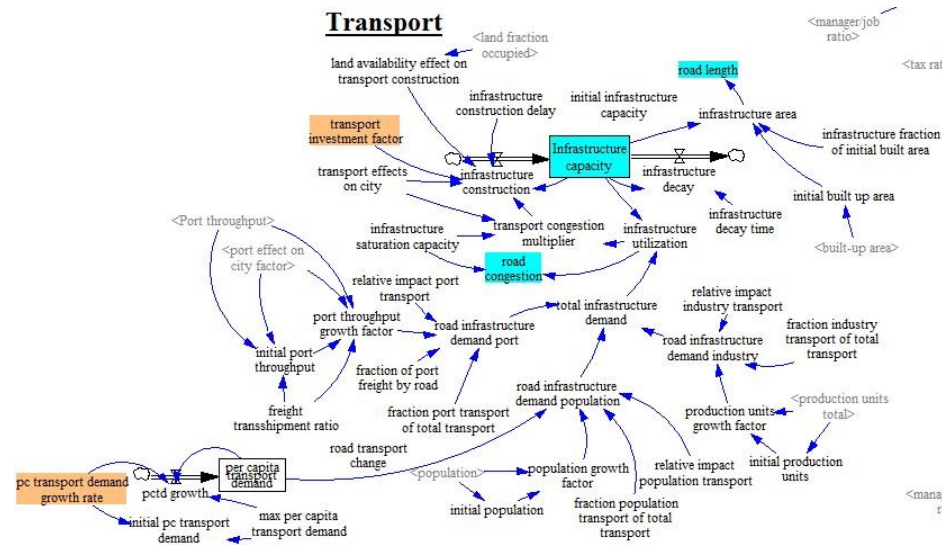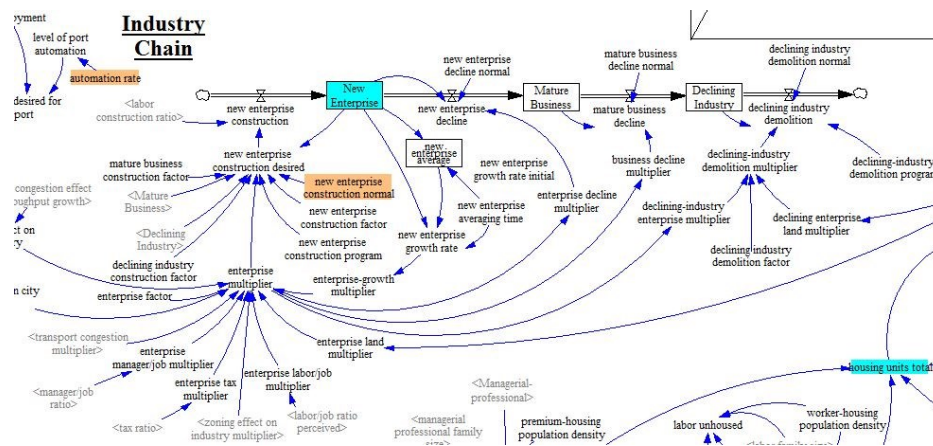

Figure 135. Tax section as specified in Vensim.
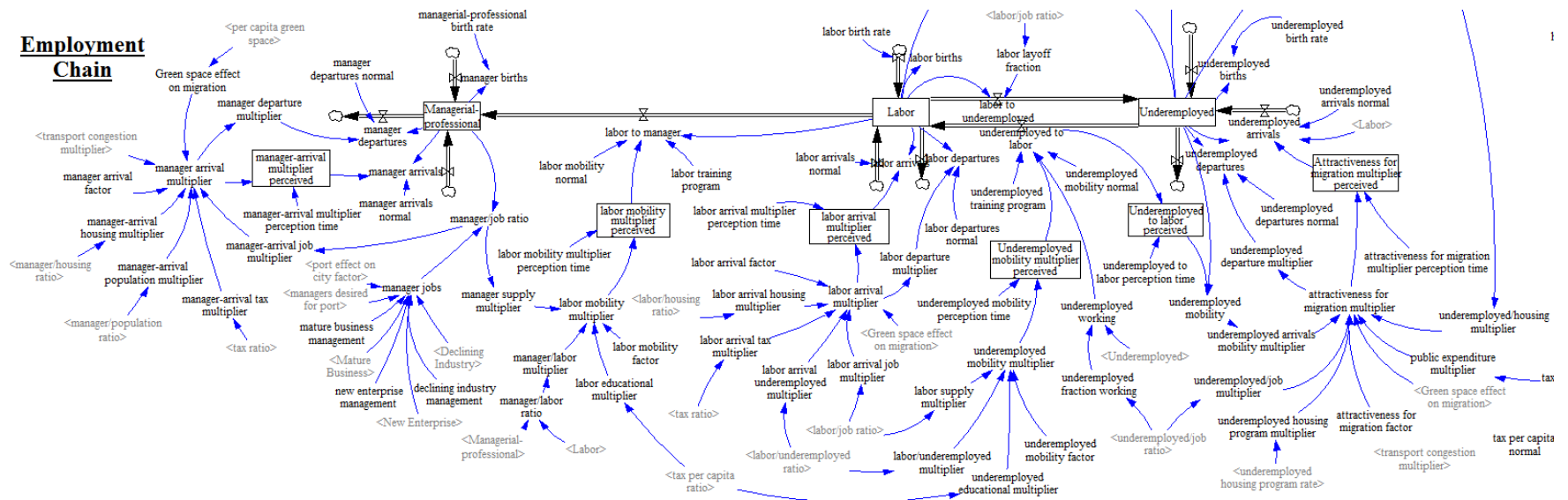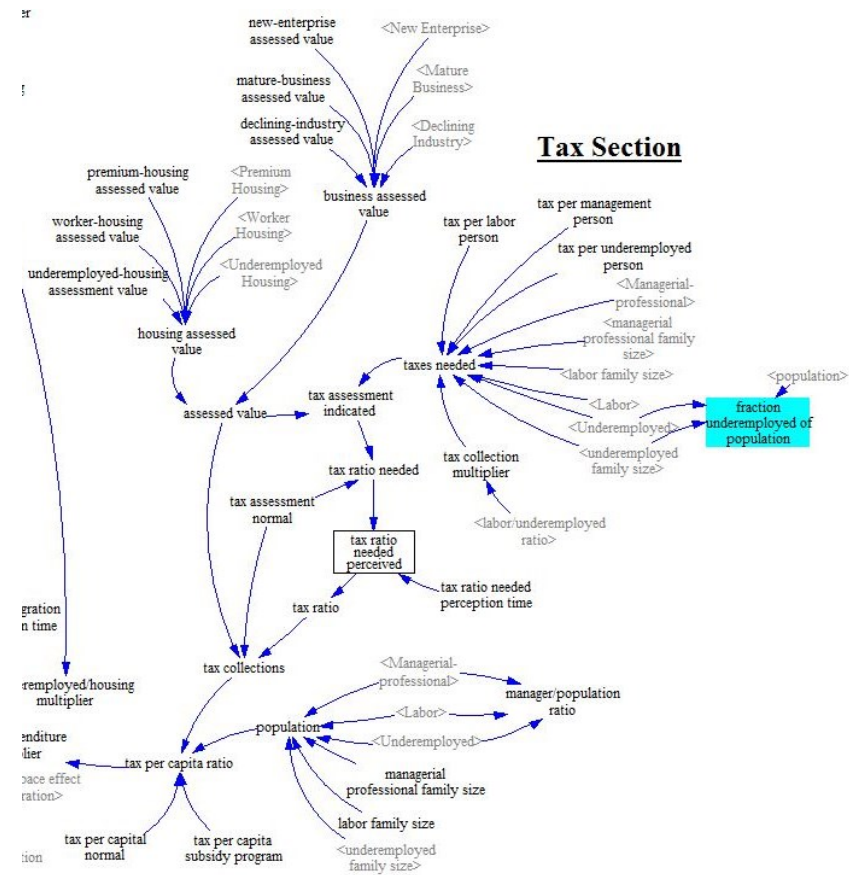

Figure 136. Informal housing as specified in Vensim.
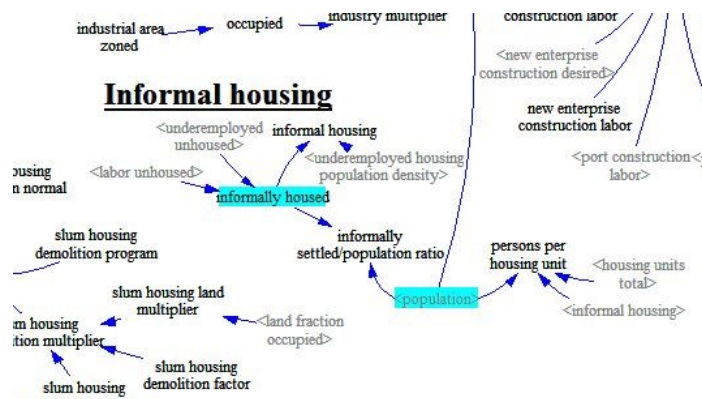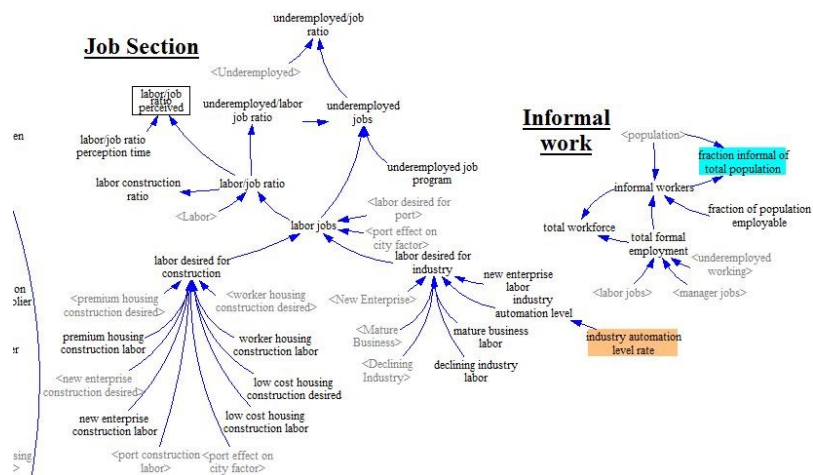
The model describes the development of the port-city as a result of endogenous processes. However, there are exogenous factors influencing urban development in the model. The behavior and impact of these exogenous factors might be subject to uncertainty. In this chapter, a scenario analysis is described. In a sensitivity analysis, external factors are inventoried, the driving forces behind them identified and scenarios written.

The goal of the scenario analysis is to construct an array of plausible (not just likely) contexts for developing country port city development. The impact of uncertain but influential factors on the system can be explored, and robustness of potential policies tested. Lastly, the scenario analysis aids in assessing the external validation of model results, by evaluating these in multiple, varying settings.

QUESTION

One of the aims of the model is to explore potential modes of port-city development and find policies and interventions that foster sustainable development as defined by the modelling outcomes of interest. The aim of the scenario analysis is to generate scenarios with which the robustness of such policies and interventions can be assessed.

In order to do this, the scenarios should be able to answer the following question: What are different plausible futures for port cities in a developing country?

CONTEXTUAL FACTORS

First, a list is compiled of external factors that might influence the port-city system development from outside model boundaries. The definition of the system boundaries partly determines which factors are considered endogenously modelled effects, policies or external (exogenous) factors. An example of an endogenously modelled impact is the effect of road congestion on the settlement of new industries. An example of a policy in the model is the investment in road infrastructure itself. An external (exogenous) factor would be the availability of resources or foreign direct investment influencing the extent of road infrastructure investments.

Whether a factor is defined as either an (uncertain) external factor or a manipulable policy depends on the perspective taken in the modelling exercise and whether the actor(s) influencing these factors are considered problem owner(s) or not. The perspective of this modelling study is broad, modelling endogenously the behavior of for example industry and urban population. However, not all driving forces driving that behavior are certain, or modelled endogenously.

The modelling perspective taken may change with the mode of model use. In using the model as a soundboard for strategic conversations (Cunningham, Hermans and Slinger, 2014) the definition of what are policies or external factors may depend on the stakeholders that are present. In Forrester's original model, local government is taken to be the problem owner, with policies taking the form of (public) interventions such as housing programs and job training (Forrester, 1970). This study takes the same perspective. As the model is extended to include port and transport infrastructure, additional actors (such as the port authority and national government) are included. A further guideline for classifying effects as interventions or external effect is

whether the problem owner has any influence over the implementation of these effects (e.g. compare investments in railroads with automation of industry).

Population car ownership	Net birthrate
Rural-urban migration	Flooding
Global trade volumes	Port automation
Competition of other nearby ports	Industrial automation
Port hinterland connections	Mobility of capital (FDI)
Political stability	Social willingness to settle green space
Family size	

Table 28 contains an overview of plausible exogenous factors that might affect model behavior. Depending on the mode of model use, port and industry automation could be considered interventions rather than external (and uncertain) effects. As port automation investments are partly determined by port terminal operators and port developers (see Actor analysis), port automation is considered an exogenous factor.

DRIVING FORCES

Next, external factors are grouped by identifying common driving forces influencing them. Table 29 groups the external factors by driving forces. Port hinterland connections is omitted as it is only one of several factors determining port competitiveness (Yuen, Zhang, and Cheung, 2012). As modelling port competitiveness is not the focus of this study, this factor is instead represented by the factor *competition of other nearby ports*, driven by economic environment.

Table 29. External factors grouped by driving forces

Economic environment
Population car ownership
Global trade volumes
Competition of other nearby ports
Mobility of capital (FDI)
Climate change
Rural-urban migration
Flooding
Technological advancement
Port automation

Industrial automation
Demographic change
Family size
Net birthrate
Political stability
Sociocultural evolution
Societal willingness to settle green space

Then, the driving forces are prioritized by their uncertainty and potential impact on the model (Table 30). Most important to evaluate are driving forces that have a high impact, and for which future development is uncertain. As demographic changes like net birth rates have limited effect on the model (see sensitivity analysis) and change rather predictably or slowly (World Bank, 2017a, b), these are not considered high priority. Traditional informal institutions governing wetlands and green space have been influential predominantly in the past, but have lost influence with rising urbanization, Christianization and migration in Ghana (Tyroller, 2016).

Table 30. Impact-Uncertainty grid for driving forces

		Uncertainty	
		Low	High
Impact	Low	- Demographic change - Sociocultural evolution	
	High	Political stability	- Technological advancement - Climate change - Economic environment

Technological advancement as a driver of industrial and port automation can significantly affect employment in the developing world (Oberhaus, 2017). A report by the World Bank states that two-thirds of all jobs in the developing world could be lost to automation (World Bank, 2016). Most at risk are low-skill and low-wage jobs, and production occupations (Frey and Osborne, 2017), which could lead to a hollowing-out of labor markets and rising inequality (World Bank, 2016).

The rate at which automation will affect labor in developing countries is uncertain and depends on the pace of technological disruption (World Bank, 2016). This makes a technological advancement a high-impact high-uncertainty driving force.

Climate change is another driving force potentially affecting the port-city system both socio-economically and ecologically. Lying adjacent to the catchment area of the Sakumo lagoon, parts of Tema flood with some regularity (Songsore et al., 2009; World Bank, 2017c; field visit). With climate change altering rainfall patterns, tending to increase storm frequency and intensity, the potential for such floods is increased (Douglas, et al.,

2008). In Ghana, rainfall patterns are cited to have become unpredictable since the 1980's. Floods and droughts associated with this increase the likelihood of seasonal and long-term rural-urban migration in Ghana, as people flee erosion of their lands or face the need to diversify their income (Faist and Schade, 2013). The port-city model is founded on the concept of relative attractiveness of the city in relation to its environment. A decline in relative attractiveness of that (rural) environment means an increase of relative attractiveness of the port-city.

The economic environment drives developmental factors both on a national and an international scale. Shipping and port throughput are closely connected to global trade and economic cycles (De Monie, Rodrigue, and Notteboom, 2011). The global financial crisis of 2008 indeed preceded a significant drop in throughput volume in the port of Tema in 2009 (Ghana Ports and Harbours Authority 2016). Nationally, the economic environment is assumed to affect cities in Ghana in a similar way, therefore not leading to changes in relative attractiveness of one city. Locally however, the economic environment for business does impact industry in an absolute manner. Holding on to Forrester's assumption of relative attractiveness would lead to skewed result, therefore an effect on the construction of new industry is included.

Transport is impacted economically with an increase (or decrease) in per capita car ownership, affecting per capita demand for road infrastructure (Faah, 2008; Obeng-Odoom, 2010). Additionally, foreign direct investment (FDI) and FDI in transport infrastructure might vary with changing global and national economic conditions and international trade demands (UNCTAD, 2017a,b; Ojo and Alege, 2010), although such infrastructure investments make up only a small portion of total FDI (UNCTAD, 2016).

The varying significant impacts of economic fluctuations and relative economic uncertainty in the wake of the 2008 financial crisis (UNCTAD, 2016) argue for the inclusion of this driving force in the scenario analysis.

Political stability as a driver is not included in the scenario analysis, partly because its impact on development is represented by the economic environment driving force, and partly because Ghana, with its functioning multi-party political system, is considered an example of a politically stable developing country (Fosu, 2013). In applying the model to other developing country port cities, the modeller should be aware of the potential impact of political unrest on the system and modelled interventions.

SCENARIO'S

Different plausible future scenarios are created by combining different potential directions of change for the drivers *Technological advancement, Climate change and Economic environment*.

Rather than designing a full-factorial set of scenarios, a more limited set of scenarios is designed. This choice is based on the notion that the drivers *technological advancement* and *economic environment* are correlated.

A stable and high growth macro-economic environment is more conducive to industry technology development than others (Lall et al., 1994). Additionally, as technological capabilities in developing countries lag behind world level, FDI and the import of capital goods into the country by multinational companies has a more prominent impact on technological advancement than domestic investments (Borensztein, De Gregorio, and Lee, 1998; Juma and Clark, 2002). That means that local technological advancement depends partly on the openness of

national policy towards imports, FDI, and the level of protectionism towards domestic industry. Such national policy cannot be directly determined from the port-city perspective.

It would however not be correct to state that the economic environment is a driver of technological advancement. In addition to aforementioned factors, economic environment alone is not a sufficient determinant of technological advancement. For instance, the state of international or 'frontier' rate of technological development, and domestic and international pressure on firms to compete and innovate, effects of globalization and the supply of human capital (skilled labor) are other influential factors (Lall et al., 1994; Archibugi and Pietrobelli, 2003). Thus, technological advancement is defined as a separate driver.

A set of five scenario's is created, each with varying impacts of technological advancement, economic environment and climate change impact severity. Four scenario's assume that *technological advancement* and *economic environment* vary in a similar direction. A fifth scenario explores what would happen if this assumption is released: progressing automation despite economically stagnating environment, in combination with climate change impacts.
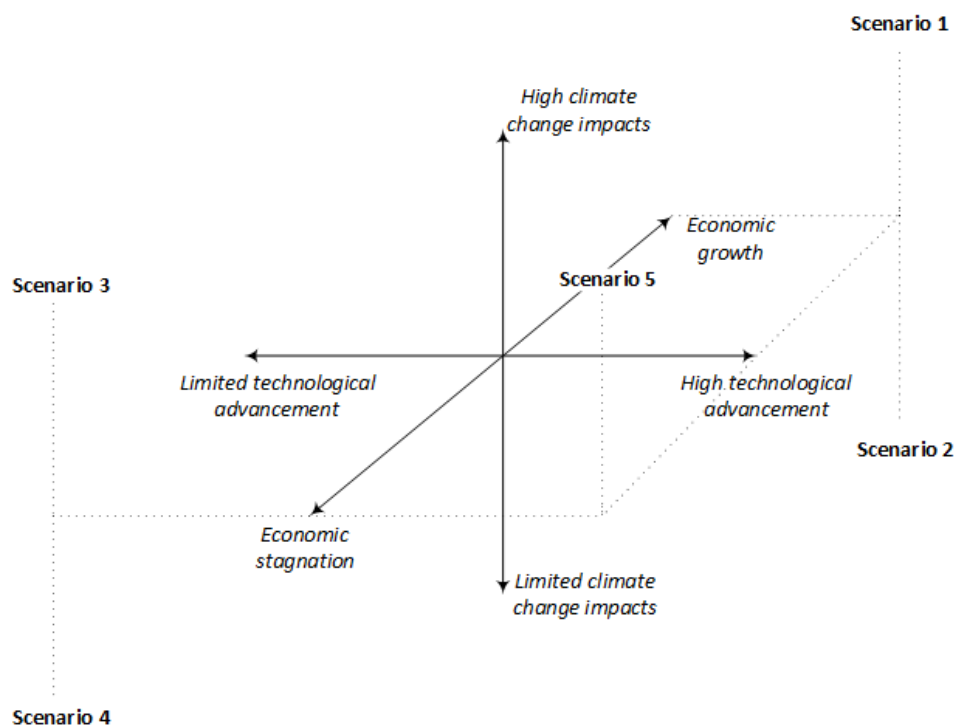

Figure 137. Scenarios mapped as a function of their driving forces

The scenarios are operationalized on the next pages in tables 31 through 35.

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Scenario 1: Technological advancement, high climate change impacts, economic growth

Table 31. Scenario 1, operationalized: Technological advancement, high climate change impacts, economic growth.

Technological advancement	
Port automatization	0.02 per year increase (ramp) from base level (2017-2047)
Industrial automatization	0.02 per year increase (ramp) from base level (2017-2047)
Climate change	
Rural-urban migration	Attractiveness for migration (underemployed) factor growing (ramp) to double between (2017-2037)
Flooding	Temporary increase (pulse train) of *min green space* by 200 ha every 5 years from 2017
Economic environment	
Population car ownership	+ 2% points (step from standard value, starting 2017)
Economic growth	+ 2% points (step from standard value, starting 2017)
New Enterprise Construction normal	+ 2% points (step from standard value, starting 2017)
Competition of other nearby ports	-
Mobility of capital (FDI)	Transport investment factor +1 (step from 2017)

Automation in industry advances quickly. Climate change is affecting rural Ghana, lowering agricultural yields and displacing rural Ghanaians, and climate refugees seek out the city in hopes of a better life. Despite this, economic environment is favourable.

Scenario 2: Technological advancement, limited climate change impacts, economic growth

Table 32. Scenario 2, operationalized: Technological advancement, limited climate change impacts, economic growth.

Technological advancement	
Port automatization	0.02 per year increase (ramp) from base level (2017-2047)
Industrial automatization	0.02 per year increase (ramp) from base level (2017-2047)
Climate change	
Rural-urban migration	-
Flooding	-
Economic environment	
Population car ownership	+ 2% points (step from standard value, starting 2017)
Economic growth	+ 2% points (step from standard value, starting 2017)
New enterprise construction normal	+ 2% points (step from standard value, starting 2017)
Competition of other nearby ports	-
Mobility of capital (FDI)	Transport investment factor +1 (step from 2017)

Automation in Ghanaian industry advances quickly. Luckily, climate change is not affecting rural Ghana in a significant way. In addition to this, the economic environment is favourable.

Scenario 3: Limited technological advancement, high climate change impacts, economic stagnation

Technological advancement	
Port automation	-
Industrial automation	-
Climate change	
Rural-urban migration	Attractiveness for migration (underemployed) factor growing (ramp) to double between (2017-2037)
Flooding	Temporary increase (pulse train) of *min green space* by 200 ha every 5 years from 2017
Economic environment	
Population car ownership	- 2% points (step from standard value, starting 2017)
Economic growth	- 2% points (step from standard value, starting 2017)
New enterprise construction normal	- 2% points (step from standard value, starting 2017)
Competition of other nearby ports	Port throughput growth -10% (ramp 2017-2027)
Mobility of capital (FDI)	Transport investment factor -1 (step from 2017)

Automation in industry and port remains limited. Climate change is affecting rural Ghana, lowering agricultural yields and displacing rural Ghanaians, and climate refugees seek out the city in hopes of a better life. In addition to this, economic growth has stagnated, and stagnation economic environment and competition by nearby ports has decreased port throughput in the port of Tema.

Scenario 4: Limited technological advancement, limited climate change impacts, economic stagnation

Technological advancement	
Port automation	-
Industrial automation	-
Climate change	
Rural-urban migration	-
Flooding?	-
Economic environment	
Population car ownership	- 2% points (step from standard value, starting 2017)
Economic growth	- 2% points (step from standard value, starting 2017)
New enterprise construction normal	- 2% points (step from standard value, starting 2017)
Competition of other nearby ports	Port throughput growth -10% (step from 2017)
Mobility of capital (FDI)	Transport investment factor -1 (step from 2017)

The economic environment is stagnating, leading to diminished increases of per capita car ownership, lower economic growth. Competition from other ports further reduces throughput of the port. FDI into road infrastructure is reduced, stifling road construction. In conjunction with the economic stagnation, technological advancement in industry remains limited. Fortunately, climate change impacts on Ghana remain limited, and do not drive large scale migration or local flooding.

Scenario 5: Technological advancement, climate change impacts, economic stagnation

Table 35. Technological advancement, climate change impacts, economic stagnation.

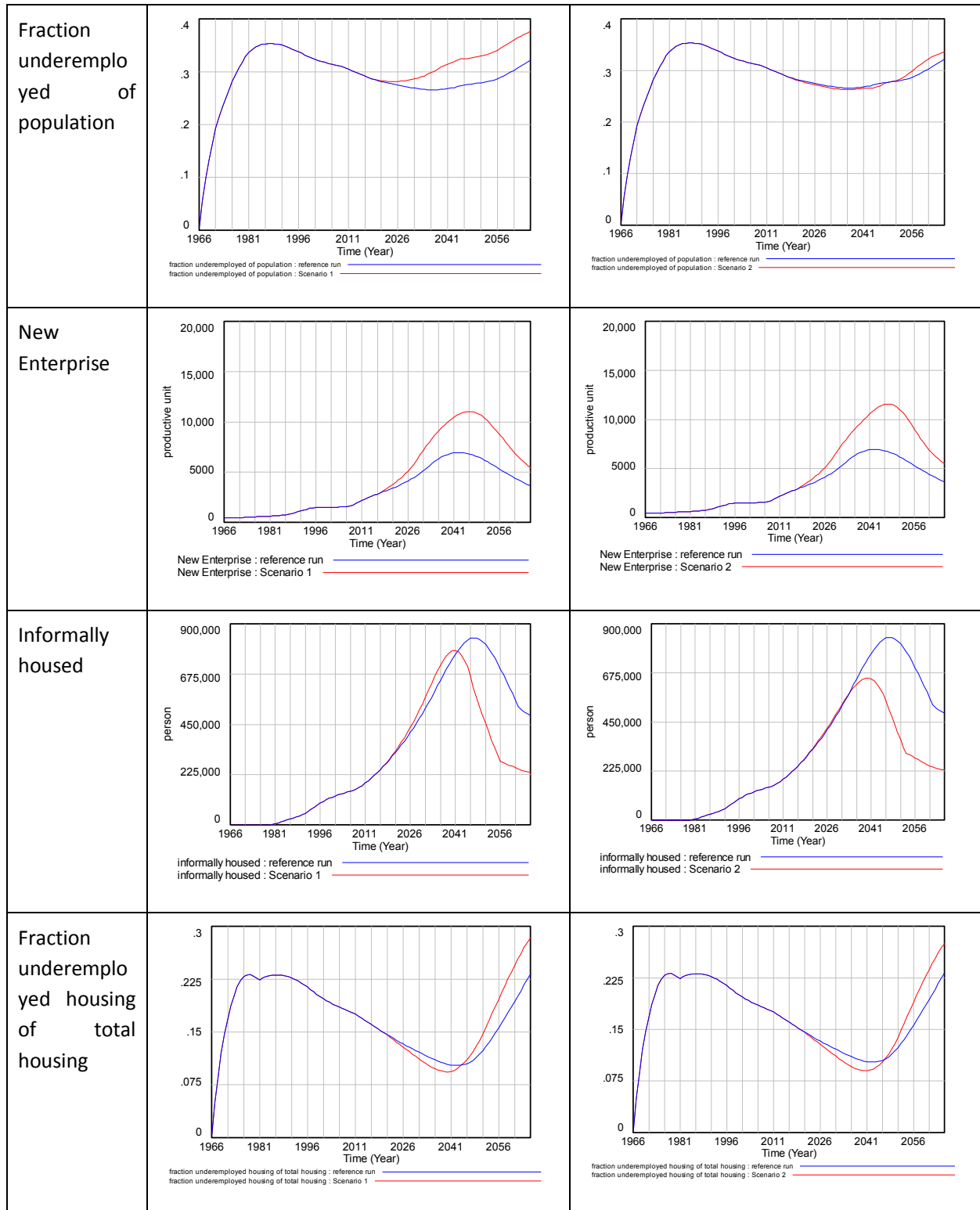| Technological advancement	
Port automation	0.02 per year increase (ramp) from base level (2017-2047)
Industrial automation	0.02 per year increase (ramp) from base level (2017-2047)
Climate change	
Rural-urban migration	Attractiveness for migration (underemployed) factor growing (ramp) to double between (2017-2037)
Flooding	Temporary increase (pulse train) of *min green space* by 200 ha every 5 years from 2017
Economic environment	
Population car ownership	- 2% points (step from standard value, starting 2017)
Economic growth	- 2% points (step from standard value, starting 2017)
New enterprise construction normal	- 2% points (step from standard value, starting 2017)
Competition of other nearby ports	Port throughput growth -10% (ramp 2017-2027)
Mobility of capital (FDI)	Transport investment factor -1 (step from 2017)

The economic environment is stagnating, leading to diminished increases of per capita car ownership, lower economic growth. Competition from other ports further reduces throughput of the port. FDI into road infrastructure is reduced, stifling road construction. Despite the economic stagnation, technological advancement in industry and the port increases. At the same time, climate change impacts on rural areas cause a rise in rural-urban migration, and regular instances of local flooding.

SCENARIO IMPACTS

The effects of the scenarios on the model are explored by comparing with standard model behavior. The results for selected KPI's are displayed below in tables 36 through 38.

Table 36. Model behavior under scenarios 1 and 2, compared with reference run.

KPI	Scenario 1	Scenario 2
Driving forces	Technological advancement, climate change impacts, favorable economic environment	Technological advancement, no climate change impacts, favorable economic environment
Port throughput		
Land fraction occupied		
Population		

Fraction underemployed of population		
New Enterprise		
Informally housed		
Fraction underemployed housing of total housing		

Road congestion		
Road length		
Green space		

Table 37. Model behavior under scenarios 3 and 4, compared with reference run.

KPI	Scenario 3	Scenario 4
Driving forces	Limited technological advancement, climate change impacts, economic stagnation	Limited technological advancement, limited climate change impacts, economic stagnation
Port throughput		
Land fraction occupied		
Population		
Fraction underemployed of population		

New Enterprise	 New Enterprise : reference run New Enterprise : Scenario 3	 New Enterprise : reference run New Enterprise : Scenario 4
Informally housed	 informally housed : reference run informally housed : Scenario 3	 informally housed : reference run informally housed : Scenario 4
Fraction underemployed housing of total housing	 fraction underemployed housing of total housing : reference run fraction underemployed housing of total housing : Scenario 3	 fraction underemployed housing of total housing : reference run fraction underemployed housing of total housing : Scenario 4
Road congestion	 road congestion : reference run road congestion : Scenario 3	 road congestion : reference run road congestion : Scenario 4

Road length		
Green space		

KPI	Scenario 5	
Driving forces	Technological advancement, climate change impacts, economic stagnation	
Port throughput	Port throughput : reference run Port throughput : Scenario 5	
Land fraction occupied	land fraction occupied : reference run land fraction occupied : Scenario 5	
Population	population : reference run population : Scenario 5	

Fraction underemployed of population	 fraction underemployed of population : reference run fraction underemployed of population : Scenario 5	
New Enterprise	 New Enterprise : reference run New Enterprise : Scenario 5	
Informally housed	 informally housed : reference run informally housed : Scenario 5	
Fraction underemployed housing of total housing	 fraction underemployed housing of total housing : reference run fraction underemployed housing of total housing : Scenario 5	

Road congestion	road congestion : reference run road congestion : Scenario 5	
Road length	road length : reference run road length : Scenario 5	
Green space	Green space : reference run Green space : Scenario 5	

Table 39. Scenarios mean impact scores on model KPIs (2017-2057, discount factor 0%).

	Weight	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
land.fraction.occupied	1	11.6%	10.4%	-8.5%	-10.0%	-6.6%
population	1	0.2%	-3.2%	-4.8%	-8.4%	-14.0%
New.Enterprise	1	42.8%	45.4%	0.5%	1.8%	42.4%
production.units.total	1	34.9%	35.8%	-11.3%	-11.1%	9.3%
Green.space	1	-15.0%	-21.7%	35.5%	30.2%	28.5%
fraction.underemployed.of. population	-1	-11.0%	0.3%	-12.4%	-1.1%	-10.4%
fraction.informal.of.total. population	-1	-4.3%	-3.0%	-1.5%	-0.6%	-5.3%
informally.housed	-1	9.8%	18.5%	7.4%	17.7%	36.0%
road.length	-1	-16.6%	-14.9%	18.6%	20.2%	17.8%
road.congestion	-1	13.8%	12.8%	-24.6%	-23.8%	-28.5%
Total score	-	**66.2%**	**80.6%**	**-1.0%**	**14.8%**	**69.1%**

INTERPRETATION

The scenario analysis is as much an investigation of plausible futures as it is a way of assessing the validity of model inferences. Partly, "model utility depends not on whether its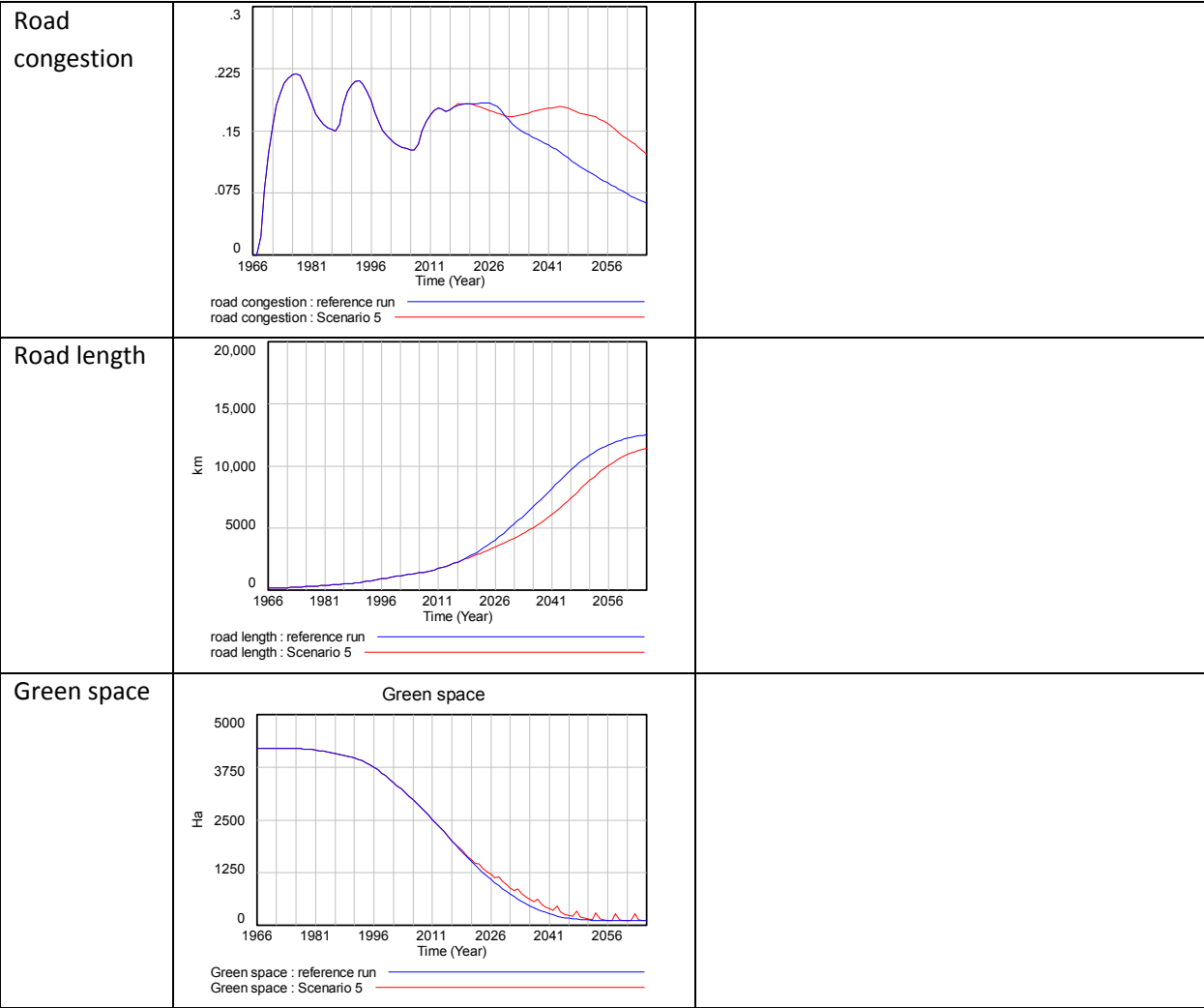 driving scenarios are realistic, but on whether it responds with a realistic pattern of behavior" (Meadows & Wright, 2008 pp.64). The question then is whether the model responses to the presented scenarios are realistic and consistent with expected patterns of behavior.

Climate change directly affects port-city socio-economic make-up and average living standards. Large influx of rural immigrants looking for employment leads to a higher fraction of underemployed class in the total population, slum formation and increased informal settlement. Increased local flooding further affects living quality of residents, but its impact on the port-city system as a whole seems negligible.

An economically beneficial environment leads to increased industrial growth in the city, leading to population growth despite the rise of industrial and port automation. Technological advancement in the form of progressing industry and port automation affect mainly labor and underemployed class: in reaction to the reduced labor needs and increased productivity, industry is seen to grow, causing a shift of port-city population composition to managerial-professional at the cost of the labor class. While this seems to improve average socio-economic status in the city, the urban population polarizes, resulting in increased inequality. While economic growth benefits the port-city system socio-economically despite climate change impacts, green space suffers when land pressure rises from urban developments.

Interestingly, an environment of economic stagnation still leads to an increase of local industry on the long term, despite reduced road infrastructure construction. The main cause of this seems to be the reduced port throughput resulting from competition and national economic stagnation. This means reduced port congestion, and a relative advantage to local businesses using the less congested port. Another factor is the reduced road length following lower port throughput, which leaves more land for the city to grow and expand. This is a prime example of the local-global mismatch of port development, where the port operations and resulting freight flows stifle the city development and keep it from flourishing, despite the stimulus to the local industry. This effect would become even more pronounced when port land use would rise as a result of increased container shipping and handling. Further research could expand the model to include port land use and the impacts of the shift to container transport.

A study limitation regarding industry automation is that it is implicitly assumes that human capital is present or can be created (i.e. through in-migration of professionals or training of labor) (Lall et al., 1994). This is not necessarily unrealistic, as the manufacturing industry in Ghana has a relatively high prevalence of in-house training of labor and a relatively well developed educational system. However, lack of human capital production has been a limiting factor for industry technological development in the past (Lall & Pietrobello, 2003). That would imply that technological advancement and automation of industry in Ghana is partly endogenously determined in the real world as well as in the model. Future research could investigate the strength of such a relation.

The limited impact of local flooding on the system could mean two things: either it is really not that important for urban development as a whole, or it is merely an indication of the limitations of the model, meaning that the chosen modelling methodology or level of modelling are not sensitive (and therefore not useful) to this problem. That means no strong inferences can be made regarding flooding on a system level.

Questions asked included:

- *Do you agree with the way the model is conceptualized (assumptions, specification)? What would you change, and how? Would you like to add something that you think is missing from the model or sub-models?*
- *Can the model be useful as a basis for strategic discussion between port-city stakeholders?*

Interview Floortje d'Hont 18-7-2017

-Traffic flow theorie relateert capaciteit van de weg en doorstroom aan congestie. Dat kan je die waarde voor saturation capacity geven, en de vorm van je lookup. Er zijn system dynamics studies gedaan naar transport die dat gebruiken (referenties worden doorgestuurd).

-Congestion effect op population – acceptabele reistijd heeft ook een omslagpunt, e.g. mensen willen niet meer dan twee uur reistijd naar hun werk. Maar dat kan in Afrika anders zijn.

-Kan ook leiden tot tijdelijke sloppenwijken, waar arbeiders voor constructieprojecten tijdelijk dichtbij een sloppenwijk beginnen, dit gebeurt in China wel.

-Underemployed: zit verborgen werkloosheid ook in het model? E.g. vrouwen die maar niet solliciteren omdat er geen werk is, maar anders wel zouden zijn gaan werken. (e.g. discussie mogelijk over wat de categorie inhoudt)

-Port conceptualization: Port throughput is ook afhankelijk van internationale economie, niet alleen nationale. Toevoegen in het model misschien als ruis.

-Havenautomatisering kan ook bijdragen aan capacity (verhoogde efficiëntie, meer kade beschikbaar). Is veel onderzoek over gedaan, Verbraeck is er mee bezig.

-Automatisering – meer hoogopgeleiden nodig? Effecten vallen mee, er is niet minder werk maar het soort werk verandert (onderhoud robots etc.).

-Transport infrastructure investment is een policy in het model: dan ook linkje ertussen in conceptualisatie

-Land use: housing area lijkt erg groot, en informal housing area dan weer weinig.

-Green space: wat wordt er precies bedoeld met green space? E.g. grasland? Definitie en verschil met *available land* niet meteen duidelijk.

-Production units total – betekenis niet meteen duidelijk

-Informal housing: interessant om de model run time te verlengen zodat je meer kan zeggen over hoe die late piek verder gaat (ook al heb je dan misschien absurd lange runtime).

Do you agree with the way the model is conceptualized (assumptions, specification)? What would you change, and how? Would you like to add something that you think is missing from the model or sub-models?

-Die traffic flow theory dan als onderbouwing van transport congestion.

Can the model be useful as a basis for strategic discussion between port-city stakeholders?

-Combinatie met group model building om *negotiated knowledge* (de Bruijn) te bouwen, mensen betrokken te maken. Het werkt niet om mensen een model in hun gezicht te duwen.

-Acceptatie model: begrijpen, geloven, er mee eens zijn --> Op te lossen door verschillende sub-modellen en relaties tussen sub-modellen goed aan te geven (conceptualisatie). Optie: alternatieve assumpties die mensen hebben en de effecten ervan dan direct verwerken in het model. De meest vette group model building sessies is als iemand meteen mee modelleert.

Via negotiated knowledge naar acceptatie van het model. Dat kan een uitdaging zijn, vergelijking Amerika met verschillen in opvatting tussen republikeinen en democraten. Maar dat kan in Ghana of andere landen in Afrika anders zijn.

Expert consultation, research integration meeting Sustainable Ports in Africa, September 1st, 2017.

Present: J.H. Slinger, W. de Boer, Kangeri, A., Vreugdenhil, H.

A presentation was held at the Sustainable Ports in Africa research integration meeting where experts on ecology and port governance were present. Model results and conceptualization were presented, after which the experts were asked to comment on the model and its output. Questions asked:

-What do you think of the model and results?

-How can the model be used in strategic discussion with port-city stakeholders?

It was explained in reaction to a question that the Tema Acquisition Area was chosen as a model boundary, as the wider area that is considered part of the Tema Metropolitan Area is not part of the city socially and economically. Guidelines are however needed on how to choose model boundaries in potential future model use.

A shortcoming of the model is touched upon that proximity to Accra and other urban areas is not considered in the model. This means the impact of commuters on the model is not considered conceptually.

The perspective taken by the model is from a city planning perspective rather than a port planning perspective, as port operations and spatial impacts are not explicitly modelled. Port planners could however the model and its inferences to agendize issues for talking to city planners.

In the context of port-city planning, the model could be used as a boundary object in discussing the effects and influences of ports, and facilitate discussion between stakeholders.

The issue is raised that the aggregate and conceptual nature of the model might make it harder for local residents of the port city to identify with its structure and model outcomes, as they know a more nuanced picture of the development of their city and could resist the simplifications made in the model.

The idea is then raised to take the model and its assumptions out of the view of the stakeholders altogether by turning it into a serious game ("Port-City game"). Players would be presented with a simplified visualization of urban development, influenced by port expansions. Players could then apply interventions to the model and get direct feedback on the impact on port-city development.

The Tema case is used as a problem in a class on the system dynamics method, given in Delft.

Comments were made on the model boundary choice, or the land area that is assigned to Tema in the model, as this influences the size the city can grow to. A discussion followed on whether green space

This section contains the R-code used for model analysis. Software requirements: The code was used with R 3.4.1, and R-studio 1.0.153. Vensim model dataset exportation settings: *Export as*: .csv, *Save list*: preferably the KPI's used in the analysis, but others are possible, *Time running*: down. The script working directory needs to set to the folder containing the exported model output datafiles.

```r
#Set working directory and load necessary libraries
setwd("O:/Afstuderen/Models final/")
library(fmsb)
library(radarchart)
library(formattable)

#load runs
refrun <- read.table("reference run.csv", header=TRUE, sep=",", stringsAsFactors=FALSE)
policy <- read.table("Slum housing demolition program (200).csv", header=TRUE, sep=",",
stringsAsFactors=FALSE)
graphtitle<-"Low cost housing program (200) (unweighted)"

##Choose weighting!
Weights<-c(0,1,1,1,1,1,-1,-1,-1,-1,-1)

#create years of interest, choose discount factor
range = seq(2017,2057, by=1)
discountingfactor<-0.0

#Set up headings for results table and weights
Scores<-policy[0,]
# Add Weights to table
for (i in 1:ncol(Scores)){
  Scores[1,i]<-Weights[i]}
Weights<-Scores
Scores<-policy[0,]

#Create results
years = range    # this can be changed to something else
pol<-c()
ref<-c()
scor<-0
rowcounter<-1

#Create results: for every year and every KPI value, calculate the relative change
between reference and intervention, and apply discount rate.
for (j in 1:ncol(Scores)){
  rowcounter<-1
  for (i in (years-1965)){
    pol[rowcounter]<-policy[i,j]
    ref[rowcounter]<-refrun[i,j]
    scor[rowcounter]<- (pol[rowcounter]-ref[rowcounter])/ref[rowcounter]
    scor<-scor[rowcounter]*(1-discountingfactor)^(i-52)
    Scores[rowcounter,j]<-scor
    rowcounter<-rowcounter+1}}

#add model time (years) to scores-table
count<-1
for(i in years){
  Scores[count,1]<-i
  count<-count+1}
```

```r
#Weighing radarchart effects: Weigh the deviation scores, add 1 for normalization
Normscores<-Scores
for (i in 1:ncol(Normscores)){
  print(i)
  Normscores[,i]<-Scores[,i]*abs(Weights[,i])+1} # abs to keep direction of impact
Normscores[,1]<-Scores[,1]

Meanscores<-Weights
for(i in 2:ncol(Scores)){
  Meanscores[,i]<- mean(Scores[,i])}
Meanscores<-Meanscores[-1]

#Sum weights to divide by later
Weights
Weightsum<-sum((abs(Weights[-1])))

#Weigh mean scores, add them up
Meanscores<-Meanscores*(Weights[-1])
Meanscores
Totalscore<-sum(Meanscores)
Totalscore<-round(Totalscore, 3)
Totalscore

##RadarChart: define years to plot##
years2 = c(2017, 2027, 2047)
Normscores2<-Normscores[ Normscores$Time %in% years2, ]
d<-data.frame(Normscores2)
d.T <- t(d[,2:ncol(d)])
colnames(d.T) <- d[,1]
labs<-rownames(d.T)
##plot radarchart
e.T<-cbind(as.character(labs), as.data.frame(d.T))
chartJSRadar(scores = e.T,labelSize=12, width=610, height=500, scaleStepWidth=0.5,
maxScale=1.5, main = graphtitle, polyAlpha = 0.1, scaleLineWidth=5)
##end##

##MCA table##
Resultstable<-t(Meanscores)
colnames(Resultstable)<-"Score"

Weights.T<-t(Weights[-1])
colnames(Weights.T)<-"Weight"
Resultstable<-cbind(Weights.T, Resultstable)
Totalscore<-cbind(1,Totalscore)
Resultstable<-rbind(Resultstable, Totalscore)

Resultstable<-data.frame(Resultstable)
Resultstable[,2]<-percent(Resultstable[,2],digit=1)

##Plot table##
formattable(Resultstable, list(
  Score = formatter(
    "span",
    style = x ~ style(color = ifelse(x < 0 , "red", "green")),
    x ~ icontext(ifelse(x < 0, "arrow-down", "arrow-up"), x))
  ))
#Restate discounting factor to check
Discountingfactor
```

A System Dynamics Exploration of Port-City Development

The Case of Tema, Ghana

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Abstract

Large-scale infrastructure projects such as ports can have a significant impact on the development of nearby cities. While economic benefits of the port spill over to other regions, often internationally operating firms, port-cities experience negative externalities like environmental and land use issues and traffic congestion. Traditional port impact studies are expensive, and offer a static picture that doesn't take into account the complex adaptive nature of the port-city system. There is a need for a comprehensive dynamic model of port-city development, incorporating beneficial and negative externalities of port infrastructure development on the city and peri-urban green space. A system dynamics modelling study is performed using the case study of Tema and its port on the Gulf of Guinea in Ghana, to evaluate interventions for sustainable port-city development in an African context.. A model is conceptualized and specified, based on Forrester's Urban Dynamics model, fit to cope with relative scarcity of available data. It incorporates and explicitly models road transport congestion, informal settlement and green space encroachment, as well as port infrastructure. Model testing and use show that the model is fit for the purpose of exploring the long term impacts of port infrastructure investments on the port-city system. Interventions aiming at sustainable development are simulated and evaluated for their performance. Recommendations regarding interventions and the potential future use of the model with stakeholders are made.

1   Introduction

Urbanization is a worldwide trend. More than half of the Earth's population already lives in urban areas, and this number is expected to rise even further in the coming decades. Rapid growth of cities and urbanization is observed and expected to continue, most prominently in Africa and Asia (United Nations, 2014). However, cities worldwide face many challenges. Congestion, housing shortages and declining infrastructure are only some of the many problems facing cities (United Nations, 2016). That is why the sustainable development of cities is one of the UN's sustainable development goals, alongside goals like climate change action and ecological preservation.

As cities expand they put more pressure on their environment, both in the form of emissions and changes in land use and encroachment. In developing countries this socio-ecological aspect of city development can be readily observed. Here urbanization generally occurs more rapidly and uncoordinated, and more haphazard development occurs

in regions of ecological importance when compared to countries that are already more developed (Cohen, 2006).

Large-scale infrastructure projects such as ports can have a significant impact on the development of nearby cities. While providing jobs and stimulating the local economy, the understanding of how such projects affect city composition and quality of life on the medium to long term is lacking, as are insights regarding effective policies to improve port-city performance (Merk and Dang, 2013).

Port infrastructure investments are often cited as being beneficial to local and regional economic development (Musso, Benacchio, Ferrari and Haralambides, 2000). However, cities hosting ports experience both beneficial and detrimental impacts from their presence. Generally speaking, the positive impacts are economic in nature, while the negative impacts take the form of externalities like environmental issues, land use and traffic congestion (Brunila, Kunnaala-Hyrkki, and Hämäläinen, 2015; Merk, 2013). Port cities experience what is deemed a local-global or port-city mismatch (Rodrigue, Comtois and Slack, 2017; Merk, 2013): benefits of the port spill over to other regions, often internationally operating firms, while the negative externalities are experienced locally in the port-city.

These negative externalities become more important as containerization and increasing contestability of port hinterlands increases competition between ports and increases the pressure for efficiency, port investments and the involvement of private parties (Musso, Benacchio, Ferrari, and Haralambides, 2000).

As the interests of ports and their cities are diverging (Merk and Dang, 2013), city budgets are constrained and negative externalities of port presence are experienced, cities and public institutions (as major shareholders in ports) put pressure on ports to engage in practices of economic development in the city (Pigna, 2014). Since the 1990's environmental and spatial impacts of port development have received increasing weight in the societal debate on port operations and development (Dooms, 2014). Social conflicts related to port development, involving port authorities, community groups, local business community, national and local government, are becoming increasingly relevant (Musso, Benacchio, Ferrari, and Haralambides, 2000). As such, port planning can no longer be based exclusively on the opinions of engineers, infrastructure specialists, transport economists or lawyers. Port planning needs to take into account the relationship between the port and the city, the

economic and environmental impacts, and the stakeholders (Moglia and Sanguineri, 2003).

As port communities provide ports with their social license to operate, port managing bodies have been pushed to adapt their strategies towards local community stakeholders, involving local stakeholders in the port planning process, strengthening communication links with local communities and incorporating sustainability indicators in their reporting on port performance (Ircha, 2012; Adams, Quinonez, Pallis, and Wakeman, 2009; Dooms, 2014).

Traditional port impact studies are still of use in such an integrated port planning process, but they have two important drawbacks: firstly, they present only a static picture of expected port impacts, ignoring the effects of port development over time, changes in port operations (e.g. automation) and uncertainties influencing the port-city system. Secondly, while they can serve as an important tool to the community in understanding the structure of a port as well as its immediate economic effects, they tend to overestimate benefits while underestimating negative impacts (Musso, Benacchio, Ferrari, and Haralambides, 2000).

An ex-ante evaluation method is needed that takes into account the trade-offs that exist regarding sustainable port-city development, including metrics for both port performance and socio-economic impacts (Fusco Girard, 2010; Xiao and Lam, 2017; Musso, Benacchio, Ferrari, and Haralambides, 2000). However, rather than as static, separate entities, ports and their cities should be considered as single complex adaptive systems, characterized by mutual positive and negative interdependencies and with non-linear processes (Fusco Girard, 2010). However, empirical studies of ports systems and urban systems often study these systems separately. The current literature regarding the integrated sustainable development of port cities is rather limited (Merk, 2013; Xiao and Lam, 2017). This study aims to contribute to deepening understanding of sustainable port-city development.

The system dynamics modelling approach is applied to model the impacts of port infrastructure investments on the development of the Ghanaian port city of Tema. Necessary assumptions regarding urban and port development in a developing country context are explicated so that the beneficial and detrimental aspects of port expansion are modelled. The resulting model is envisaged to support stakeholder-inclusive port design in the future (cf. Slinger et

al., 2017), and to enable the generation and evaluation of interventions for sustainable port-city development.

The research forms a component of the Integrated and Sustainable (Green) Ports in Africa study carried out in response to a research call from the research and innovation programme 'Urbanising Deltas of the World' (Slinger et al., 2017;). It addresses a gap within that project by investigating and modelling the socio-economic impact of port infrastructure developments in on their cities in developing countries.

1.1 Research Objective

The research aims to use system dynamics modelling to represent the development of the city of Tema and its port, and evaluate interventions for sustainable port-city development in African context.

The modelling output include both potential development dynamics of the city with and without the impacts of port infrastructure expansions, and the exploration of robust interventions for sustainable port-city development, mitigating port negative externalities.

1.2 Outline of the paper

The paper is structured as follows: first a brief overview of model conceptualization process is provided. Then model verification and validation are discussed. Chapter 3 provides an overview of modelling results, including the modeling of port expansion impacts on the port-city system. Lastly, the conclusion addresses the research objective, and avenues for further research are presented.

2 Model Development

The system dynamics modelling approach is used for the modelling of the port-city system. Reasons for this include its ability to include a wide breadth of potential feedback loops and effects in the model, its limited computational requirements facilitating experimentation and testing, and its strengths in explaining observed model behavior due to its explicit causal structure.

Rather than developing an urban model from scratch, Forrester's Urban Dynamics model (1970) is selected as a base for the modelling effort given its ability to model urban development in response to processes endogenous to the urban system and its modest data needs. The latter factor is particularly advantageous when modelling in a developing country context, where data availability may be poor.

Other reasons include arguments that the model is appropriate for representing a developing country city (Saeed, 1994), its ability to facilitate the impacts of different assumptions and interventions on model behavior, and its potential ability to function as a sounding board to strategic conversations on sustainable port expansion with stakeholders (Lee Jr., 1973; Alfeld, 1995; Cunningham, Hermans, and Slinger, 2014).

Conceptualizing the model presents a threefold challenge:
1) Adding model structures for port infrastructure, road transport infrastructure, and green space encroachment,
2) Adapting model structure to represent the urban development of a developing country city (i.e. informal settlement, economy),
3) Adapting existing model parameters to local (Tema) conditions (e.g. housing densities, birth rates).

The modelling effort is grounded in scientific literature on the relevant topics, and on knowledge obtained in a participatory stakeholder engagement setting to extract local priorities and values regarding sustainable port-city development (Slinger et al., 2017).

Figure 1 depicts a boundary diagram of the model, showing how various concepts are represented in the model.
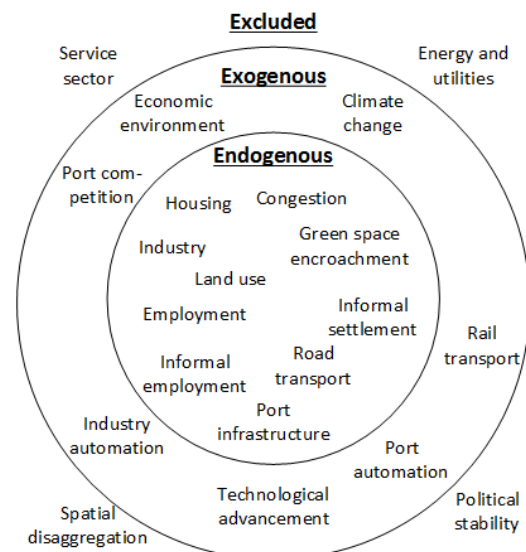
Forrester's modelling of the housing market is particularly suitable for Tema, where large worker housing
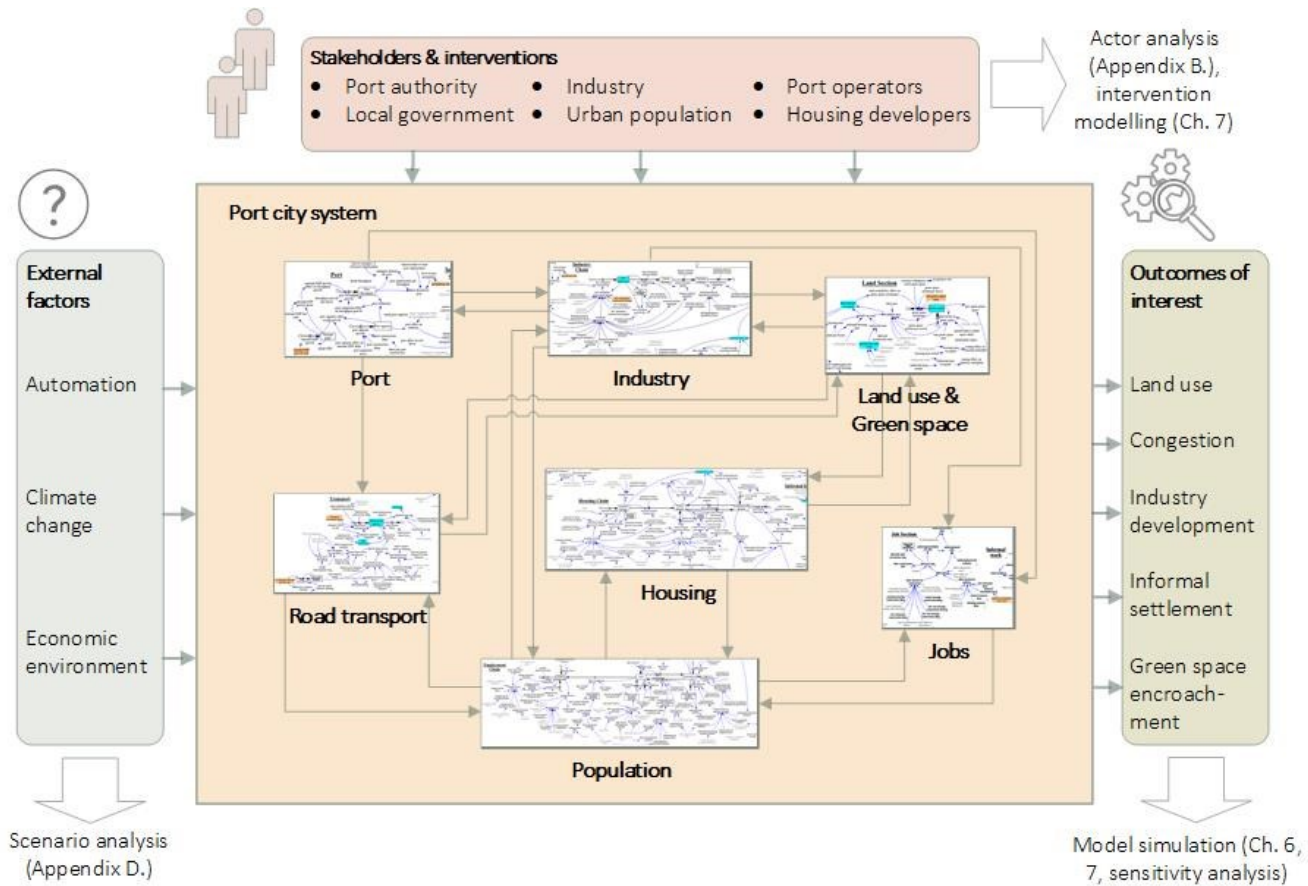

Figure 2. System diagram of the research problem, showing model elements, external factors, relevant stakeholders and a selection of model outcomes of interest

estates were built that have since degraded to slum status (UNCHS (HABITAT), 2003). Tema is an appropriate case study with its industrial character and substantial port prominence (Apeaning and Thollander, 2013; Ducruet and Lee, 2006). Green space is modeled to represent Sakumo and Chemu lagoons, (former) wetland estuaries, the first of

capacity, infrastructure supply/demand perspective (Brebbia, 2007; Shuo, 1999; European Conference of Ministers of Transport, 2007), demarcating the problem to focus on urban road transport only. Urban road demand is generated by port freight, population and industry in the urban system, and modeled based on growth factors as to limit data needs and model complexity.

Port infrastructure capacity and throughput are modeled on an aggregate scale and affect the city through road

which is a RAMSAR site of ecological importance (Kangeri, fortcoming; Appiah and Yankson, 2012). Both experience the threat of pollution and urban encroachment.

To make the model robust to potential data availability issues, transport congestion is modeled from a macro demand, and direct and indirect employment from construction and operation and an industry multiplier effect.

Informal settlement in the model results from a shortage of formal housing construction, and houses both laborers and underemployed, reflecting local settling behavior (Owusu, 1991).

Several influential exogenous factors have been identified and included in a scenario analysis (Figure 2). Port and industry automation reflect the impacts of

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containerization on port direct employment and potential impacts of technological advancements in industry on labor (Rodrigue, Comtois, and Slack, 2017; World Bank, 2016). The economic factors included are economic impacts on shipping volumes, infrastructure investments

and population car ownership rates. Climate change impacts on the city comprise local flooding risk and increased rural-urban migration (World Bank, 2017; Gomez et al., 2008; Faist and Schade, 2013). The model is not spatially disaggregated.

The model has been specified in the simulation package Vensim, based on Forrester (1970) and estimations of causal relations drawn from literature. The final model contains 27 stocks and some 220 variables in total. Model verification tests have been performed based on the guidelines laid out by Sterman (2000), and model validation was done by performing a full sensitivity analysis, comparing model output with available historical data, and expert consultation.

The model verification and validation process showed that the model, despite some conceptual limitations owing to the lack of spatial disaggregation, adequately models the development of the city of Tema and the impacts resulting from port infrastructure expansion.

3 Modelling results

3.1 Basic run

The basic run describes urban development filling the available land (Figure 3).
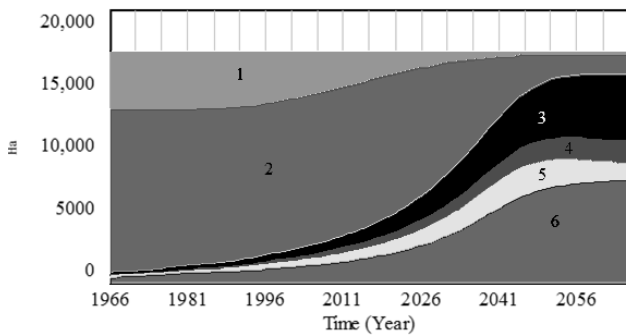

Figure 3. Cumulative land use. (1) Green space, (2) available land, (3) road infrastructure, (4) industry, (5) informal settlement, (6) formal housing

As urban area land pressures mount, green space is encroached upon (Figure 4). To compensate for the lack of spatial disaggregation, a proximity effect is included to represent green space proximity to urban centers influences on settlement.

3.2 Port expansion impacts on informal settlement, congestion and green space encroachment

Following the proposed 2015 port expansion, port throughput may triple from 2015 values, if it rises to the new port capacity. This will significantly add to the demand for urban road infrastructure: congestion levels are seen to rise dramatically, up to 45%, if no measures are taken to divert cargo transportation away from the urban road system (Figure 4).
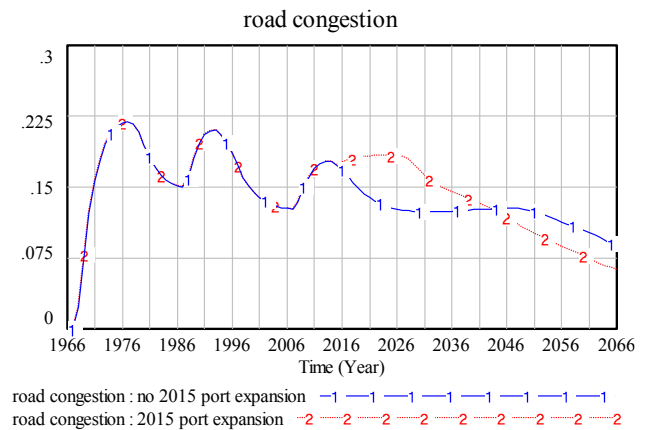

Figure 4. Simulated road congestion levels over time without (1) and with (2) 2015 port expansion

However, this increase results both from port direct impacts, and from indirect effects of increased industry and population growth. The progressive throughput growth means that the simulated congestion increase lasts nearly a quarter of the model run time horizon of 100 years, despite increased investments in road infrastructure. The lack of spatial detail in the model however precludes the modelling of localized bottlenecks, which likely results in an

underestimation of actual congestion levels.

Green space

Figure 5. Accelerated green space encroachment after 2015 port expansion (2)

While green space encroachment is sped up with port infrastructure investments, eventually all peri-urban green space is encroached upon in both scenarios (Figure 5).

3.3   Port city developmental patterns

Simulation shows that progressive port and industry automation can have significant impact on the city socio-economic climate. While mostly affecting labor-class residents, the urban population polarizes and inequality is increased.

Impacts of different modes of port expansion and retreat on the port-city system are explored.

Port capacity

Figure 6. Port capacity for modular port expansion (1) vs. actual 2015 port expansion scheme (2) over time

Modular port expansion (Figure 6) has both beneficial and detrimental effects on the port-city compared to a single

larger expansion. The stimulating effect on local industry is more spread out over time, leading to a longer lasting impulse for the local economy. However, congestion is increased dramatically even though the total expansion amount is ultimately the same for both situations. Green space is also adversely affected on the longer term, indicating increased land pressure arising from paced port development. In scenarios of economic growth this can lead to serious congestion in the long term (Figure 7).

road congestion

Figure 7. Congestion resulting from modular port expansion (1) vs. 2015 port expansion (2)

As the city profits from a dosed increase of port negative externalities, it can more readily develop (Figure 8). Subsequent port capacity expansions are then met with serious land scarcity constraints, as the city has claimed port-city land area. Conversely, in a single, larger port expansion scenario, the port claims the space first, and congestion is reduced partly by a stifling of the city population and industrial development.
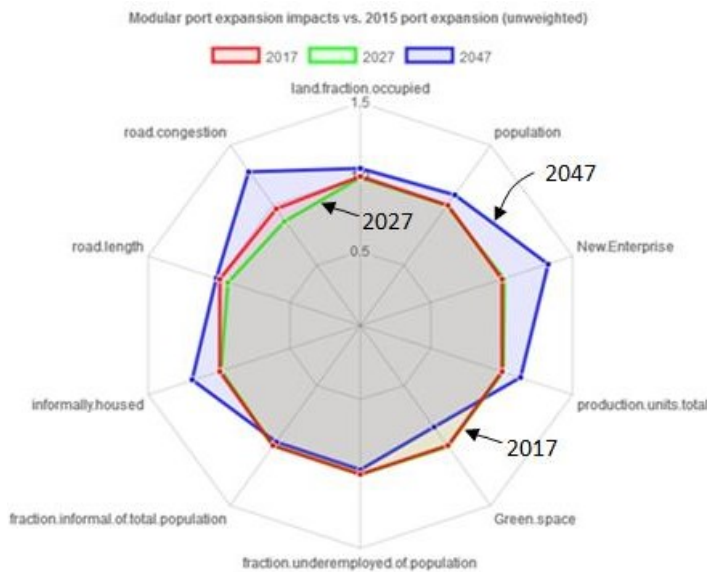
Figure 8. Radarchart of relative changes per model outcome of interest between 2015 port expansion and modular port expansion for 2017, 2027, 2047

From the perspective of a port it is better to expand dramatically and stifle urban development, claim infrastructure and port space before land is taken for other (urban) developmental needs and developments. From the perspective of the port-city, a less rapid port development is preferred.
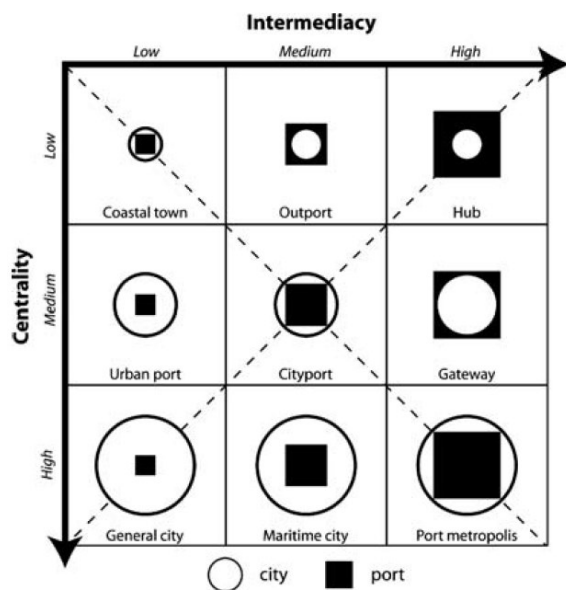

Figure 9. Matrix of port city relations (Ducruet and Lee, 2006)

This relates back to the theory of port city evolution by Ducruet and Lee (2006), which sought to describe port city evolution patterns over time, based on port and city characteristics (Figure 9).

By expanding the port so dramatically at one time (2015), Port of Tema might have set out the path of development for the port-city of Tema. If port throughput indeed rises to port capacity, urban development may increasingly suffer from the negative externalities and developmental constraints. In that case the city might be 'doomed' to exist as a gateway for Accra and the port hinterland (Figure 10), at the cost of its own socio-economic development. The port would 'use' the city for its labor and road infrastructure. This parasitic effect would be even greater if port operations are automated, reducing port employment of local workers. This may further threaten the port's social license to operate (Ircha, 2012; Adams et al., 2009; Dooms, 2014).
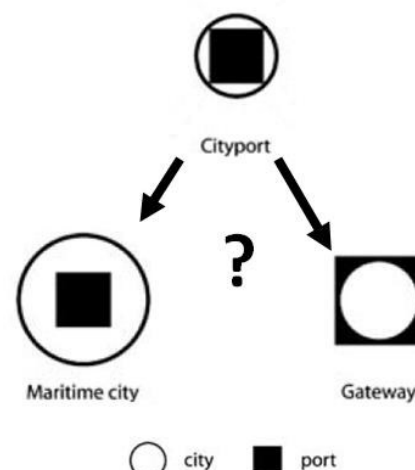
Figure 10. Port city evolution: a question of dominance (Adapted from Ducruet and Lee, 2006)

Interventions that reduce port negative externalities might mean the difference between that scenario, and the existence as a more balanced city.

3.4   Exploring and evaluating strategies for sustainable urban development

The model and its structure have been used to systematically generate potential interventions on the port-city system. Systems thinking and archetypes, and sensitivity analysis results were then applied to look for high-leverage,

systematic solutions to the externalities of port expansion such as congestion and green space encroachment.

Promising approaches were simulated and evaluated for effectiveness and robustness. Model results show how interventions aiming at reducing traffic congestion are relatively ineffective as improvements are offset by increased migration and industrial activity, in term raising road demand. However, they allow the urban system to function at a higher developmental density and economic level.

Interestingly, moving port freight by rail is only partly effective in reducing congestion in the city. While it reduces the need for road investments especially on the short term by relieving congestion, later in the model run subsequent increases of port freight add additional congestion to the now locked-in urban transportation network and more densely developed city.
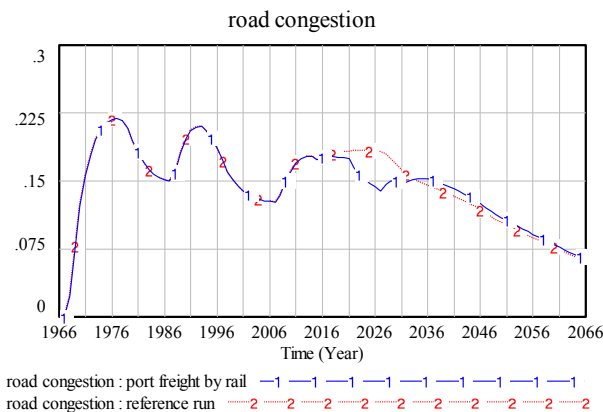
Figure 11.. Road congestion over time for increased port freight by rail (1) vs. the reference run (2)

Combining port road demand reducing interventions with interventions that target per capita road use, such as public transportation or the stimulating of bicycle use, do have a lasting reductive effect on congestion. Offering an alternative to road use to both urban residents and port freight transportation seems to facilitate sustainable port and city co-existence.

Green space encroachment proves more difficult to control. Model structure suggests two approaches 1) limiting urban growth and 2) enforcing a minimum size by conservation. Simulation shows how zoning area restrictions have little beneficial impacts on green space, while harming

the port-city socio-economically. The possibility of informal housing renders such policies ineffective.

Active green space protection is effective however. This intervention may be difficult to achieve in developing countries, which often experience resource constraints and political interference circumventing regulations. However, if those constraints can be lifted, simulation shows it may conserve greenspace (1350 Ha) with little detrimental impact on the port-city system: population reduction would be less than 5% and New enterprise stock reduction would be less than 6% averaged over the model run in all modelled scenarios.

The city would be slightly smaller, with the stock of new enterprises peaking only 3% lower than in the reference scenario, and would only be marginally worse off socio-economically. This effect is robust to uncertainty regarding external factors.

Green space conservation is significant especially in scenarios of economic growth: averaged over the model run green space area would increase at least 250%, with a maximum of 600% in scenarios with a favourable economic environment and automation.
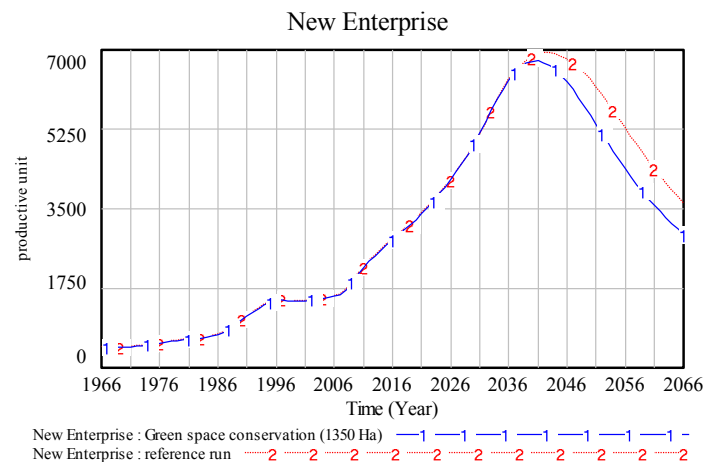
Figure 12. Stock of New enterprises over time, with green space conservation (1350 Ha) (1), and in the reference run (2).

Simulation of slum housing interventions proposed by Forrester in his original Urban Dynamics study (1970) show that these are not effective in developing country context. Rather than reducing the population of underemployed in the city and acting as a source of urban renewal, demolition of 'slum estates' in Tema (comprising former housing constructed for workers that has dilapidated) is shown to lead to an increase of informal settlement. Similarly, low-

income housing programs (200 housing units/yr) do little to reduce informal settlement: a less than 5% reduction is simulated, owing to increased influx of rural-urban migrants. The best solution seems to be to empower residents to finance formal housing: a 25% increase in worker housing construction would lead to a 28% decline in informally settled/population ratio.

Modelling shows interventions may be combined to beneficial effect. A combination of the most effective interventions aimed at reducing port externalities show that improvements can be made to the port-city system without adverse long-term impacts (Figure 13).
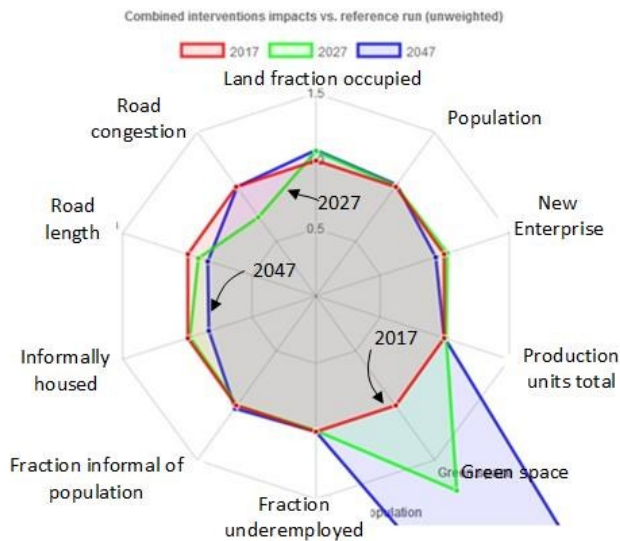

Figure 13. Combined intervention relative impacts in 2017, 2027 and 2047

4   Conclusions

Model use its ability to simulate the effects of port expansion on the port-city system. The explicit causal structure of the model facilitates the identification of potential interventions for sustainable port-city development.

The port-city system follows a developmental pattern that is a variation of logistic growth in a resource-constrained environment, with the urban land area being the limiting resource. Port infrastructure investments tend to trigger the system to behave more dynamically, attracting more industrial development and migration to the city based on increased employment opportunities. This accelerates the encroachment of Tema on its green space by ca. 10%.

Green space acts as a buffer for the city to expand into, postponing the actual constraining of the port-city system

until green space is consumed as well, and growth stagnates. Simulation shows green space is eventually completely encroached upon unless it is actively protected. The possibility of informal housing renders housing and industrial zoning policies less effective for this. Conservation of green space is shown to have limited consequences for the port-city socio-economic climate, but may be difficult to achieve due to resource constraints, the influence of traditional authorities and potential political interference.

The possibility of informal settlement around the city renders policies that involve the demolition of (formal) slum estates ineffective, as evicted people settle informally. Refurbishment of slum estates, increasing their socio-economic status, would have a similar little impact, due to a 'waterbed effect': while the policy benefits labor-class families in the city, up to 20% increase of underemployed is observed. However, refurbishment of slum estates becomes more effective when land area is filled.

Scenario analysis shows how the city of Tema might become 'locked' in a state of increased informal housing, for example triggered by port expansion. As informal housing rapidly claims available urban land, less is available for formal and industrial housing developments, stagnating urban growth. Increasing the capacity of residents to finance formal housing may relieve this situation.

Assessing different modes of port expansion reveals a key finding for port-city development patterns. The question of port-city development revolves around the notion who claims the most land the first: the port or the city. If port development holds back or takes a dosed approach, urban activities benefit and claim the available land. Subsequent port development is then met by serious constraints regarding transport infrastructure construction limitations, due to increased urban developments in the land.

From the perspective of a port it is better to expand dramatically and stifle urban development, claim infrastructure and port space before land is taken for other (urban) developmental needs and developments. From the perspective of the port-city, a less rapid port development is preferred, although negative externalities may be more pronounced on the long term as options to mitigate road congestion may be more (space-) constrained at that point.

These findings connect to theory on port-city evolution which categorizes port-cities by respective urban and port

prominence. It suggests that port-city evolution is not merely something that happens organically, but is actively decided by certain stakeholders in the port-city system. More concretely, port-city evolution may be (partly) the result of investment decisions by international shipping lines and terminal operators, who thereby increase port intermediacy and prominence which may in turn stifle urban development through externalities.

If port prominence is claimed like it is right now in Tema, investments by private parties may dictate the development of African port-cities by constraining their urban development. Port authorities are torn between a responsibility for and pressures from their local communities on the one side, and the commercial requirements of terminal operators regarding the exploitation of their port on the other. Active mitigation of port externalities with lastingly effective interventions may allow for sustainable African port-city development that benefits both parties.

In general, both port expansion and port retreat can be a source for urban renewal for a African port cities that have reached a phase of stagnation. Port expansion could provide a stimulus to the local economy, increasing industrial developments, but land area scarcity and port negative externalities mean that such an economic improvement would be short-lived unless externalities are actively mitigated. Port retreat, while leading to short term loss of direct employment, may be a source of more lasting urban renewal when port negative externalities reduce their constraining effect on the city.

The model has been proven useful in simulating developing country port-city development challenges and port infrastructure expansion impacts, and in the generation of high-leverage interventions. It shows how system dynamics can be effectively used in a relatively data-poor environment, to model the development of the city of Tema and its port and evaluate interventions for sustainable port-city development in an African context.

While its level of aggregation may preclude its use as an urban planning or prediction tool, it may be used as part of the port planning process to convey to key stakeholders a systems perspective and understanding of port-city development dynamics. The relative complexity and high level of aggregation of the model however suggest that a strategy needs to be designed for this.

5   Recommendations

Recommendations for further research include the application of the model to other developing country port cities to evaluate external validity of model results and causal relations, and the applicability of the model to other port cities. Suggestions are made for model adaptations that could be relevant in other port cities, such as port land use impacts, which were not a priority in Tema.

Further research is proposed on the use of the model as a boundary object in strategic conversation, combining principles from group model building and network management and process design. An alternative approach may be the conversion of the simulation model into a serious game of port city development, facilitating discussion and the evaluation of interventions for port-city sustainable development amongst stakeholders.

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