Adaptation of a System Dynamics generic structure to Urban Resilience case-studies in Latin-America

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Thesis submitted in partial fulfillment of the requirements of

Master of Philosophy in System Dynamics

(Universitetet i Bergen)

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July 2021

Acknowledgments

Initially, I would like to thank life and God for giving me the opportunity to be in Bergen for the last two years studying something I love surrounded by amazing people. I believe the timing is perfect, situations happen when they have to happen, and opportunities come when you need them. The experiences lived during this masters have been life-changing for me and I cannot wait to see how the life of my professors, colleagues, and other folks will change too.

My people back in Colombia were enormous support in the process of studying abroad. My family always had my back in this crazy idea, it is crazy in the sense that I am the first member that studied outside the country. My father was very happy about the idea of seeing me progressing and helped me so much with the logistics. My mother, my emotional pillar, always trying her best to be strong for me, cheering me up when I felt my thesis was not going well and saying that everything was going to be fine (as it is always just because she says so). My sister, my best friend, heard me every time I needed someone to talk to and stayed digitally by my side in all the process. Also important, thanks to all my friends who were there for me even with the challenge of 7-hour difference; especially Carol, Mateo, and Sebastían. Lastly, thanks to my system dynamics mentor, Fernando, who had his office door opened for me and made me realize the opportunities I had out of my comfort zone.

Here comes a special acknowledgment to my dear supervisor, Birgit Kopainsky. Thanks for the support along the process, for all the time spent and patience, even for the sporadic talks about books each one has enjoyed reading. She has been such a life saver and an inspiration as a representation of women in the SD field. Additionally, I feel grateful for the opportunity of meeting amazing professors and folks in the field that have thought me and inspired me to thrive.

To all the friends in Bergen that welcomed me and made me feel at home, a hundred thanks. I enjoyed every gathering we had, even if we had challenges to socialize due to the pandemic, we managed to stay close. Special thanks to Jane, Svein, Jessica, and Daniel. Finally, I would like to thank myself for being so brave during this journey.

Abstract

Historically, the System Dynamics field has been using generic structures to transfer general knowledge from one dynamic situation to another. Although generic structures are widely used, there are still opportunities to explore how to use them in specific situations. This research project aims to determine the applicability of a generic resilience structure to different resilience assessment cases/contexts and based on that derive a framework for using generic structures. To achieve that, a resilience generic structure was adapted to five case studies in different Latin-American cities with the same purpose, to analyze the city's ability to withstand disturbances. The original structure, proposed by Zhao et al. (2019), is a canonical situation model designed for assessing resilience of social-ecological systems (SES) with two stocks connected through density-dependence mechanisms. The use of the generic structure through the cases has shown that updates for the model include the extension of disturbance's definition and the re-scale of the model to relative terms when lack of data and short time frame are limitations in the modelling process. The framework for adapting generic structures to case studies follows the same modelling steps described by Sterman (2000) with a sub-step called *Type of situation* in which the modeller can reason about how appropriate is the generic structure for the type of situation of the case study. An important insight related to validation is that a generic structure must fulfill at least the tests used for case-specific models plus being validated through the case studies in order to show its generality. The results made evident that using generic structures is practical and saves time in the modelling process since it does not require building a structure from scratch; however, there is a trade-off with the model's level of aggregation. Also, when using canonical situation models, it is important to identify the nature of the case study problem from the beginning, so the modeller can identify if the generic structure works or if a more specific/detailed structure is needed. Finally, the exercise made in this research project demonstrated that generic structures make the learning process of the feedback and behavioral mechanisms behind complex systems faster and more intuitive over time.

Content

Chapter 1: Introduction

Problem statement

The creation and use of generic structures in System Dynamics have been evolving as the field also evolves. The main idea behind the generic structures is that they support the transferability of insights and general knowledge about certain systems or dynamic problems. This is concluded by Lane & Smart (1994) in their research: Generic structures in all theirs forms express the basic ambition to transfer experience and understanding from one dynamic situation to another. They also mention that in the last three or four decades, in the '90s, the creation and evolution of 'generic structures', as a vehicle for storing and applying these insights, has been one of the ways in which this aspiration has advanced (Lane & Smart, 1994).

In contrast, the big majority of System Dynamics (SD) studies are case-specific, the analyst approaches the problem, creates a hypothesis about the structure that reproduces the behavior, formulates a model and comes up with policy recommendations that are specific to the circumstances (Paich, 1985). On one side, the trend of SD has been customized studies for the specific circumstances of a problem and on the other side, it is important to gain general insights about these structures so the knowledge can be transferred for the benefit of the field. Hence, there is a dance between case-based structures and generic structures in which the field still has opportunities to figure out how to move.

As Paich (1985) stated, the System Dynamics method offers no guidance about how to move from a group of case-specific models to generic structures and it is unlikely that much progress will be made on generic structures until there is some accepted research method. If there is no procedure to do so, there is neither an accepted research method to do the opposite, adapting a generic structure to a case-specific study. This is one of the motivations of this thesis, to provide a framework for adapting generic structures.

In the case of resilience assessments, there has been a need to operationalize it and study resilience in a systemic way. Different authors have offered solutions for the identified need through diverse methodologies, including systemic approaches. For instance, Walker et al. (2002, as cited in Zhao et al., 2019) suggested a participatory framework for analyzing social-ecological resilience and defining a procedure in work-steps for carrying out such analysis. Using System Dynamics, Bueno

(2012, as cited in Zhao et al., 2019) developed a single-stock model with three flows, namely ‘regular flow in’, ‘regular flow out’, and ‘disturbance flow’ as a core stock-flow structure to test the system’s stability. Also, Herrera (2017, as cited in Zhao et al., 2019) operationalizes resilience analysis using SD, allowing policy testing in terms of five fundamental resilience characteristics. The added value of SD in resilience analysis is noticed by Hawes & Reed (2006, as cited in (Herrera de Leon & Kopainsky, 2019): This focus on how stocks, flows and feedback structures drive behaviour makes SD a great candidate for exploring how systems react and adapt to change.

Zhao et al. (2019) developed a generic structure for resilience assessments from a case-study model related to water stress in the city of Lisbon, Portugal. The proposed generic structure works for social-ecological systems (SES) and has two stocks that interplay under the concept of density-dependent responses. The model is taken to be used in this research project as a continuation of the further steps suggested by the authors: “More applications of the proposed generic structure and consequent critical research is needed to determine its generality when applied to different resilience assessment contexts and projects. As consultants, we intend to utilize it in our next resilience assessment projects and encourage other practitioners and researchers to explore it” (Zhao et al., 2019).

Research objectives and questions

This research aims to determine the applicability of a generic resilience structure to different resilience assessment cases/contexts and based on that derive a framework for using generic structures. The next research questions will be answered through the different chapters as showed in the table below:

Research questions	*Chapter where it is answered*
How is resilience represented in a generic structure?	Chapter 3. Resilience generic structure analysis
How to adapt a generic structure to different cases/contexts?	Chapter 5. Adaptation of the generic model
How to validate the generic structure through the cases?	Chapter 6. Results
How does the generic structure and adaptation framework need to be updated?	Chapter 7. Update of the generic structure and framework
What insights can the field gain from the adaptation of generic structures?	Chapter 8. Discussion

Table 1. Research objectives related to the chapters where they are answered

Chapter 2: Literature review

Origin of generic structures

The transferability of System Dynamics structures has been widely discussed among experts in the field. As Forrester recognized in 1961 (as cited in Paich, 1985), in management situations, it is expected that students learn about the principles underlying the cases they study but the rapid stride of professional progress comes when those identified structures or principles can be taught explicitly so the student can inherit an intellectual legacy from their predecessors rather than start over again.

The evolution of generic structures was pictured by the pioneer of the field, Jay Forrester, back in (1989). He mentioned that whether we think of pre-collage or management education, the emphasis will focus on 'generic structures'; a rather small number of relatively simple structures will be found repeatedly in different businesses, professions, and real-life settings. Forrester went even beyond the SD scope, stating that such transfer of insights from one setting to another will help to break down the barriers between disciplines, which means that learning in one field becomes applicable to other fields. Peter M. Senge (1990) also identified the potential of generic structures in systemic approaches: One of the most important, and potentially most empowering, insights to come from the young field of systems thinking is that certain patterns of structure recur again and again. These "system archetypes" or generic structures embody the key to learning to see structures in our personal and organizational Jives.

Definition of generic structure

There is not an official definition of what a generic structure is, but there have been several attempts. Paich (1985) defined it in this way: Generic structures are dynamic feedback systems that support particular but widely applicable behavioral insights. Andersen and Richardson (1980, as cited in Lane & Smart, 1994) said that generic structures are elementary structures, simple feedback structures, which can be used "to approach understanding of real-world problems". Also, these structures were defined as "Ways of storing knowledge and feedback structure of social and business systems" (Morecroft, 1988, as cited in Lane & Smart, 1994). Alternatively, Paich (1985) proposes that is perhaps better that there is not a unique definition because diversity of opinions is healthy for the field.

Lane (1998) opens the definition of a generic structure into three sub-operating definitions based on the style, purpose, and application. Figure 1. Three sub-types of the concept 'generic structure', with brief definitions and examples (Lane, 1998).illustrates a summary of the definitions and some examples.

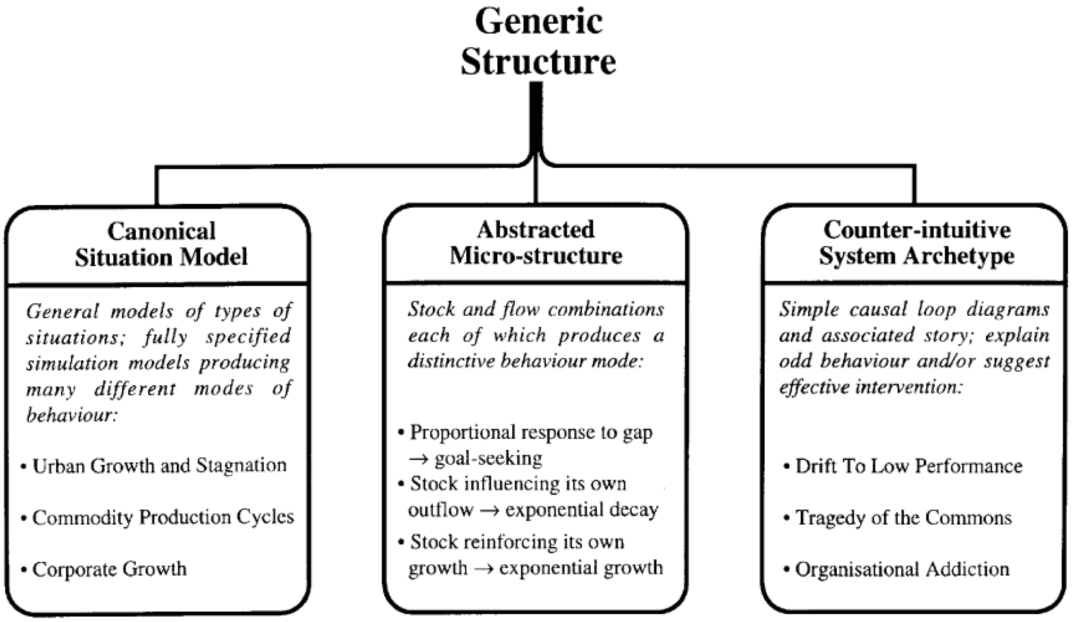


Figure 1. Three sub-types of the concept 'generic structure', with brief definitions and examples (Lane, 1998).

Canonical situation models are basically case studies reduced to their essentials in order to make explicit the causal explanation of the dynamic behavior that the structure generates. This type of models can reproduce different modes of behavior. In terms of practical applications, canonical situation models are pre-existing simulation models which are adapted to a particular situation. One example is the theory created by Meadows (1970, as cited in Lane, 1998) for commodity cycles applied to pork, beef, and chickens.

Abstracted micro-structures are mostly used as building blocks of larger models; they are combinations of stocks, flows, and auxiliary variables that reproduce a particular behavior mode. For instance, the combination of a stock with an inflow or outflow proportional to the gap between the stock and a desired condition of the stock is known as a goal-seeking structure, that reproduces an exponential adjustment towards the goal.

The last type of generic structures is the counter-intuitive system archetypes, which are simplified causal loop diagrams (CLD) associated with a story that encourages the development of feedback thinking. One known archetype is the tragedy of the commons, which shows how can be degraded a common resource, such as grazing land, when several individuals with goals and objectives related to the use of the resource (Senge, 1990).

Confidence in generic structures

Validation tests in SD are used to generate confidence in the model both to the modeller and to the stakeholders using the model. There are frameworks already to validate SD structures, like the one proposed by Barlas (1996) with three major steps: direct structure testing, structure-oriented behavior testing, and behavior pattern accuracy test. In the case of generic structures, the framework is not as clear as for case-specific structures. Paich (1985) stated that generic structures must meet all the tests required of a case-specific model, and in addition, the analyst must be able to argue that the model is in some senses, general. In the same line, Lane & Smart (1994) conclude that "Greater confidence in using a canonical situation model for a particular problem situation can only come about when the structure is accepted within the application domain as a valid theory for interpreting a particular class of problems".

Hence, can we have confidence when using a canonical situation model? According to Lane (1998) a modeller can be confident that it will be well constructed, will generate interesting modes of behaviour and can yield interesting insights; but we might have reduced the confidence that users will accept that such a model represents their system, or that they will be able to check that its structure and variables fit the system of interest. The representativeness of canonical situation models can thus be tested, and, in principle, we can have confidence that it is appropriately applied to a given situation (Lane, 1998).

Concept of resilience in Social-ecological systems

Resilience is a relatively new used concept and has diverse interpretations depending on the context where is applied. As Fiksel (2006) mentioned, the concept of resilience has emerged as a critical characteristic of complex, dynamic systems in a range of disciplines including economics (Arthur, 1999), ecology (Folke et al., 2002), pedology (Lal, 1994), psychology (Bonanno, 2004), sociology (Adger, 2000), risk management (Starr et al., 2003), and network theory (Callaway et al., 2000).

Bhamra et al. (2011) also recognized the use of resilience in the context of small and medium enterprises in a wide variety of fields as ecology (B. Walker et al., 2002), metallurgy (Callister, 2003), individual and organisational psychology (Barnett & Pratt, 2000)(Powley, 2009), supply chain management (Sheffi, 2005), strategic management (Hamel & Valikangas, 2003) and safety engineering (Hollnagel et al., 2006). The authors say that although the context of the term may change, across all these fields the concept of resilience is closely related with the capability and ability of an element to return to a stable state after a disruption (Bhamra et al., 2011).

The concept of resilience was first popularized by Holling in 1973 within the seminal work titled 'Resilience and Stability of Ecological Systems', work that has formed the foundation for most studies of the concept of ecological resilience as well various other forms of resilience (Bhamra et al., 2011). For Holling (1973), resilience, in ecological systems, determines de persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables and parameters, and still persist.

Specifically for Social-Ecological Systems (SESs), Walker et al. (2002) defined resilience as the ability to maintain the functionality of a system when it is perturbed or the ability to maintain the elements required to renew or reorganise if a disturbance alters the structure of function of a system (as cited in Bhamra et al., 2011). Based on Petrosillo et al. (2015), systems where social, economic, ecological, cultural, political, technological and other components are strongly linked are known as SESs, emphasizing the integrated concept of the 'humans in nature' perspective. The authors mention that SESs are truly interconnected and co-evolving across spatial and temporal scales, where the ecological component provides essential services to society such as supply of food, fiber, energy, and drinking water (Petrosillo et al., 2015).

Modes of behavior in resilience studies

Resilience is often measured through the behavior of system outcomes (e.g. food security, energy supply, or quality of drinking water) during and after the system has been shocked by a change in the environment (Biggs et al., 2012, as cited in Herrera de Leon & Kopainsky, 2019). Considered F(x) as the outcome function, Walker et al. (2004, as cited in Herrera de Leon & Kopainsky, 2019) describe three general changes that F(x) might exhibit after the system has been affected by a disturbance:

Stability (no change): based on Herrera de Leon & Kopainsky (2019), the system outcome F (x) shows the same behavior that it will show otherwise, despite the system being affected by a disturbance, as observed in Figure 2. The concept of stability is not necessarily a synonym of a constant or a linear behaviour. For instance, the amount of available crops might remain stable despite the presence of moderate droughts if sufficient crops are maintained in storage facilities.

Adaptation: The behaviour of the system “bends” when affected by a disturbance and eventually bounces back while retaining its current nature (Herrera de Leon & Kopainsky, 2019). Walker et al. (2004, as cited in Herrera de Leon & Kopainsky, 2019) emphasize that this return to normal behaviour is not given but driven by factors (e.g. resources, decisions, actions) within the system. For instance, food systems might adapt to changing weather conditions if farmers introduce different seed varieties or different crops that require less water.

Transformation: The system as it currently exists “breaks” and changes into a new system with a fundamentally new structure, relationships, and identity (Ludwig et al., 1997; Walker et al., 2004, as cited in Herrera de Leon & Kopainsky, 2019). The new system might or might not produce the same outcomes or just might not produce them at the same rate. Based on Herrera de Leon & Kopainsky (2019), while certain transformations might be positive, risk management is concerned with those transformations that are not positive and the cases in which the system might collapse (see Figure 2). For example, food systems might become economically unfeasible if they are not able to recover from severe weather disasters.

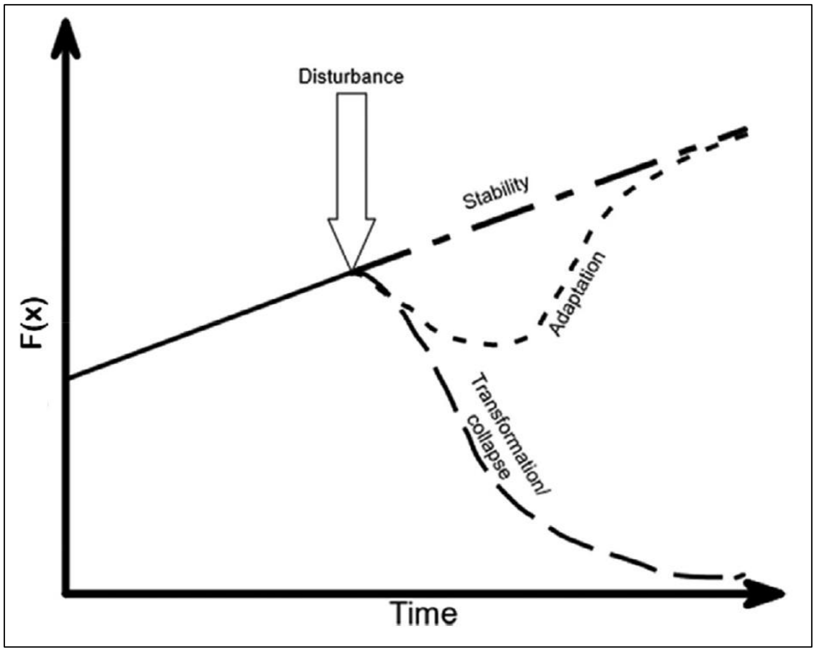


Figure 2. Generic system responses to a disturbance affecting one of its outcomes (Herrera de Leon & Kopainsky, 2019).

Chapter 2: Resilience generic structure analysis

The Resilience Generic Structure this study is using is classified as a canonical situation model according to the sub-types explored by Lane (1998). The first reason for such a classification is that the generic structure (see Figure 3.) is a generalization of a case study from Zhao et al. (2019), that represents the dynamics of resilience in terms of slow and fast variables. In addition, the model can reproduce several modes of behavior like equilibrium, recovery after an external disturbance, and regime shift after an external disturbance. Lastly, in practice, the structure has been adapted to different situations where urban resilience is being assessed.

The concept of resilience behind the generic structure is based on the research made by Holling (1973, as cited in Zhao et al., 2019), who characterizes resilience as the ability of a system to absorb changes of different variables. It is also important to establish that the type of systems for which the structure is designed is defined as social-ecological systems, which are complex adaptive systems where ecological (nature) and social (humans) components are interconnected and interact dynamically.

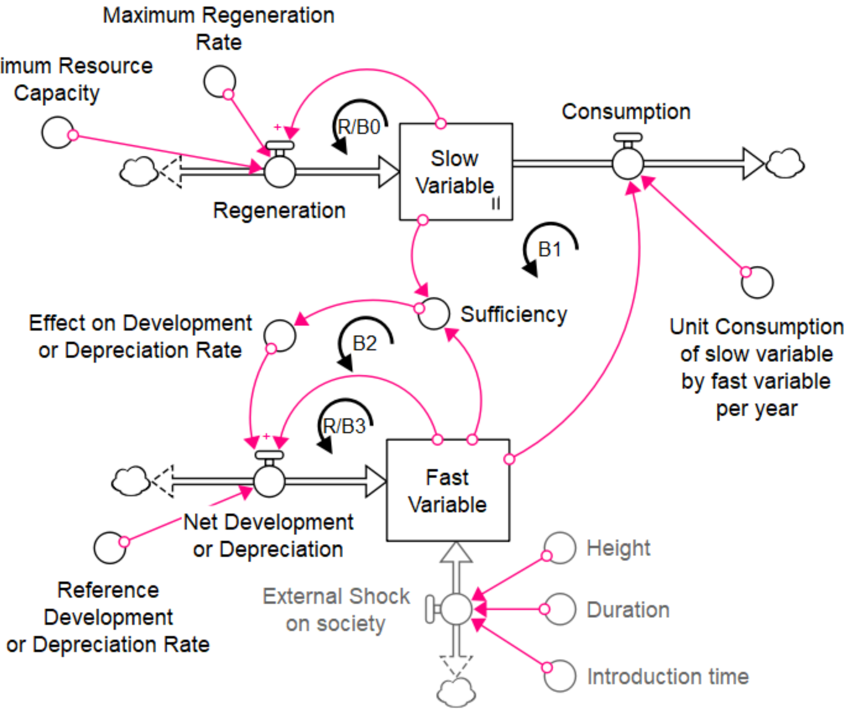


Figure 3. Resilience generic structure proposed by (Zhao et al., 2019)

Structure analysis

The resilience generic model is represented in a stock and flow diagram (SFD) in Figure 3. which also indicates the feedback loops interplaying in the model. It contains two stocks under the concept of 'slow' variables and 'fast' variables that are used in social-ecological systems for some authors and ecosystems for other authors. The stocks are interconnected by a density-dependent mechanism that determines how the fast variable changes based on how available the slow variable is. Also, the system is affected by external circumstances that can change the behavior in different ways that will be analyzed later. The logic for describing the structure will be taking a feedback loop, define the meaning of the variables involved, and then reason about the interconnections.

Regeneration feedback loop (R/B0)

Slow variable, in social-ecological systems, is a variable that changes slowly in relation to the timescale of ecosystem service provision and management. They are typically natural resources consumed by a certain type of user. This variable determines how the fast variable reacts to external shocks. Slow variables are commonly harder to measure than fast variables because of their magnitude; when is very hard to measure the stock size, estimates or predictions are used, rather than the real value. Example: The slow variables, such as amount of soil organic matter, shape how a fast variable, such as crop production, responds to variation in an external driver, such as variation in rainfall during the growing season (Walker et al., 2012).

The maximum regeneration rate is the maximum rate at which the slow variable can regenerate based on natural laws or another type of restrictions.

The maximum resource capacity is the maximum amount of the resource that the system can contain, that controls the system from growing infinitely, playing the role as the carrying capacity (CC) of the environment for that resource.

The regeneration variable represents the self-regeneration of the slow variable when is assumed that typically it is a natural resource. A great number of types of natural resources are able to regenerate but only within a certain growth rate. There is a non-linear relationship between the slow variable stock and the regeneration which is represented by a parabola equation:

$$Max\ regeneration\ rate \times 4 \times \frac{Slow\ variable}{Max\ resource\ capacity} \times \frac{(Max\ resource\ capacity - Slow\ variable)}{max\ resource\ capacity}$$

The interpretation of the equation is better explained by the structure graph in Figure 4. The maximum resource capacity plays the role of the carrying capacity (CC) of the resource (assumed as 2 in the structure graph). The maximum regeneration rate (value of 0.5) is reached when the slow variable is at the resource capacity that generates the maximum sustainable yield (MSY). In this model, the MSY (value of 1) is reached at half of the CC. That point defines the behavior of the regeneration as can be observed in Figure 4. For values of the slow variable between 0 to 1, the regeneration rate increases driven by a reinforcing loop mechanism. The regeneration rate reaches its maximum point of 0.5 when the slow variable is at the MSY, the exact point where the two variables are in equilibrium. For values of the stock above 1, the regeneration rate starts decreasing again towards zero, as shown in the structure graph. This relationship indicates that the behavior will be driven by a balancing feedback mechanism. After the slow variable reaches the Maximum resource capacity (2 slow variable units) the regeneration is negative, indicating that the system tends to put the slow variable again at the CC or below it, as a control mechanism.

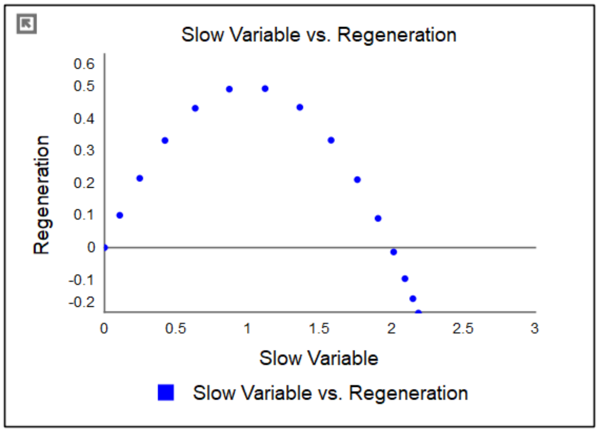


Figure 4. Structure graph of the stock 'slow variable' and its flow 'regeneration'

The reinforcing loop (R0) story explains that the more slow variable, the more regeneration, and the more regeneration, the more slow variable. On the other way, the less slow variable the less regeneration rate, and the less slow variable the next time around. This is applicable for values of the stock below the maximum sustainable yield. The balancing loop (B0) story explains why an increase in the slow variable causes a decrease in the regeneration rate, generating a slower increase in the stock for values after 1.

Development or depreciation feedback loops (R/B3)

The fast variable is a stock that changes rapidly in relation to the timescale of the slow variable. They are typically those factors that are primarily concern to ecosystem users, for example, a pest species or (often) ecosystem goods and services, such as crop production, clean water extraction, oil consumption, and so on (Walker et al., 2012). The fast variable can develop or depreciate over time and change through the introduction of external shocks. They are most easily measured and immediately altered by some system of management.

The reference development or depreciation is the normal or average change over time of the fast variable development or depreciation. The net development or depreciation is the resultant rate influenced by the fast variable, the reference rate, and the effect of sufficiency, as can be observed in the equation:

$$Net\ development\ or\ depreciation\colon fast\ variable\ \times\ reference\ development\ or\ depreciation \\ \times effect\ on\ development\ or\ depreciation\ rate$$

R3 is a reinforcing loop that represents the development of the fast variable as long as it brings progress to the territory/society where it operates. The more fast variable, the more development, and the more development, the more fast variable, as represented in the CLD of Figure 5.

B3 is a balancing loop that represents the self-depreciation of the fast variable considering that are human-made and managed processes or assets, commonly. The more fast variable, the more depreciation, the more depreciation, the less fast variable next time around, as portrayed in Figure 5.

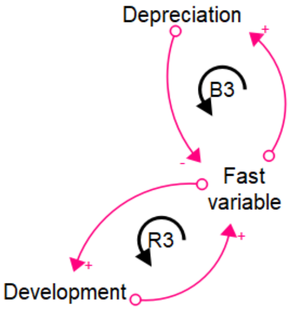


Figure 5. CLD of the processes of development or depreciation of the fast variable

Consumption feedback loop (B1)

Consumption is the use over time of the slow variable. It is given by the fast variable value and by the units of consumption of the slow variable per each unit of the fast variable, as represented in the equation below. As an example, being the slow variable a water resource and the fast variable water treatment plants, per each treatment plant there will be a certain amount of water that is extracted per time. That value will be the unit consumption of slow variable by fast variable.

$$Consumption = fast\ variable\ \times unit\ consumption\ of\ slow\ variable\ by\ fast\ variable\ per\ year$$

Sufficiency is the ratio between the slow variable level and the fast variable level which establishes how adequate is the amount of the slow variable for the fast variable (see equation below). The higher the ratio, the more adequate is the slow variable in relation to the fast variable. Staying the slow variable constant, an increase in the fast variable will decrease the sufficiency, and a decrease in the slow variable will increase the ratio. On the other hand, staying the fast variable constant, an increase in the slow variable will increase the sufficiency and a decrease will decrease the ratio.

$$Sufficiency = \frac{slow\ variable}{fast\ variable}$$

The effect of sufficiency on development or depreciation rate (see Figure 6) is based on the initial scale of the stocks, this is, how sufficient was the slow variable to the fast variable at the beginning of the simulation (equilibrium). This linear relationship is assuming that whenever the sufficiency is 10 there is zero effect on the development/depreciation rate. When the sufficiency is more than 10 (the resource is more available than in the equilibrium/initial situation) the effect is positive, which means the fast variable is going to develop. When the sufficiency is less than 10 (the slow variable is less available than the initial situation), the effect is negative, which means the fast variable is going to depreciate.

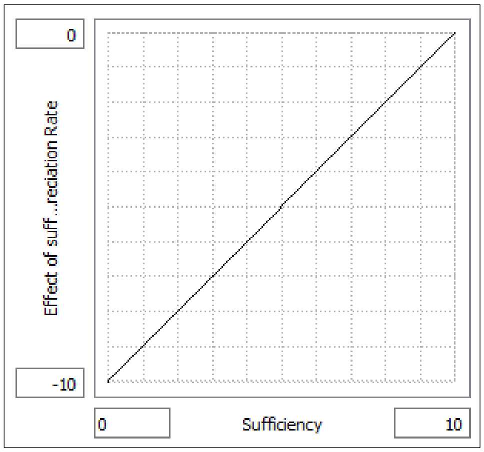


Figure 6. Effect of sufficiency on Net development or depreciation rate.

This balancing loop represents the consumption of the natural resource that is controlled by its availability. When the fast variable increases, consumption also increases, decreasing the slow variable and making it less sufficient. The less sufficiency, the less effect on Development or depreciation rate and the less net development or depreciation, decreasing the fast variable next time around.

Development or depreciation control feedback loop (B2)

This loop represents the control of the development or depreciation rate based on how sufficient the slow variable is. The more fast variable, the less sufficiency, and the less effect. The less effect, the less net development or depreciation, and consequently the less fast variable.

External shock mechanism

This mechanism, which is exogenously influencing the system, created a disturbance for which the slow and fast variables will try to adapt. Thanks to this mechanism resilience can be analyzed. An external shock is an external sudden short-term deviation from long-term trends that has the potential to change substantially the current state of a system and/or the ability of the system to withstand future disturbances (Zseleczky & Yosef, 2014). In this generic structure the shock is thought to be a disturbance for the system through society, hence, it directly impacts the fast variable which is the human component.

The external shock on society is represented by a step function, as shown in Figure 7, that at given introduction time increases a certain height of fast variable units with a specific duration.

In Figure 7. the introduction time is at 10 years, the magnitude of the shock is 0.06 and the duration is 2 years. The magnitude of the shock can be a positive or negative value, based on the given meaning to the disturbance. As positive it will add to the fast variable and as negative will drain the fast variable.

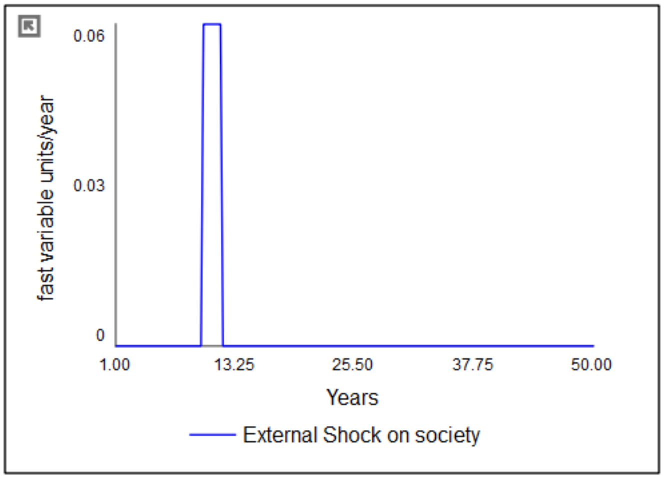


Figure 7. Behavior's example of the external shock on society

Behavior analysis

As this generic structure is centered on resilience analysis there are three main types of behavior that the outcome variable F (x) can generate. The three types portrayed previously in Figure 2 are stability, adaptation, and transformation/collapse. The F(x) of the system for this structure is considered to be the slow variable and Figure 8 shows the possible responses of the outcome to a disturbance.

The equilibrium state (blue line) can be compared to the stable state that occurs when the slow variable shows the same behavior even if there are disturbances. In the generic modell, the slow variable stays in equilibrium for a certain range of the shock. If the shock passes the stability threshold, the behavior is then recovery (red line in Figure 8). The system "bends" and is capable to go back to the equilibrium situation after a while by its internal mechanisms.

The last type of behavior is the transformation, called regime shift (green line) in Figure 8. Regime shift occurs when the current system "breaks" (does not go back to the equilibrium situation) and its structure is transformed into a new structure. It is possible for the system to find another equilibrium situation after the transformation. Also, it can be said that a transformation is a collapse of the system when the change represents something negative or unfavorable for the outcome variable.

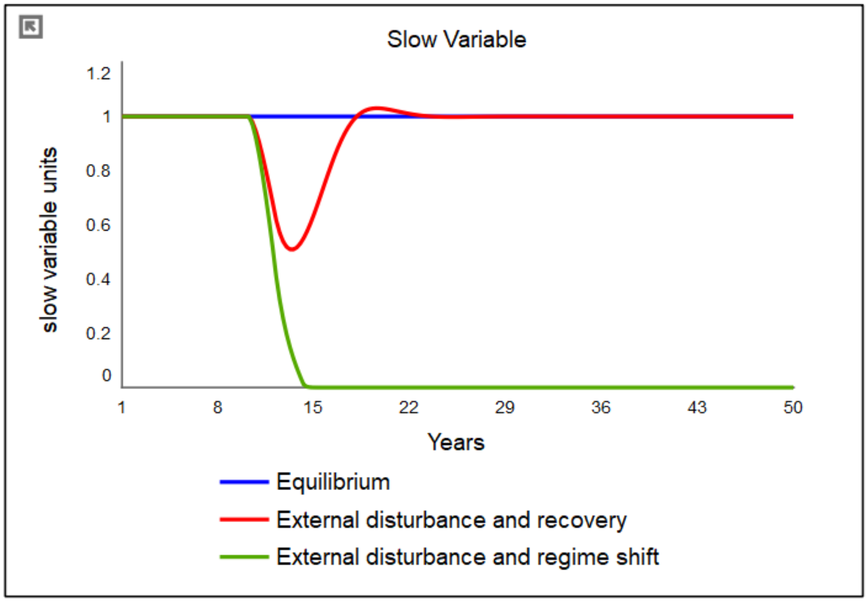


Figure 8. Types of responses of the slow variable to a disturbance in the generic model.

Chapter 3: Case studies

The analysis resulting from this research is thanks to the application of the previously discussed generic structure to case studies. The cases come from the evaluation that a private foundation is leading of resilience-oriented innovation programs in Latin American cities, in partnership with the city's governments. The name of the foundations and companies involved are reserved for privacy condition terms. The information that can be shared freely is variable names, model structure, city names, and other open-access information.

Each case study is derived from an "Innovation Challenge" that was launched by different organizations/foundations and the government of the respective city. The general process of the Innovation Challenge is described in Figure 9.

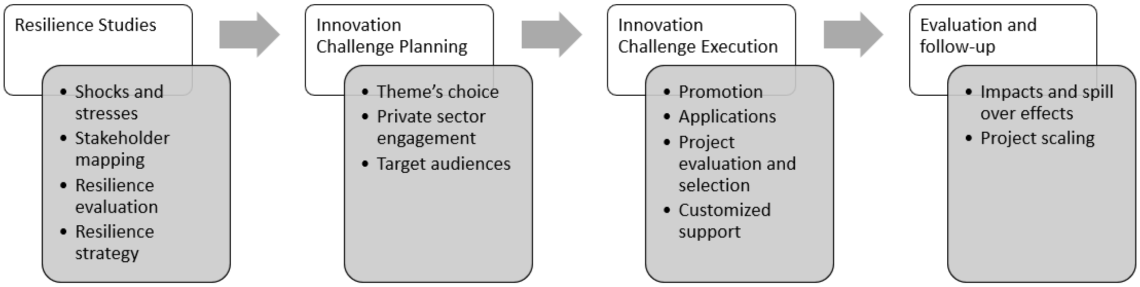


Figure 9. Description of the meta-process involving the Innovation Challenge

First, the organizers consider the previous Resilience studies made in the city as a precedent to plan the challenge. Some of the cities do count with a Resilience strategy and some do not. Based on that, the analysis of the challenge's impact can be done differently.

Secondly, for the planning phase, the organizers decide on the theme they want to focus. They can use the Resilience studies as a starting point or choose an emergent problem that the city is facing. Here, the organizers make important efforts to involve the private sector in the process. Also, they decide what is the type of audience the challenge should target to receive project proposals in specific stages. In most of the Innovation Challenges, projects since early stages but with high growth potential are allowed to participate, until projects that have products/services on the market already.

Later, the Innovation Challenge is launched, promoted, and closed. The winning projects are selected based on criteria with weights and there can be several winners per challenge. The winners receive two types of support: monetary investment and entrepreneurial customized support.

Finally, there is an evaluation of the impact of the winning projects focused on Urban Resilience. In this context, urban resilience is the capacity of the city to withstand shocks or stressors. This is the part of the process where System Dynamics takes place. Using a generic structure each case study is modelled to analyze how some important variables for the city's resilience respond to external disturbances. Also, three types of scenarios are created to study the scaling of the projects (policies): base, pessimistic and optimistic. In this last stage of the meta-process, there is a deliverable for the organizers called Systematization report. The report consists of the next sections, and it is especially in the last ones (4, 5, and 6) where System Dynamics modelling is used:

1. Challenge process development
2. Problem to solve
3. Proposed solutions
4. Scaling models
5. Potential impact on Urban Resilience analysis
6. Conclusions

In Table 2 there is a summary of the Innovation challenges with the respective order, city, themes and objectives, and the number of resulting winning projects. Something important to notice from the table is the order of the cases because the insights (discussed in Chapter 8) were accumulating through them, and different decisions were made along the process.

Order	*City, country*	*Resilience challenge themes*	*Resilience challenge objective*	*Number of winning projects*
1	Buenos Aires, Argentina	Gender equity and circular economy	Contribute to the city's resilience by means of private sector participation, incorporating actions, projects, or novel strategies to increase resilience in their business models.	4
2	Quito, Ecuador	Eco-efficient industrial polygon	The innovation process should respond to a strategic axis of the industries inside the polygon and should fit with the analysis process of solutions and alternatives to the problems raised.	2
3	Mexico City, Mexico	Ecosystem-based adaptation to climate change	Strengthen the sustainable agroecological production and merchandizing in the chinampa area; as well as improve and regulate water quality in the area.	1
4	Salvador Bahía, Brazil	Circular economy	Contribute to Salvador's resilience through the participation of the private sector, as well as reduce social inequality.	3
5	Córdoba, Argentina	Urban circular economy and Urban social economy	Contribute to the city's resilience through the participation of the private sector, incorporating novel actions, projects, or strategies or triple impact that contribute to the economical renovation post-pandemic, in the framework of circular economy.	3

Table 2. Summarized information regarding the innovation challenges launched

Chapter 4: Framework for the adaptation of the generic structure

As mentioned earlier, there was a process of adaptation of the Resilience Generic Structure to different case studies. Each case study was an opportunity to iterate the adaptation process and gain insights. During this chapter, the general framework for adaptation is going to be discussed and later, in Chapter 6, the identified improvements of the framework after the iterations will be established.

Paich (1985) mentioned that the System Dynamics method offers no guidance about how to move from a group of case-specific models to generic structures. That statement remains true if it is considered that there is no official method. The procedure to do the opposite is also not clear, reason why this thesis will give an attempt in operationalizing the way a modeller can move from a generic structure to a case study, adapting the structure in the way.

Sterman (2000) offers a guideline for the modelling process with SD that has been used extensively, especially for the case-specific modelling approaches. The steps consist of: (1) articulating the problem to be addressed, (2) formulating a dynamic hypothesis or theory about the causes of the problem, (3) formulating a simulation model to test the dynamic hypothesis, (4) testing the model until you are satisfied it is suitable for your purpose, and (5) designing and evaluating policies for improvement. It is also considered that modelling is a feedback and iterative process (Sterman, 2000), which means that has the potential to be flexible enough to adapt to different modelling approaches. Given that, the modelling process steps are adjusted as shown in Figure 10, where key questions for the adaptation of generic structures are raised.

It is important to clarify that the proposed framework is the one followed in general through the case studies described in Chapter 3. The steps order could vary from case to case, as well as the questions to be answered. The outcomes also varied, in some of the cases the generic structure was more followed than in others, based on the client and case needs. Let us detail more each step and talk about insights gained.

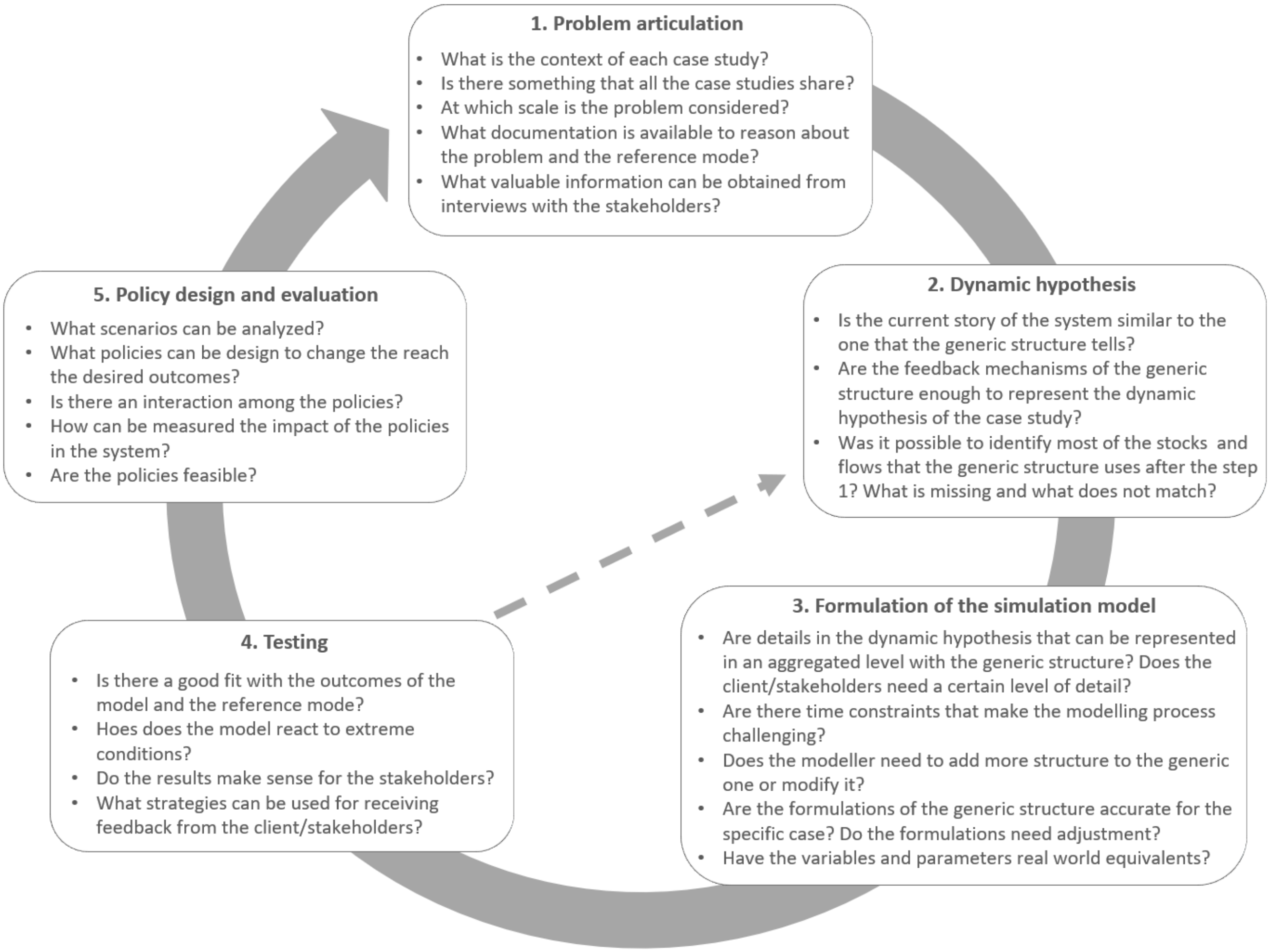
Problem articulation

The problem articulation started with the analysis of the existing documentation about the case study (the innovation challenges per city). For the client, there are two main deliverables: a report and a model. The modellers had to make sure to obtain all the information required to complete both deliverables in a maximum term of one month.

Interviews were carried out to contrast the existing information and obtain new information from the stakeholders. The interviews were usually with the organizers or the challenges and with the leaders of the winning projects. During the interviews with the project's leaders, the modellers made questions focused on gaining a better sense of the case and identifying possible variables involved in the modelling process.

All the case studies had the same scale which was local dynamics due to the focus on Urban Resilience. The information about the innovation challenge and the winning projects was clear, since is information the client can directly control. The Information related to the problems that the challenges tried to solve was clear but not very detailed. That fact created an extra burden for the modellers, who had to research for open access information related to the socio-ecological systems involved. An important learning from this process of problem articulation is that, if the deadline to finish each case study is as short as mentioned, it is very convenient that the modeller has experience with Resilience assessments and with socio-ecological systems in general. This is an advantage when conceptualizing the problem and having the big picture of the modelling process.

Additionally, with the iteration of the problem articulation step through the cases, the modellers learned what information was more useful for the process, what sources to use and how to conduct the interviews to be more effective.



1. Problem articulation

- What is the context of each case study?
- Is there something that all the case studies share?
- At which scale is the problem considered?
- What documentation is available to reason about the problem and the reference mode?
- What valuable information can be obtained from interviews with the stakeholders?

2. Dynamic hypothesis

- Is the current story of the system similar to the one that the generic structure tells?
- Are the feedback mechanisms of the generic structure enough to represent the dynamic hypothesis of the case study?
- Was it possible to identify most of the stocks and flows that the generic structure uses after the step 1? What is missing and what does not match?

3. Formulation of the simulation model

- Are details in the dynamic hypothesis that can be represented in an aggregated level with the generic structure? Does the client/stakeholders need a certain level of detail?
- Are there time constraints that make the modelling process challenging?
- Does the modeller need to add more structure to the generic one or modify it?
- Are the formulations of the generic structure accurate for the specific case? Do the formulations need adjustment?
- Have the variables and parameters real world equivalents?

4. Testing

- Is there a good fit with the outcomes of the model and the reference mode?
- Hoes does the model react to extreme conditions?
- Do the results make sense for the stakeholders?
- What strategies can be used for receiving feedback from the client/stakeholders?

5. Policy design and evaluation

- What scenarios can be analyzed?
- What policies can be design to change the reach the desired outcomes?
- Is there an interaction among the policies?
- How can be measured the impact of the policies in the system?
- Are the policies feasible?

Figure 10. System Dynamics modelling process tailored for the adaptation of generic structures

Dynamic hypothesis

At this step, with the main variables identified, it is possible to create a visual representation of the system. For the first two case studies, the modellers departed from a Causal Loop Diagram and then realized that it did not add the expected value. After that experience, the process started directly with the Stock and Flow Diagram of the generic structure presented in Chapter 2.

Since the starting point of the modelling process is the generic structure, that made it easier to accommodate the variables and create a first version of the dynamic hypothesis and saved some time that could be used in the next step. In that first version what the modeller tries to do is to accommodate the variables in the generic structure and make the connections and check what level of matching can be accomplished to take that as a departure point. The final version of the model might be or might not be similar to the generic structure, which depends on the needs.

Formulation of the simulation model

An important limitation for this step and the previous one was the time of only one week. That reduced the level of detail and forced the modeller to stay at a more aggregated level, which is one of the advantages of using the generic structure. Due to the same time constraint and the role of the client in the simulation process for this particular project, the involvement of the client was low. The involvement was bigger in the testing step.

Knowing the level of aggregation that needed to be kept, even if the simulation model was different from the generic structure, the modellers tried to make simple structures. There were several iterations at this step after calibrating the structure and testing it. Some crucial variables in the simulation model were the outcome variables, the most important ones for the client to make decisions.

Another big limitation in the formulation of the simulation model was the lack of precise data. As mentioned earlier, information about the projects (policies) was clear but information about the socio-ecological systems relied on open-access information. For the information that was difficult to find within the time frame, the modellers used validation with the stakeholders, calibration with other equivalent information or assumptions.

Testing

One of the biggest sources of validation was the stakeholders. As there was a lack of information and little time, in most of the cases there was no reference mode of behavior. That is why the models were usually calibrated to start in equilibrium, assuming that the intermediate parameters are right to deduce other values, as the initial values of the stock for instance. It is based on deductive reasoning: if the parameters are right, the impact of a policy can be measured, and the results are valid.

The validation process with the stakeholders is mainly made throughout an interface designed in Stella Architect ® software, where the modellers try to validate the main variables used and calibrate the main values based on the stakeholder´s feedback. Depending on the stakeholder´s level of knowledge on the case, the modellers decided to show the model (represented in an SFD) and discuss it with more detail.

Policy design and evaluation

The policy component of the modelling process is the different projects that won the Resilience Challenges, and their impact is analyzed based on three main scenarios: base, pessimistic and optimistic. In the base scenario, the modelers assume that the growth of the project is the same that the one that they estimated they will have. In the optimistic scenario, the modelers assume a growth x times bigger than the base scenario. And the pessimistic scenario assumes a growth x times smaller than the base scenario. In this way, there is a way to compare the state of the system without and with interventions and see how much the projects can improve the outcome variables the stakeholders are interested in.

Iterations and feedback

Although all the steps of the modelling process have feedback between them and there is constant iteration, continual questioning, testing, and refinement (Sterman, 2000), a common iteration in the adaptation of the generic structure was the one from testing to dynamic hypothesis (dotted arrow in Figure 10). It is common because there is a constant process of adjusting the generic structure based on the calibration process, results, and feedback from the stakeholders. In this process, is completely possible that the final version of the model is a case-specific structure instead of the generic one. The adaptation process of generic structures to case studies has to be flexible enough to create a fairly good representation of the reality while fulfilling the client's purposes.

Chapter 5: Results of the adaptation process

Generic structure validation through the case studies

The case studies enriched the process of gaining confidence and validating the generic structure. As Paich (1985) stated, generic structures must meet all the tests required of a case-specific model, and in addition, the analyst must be able to argue that the model is in some senses, general. The next tests applied to the generic structures are the ones proposed by Barlas (1996) for case-specific models (see Table 3). Later, in Chapter 7, more about validation will be discussed.

Structure confirmation test

The structure of the model is supported by an exercise made by Zhao et al. (2019) of creating a generic structure for resilience assessments from a case study. Both the creation of the case-specific model and the generic model has proper research methodology. The structure is considered a canonical situation model for resilience assessments in social-ecological systems.

The model uses the concept of slow variable and fast variable for social-ecological systems (Walker et al., 2012). Also, the structure has two stocks related in a density-dependence that can generate several behaviors as the predator-prey model (Swart, 1990). Finally, in the adaptation of the generic structure to each case, there was a process of adjusting and validating the structure.

The model of each case study is built based on sources of information as official documents, business plans, and interviews with the stakeholders. There were also sessions of validation with the stakeholders for the structure and behavior of the model.

Parameter conformation test

The cases use similar parameters to the ones used in the generic structure with additional parameters specific to each of the cases, validated with the stakeholders. The generic parameters are Maximum resource capacity, Maximum regeneration rate, Unit Consumption of Slow variable by Fast variable per year, Reference development or depreciation rate, disturbance height, disturbance introduction time & disturbance duration. Parameter units are consistent with the model calibration. All the case’s specific parameters have real-world equivalents.

Extreme conditions test

The behavior of the outcome variables of the model makes sense when it takes extreme values in the parameters (see Appendix 2).

Dimensional consistency test

The models are dimensionally consistent without the use of fudge factors.

Integration error test

The behavior of the output variable does not change dramatically with changes in the integration method. The ones that seem more precise in behavior reproduction are RK2 and RK4 (see Appendix 3). With the chosen integration method RK4, after DT=5 the behavior stays with the same shape. The one used by the model is DT=15.

Behavior reproduction test

The model reproduces the real data with some point-to-point differences. The case studies behavior reproduces the behavior patterns stated in resilience theories when their structure is the same or similar to the generic one. As the case studies model has fewer and fewer mechanisms present from the generic structure, the behavior patterns change as consequence.

Behavior sensitivity test

Since the model is designed to test how disturbances change the system, the generic model is highly sensitive to changes in the parameters, especially the one related to disturbances. The study of the system's reaction to disturbances is a sensitivity analysis per se. Based on the specific characteristics of the system, the behavior can be more or less sensitive to certain parameters.

In Appendix 4 can be found how the generic structure reacts to changes 20% below and above the normal value of the different parameters. For the analysis of the parameters not related to the disturbance, a recovery type of behavior is assumed as the base. The possible combinations are infinite and can generate several behavior variations within the ones already studies in Chapter 2.

Generality of the generic structure

This analysis is more a discussion than a test per se. After the process of building five different models with the generic model as a departure point, one of the characteristics that was followed more precisely is the type of system. Almost all the pairs of slow-fast variables represented social-ecological systems, being the slow variable a representation of nature and the fast variable the human component. This is followed in all the cases except in one (Buenos Aires model), where the slow variable was social cohesion and the fast variable was Gender salary gap, both social variables. Later in the behavior analysis will be observed that the mentioned pair of variables could not represent the three generic modes of behavior. This might indicate that the generic structure can include several socio-ecological systems but not only social systems, at least that is what the evidence shows. More testing is needed to challenge the definition of the structure's boundaries.

Also, it can be claimed that the structure is general because the concepts of slow variable and fast variable are general and encompass a great bunch of variables. Additionally, the concept of the external disturbance is flexible enough to represent several patterns, short-term and long-term alterations with different trends. Finally, the concept of sufficiency and the effect of sufficiency in the development or depreciation rate is flexible to represent any type of relationship, linear, non-linear, and so on.

Structure analysis

The results of the modelling process of the case studies are summarized in Table 3, which contrasts the feedback loops from the generic structure and the ones from the cases. For a better interpretation of the results, it is important to remember that the cases are chronologically organized, the first model developed was Buenos Aires and the last Cordoba.

It can be observed that the first two models kept all the loops from the generic structure. Starting from Mexico City model, the original loops were less represented in the case study models. Mexico City model had the loops associated with the slow variable regeneration process and the consumption of the slow variable with some constraints of capacity that represented partially the sufficiency concept. Later, in Salvador model, the concept of regeneration was included but not the concept of sufficiency in the consumption. The same case happens in Cordoba model, the fast variable dynamics from the generic structure are not represented, only some of the slow variable dynamics.

The fact that the models represented less and less the generic structure loops does not mean the structures are a more simplified version of it. There are other feedback mechanisms present in the case-specific models, especially associated with material delays of the slow variables. Those details are not analyzed in the current research project.

Generic model feedback loops	*Description of the feedback loop*	*Buenos Aires model*	*Quito model*	*Mexico City model*	*Salvador model*	*Cordoba model*
R/B0	These loops represent the self-regeneration of natural resources. A great number of types of natural resources are able to regenerate but only within a certain growth rate, that is why the parameter maximum resource capacity is introduced, to control the upper limit of the stock.	R/B0	R/B0	R/B0	R/B0	R/B0
B1	This loop represents the consumption of the natural resource that is controlled by its availability. When the slow variable is less sufficient for the fast variable, the fast variable develops slower and consumes less of the slow variable next time around.	B1	B1	B1	Consumption is represented without the sufficiency concept	Consumption is represented without the sufficiency concept
B2	This loop represents the control of the development or depreciation rate based on how sufficient the slow variable is. It makes the development not to be reinforced every time the fast variable grows.	B2	B2	None	None	None
R/B3	R3 loop represents the development of the fast variable as long as it brings progress to the territory/society where it operates. B3 loop represents the normal depreciation of the fast variable.	R/B3	R/B3	None	None	None

Table 3. summarized results of the generic structure adaptation to the case studies

Behavioral Analysis

In this sub-section, the behavior of the output variable of the generic model (slow variable) will be compared to the behavior of the output variables of the five cases. For a better interpretation, let us notice that some of the values are in relative terms (further explanation in Chapter 6) and some of the values are in real-scale terms. Three essential types of behavior are going to be identified through the cases: equilibrium, external disturbance and recovery, and external disturbance and regime shift. In the different figures, the slow variable is always represented by a blue line and the fast variable by a red line.

Generic structure

As analyzed in Chapter 2, the three types of behavior, based on resilience theories, for the outcome variable F(x) are Stability (Figure 11), adaptation (Figure 12), and transformation/collapse (Figure 13). In the case of the last behavior, collapse is the one commonly represented. Transformation can also be observed, based on the particular problem and loops interactions. For this model, the system can recover to shocks less than 0.08 fast variable units approximately. After that, the system collapses (Figure 13).

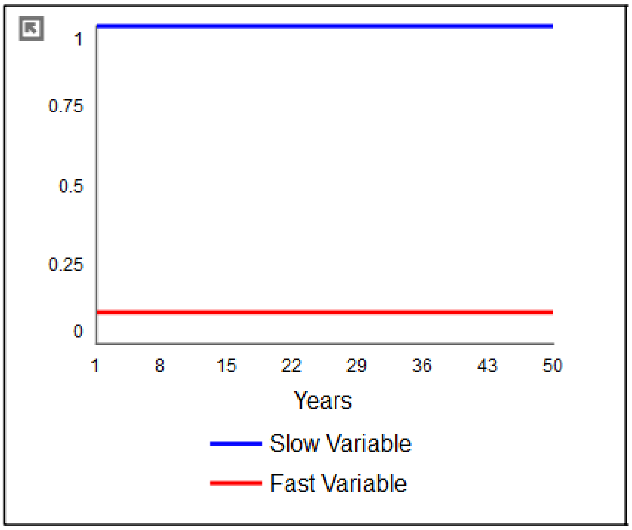


Figure 11. Equilibrium - Generic model

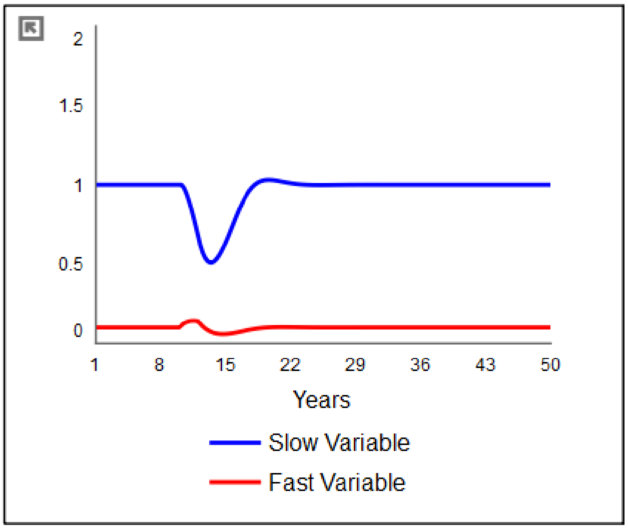


Figure 12. External disturbance (0.06 units) and recovery - Generic model

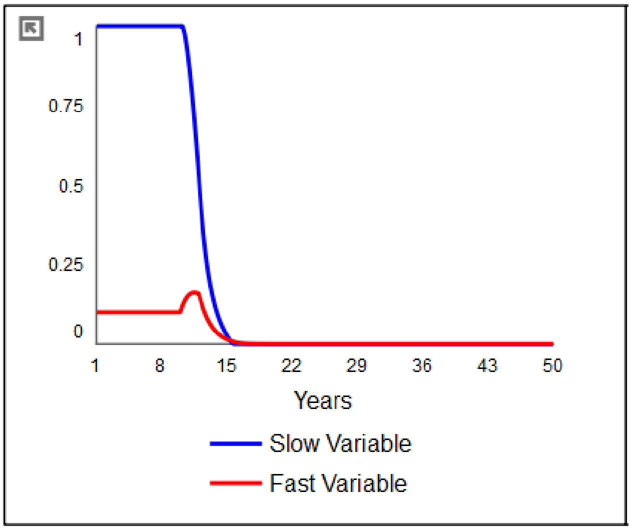


Figure 13. External disturbance (0.0856 units) and regime shift - Generic model

Buenos Aires model

In the case of Buenos Aires, all the feedback mechanisms of the generic model are represented in two sets of structures. The first one is related to the energy balance of the city and how the consumption of plastics and textiles can affect the energy matrix. It is expected that if the relative use of home cleaning plastics and textiles increases, the consumption of energy increases, and the energy balance decreases as a consequence. In the Figures 14, 15, and 16 can be seen the three types of behavior from the generic structure.

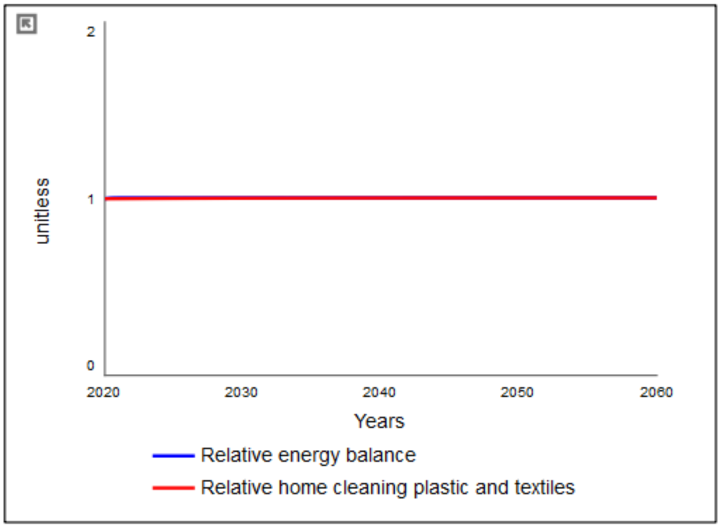


Figure 14. Equilibrium - Buenos Aires model - Energy balance

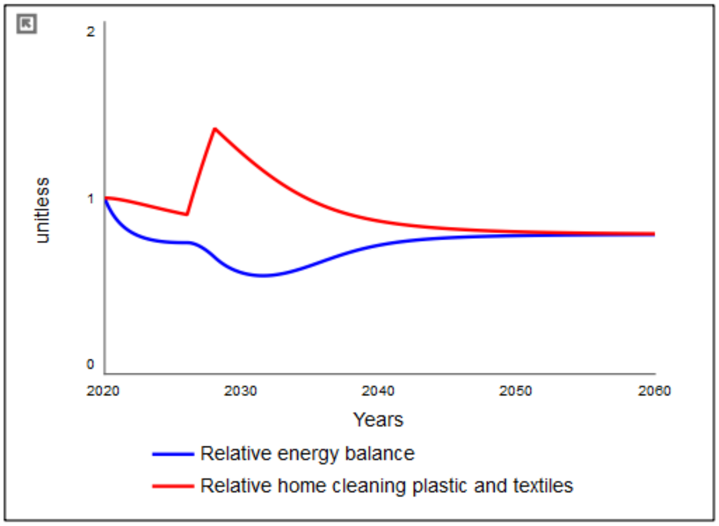


Figure 15. External disturbance (0.29 units) and recovery - Buenos Aires model – Energy balance

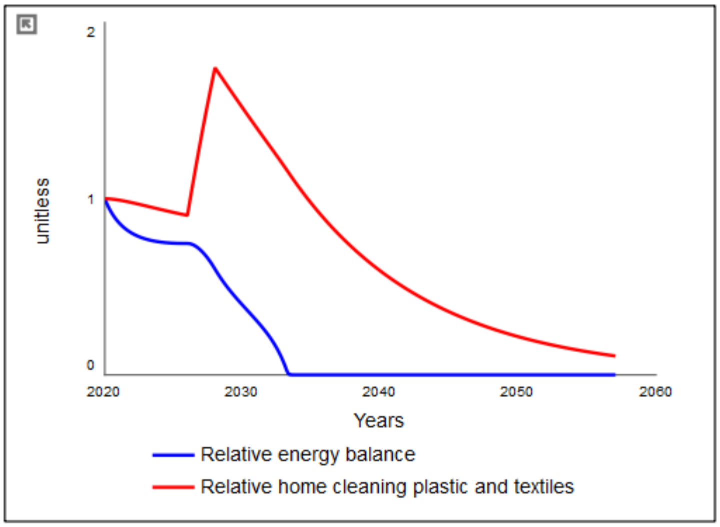


Figure 16. External disturbance (0.44 units) and regime shift - Buenos Aires model – Energy balance

For the second structure, social cohesion is represented in relation to the gender pay gap. If women's salary is closer to men's salary, there will be less pay gap and social cohesion will increase, as social cohesion involves reducing disparities in wealth and income. This effect is observed in Figure 17. This structure can be considered as a social system more than a purely social-ecological system.

In this can, it can be observed that the model, although having the same loops of the generic structure, does not reproduce the three types of behavior mentioned. The structure itself is capable to do so because contains the same mechanisms; however, the nature of the problem defined by the intermediate parameters and additional variables does not allow the same behavior of the generic structure.

The fact that this set of variables do not include the ecological component directly can influence the resultant behavior. More applications of the generic structure would be needed to define better the boundaries of the type of systems it can represent.

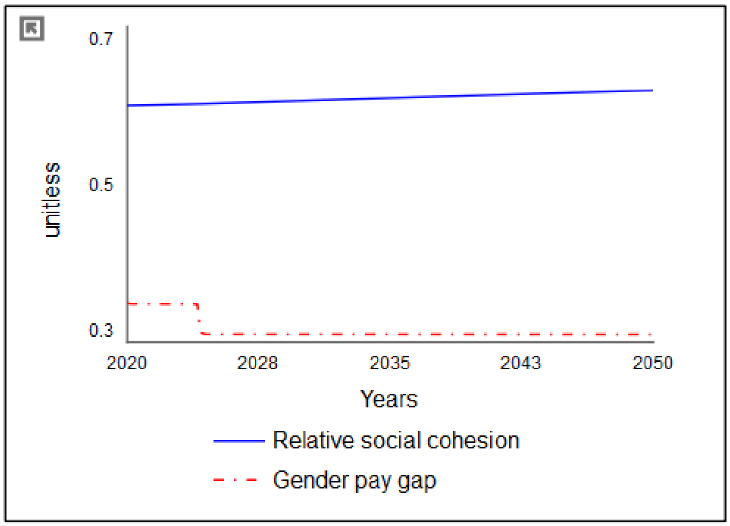


Figure 17. Behavior of the slow variable - Buenos Aires model - Social cohesion

Quito model

For Quito, two structures were built, one related to unused waste with the potential of being recycled and the other related to petroleum availability. As portrayed in the different figures, both systems are able to reproduce the behavioral modes: equilibrium, recovery, and regime shift.

The exception comes from the relative unused waste in Figure 22. The system can reproduce a recovery behavioral model as in Figure 20 if all the loops are activated. Although, in practice, the relative unused waste does not have a regeneration process since it is not a natural resource. It can have on the other side a degradation that is not considered in this exercise because the waste is mainly plastic, which takes a relatively long time to degrade. For this system of waste management, the behavior of recovery is not natural, but the regime shift is.

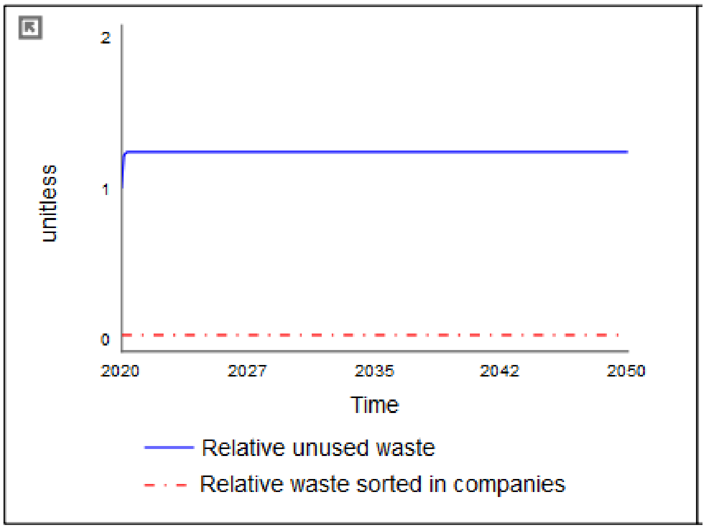


Figure 18. Equilibrium - Quito model – Waste management

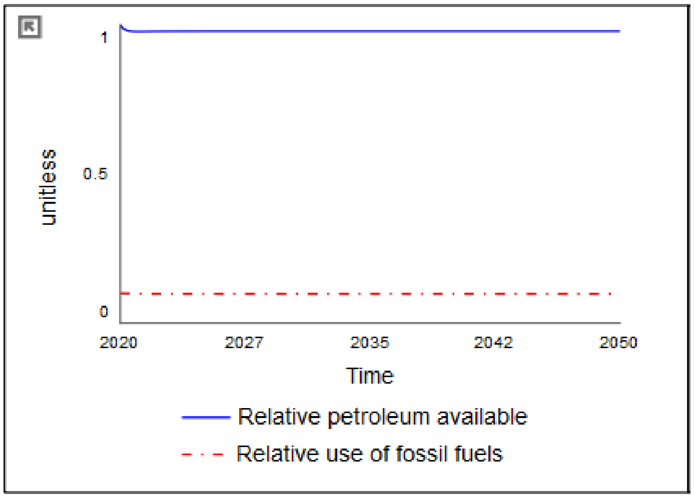


Figure 19. Equilibrium - Quito model - Fossil fuels

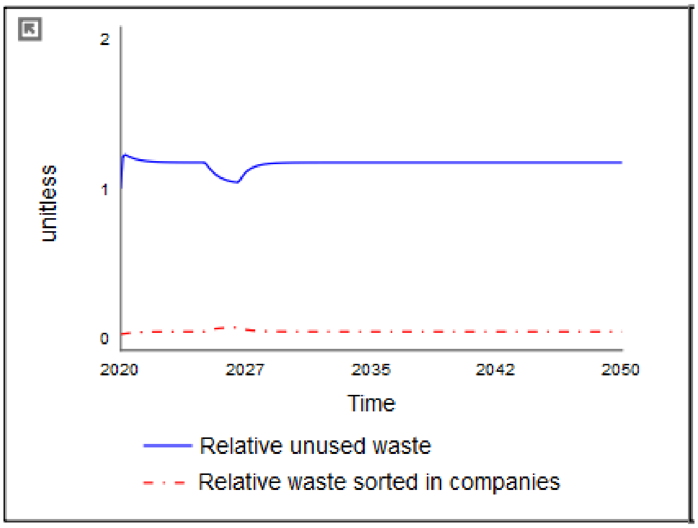


Figure 20. External disturbance and recovery - Quito model - Waste management - All loops activated

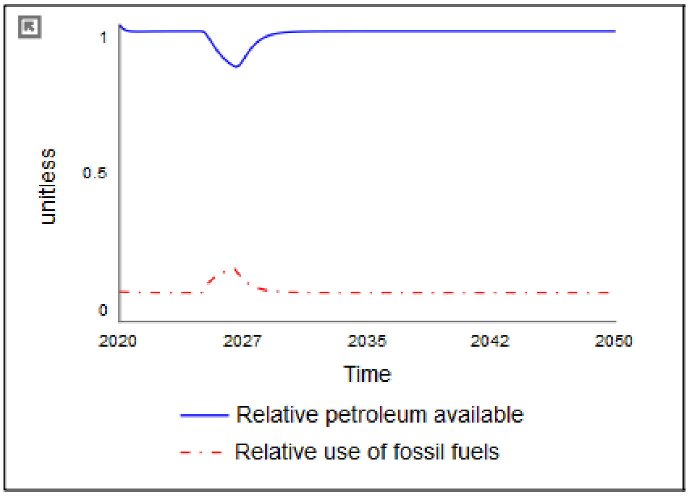


Figure 21. External disturbance (0.1 units) and recovery - Quito model - Fossil fuels

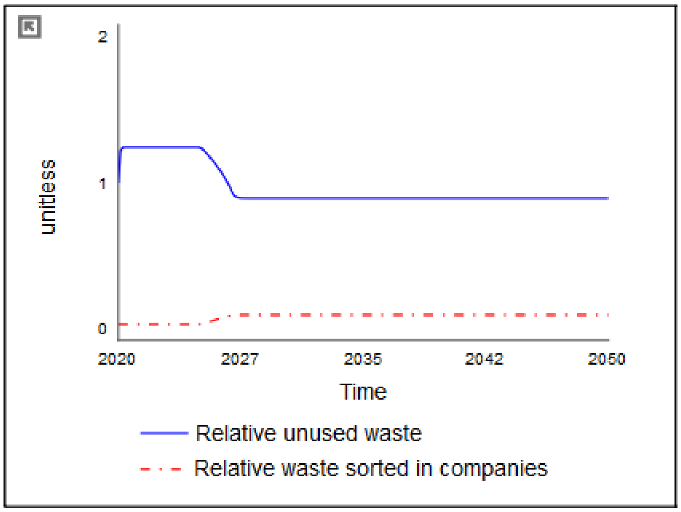


Figure 22. External disturbance (0.03 units) and regime shift - Quito model - Waste management - not regeneration loop

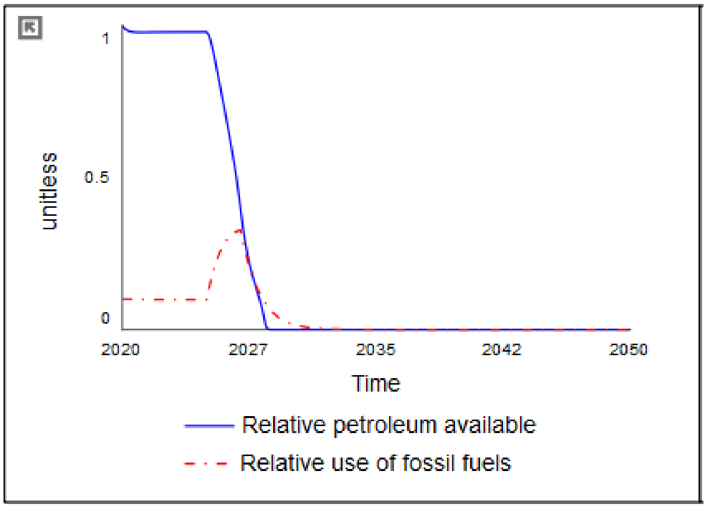


Figure 23. External disturbance (0.3 units) and regime shift - Quito model - Fossil fuels

Mexico City model

As mentioned earlier, from this case study the models start changing significantly in structure. Having the SD principle that structure drives behavior in mind, it can be said that the differences of structure make the system behave as in Figure 24. The system now does not reproduce the three types of behavior of resilience. For this system, the water resource of Xochimilco is decreasing at a constant pace, even with the policies implemented (winning projects).

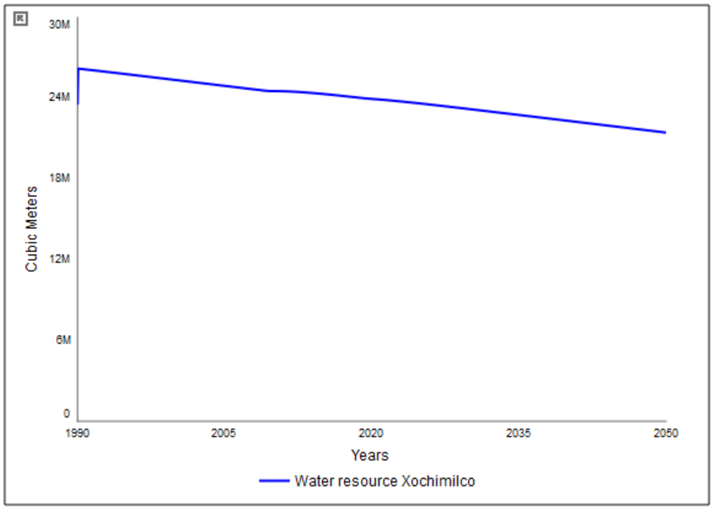


Figure 24. Behavior of the slow variable - Mexico City model

Salvador model

Similar to Mexico City case study, the changes in the structure create a change in the behavioral modes. Here, the water availability increases decreasingly due to the impact of policies implementation.

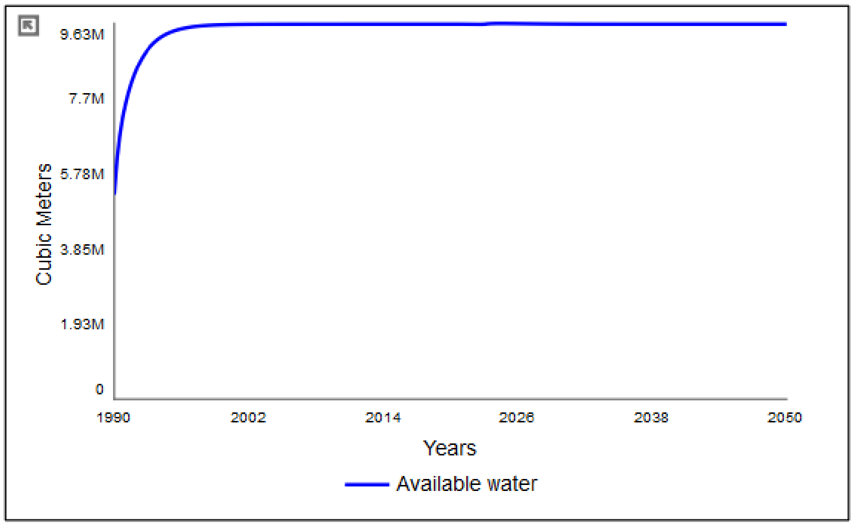


Figure 25. Behavior of the slow variable - Salvador model

Cordoba model

For Cordoba, non-classified residues is the representation of the slow variable. Given the policy's intervention, the amount of residues is decreasing over time. Another output variable, important for the client, is the contribution of the policies to the reduction of living costs of the local population (see Figure 27). As in Mexico City and Salvador, the model is not able to reproduce the same behavioral modes of the generic structure.

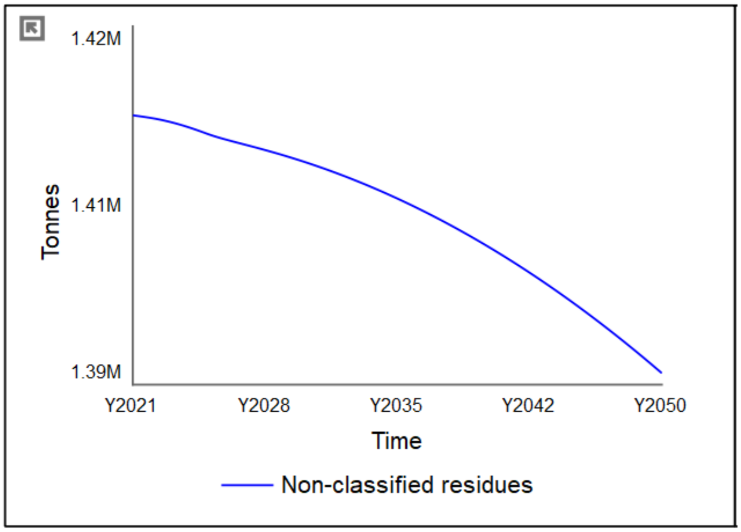


Figure 26. Behavior of the slow variable - Cordoba model

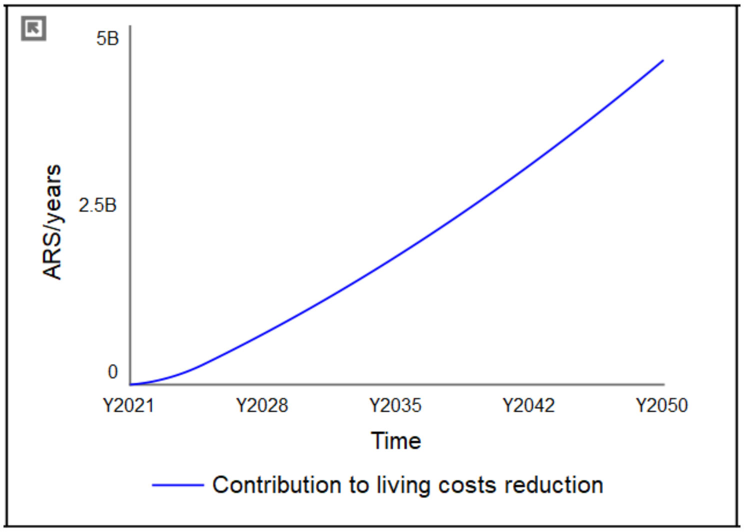


Figure 27. Behavior of the output variable 'contribution to living costs reduction' - Cordoba model

Chapter 6: Update of the generic structure and framework

Generic structure

After the adaptation of the Resilience generic structure through the case studies there are two main identified updates: the concept of disturbance and model scale. Regarding the first update, the original model proposed by Zhao et al. (2019) manages the disturbances in the resilience assessment as shocks, which were defined in Chapter 2. as short-term deviation from long-term trends. As systems can also be affected by long-term deviations, the variable before called “External shock on society” changes to “External disturbance” as portrayed in Figure 21. The structure does not change but the definition of external disturbance does: an external sudden short-term deviation from long term trends (shocks) or long-term trends or pressures (stressors) that have the potential to change substantially the current state of a system and/or the ability of the system to withstand future disturbances (Zseleczky & Yosef, 2014).

This change in the definition of the disturbance opens the spectrum of deviations that can be modelled, adding more flexibility. The equation behind the external disturbance can be changed to represent longer disturbances and the parameters defining the equation as height, introduction time and duration can be customized too.

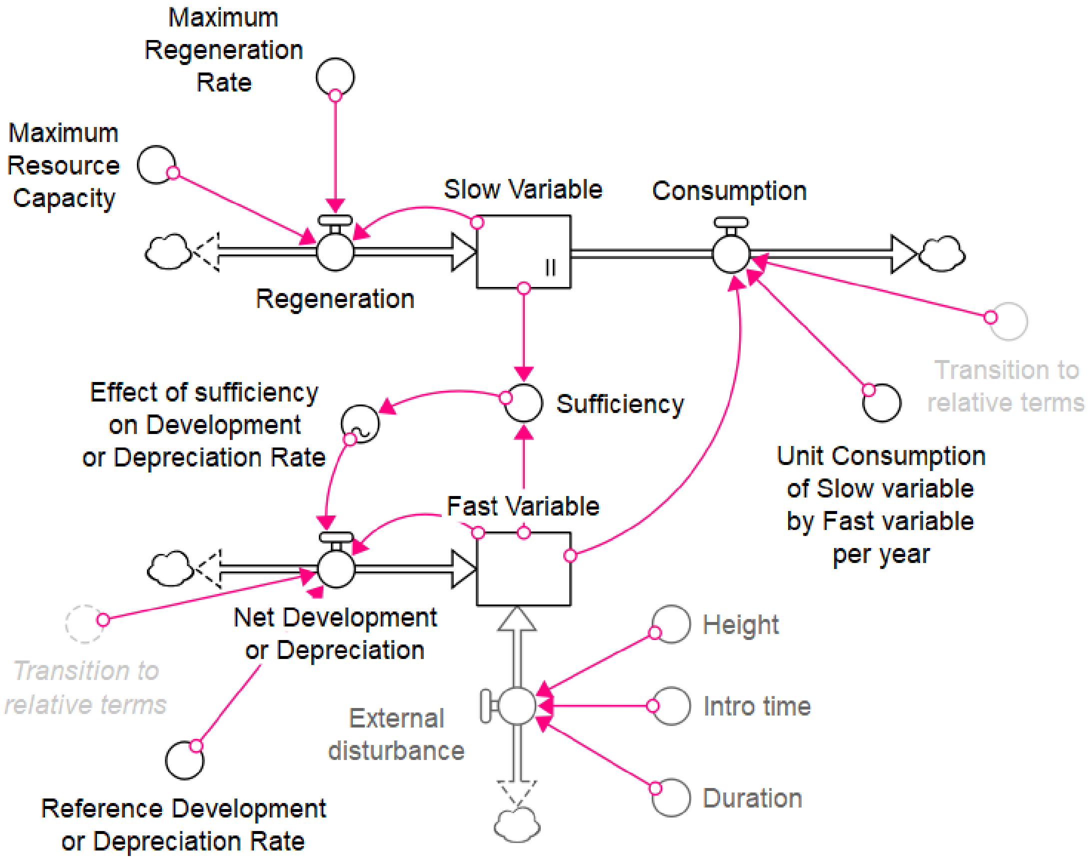


Figure 28. Updated resilience generic structure

In Figure 29 can be found an example of the behavior of the system where it is exposed to a long-term stressor. It can be observed that for run 1, the disturbance magnitude is so large that generates a collapse of the system, which is a behavior a short-term disturbance can also generate. Now, for runs 2 and 3, the disturbance does not create a collapse in the system but a transformation. If the system is permanently exposed to a disturbance, it adjusts and finds a new stable situation, it does not come back to the previous equilibrium. This a variation of the behavior called 'regime shift' with a pattern it has not been seen for short-term disturbances. Hence, the opportunities for analysis are more open.

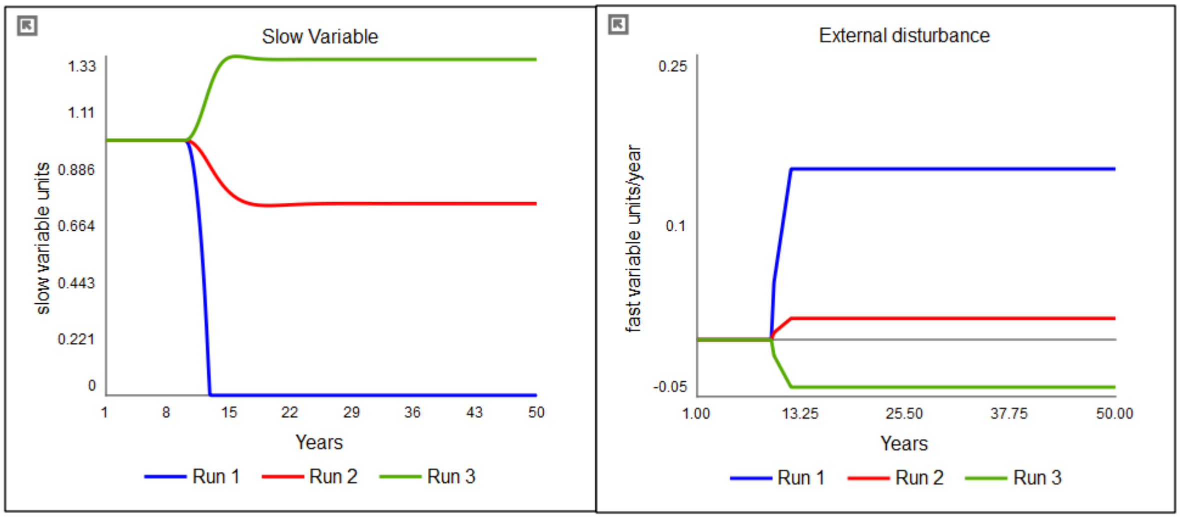


Figure 29. Response of the slow variable to a long-term external disturbance

Regarding the model scale, it was discovered as useful in practice the use of relative terms for the resilience assessment when there is uncertainty or lack of data, being these problems considered as common in practitioner's applications. The model is re-scaled in values around 0 to 1, and the logic of proportions in the model works around the Slow variable. The slow variable is initialized in 1, assuming that is the original value of the stock when the simulation starts. The fast variable is initialized in 0.1, assuming that the fast variable is 10 times less than the slow variable. That assumption changes based on the application of the generic model to a specific problem. The other variables and parameters are calculated as proportions of the relative terms. If the slow variable a is a groundwater source with an initial value of 3 million cubic meters and the maximum regeneration rate is 1 million cubic meters, in relative terms the value of the stock is 1 and the maximum regeneration rate 0.33.

Because the model is now working with decimal numbers, the parameter "transition to relative terms" is used, to adjust some of the variables to the right magnitude when the model is on relative terms (see Appendix 1 for more details). This parameter keeps the behavior consistency and scale. It was calibrated based on the original model in equilibrium first and then tested by its ability to reproduce the modes of behavior. When there is plenty of data and time, the model can be adjusted to the normal scale by removing the parameter "transition to relative terms".

Framework

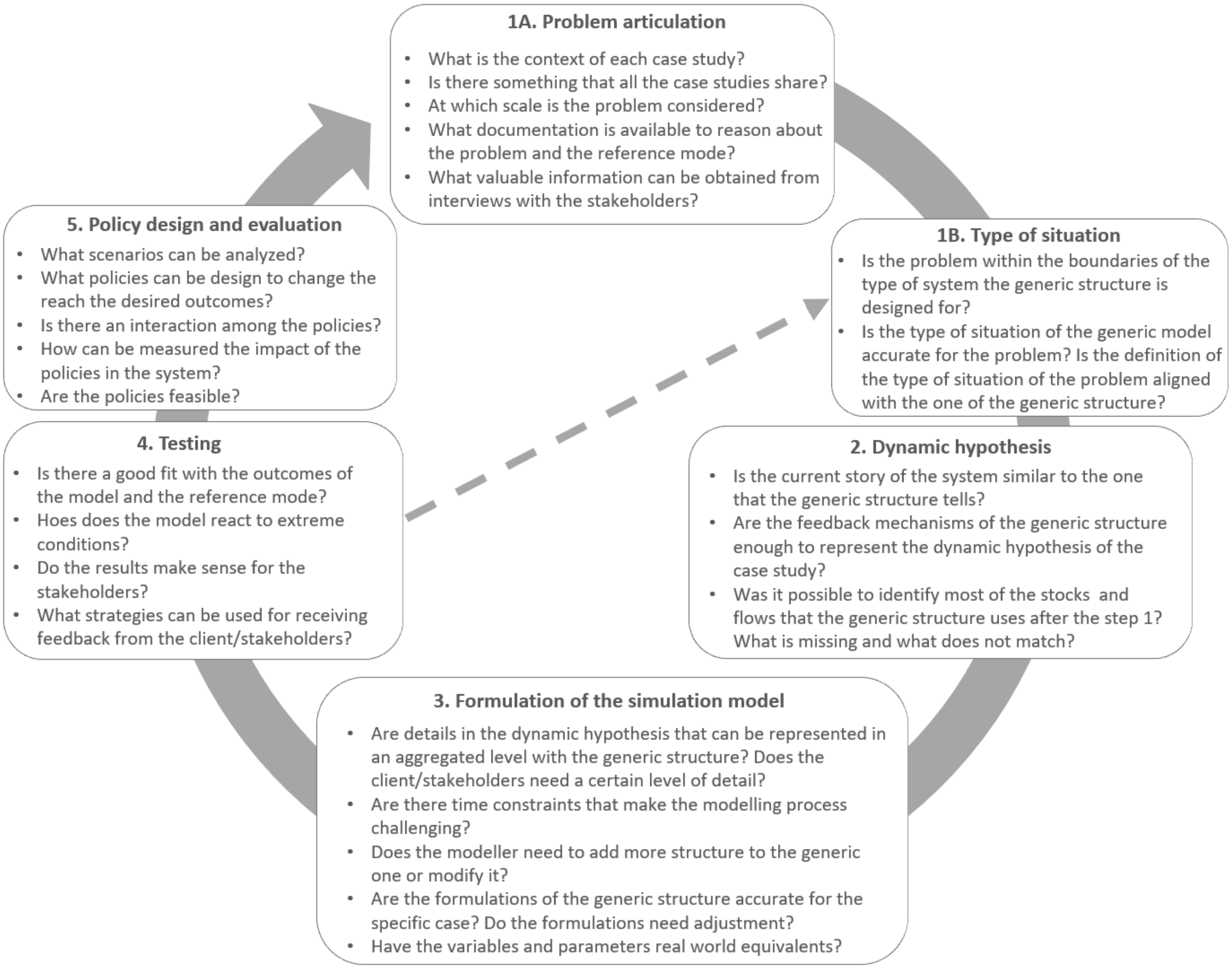
Along the modelling process through the cases, it was observed that the simulation models were moving farther and farther away from the generic structure. The modellers assumed, given the nature of the cases (resilience oriented), that the type of situation that applied for the generic structure could also be applied for the cases. This assumption was rediscovered later when the real nature of the assessments showed up. Although the client considered the approach of the challenges as resilience-oriented, they were more close to sustainability-oriented.

Thanks to this finding, a sub-step of problem articulation in the adaptation framework proposed in Chapter 4. was added. The sub-step defined as Type of situation (see Figure 22) seeks to avoid the use of generic structures that do not fit with the actual problem. Asking questions like "is the problem within the boundaries of the type of system the generic structure is designed for?" will make the modeller reason about the right fit between structures. In the case studies used in this research, most of the problems were identified as part of social-ecological systems; hence, the fit between types of systems was appropriate.

Now, with the type of situation is where the disagreement comes. The generic structure was designed for resilience situations where resilience has a specific meaning. The case studies, as mentioned above, had a different approach to resilience, focused on sustainability. This deviation made it unnecessary to use the same mechanisms of the generic structure, simplifying the feedback loops interplaying but increasing the time spent in the formulation of the simulation model step.

The same feedback (dotted arrow) that was proposed in Figure 10. is present in the updated framework with a variation, the relationship goes from testing to type of systems, instead of dynamic hypothesis. This is because the testing process will question the fit between the generic structure and the adapted structure, reassuring or altering the previous perception about the fit with the type of system or situation.

For resilience assessments particularly, a good question to be answered since the problem articulation that will benefit the analysis of the type of situation is the one presented by Herrera (2017) is: resilience of what to what? With this question, the modeller can identify which is the system's response represented by an outcome function F(x) to analyze and what is the specific disturbance to analyze (Herrera, 2017). If the client can identify the outcome function for the resilience analysis and the disturbance, it can be said that the type of situation that the resilience generic structure proposed in this research is design for can fit with the problem.



1A. Problem articulation

- What is the context of each case study?
- Is there something that all the case studies share?
- At which scale is the problem considered?
- What documentation is available to reason about the problem and the reference mode?
- What valuable information can be obtained from interviews with the stakeholders?

1B. Type of situation

- Is the problem within the boundaries of the type of system the generic structure is designed for?
- Is the type of situation of the generic model accurate for the problem? Is the definition of the type of situation of the problem aligned with the one of the generic structure?

2. Dynamic hypothesis

- Is the current story of the system similar to the one that the generic structure tells?
- Are the feedback mechanisms of the generic structure enough to represent the dynamic hypothesis of the case study?
- Was it possible to identify most of the stocks and flows that the generic structure uses after the step 1? What is missing and what does not match?

3. Formulation of the simulation model

- Are details in the dynamic hypothesis that can be represented in an aggregated level with the generic structure? Does the client/stakeholders need a certain level of detail?
- Are there time constraints that make the modelling process challenging?
- Does the modeller need to add more structure to the generic one or modify it?
- Are the formulations of the generic structure accurate for the specific case? Do the formulations need adjustment?
- Have the variables and parameters real world equivalents?

4. Testing

- Is there a good fit with the outcomes of the model and the reference mode?
- Hoes does the model react to extreme conditions?
- Do the results make sense for the stakeholders?
- What strategies can be used for receiving feedback from the client/stakeholders?

5. Policy design and evaluation

- What scenarios can be analyzed?
- What policies can be design to change the reach the desired outcomes?
- Is there an interaction among the policies?
- How can be measured the impact of the policies in the system?
- Are the policies feasible?

Figure 30. Update of the System Dynamics modelling process tailored for the adaptation of canonical situation models

Chapter 7: Discussion and conclusion

This section pretends to highlight the main findings obtained from the research exercise. It will start with an overview of the research questions answered through the document and will finish with a detailed answer to the last question, which summarizes the insights for the field in the use of generic structures.

How is resilience represented in a generic structure?

Resilience can be represented in a generic structure with two stocks that follow a density dependence relationship. In social-ecological systems there is a classification that divides variables into slow variables and fast variables, being slow and fast relative terms. The slow variable is usually a natural resource that changes slowly over time relative to the time horizon of the problem. This variable has a self-regeneration capacity and can be difficult to measure due to its magnitude. The fast variable is usually the human activities that influence the slow variable through consumption. The fast variable changes relatively rapidly and can be measure easily since they represent human-controlled systems. The behavior of the slow variable in relation to the behavior of the fast variable, called sufficiency in the model, determines how the fast variable will develop or depreciate.

One of the key pieces of the generic structure is the representation of external disturbances which allows to shock the system and analyze how the variables respond to that, answering questions like: Can the system recover after a certain disturbance? If it cannot recover, what is the new state that the system reaches? How large can the disturbance be before the system breaks? Is the system more vulnerable to shock or stressors? In this generic structure, the slow variable is the outcome variable where the response of the system to a disturbance can be measured.

The generic structure can reproduce the three types of responses to disturbances proposed by Walker et al. (2004, as cited in Herrera de Leon & Kopainsky, 2019). The system can remain stable after being shocked, it can also 'bend' and adapt to the change, or it can transform into a new system. The transformation can also be a collapse when it is considered as a negative response for the system. For the resilience generic structure, the stability mode is called *equilibrium,* adaptation is called *recovery,* and transformation is called *regime shift*.

How to adapt a generic structure to different cases/contexts?

The resilience generic structure is adapted based on the needs of each case and the limitations of the project. The result can be either the same as the generic structure, an enlarged version of the generic structure, or a totally different model. As the modelling process proposed by Sterman (2000) is flexible to adapt, the same modelling steps can be used as a framework for adapting a generic structure to a case study.

Particularly when using generic structures, the modeller should have an especial focus in each stage. For the problem articulation step, the modeller can focus on which is the context of the case study and how does that relate to the context of the generic structure. Then, in the Dynamic hypothesis step, there should be special attention to the fit of the case feedback mechanisms in the generic structure feedback mechanisms. At the moment of formulating the simulation model, there are decisions in adding more structure to the generic one or not based on the needs. The test step is there to challenge the adapted structure and make it more robust for the specific context. Finally, the policy design and evaluation step will focus on how the system can give different outcomes, which in the type of situation of the generic model is related to how can the system be more resilient.

How to validate the generic structure through the cases?

The validation of the resilience generic structure through the cases consists of analyzing the representation of the structure and behavior of the adapted structure. The more case studies can represent the main mechanisms and, as a consequence, behavioral modes of the generic structure, the more confidence can a modeller have when using the generic structure proposed in this research project.

As mentioned earlier, generic structures must meet all the tests required of a case-specific model, and in addition, the analyst must be able to argue that the model is in some senses, general (Paich, 1985). The modelling framework followed along this research project is aligned with that conception. Hence, the tests for creating confidence in generic structures proposed by Barlas (1996) are followed. In addition to that, an analysis of the generality of the structure was made, showing that the generic structure is quite general regarding the context to which can be applied. For the variety of socio-ecological systems studies, the results seem reasonable and realistic. There was one case of a system without an ecological component directly involved that could not significantly represent the behavioral modes of resilience responses. This strengthens the assumption behind the generic structure that the mechanisms apply within the boundaries of socio-ecological systems.

How does the generic structure and adaptation framework need to be updated?

After the adaptation exercise, there was a process of auto-evaluation where some opportunities for improvement came out. Regarding the generic structure, there was a change in the way of understanding the external disturbances sector. The original model proposed an external shock on society, which limited the type of disturbances that the system could experience. In the updated version, the external disturbance could be either a short-term deviation or a long-term stressor, making the generic structure more flexible. Given that in practice was useful to rethink the model scale due to the lack of precise data, the last update is the transition of the model to relative terms. This allows the modeller to work in projects that have uncertainty in the data while using not the real value but proportional values of the variables.

Regarding the framework, a sub-step of the problem articulation step is added in order to make easier the adaptation process of generic structure. The sub-step is called Type of situation and seeks to assure from early stages that the case study can be well represented by the generic structure. If the modeller discovers that the type of situation of the problem, in case of canonical situation models, is different from the one in the generic structure, can shift to another structure proposal faster.

What insights can the field gain from the use of generic structures?

Practicality/time

Generic structures could demonstrate to save time in the modelling process. During this exercise, the modellers could prove that when the generic structure was used the modelling time was within the deadline, which was one week. As can be observed in Table 3, the further the modellers advanced the smaller number of loops from the generic structure were represented. With this, the modellers also experienced more delay in the modelling process, the time was duplicated in most of the cases, from one week to two weeks when the generic structure was considerably adapted.

Even when the number of feedback loops in the structures was less than in the generic structure and not major loops were added, the modelling time was more.

Generic structures can be very well used when the boundaries of the project are tight and do not include a deep stakeholder's involvement in the modelling process. Since the feedback mechanisms are already there, the need for iterating in the modelling steps decreases. The modellers adjust the model based on the available information and can socialize mainly the behavior of the model, not necessarily the structure. Also, the aggregation level of the project should be considered. If the client requires a very detailed analysis, a generic structure is not the best option. It can be useful as a departure point, but the final structure might be quite different, or the generic structure can be a component of a bigger model in that case.

The practicality property of generic structures was already recognized by the authors of the original structure: "By comparing the final generic structure to the Lisbon water model, we realize that the generic structure could have facilitated our initial conceptualization efforts with the client, as we could have started from a holistic understanding from the beginning instead of eliciting each relationship. Even the problem definition could have been made easy if we had proposed the definition of key variables within the proposed generic structure" (Zhao et al., 2019)

In conclusion, the use of generic structures makes the modelling process faster and simpler. What the modeller does is associate the variables of the structure with the variables in real life, without thinking from zero about the structure per se. This characteristic of being practical to use can be a very good asset for consultant projects.

Type of situation

As Lane (1998) said, canonical situation models represent a type of situation, which in this case is resilience as the ability to adapt to external disturbances, in social-ecological systems. It was observed as a phenomenon in the process of adaptation through the cases that the models represented less and less the generic structure loops. Parallel to that, there was a process from the modellers of realizing that the focus that the client was putting on the assessments was not resilience but sustainability. The challenges made by the client were identified as Resilience challenges, although, resilience was not understood as the ability to adapt to external disturbances. As the modellers realized that they adapted the focus of the models towards sustainability assessments. The new focus then was to identify the variables that the winning projects were supposed to impact, identify the feedback mechanisms involved (usually minor feedback loops), and then create scenarios of growth of the projects with an estimation of the impact in the main variables or indexes, usually associated with sustainability as water quality, land use, waste management, vulnerable population employment, gender gap, CO2 generation, among others.

Under the mentioned conditions, an important insight from the adaptation process is that the generic structure is indeed designed for a specific type of situation. Hence, in order to use it in case studies, it is crucial to have a minimum match with the type of situation for which the generic model is designed. Reducing the probabilities of misperception of concepts will save effort in the dynamic hypothesis step of the modelling process that can be invested in making the model more robust. The more applications the canonical situation model has, the better defined the boundaries of applicability across context and/or systems will be.

Educational tool

Generic structures are recognized by several members of the System Dynamics field as tools for knowledge transfer: "Generic structures would make it unnecessary for each new analyst to relearn the same lessons" (Paich, 1985). In the adaptation exercise, the modellers acquired more knowledge with each iteration and case, and spent less time thinking about the mechanisms behind the structures.

The generic structure proposed in this research paper has demonstrated to be aligned with the theories related to social-ecological systems and resilience. Hence, it can be used as an interactive way of learning from the mentioned domains. For SES, it can be used to learn about some of the fundamentals of this complex adaptive system, especially the concepts of slow variable and fast variable, and their interactions. For resilience, it can be used to learn about the different responses that an SES can generate when is disturbed by an external factor.

Limitations and future steps

One of the biggest limitations of the adaptation process was the lack of data acquisition and analysis. That generated extra uncertainty in the modeling process and consequently increased the need of creating assumptions. The way the modellers mitigated risks was re-scaling to relative terms. The use of reference modes for the models could have made the adaptation and validation process more robust. The data could have been more accurate not only through the availability path but through the time path. The time expected from the client for each city's report was another limitation. The time was one month for all deliverables, being the model only a piece of the report, the modeling time reduces even more.

For future steps, a more robust validation exercise might include finding resilience assessments made with case-specific SD models and translate those models into the generic structure presented in this research study. After the adaptation, check how many loops are still present and how many loops are left out. Also, check how well the generic structure reproduces the behavior of the case studies using the results of the case study as a reference mode for the generic structure. This can be considered as a Family member test based on Lane (1998).

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Appendices

Appendix 1. Model documentation

	Equation	Properties	Units	Documentation	Annotation
Top-Level Model:					
Fast Variable(t)	Fast_Variable(t - dt) + (Net_Development_or_Depreciation + External_disturbance) * dt	INIT Fast_Variable = 0.1	fast variable units	Variable that changes rapidly in relation to the timescale of the slow variable. They are typically those factors that are primarily concern to ecosystem users, for example, a pest species or (often) ecosystem goods and services, such as crop production, clean water extraction, oil consumption, and so on. The fast variable can develop or depreciate over time and change through the introduction of external shocks. They are most easily measured and immediately altered by some system of management (Walker et al.,2012).	NON-NEGATIVE
Slow Variable(t)	Slow_Variable(t - dt) + (Regeneration - Consumption) * dt	INIT Slow_Variable = 1	slow variable units	In social-ecological systems, it is a variable that changes slowly in relation to the timescale of ecosystem service provision and management. They are typically natural resources consumed by a certain type of user. This variable usually determines how the fast variable reacts to external shocks (Walker et al., 2012). Slow variables are commonly harder to measure than fast variables because of their magnitude; when is very hard to measure the stock size, estimates or predictions are used, rather than the real value. Example: The slow variables, such as the amount of soil organic matter, shape how a fast variable, such as crop production, responds	NON-NEGATIVE

				to variation in an external driver, such as variation in rainfall during the growing season.	
Consumption	Fast_Variable*Unit_Consumption_of_Slow_variable_by_Fast_variable_per_year*Transition_to_relative_terms		slow variable units/year	Consumption over time of the slow variable given the fast variable value and the unit of consumption per fast variable of the slow variable.	UNIFLOW
External disturbance	STEP (Height, Intro_time) - STEP (Height, Intro_time+Duration)		fast variable units/year	An external sudden short-term deviation from long-term trends (shocks) or long-term trends or pressures (stressors) that have the potential to change substantially the current state of a system and/or the ability of the system to withstand future disturbances (Zseleczky & Yosef, 2014). In this model, the disturbance is programmed as a step function. The model has the ability to adapt to different types of functions based on the disturbance. For stressors, a ramp function might work properly, for instance.	
Net Development or Depreciation	Fast_Variable*Effect_of_sufficiency_on_Development_or_Depreciation_Rate*Reference_Development_or_Depreciation_Rate*Transition_to_relative_terms		fast variable units/year	Resultant development or depreciation rate from the normal rate affected by the sufficiency and by the previous level of the fast variable.	
Regeneration	Maximum_Regeneration_Rate*4*(Slow_Variable/Maximum_Resource_Capacity)*(Maximum_Resource_Capacity-Slow_Variable)/Maximum_Resource_Capacity		slow variable units/year	This variable represents the self-regeneration of the slow variable when is assumed that typically it is a natural resource. There is a non-linear relationship between the slow variable stock and the regeneration which is represented by a parabolic equation. The maximum resource capacity plays the role of the carrying capacity (CC) of the resource. The maximum regeneration rate is reached when the slow variable is at the resource capacity that generates the maximum sustainable yield (MSY). In this	

				model the MSY is half of the CC. That point defines the behavior of the regeneration, If the slow variable is increasing above the MSY, the regeneration rate decreases driven by a balancing loop mechanism. If the slow variable close to zero and moves towards the MSY, the regeneration rate increases driven by a reinforcing loop mechanism. After the slow variable reaches the Maximum resource capacity the regeneration is negative, and the mechanisms will tend to put the slow variable again at the CC.	
Duration	2		years	The timeframe in which the external disturbance is actively affecting the system	
Effect of sufficiency on Development or Depreciation Rate	GRAPH(Sufficiency) Points: (0.00, -10.00), (1.00, -9.00), (2.00, -8.00), (3.00, -7.00), (4.00, -6.00), (5.00, -5.00), (6.00, -4.00), (7.00, -3.00), (8.00, -2.00), (9.00, -1.00), (10.00, 0.00)		dmnl	This effect is based on the initial scale of the stocks, this is, how sufficient was the slow variable to the fast variable at the beginning of the simulation (equilibrium). This linear relationship is assuming that whenever the sufficiency is 10 there is zero effect on the development/depreciation rate. When the sufficiency is more than 10 (the resource is more available than in the equilibrium/initial situation) the effect is positive, which means the fast variable is going to develop. When the sufficiency is less than 10 (the slow variable is less available than the initial situation), the effect is negative, which means the fast variable is going to depreciate.	GF EXTRAPOLATED
Height	0.05		fast variable units/year	Magnitude of the external disturbance that the system will experience. It could be a positive or negative value, based on the given meaning to the disturbance. As positive it will add to the fast variable and as negative will drain the fast variable.	

Intro time	10		year	Point of the time horizon in which the external disturbance is going to be introduced to the system.	
Maximum Regeneration Rate	0.5		slow variable units/year	Maximum rate at which the slow variable can regenerate.	
Maximum Resource Capacity	2		slow variable units	Maximum capacity of the resource that controls the system from growing infinitely, playing the role as the carrying capacity (CC) of the environment for that resource.	
Reference Development or Depreciation Rate	0.0001		Per Year	Normal or average change over time of the fast variable development or depreciation.	
Sufficiency	Slow Variable/Fast Variable		slow variable units/fast variable units	Ratio between the slow variable level and the fast variable level, which establishes how adequate is the amount of the slow variable to respond to the fast variable level. The higher the ratio, the more adequate is the slow variable in relation to the fast variable. Also, as long as the fast variable develops and increases, the slow variable might be less sufficient.	
Transition to relative terms	1000		dmnl	Parameter used to adjust some of the variables to the right magnitude when the model is on relative terms. This parameter keeps the behavior consistency and scale.	
Unit Consumption of Slow variable by Fast variable per year	0.005		slow variable units/fast variable units/year	Slow variable units consumed per each fast variable unit per time.	

Total	Count	Including Array Elements
Variables	16	16
Stocks	2	2
Flows	4	4
Converters	10	10

Constants	8	8
Equations	6	6
Graphicals	1	1

Run Specs	
Start Time	1
Stop Time	50
DT	1/15
Fractional DT	True
Save Interval	0.0625
Sim Duration	1.274
Time Units	Years
Pause Interval	0
Integration Method	RK4
Keep all variable results	True
Run By	Run
Calculate loop dominance information	True
Exhaustive Search Threshold	1000

Appendix 2. Extreme conditions validation test

For the parameter *Unit consumption of slow variable by fast variable*, it is logical that when it takes extreme high values the slow variable decreases rapidly (depletes), and when it takes extreme small values, the slow variable increases above the equilibrium because of its natural regeneration.

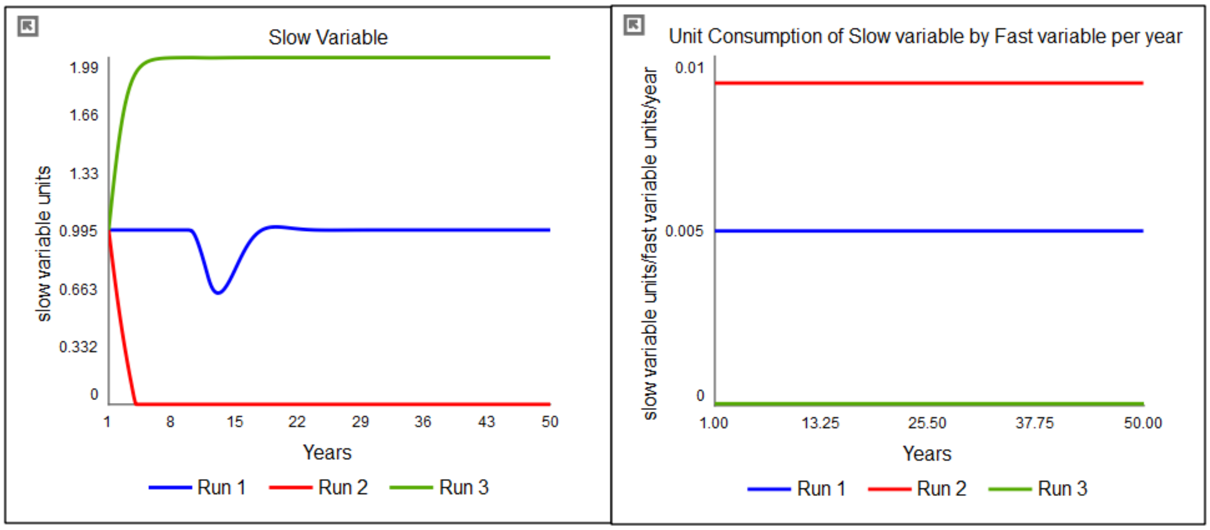

Figure 31. Extreme conditions test for the parameter Unit consumption of slow variable by fast variable

For the parameter *Maximum Regeneration Rate*, it is normal that when the parameter is close to zero, the slow variable depletes because cannot be regenerated. On the other hand, when the *Maximum regeneration rate* is very high, it makes sense that the slow variable grows fast because it is regenerating more. Due to the *maximum resource capacity*, even if the maximum regeneration tends to infinite, the slow variable will not grow to infinite.

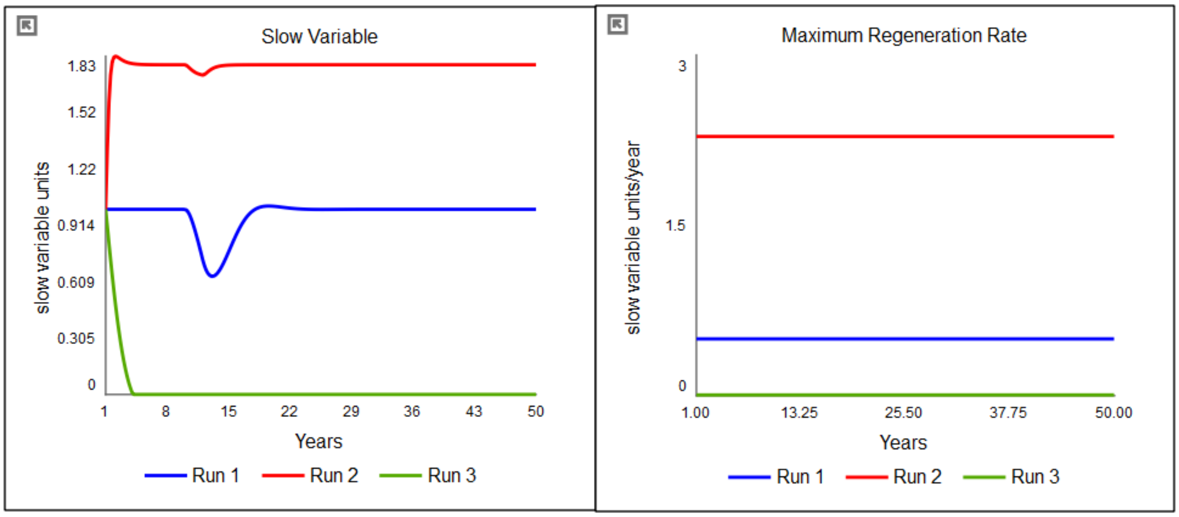

Figure 32. Extreme conditions test for the parameter Maximum regeneration rate

In the case of the *Maximum Resource capacity*, it makes sense that the slow variable depletes when the parameter is zero because there is no capacity for the stock to grow. Now, when the Maximum regeneration rate stays fixed, and the *Maximum resource capacity* takes extreme high values, the slow variable also depletes. This is logical when analyzing the structure graph because the parabola is less narrow than before which indicates that is harder for the slow variable to move in it, and more difficult to change the behavior. Also, the *Maximum regeneration rate* is constraining the slow variable to grow when the *Maximum resource capacity increases*.

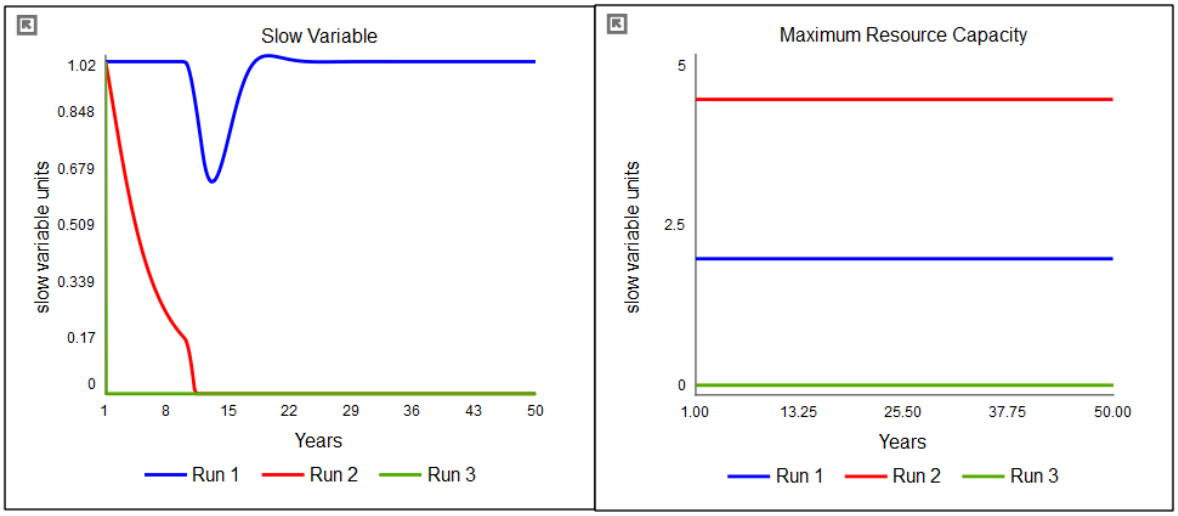

Figure 33. Extreme conditions test for the parameter Maximum resource capacity

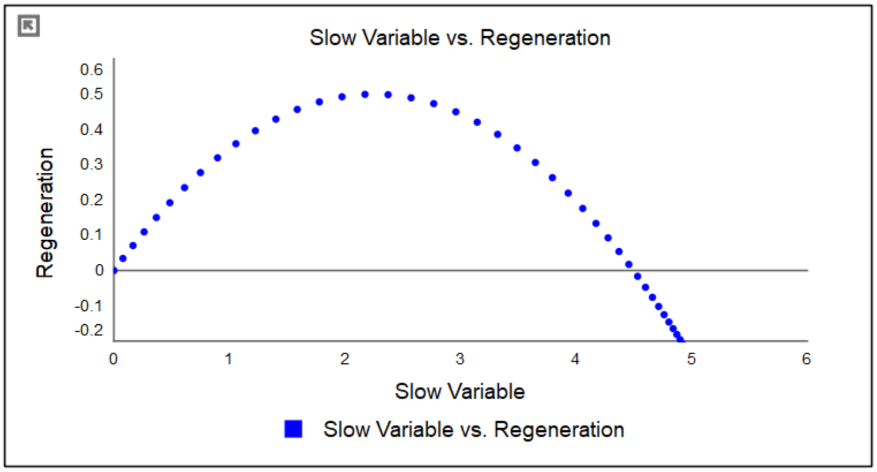

Figure 34. Structure graph of the stock 'slow variable' and its flow 'regeneration' when a extreme condition in the Maximum resource capacity

For the Reference Development or Depreciation rate, when the parameter value is high, the fast variable adjusts much more quickly (see Figure 28), having smaller peaks and making the slow variable recover faster too. When the parameter is small (close to zero), an increase in the fast variable due to the disturbance is much more aggressive and takes longer to depreciate, which causes the slow variable to cross the recovery threshold and turn into a collapse. These behaviors in extreme conditions make sense because based on how quickly the fast variable will react to the disturbance and the sufficiency, is easier for the slow variable to adjust.

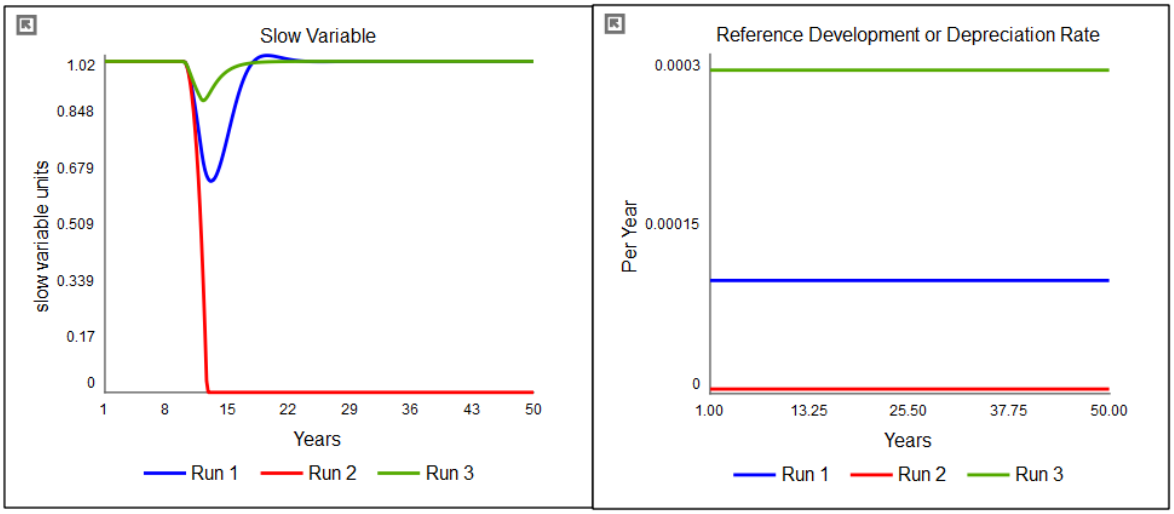

Figure 35. Extreme conditions test for the parameter Reference development or depreciation rate

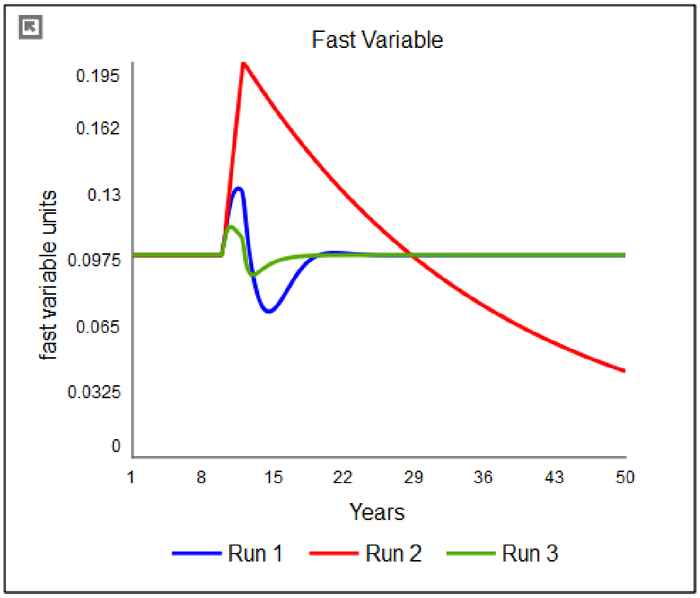

Figure 36. Extreme conditions test for the parameter Reference development or depreciation rate on the fast variable

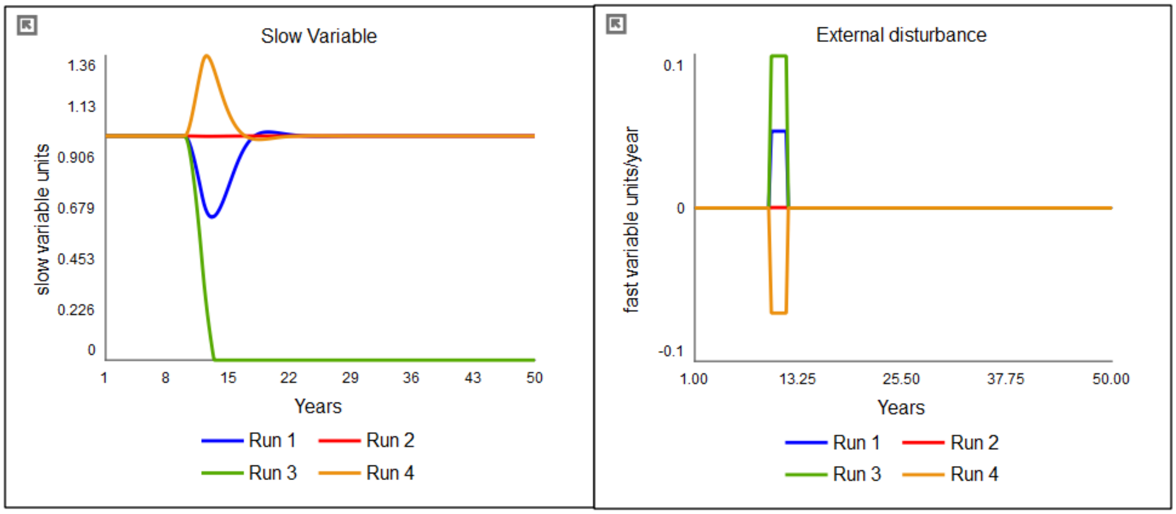

Figure 37. Extreme conditions test for the parameters regarding a short-term external disturbance on the slow variable

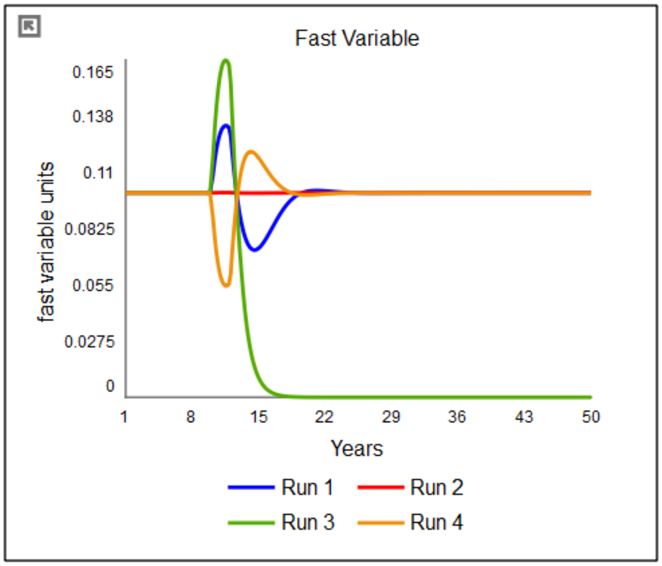

Figure 38. Extreme conditions test for the parameters regarding a short-term external disturbance on the fast variable

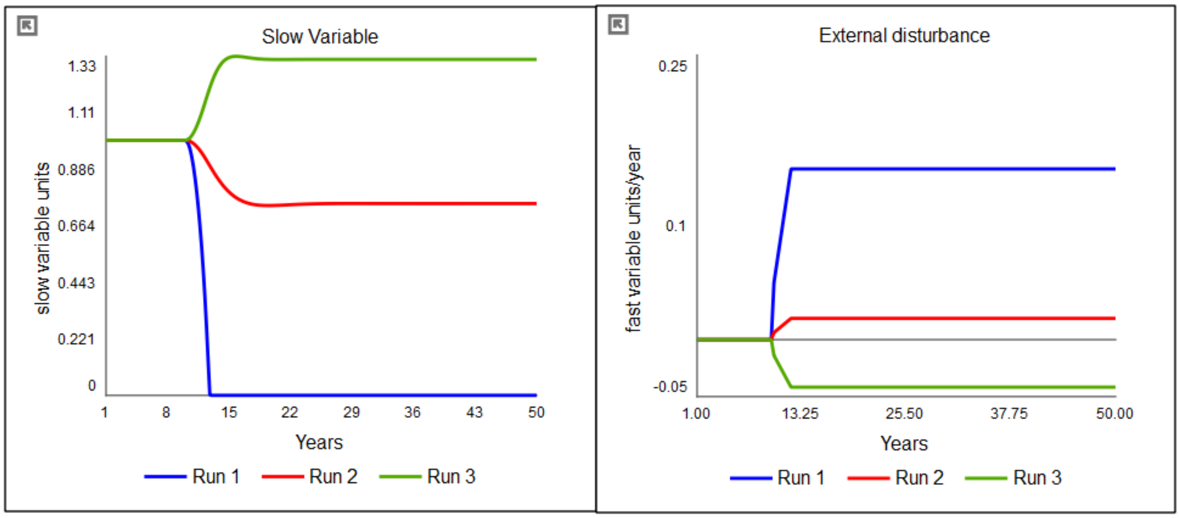

Figure 39. Extreme conditions test for the parameters regarding a long-term external disturbance on the slow variable

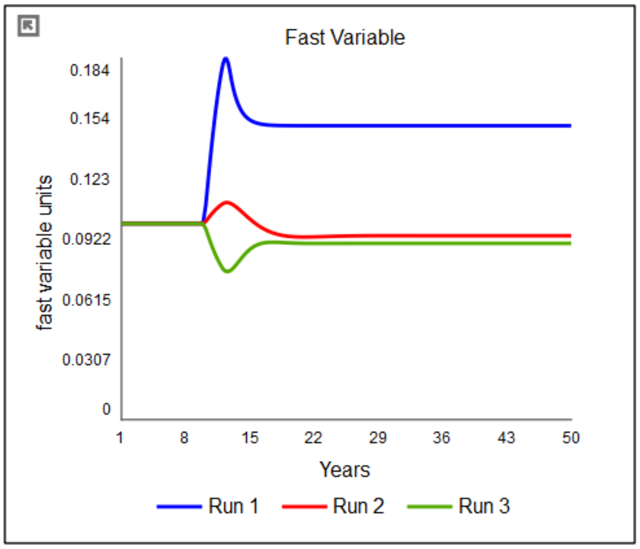

Figure 40. Extreme conditions test for the parameters regarding a long-term external disturbance on the fast variable

Appendix 3. Integration error test

The behavior of the output variable does not change dramatically with changes in the integration method. The ones that seem more precise in behavior reproduction are RK2 and RK4.

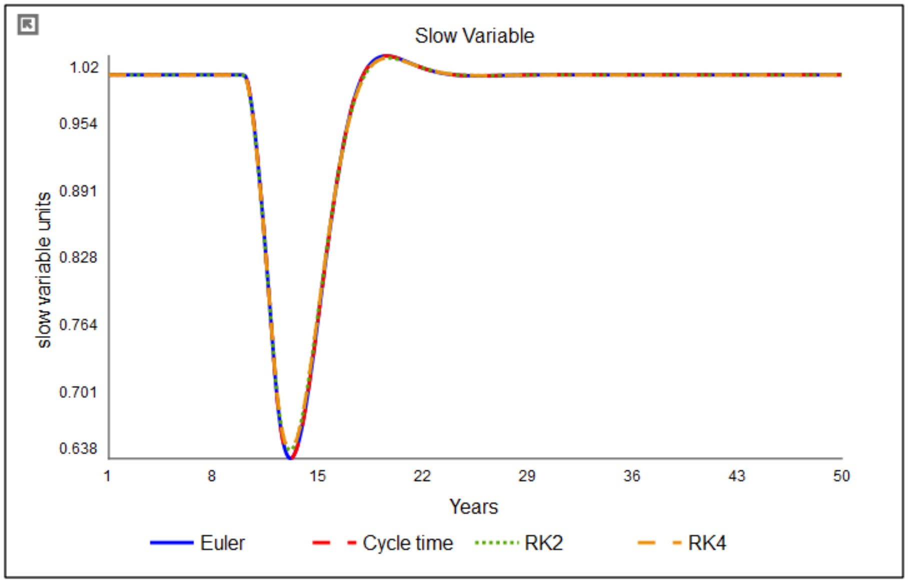

Figure 41. Integration error test

The behavior of the output variable does not change dramatically with changes in the integration method. The ones that seem more precise in behavior reproduction are RK2 and RK4.

With the chosen integration method RK4, after DT=5 the behavior stays with the same shape. The one used by the model is DT=15.

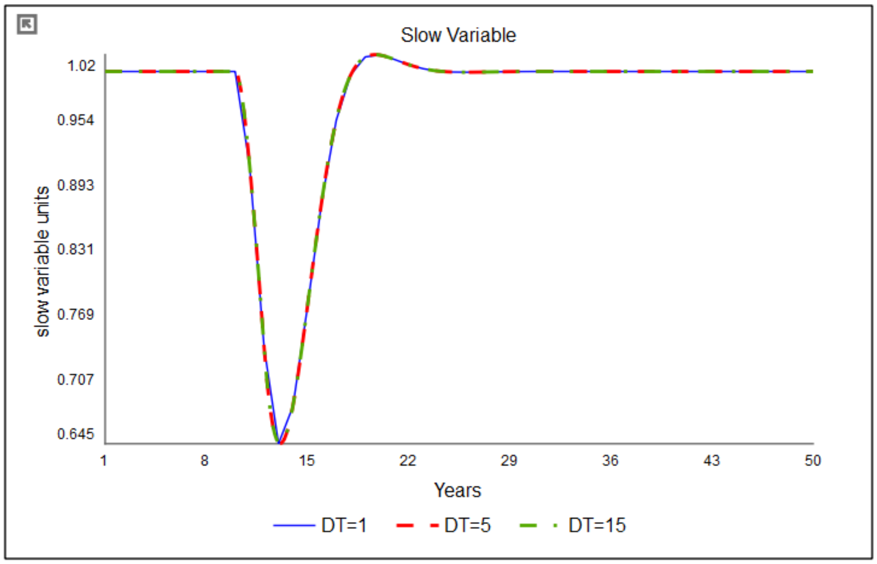

Figure 42. DT test with RK4 integration method

Appendix 4. Behaviour sensitivity test

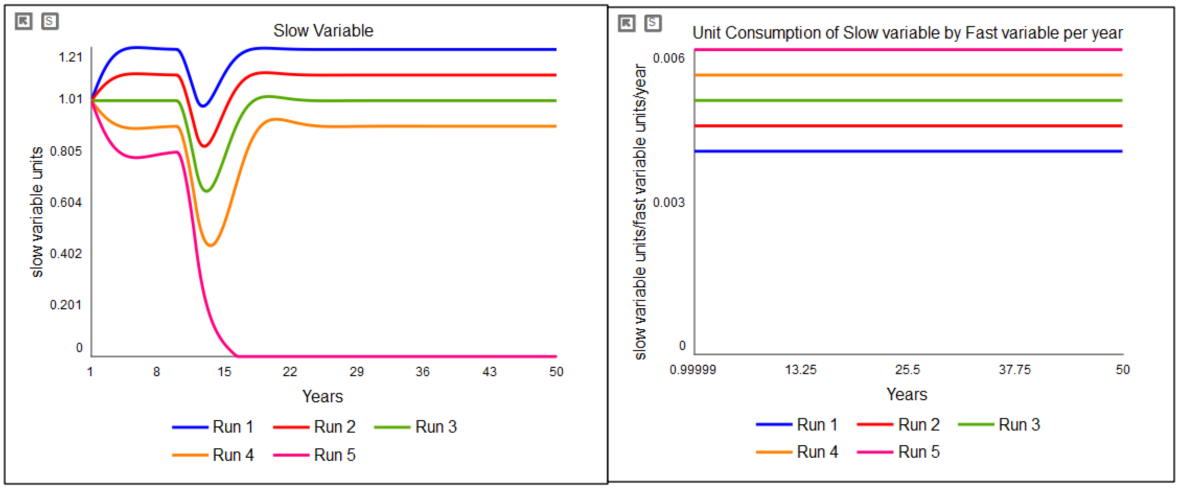

Figure 43. Systems' sensitivity to changes in Unit consumption of Slow variable by Fast variable per year

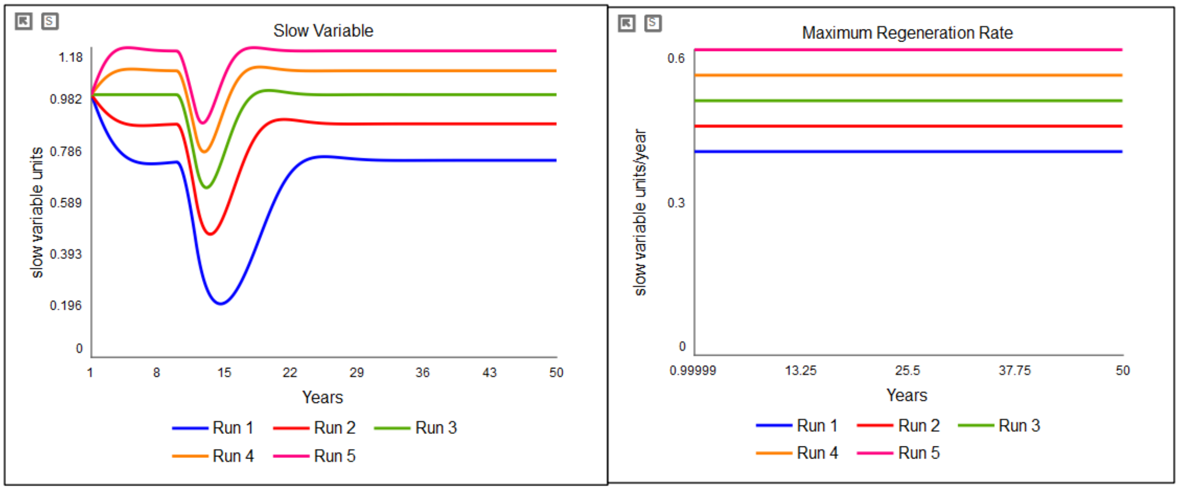

Figure 44. Systems' sensitivity to changes in Maximum regeneration rate

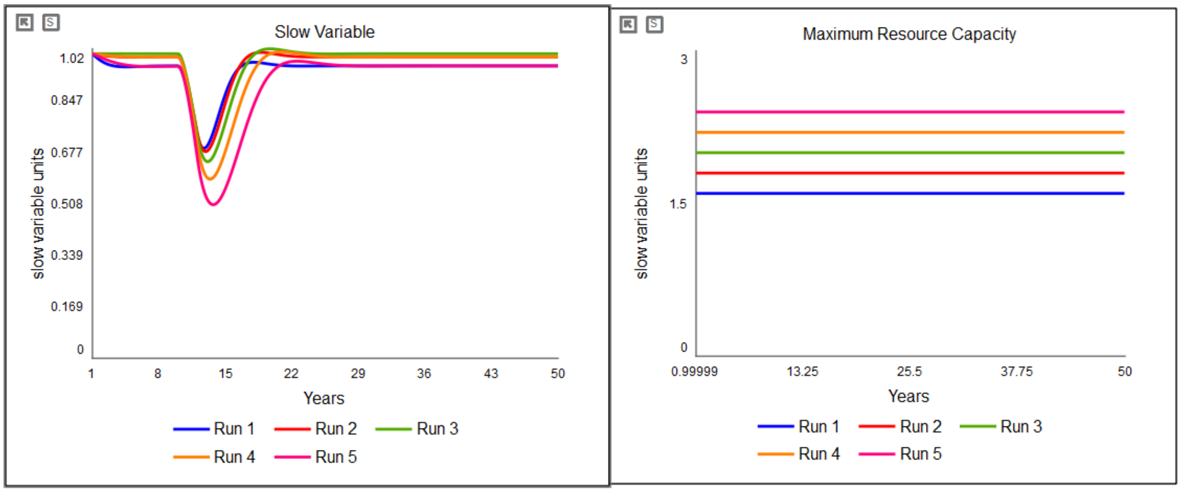

Figure 45. Systems' sensitivity to changes in Maximum Resource Capacity

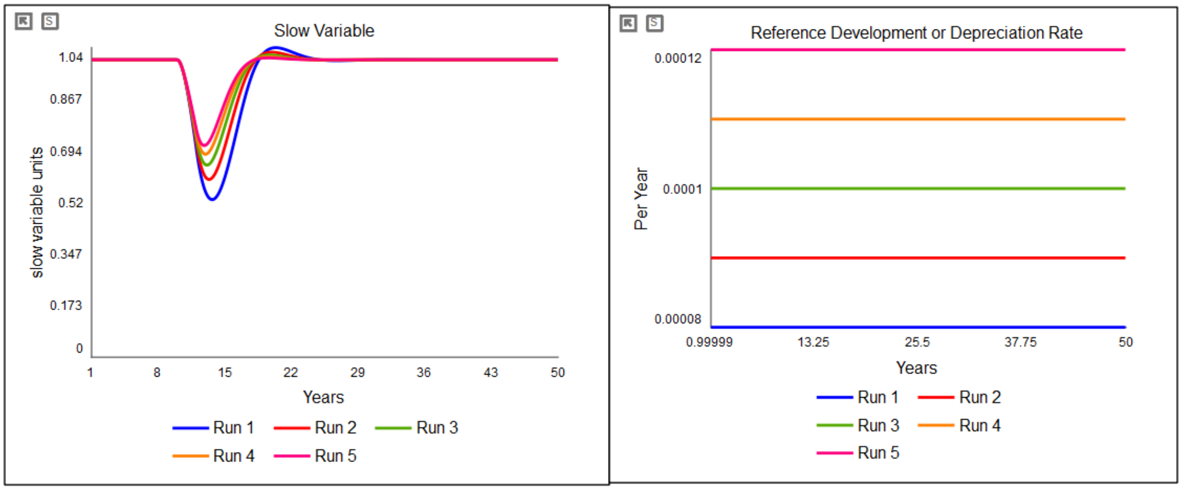

Figure 46. Systems' sensitivity to changes in Reference development or depreciation rate

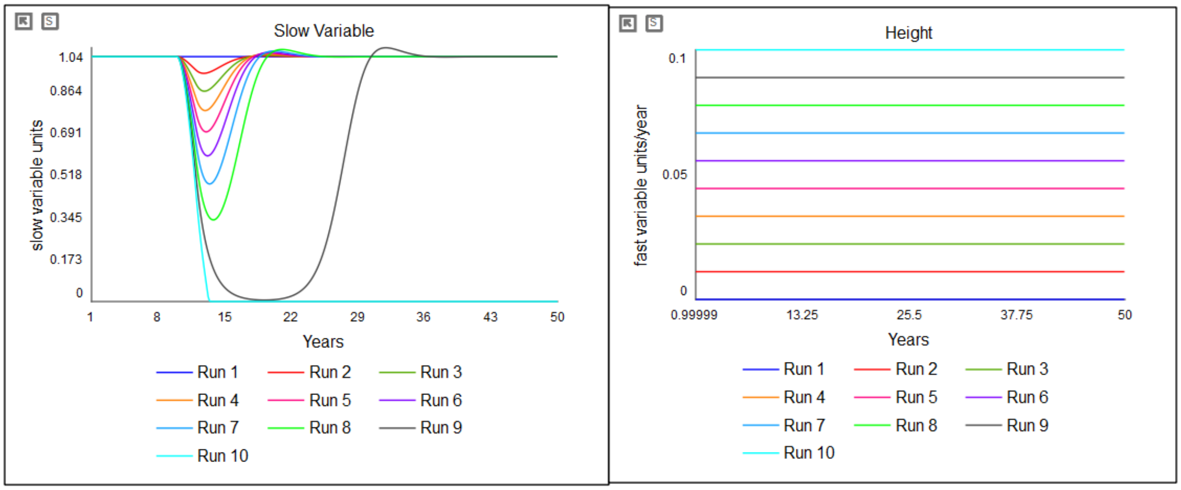

Figure 47. Systems' sensitivity to changes in the disturbance's height

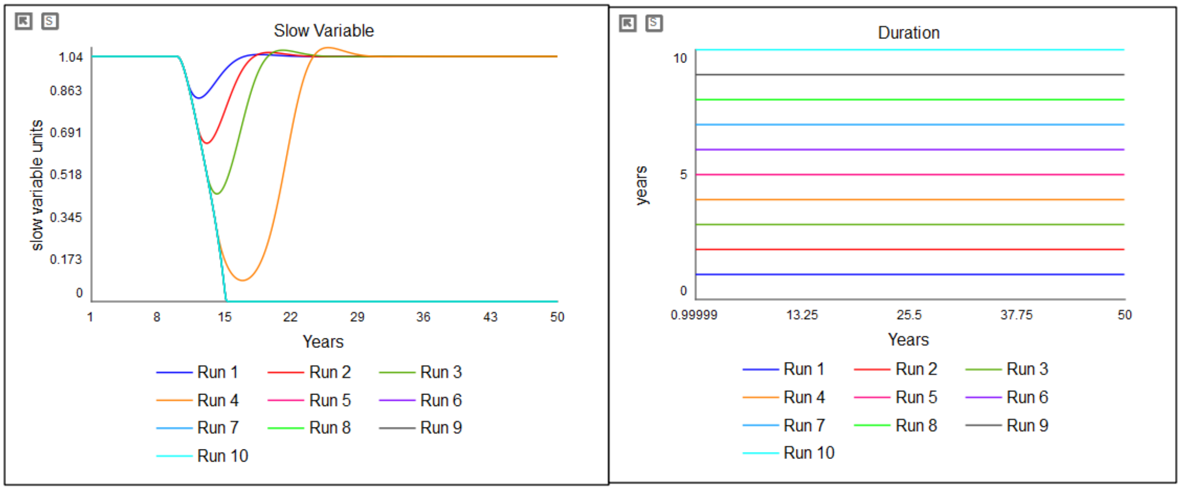

Figure 48. Systems' sensitivity to changes in the disturbance's duration