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Application of Systems-Approach in Modelling Complex City-Scale Transdisciplinary Knowledge Co-Production Process and Learning Patterns for Climate Resilience

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Abstract: Literature shows that much research has been conducted on the co-production of climate knowledge, but it has neither established a standardized and replicable model for the co-production process nor the emergent learning patterns as collaborators transition from the disciplinary comfort-zone (disciplinary and practice biases) to the transdisciplinary third-space. This study combines algorithmic simulation modelling and case study lessons from Learning Labs under a 4-year (2016–2019) climate change management project called Future Resilience of African CiTies and Lands in the City of Blantyre in Malawi. The study fills the research gap outlined above by applying a systems-approach to replicate the research process, and a Markov process to simulate the learning patterns. Results of the study make a number of contributions to knowledge. First, there are four distinct evolutionally stages when transitioning from the disciplinary comfort-zone to the transdisciplinary third-space, namely: Shock and resistance to change; experimenting and exploring; acceptance; and integration into the third-space. These stages are marked by state probabilities of the subsequent stages relative to the initial (disciplinary comfort-zone) state. A complete transition to the third-space is marked by probabilities greater than one, which is a system amplification, and it signifies that there has been a significant increase in learning among collaborating partners during the learning process. Second, a four-step decision support tool has been developed to rank the plausibility of decisions, which is very hard to achieve in practice. The tool characterizes decision determinants (policy actors, evidence and knowledge, and context), expands the determinants, checks what supports the decision, and then rates decisions on an ordinal scale of ten in terms of how knowledge producers and users support them. Third, for a successful transdisciplinary knowledge co-production, researchers should elucidate three system-archetypes (leverage points), namely: Salient features for successful co-production, determinant of support from collaborators, and knowledge co-production challenges. It is envisioned that academics, researchers, and policy makers will find the results useful in modelling and replicating the co-production process in a methodical and systemic way while solving complex climate resilience development problems in dynamic, socio-technical systems, as well as in sustainably mainstreaming the knowledge co-produced in policies and plans.

Keywords: climate change; complex social-technical systems; decision-support; systems-theory; third-space-transition modelling

Citation: Mkandawire, B.; Thole, B.; Mamiwa, D.; Mlowa, T.; McClure, A.; Kavonic, J.; Jack, C. Application of Systems-Approach in Modelling Complex City-Scale Transdisciplinary Knowledge Co-Production Process and Learning Patterns for Climate Resilience. *Systems* **2021**, *9*, 7. https://doi.org/10.3390/systems9010007

Received: 22 October 2020
Accepted: 8 January 2021
Published: 22 January 2021

1. Introduction

1.1. Systems-Approach

Many studies have been conducted to explore ways of improving the modes of co-production of climate science and mainstreaming of the same in the city decision-making process, which have ranged from engagements between decision makers and scientists [1,2], the application of empirical studies of specific actions and activities that foster trust and build lasting relationships [3], and utilization of boundary organizations to aid engagements that link knowledge producers and users [4,5]. Much of these studies have managed to unpack crucial research questions in climate science knowledge production within complex city policy and governance contexts; they have been unidirectional and not driven by theory; have failed to establish a systematic, methodical, and replicable model for the co-production process; and have focused more on units of analysis and detail complexity, and less on dynamic complexity of emergent properties of complex socio-technical systems. These shortfalls have made it difficult to replicate the research methodology and to depict useful archetypes (leverage points for the improvement of systems). This research paper has applied a multi-directional, general systems-theory (see Section 2.1) to urban climate science knowledge co-production to reinforce the previous studies. The general systems-approach or theory, has six characteristics on which this study has leveraged, namely [6], ([7], p. 322): It is holistic—whereby, emergent issues that cannot be quantitatively resolved are explored to reveal salient linkages; systematic—employs a methodological, consistent, and repeatable approach; systemic—considers decision-making as an emergent system where small things integrate into complete wholes; risk-based—sets priorities to identify risks associated with the domain being explored; optimal—determines trade-offs between competing factors such as quality of the knowledge produced, time, and costs associated with the learning processes; and sustainable—considers specific actions which are capable of creating a lasting footprint of networks and best practices and reveals possible up-scalable activities. Researchers in engineering and social science have come to realize that systems-thinking, once perceived as a theory without context and superficial, has potential in solving complex chaotic phenomena such as urban climate resilience development [8] (pp. 1185–1186). This research engages in that discourse and sets policy and communication fora, through real case studies and simulations.

1.2. Background and Context

Being an agro-based economy and relying on hydro-power generation, the development of Malawi is climate sensitive. In Blantyre, risks are already being experienced as climate events intersect with other socio-economic drivers. In the last decade, record low water levels have been registered in Lake Malawi (see Figure 1), the major source of water for Shire River, which is used for hydro-electric power generation and water supply to the City of Blantyre.

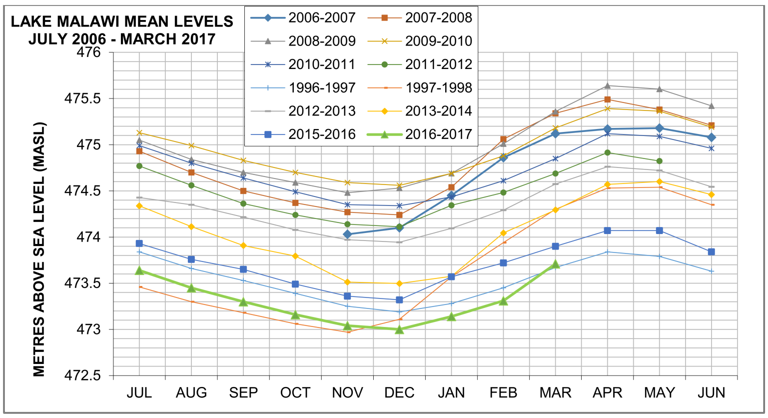

Figure 1. Record low water levels in Lake Malawi as an adverse impact of climate change experienced in Malawi in half a century [9].

Extreme hot and dry climate conditions experienced in recent years have led to the shrinkage of many rivers, for instance, the Lisungwi River (see Figure 2), a major tributary of the Shire River.

(**a**) A normal dry season status

(**b**) A dry season influenced by extreme climate change

Figure 2. Shrinkage of Lisungwi River (a Shire River tributary) due to the adverse climate change (Source: Authors).

Rapid urbanization and growing informal settlements in and around the city have resulted in degradation of natural resources [10]. For example, deforestation has occurred as charcoal industries have grown to supply energy to many informal households [11], see, e.g., Figure 3. These dynamics, coupled with a limited capacity of responsible authorities to manage water at a catchment scale, have resulted in risks associated with water security and energy for Blantyre City and its residents.

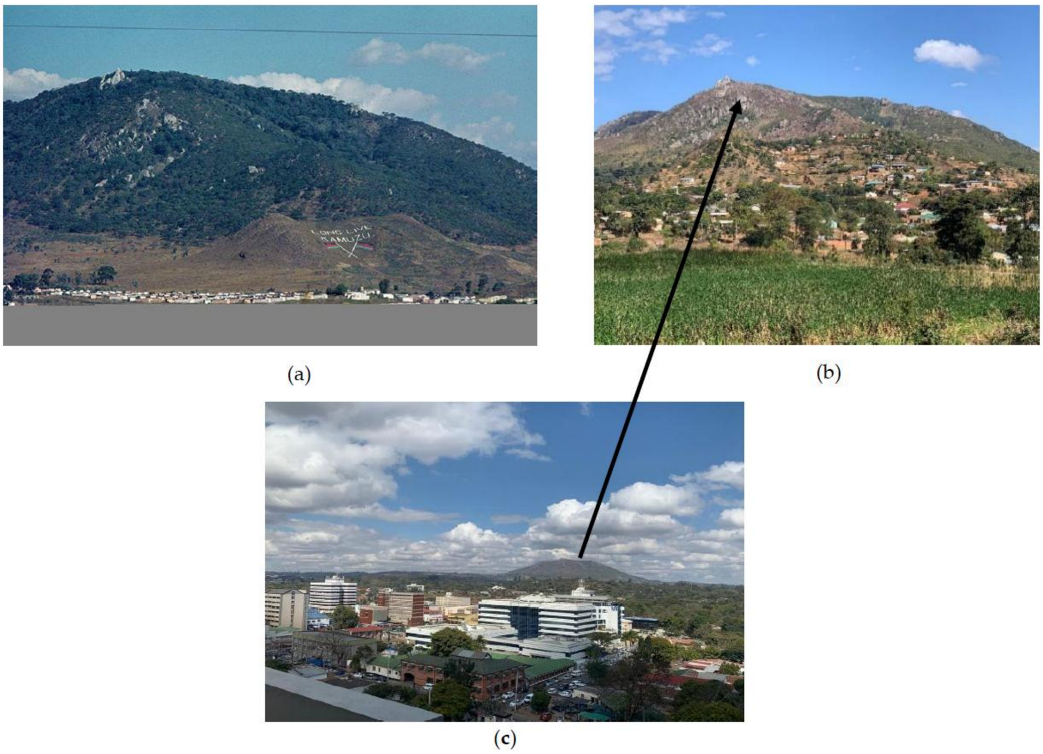

Figure 3. Impact of rapid urbanization and informality on the environment in Blantyre City. (**a**) A view of Soche Mountain in Blantyre City in the 1970s; with a well filled dam at the foot of the mountain [12]. (**b**) A view of Soche Mountain, in 2020; with the well-filled dam at the Mt. foot disappeared and the mountain encroached (Source: Authors). (**c**) Blantyre Central Business District with the Soche Mountain in the background (Source: Authors).

Within the context of the development challenges facing the City of Blantyre, the Future Resilience for African CiTies and Lands (FRACTAL) project (from 2015 to 2019) provided an opportunity for city stakeholders to work with one another and partners across southern Africa (including climate scientists) towards the co-production of knowledge for building city-region resilience to climate change. FRACTAL is part of the Future Climate for Africa (FCFA) multi-consortia programme, which has the overarching aim to "generate fundamentally new climate science focused on Africa, and to ensure that this science has an impact on human development across the continent" [13]. The main objective of the FRACTAL project was to generate usable climate resilience knowledge at city-region scales in southern Africa. FRACTAL took place in nine cities, namely: Cape Town (South Africa), Blantyre (Malawi), Durban (South Africa), Maputo (Mozambique), Lusaka (Zambia), Harare (Zimbabwe), Gaborone (Botswana), Windhoek (Namibia), and Johannesburg (South Africa) but this study focuses on the case study content derived from the City of Blantyre. A transdisciplinary approach was implemented in Blantyre to co-produce requisite knowledge to solve several climate-related research questions aimed at ensuring that city development stakeholders mainstream climate resilience strategies in their policies and planning processes. City Learning Labs anchored the transdisciplinary processes in Blantyre. These labs are multi-stakeholder learning processes that support the co-exploration and co-production of knowledge on climate-sensitive burning issues.

Transdisciplinary co-production of climate change knowledge has two primary leverage points, namely: The capacity to formulate contextual research questions [5], and mainstreaming the knowledge into the decision space [14]. An effective transdisciplinary knowledge co-production process should entice collaborating partners to move from their comfort-zones (disciplinary and practice biases) into the third-space where a horizontal cross-fertilization of knowledge takes place and there is buy-in and loyalty from the knowledge users to sustain and mainstream the learnings in decision-making [15].

The concept of co-production of knowledge dates back to 1989, when [16] proposed four overarching co-production approaches that have proven efficient in the last few decades, namely contractual, consultative, collaborative, and collegial, and argues that collegial approaches best strengthen local research and development capacity. The learning outcomes for collaborators involved in collegial, transdisciplinary co-production processes are influenced by many different factors including inter alia the size of the network and stakeholders involved, as well as the approach adopted. Large networks can enhance the transfer of usable information to stakeholders at reduced initial costs and the rapport building with multiple stakeholders in the shortest possible time [4]. The importance of building trust between science users and producers to promote the usability of science has been emphasized by [3]. Trust emerged as a key driver of effective co-production engagements in all FRACTAL partner institutions and cities. Trust was engendered through several activities that were included in formal engagements, focus group discussions, Learning Lab sessions, think-tank seminars, and virtual platforms.

Despite the growing body of literature that reports on lessons learned through collegial, transdisciplinary co-production processes, there is still much to understand about this approach. A crucial knowledge gap relates to how methodologies might be systematically implemented during transdisciplinary co-production to build trust and support long-term relationships and sustainable outcomes. This paper offers a fresh perspective on transdisciplinary co-production processes, and the learning characteristics thereof, by applying the lens of simulation studies on (the FRACTAL) research, which has leveraged substantial capabilities within Blantyre. It has examined the complex dynamics of the synergy between knowledge producers and the users by exploring the following questions:

1. What city-region decision pathways can be identified for the uptake of increasingly detailed and complex climate information?
2. How can the city decision makers leverage a multi-stakeholder participatory approach to mainstream climate information or science in policy and city development decision-making processes (and sub-questions: What are the first crucial steps for a successful

transdisciplinary climate knowledge co-production; how can trust be inculcated among the partners)?
3. What is the structure or form of the city regions' water supply system and its associated regional dependencies?
4. How does Blantyre City account for and deal with uncertainty in its medium-term decision-making or how can the city account for and deal with uncertainty, specifically relating to climate information, in its medium-term decision-making?
5. How can the transitional behaviour from the disciplinary comfort-zone to third-space be modelled and simulated?
6. How can the learnings be sustained and adapted to the best practices from the knowledge co-produced?

Apart from the simulation study which is quantitative and can be easily replicated, this research also incorporates a great deal of qualitative data, which, in tandem with the best practices, can be replicated based on the lessons learned as propounded by [17], as well as based on system-archetypes depicted from the systems-approach developed. The systems-method subsequently helps to ensure that the learning processes are systematic and systemic.

2. Materials and Methods

2.1. Overview of the Methodological Approach

The choice of a research method used should depend on the underlying research questions [17,18]. The six research questions that were formulated (see Section 1.2) entailed determining city-region decision pathways for climate resilience development, encouraging stakeholder participatory approach, dealing with uncertainty in the medium term decision-making, modelling and simulation of learning patterns, as well as sustaining the lessons from the research. Two constructs or aspects characterize these questions, namely: Transdisciplinary co-exploration, which necessitates the application of focus group discussions and self-directed enquiry (see, e.g., [19]) which may be adequately implemented through Learning Labs [20], as well as case studies as a means of chronicling findings [17]; and simulation, which demands the use of a sensitivity analysis with the aid of computers. Therefore, the research method was driven by those research questions and hinged around the two constructs.

The general systems approach (see Section 1.1) is one of the three facets of the systems approach, with the other two being the complexity science and the systems research (science). The systems approach is very useful in managing the complexity of socio-economic and environmental challenges that decision-makers face [21]. The approach encompasses many methodologies that focus on different aspects of complexity. In addition, the best way of tackling complexity is to understand the merits and demerits of the various methodologies and learn how to combine them to achieve the intended objective. There are varying viewpoints by different authors on what constitutes "complexity", however [22], provided a good summary of features that best summarize the term, namely: Systemic and synergistic; multi-scalability, variability, diversity, and fluctuations (which are needed for resilience and adaptability); path-dependency; varying episodicallity (i.e., possibility of either becoming resilient or slipping into new, undesired regimes); multi-futuristic; and chaos, self-organizing, and self-regulating capability. Complexity can best be exemplified by the global climate and other systems that portray self-renewal and co-evolution with the environment [23] (p.354).

There is a large body of knowledge on the systems approaches, for example, [6,21,24–26]. Nineteen commonly used systems approaches are as described by [25]; and these can be grouped into six depending on the type of complexity they aim to deal with, as follows [21] (pp. 171–473):

1. Systems approaches for Technical Complexity: Consisting of Hard Systems Thinking;
2. Systems approaches for Process Complexity, e.g., the Vanguard Method;
3. Systems approaches for Structural Complexity: Consisting of System Dynamics;

4. Systems approaches for Organizational Complexity, namely: Socio-technical Systems Thinking, Organizational Cybernetics, and the Variable Systems Model;
5. Systems approaches for People Complexity, which are often presented as Strategic Assumption Surfacing and Testing, Interactive Planning (aimed at tackling subjectivity), and Soft Systems Methodology; and
6. Systems approaches for Coercive Complexity, which comprise Team Syntegrity and Critical Systems Heuristics; aimed at helping the disadvantaged in situations of conflict.

In recent years, systems thinkers have attempted to respond to critics of the systems approach, who argue that it is a theory of everything and is therefore neither contextual nor authentic [8]. They have responded successfully by acknowledging that no theory can solve everything and, at the same time, asserting that the systems approach is the most inclusive as it ensures that all essential aspects of a situation or paradigm have been captured, interrelationships are understood, multiple perspectives are taken, and boundaries are established and reviewed to retain the relevance of the problem context [25]. The process of combining the best systems approaches and integrating them with participatory methods (as in the transdisciplinary co-production employed in this research) to address the challenges posed by large-scale and complex problems is referred to as Critical Systems Thinking [27], ([28], p.238).

The general systems theory was chosen for this research since it is the most suitable for the problem context that has been highlighted in Section 1.1. Specifically, the research seeks to develop and synthesize models for a better understanding of a phenomenon, in this case the transdisciplinary co-production, where the general systems theory has proven effective [26]. In addition, causal linkages of various aspects of climate science knowledge co-production are explored, and the theory can be used to reveal such underlying structures or interrelationships [7] (pp. 323–324), [24] (p. 65). Furthermore, as [6] propounded, the general systems theory helps manage entropy or disorder in systems. In addition, within the context (background) of lack of a systematic and replicable co-production approach, and the need to flush-out aspects that can garner high leverage changes and to better understand the process of change [24] (p. 85) (in this case the transdisciplinary co-production process and its associated archetypes, e.g., see [7] (p. 325), it is envisioned that the theory offers useful insights for the current problem context. Moreover, the general systems theory is viewed to be the most suitable for transdisciplinary learning spaces, where collaborating partners engage in knowledge generation regardless of their disciplinary-biases. This notion is supported by [29], who advances that the general systems theory is useful when analogies that can be revealed between systems originating from various branches of science do not matter much, provided they generate useful knowledge among researchers and can form valid scientific contributions by suggesting new or improved ways of expounding phenomena.

The general systems approach chosen for this research is applicable to all kinds of systems and thus is transdisciplinary, but it falters when used as a standalone method as it fails to explicitly discover underlying structures, where the System Dynamics provides great leverage. Therefore, Critical Systems Thinking was applied to exploit the capabilities of System Dynamics, in order to discover patterns that govern change, such as feedback, and feedforward loops that, in turn, give rise to underlying structures [7,8]. This complementarity of the general systems approach and the System Dynamics is particularly demonstrated earlier in the paper (see Section 2.2, Figure 4) and later in the synthesis of the model developed (see Section 3.7).

A transdisciplinary approach was taken in all FRACTAL research projects, and all engagements were either proceeded by or contained team-building components in the form of activities under the guidance of experienced facilitators. One of the core characteristics of a sustainable knowledge co-production process is to discuss mechanisms for achieving long-term relationships between scientists (researchers) and knowledge users while sustaining a two-way line of communication among the partners and focusing on usable science, but not much has been done by the research community on this [3]. In view of this background, the FRACTAL transdisciplinary research approach focused on not only ensuring long term communication but also immediate, instantaneous communication and feedback. To achieve this, the research applied participant observation in focus group set ups that were in the form of Learning Labs [15,20], think-tank sessions, and seminar series. Based on purposive sampling, it drew participants from the academy as research leaders and a wide range of key management decision-makers from city councils, government institutions, statutory corporations, and non-governmental organizations as collaborating partners. Learning Labs are multi-stakeholder learning processes to co-explore and co-produce knowledge on climate-sensitive burning issues. The nine FRACTAL partner cities (see Section 1.2) were divided into two: Tier 1 and Tier 2, and the City of Blantyre belonged to Tier 2. The Tier 1 cities were those that were already advanced in climate resilience building initiatives at the onset of the FRACTAL research project and they were instrumental in the piloting of the transdisciplinary collaboration process. On the other hand, Tier 2 cities demonstrated that climate resilience building activities were either at initial stages or that there was a need for a more structured approach to streamline climate resilience development measures in policy formulation and planning processes. Lessons from Tier 1 cities informed research in Tier 2 cities and vice versa. In addition, a simulation study was applied to model learning patterns in transdisciplinary knowledge co-production processes. A six-step general systems approach, as introduced in Section 1.1, cascaded through Section 2, and expounded and synthesized in Section 3.7, was applied in order to determine causal typologies and to establish a systematic and replicable knowledge co-production model.

2.2. Systems Concept: Application to Decision Processes

Researchers have come to terms with the reality that climate science, policy, and decision-making systems in cities are non-linear and so complex and distributed that they require a multi-faceted approach to adequately co-produce usable knowledge [2]. Since the year 2017, the complexity of climate change management has been aggravated by withdrawal of the USA from the Paris Agreement and consequently stalling commitments to Nationally Determined Contributions (NDCs), thereby exerting pressure to reduce emissions and to provide funding to low-income countries (for the NDC initiatives) on China and Europe [30]. The withdrawal has led to the imperative on low-income countries for innovative and cost effective decision mechanisms for combating climate change and improving communication. Like any other management decision-making process, city decision processes consist of unstable, dynamic, messy systems, and to solve these calls for a holistic, systems-thinking approach. Through mess-mapping, the systems-thinking approach is able to show how small components make complete wholes, and how causal typologies amplify or attenuate decisions [8]. Accordingly, this study began with a mess-mapping process (with feedforward and feedback loops showing the underlying structures), where salient features of urban climate resilience strategies and their synergies were developed in the context of the Blantyre City, as shown in Figure 4. The figure shows seven thematic research areas that arose from Legislation and Policy; however, this research only tackled four, namely: Water, energy, waste, and environment. The reason for choosing the four thematic areas is that the project was linked to a funding period of 4 years, which could not accommodate all the seven themes. Therefore, the selection of the four themes was based on the top priority areas of the City Council, and were determined through situational analysis and consultations with the Council's management.

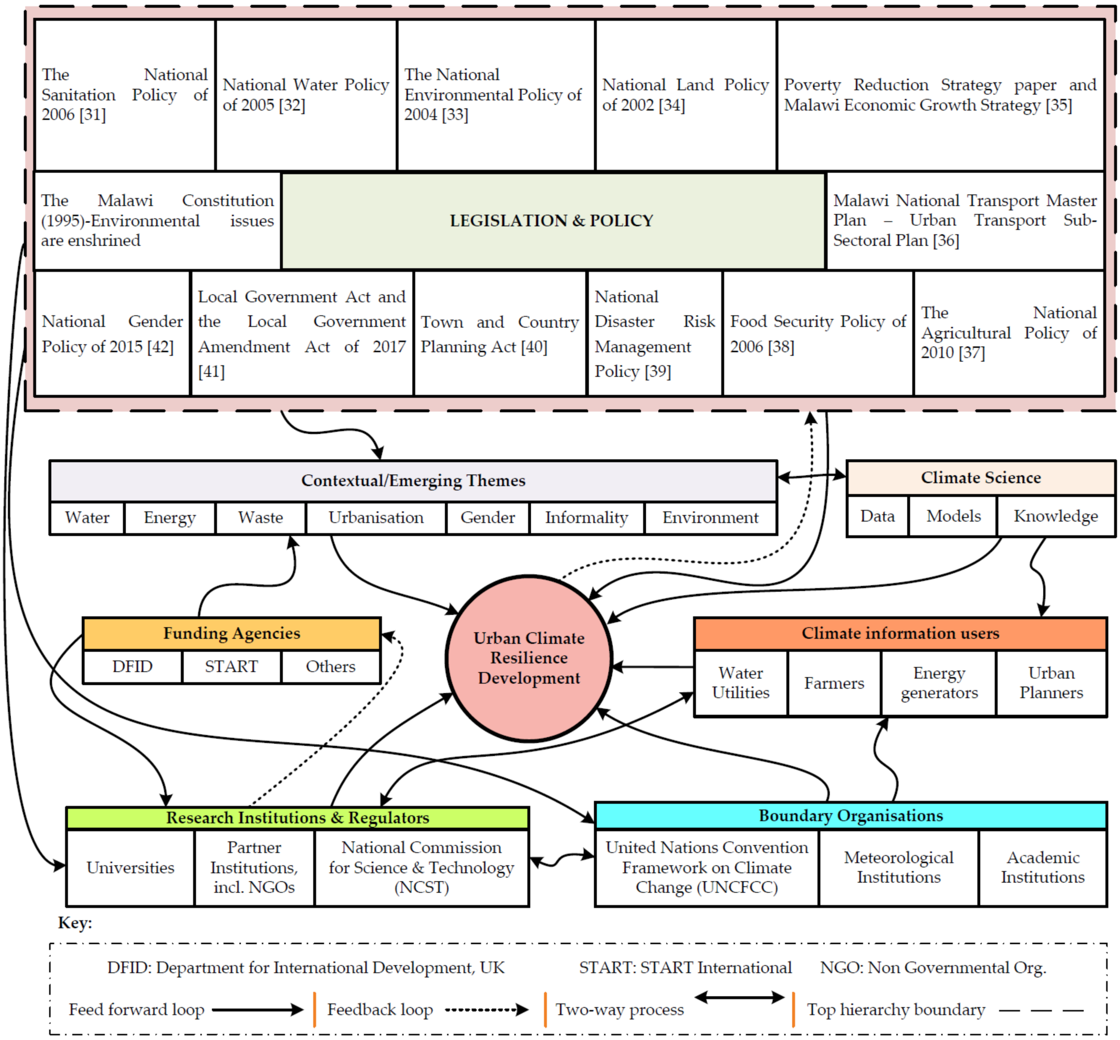

Figure 4. Mess-mapping of Blantyre City climate resilience development framework (Policies: [31–42]).

2.3. Contextualization

The mess-mapping was followed by contextualization of the problem to give climate change researchers the understanding of the context in which collaborating partners are in right at the inception of the learning process. This saves a lot of time, financial, and human resources, as it gives an understanding of where the various partners are pitched in terms of what they already know, climate resilient decision-mechanisms which are already being employed, and the mode and medium of communication that makes them understand climate information better. For example, [4] advanced that collaborating partners mostly prefer specific locally relevant climate narratives about climate change impacts to complex simulation models, and they would settle for simple abridged ways of data presentation such as graphical and tabulated formats, whereas raw downscaled climate data should be kept to a minimum for purposes of numerical climate modelling, quantifying decisions over a range of values, and developing quantitative climate change scenarios. In addition, the expectations and perceptions of partners and stakeholders differ. These should be charted and chronicled at the planning stage. From the mess-mapping, the key stakeholders should be mapped, and for this study, stakeholders were divided into four, namely: Universities and FRACTAL secretariat as lead partners, governmental organizations, non-governmental organizations (NGOs), and private sector and quasi-government (parastatal) organizations as collaborating partners, as shown in Figure 5.

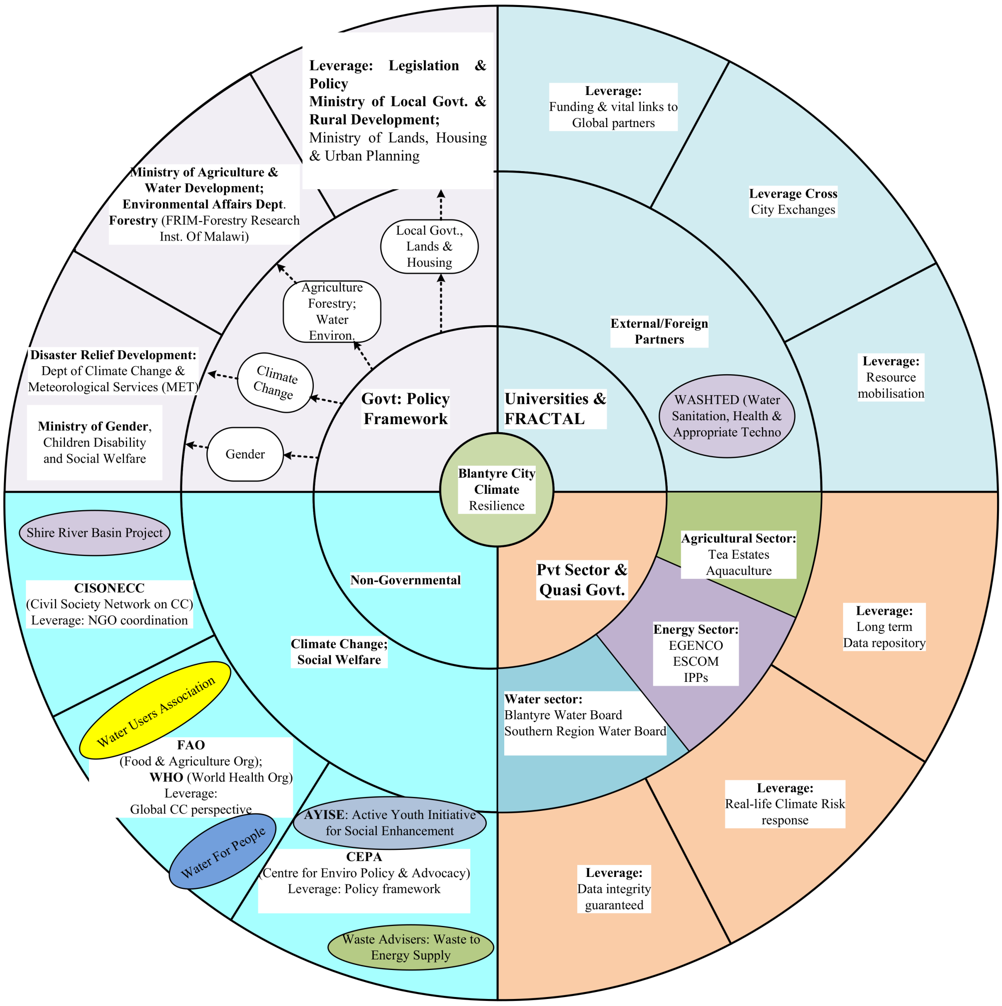

Figure 5. Stakeholders' map for Blantyre City and leverage points for Urban Climate Resilience.

2.4. Conceptual Framework for Transitional Behaviour Modelling

Although many studies have been done on the co-production of climate knowledge, patterns of the learning process as collaborators transition from the disciplinary biases to the third-space have neither been modelled nor graphically visualized. Therefore, in this study, authors parametrically model and simulate transitional stages of learning in a transdisciplinary co-production using a Markov-model by envisioning the learning system as a system in spatial transitional states (with causal linkages)—where collaborating partners transition from the disciplinary-comfort-zone space to a transdisciplinary-learning third-space, as shown in Figure 6.

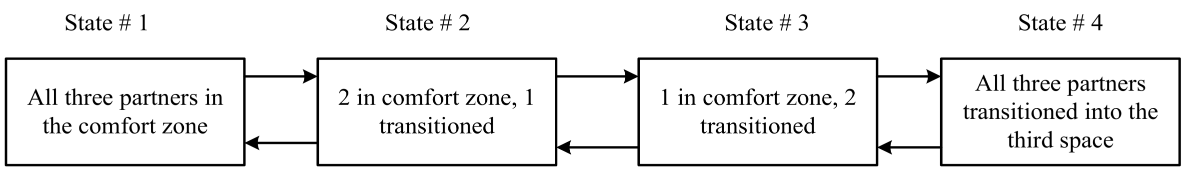

Figure 6. Transition from the disciplinary-comfort-zone to third-space.

Figure 6 is a case of three collaborating partners which are transitioning from State #1, where all the partners are in their respective disciplinary comfort-zones marked by conservative norms, perceptions and practices, through a number of stages up to State #4, which is the third-space. In the transitional process, it is possible and most likely for partners or stakeholders to migrate into an intermediate stage where they stay for a while before finally shifting into the third-space, in which case the third-space is State #5 and the intermediate one is State #4, as shown in Figure 7. It is envisioned that when they reach the third-space, learning should have taken place and trust produced among the partners.

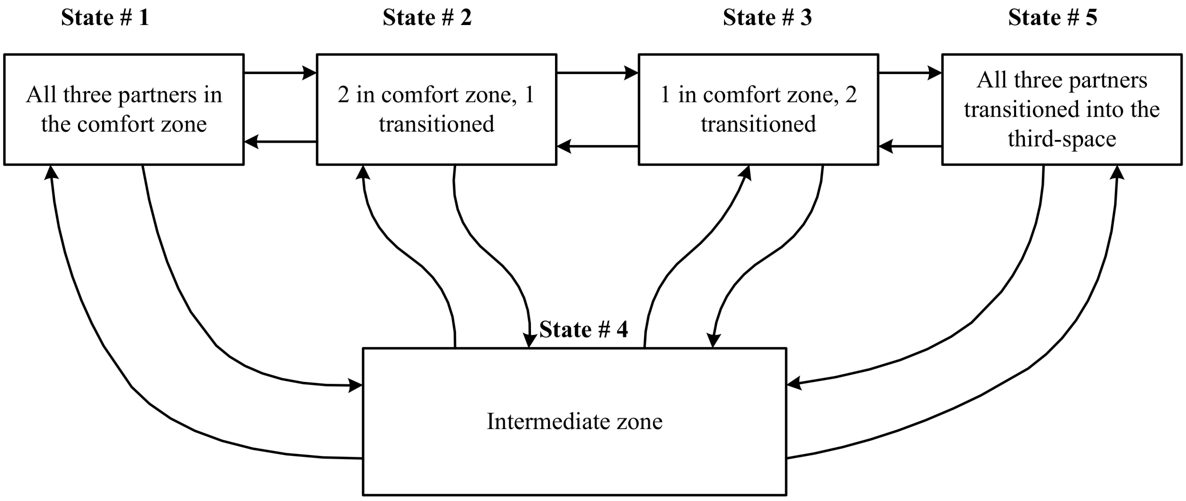

Figure 7. Transition to the third-space through an intermediate zone.

These transitions can be represented by a generalized Markov process by assuming that conditional probabilities of events apply when transitioning from State i through State k to the final State j, as follows [43]:

$$p_{i,j}(t+x) = \sum p_{ik}(t)p_{kj}(x) \tag{1}$$

$$\sum_j p_{ij}(x) \leq 1, \text{ for all } i \text{and } j \tag{2}$$

where t is time and x is the incremental time or time-interval (time-space), and

$$p_{i,j}(x) = P(z(t+x)) = j|z(t) = i\ ; 0 \leq p_{i\,j} \leq 1 \tag{3}$$

If P (0) is the initial state vector, the probability of being in a certain state after n time-steps can be computed by [8]:

$$P^n = P(0)\, P^n \tag{4}$$

Section 2.6 discusses how matrices are generated and algorithms developed to carry out simulations of the state transitions.

2.5. Case Study Lessons

2.5.1. Think-Tanks

Within the context of FRACTAL research, an "innovation-project" was designed to respond to research questions one and two as outlined in Section 1.2, by bringing together stakeholders to explore perspectives that underpin decisions for southern African urban development in the form of "think-tank" sessions (of about 10 people per group). Through very rich, facilitated, semi-structured conversations among stakeholders that had been involved in a relevant decision-making process (i.e., city-specific case studies), these think-tanks provided an opportunity to explore the perspectives that influence development decisions in the cities in a changing climate, using Tier 2 cities (Blantyre, Harare, and Lusaka) as a model. One of the main objectives of these think-tanks was to break away from conventional worldviews related to these issues. The success of these conversations was hinged on the ability to form teams with very cohesive bonds and great trust through bonding exercises in the form of games and personal story-telling sessions. One of such team-bonding exercises with a tremendous impact was a story-telling session called the "river of life", where each participant made an audio-visual map of their life story as a river that passes through rapids (representing hardships) and flat valleys (standing for serenity), from birth up to career paths taken to date and presented it to other partners. The other one was a carousel technique of knowledge co-production, where groups generated solutions to thematic areas and posted them on the wall, then members rotated to other groups to make additional contributions except for one member in each group who remained (emulating a partner who had an institutional memory) to provide clarifications to the new (incoming) group members.

The outcome of these think-tanks was information on the place-based human factors that affect decision-making, and were therefore considered when designing transdisciplinary climate change research for societal impact. This information was consolidated in the form of a seminal series of high-quality, Africa-focused thought pieces to support activities in this field. Since waste management remains a major problem in developing countries, including Malawi [44], for Blantyre, the theme for the think-tank was relevant to the climate-related problem statements in Section 1.2, namely: Exploring the decision process by the Blantyre City Council to turn solid wastes into energy to enhance the power infrastructure development. The exploration of waste-to-energy value chain generated a number of insights that helped shape or refine the co-production methodology and chief among them are as follows: First, decisions depend on the responsibilities and mandates of the key collaborating partners or players, and some players tend to be louder than others during the knowledge co-production process depending on their domains of influence. Therefore, when encouraging transdisciplinary collaborations, it is necessary that the facilitator exercises caution so that the louder partners are not unduly dominant (which is unhealthy for the co-production of knowledge) so that there is a balance between democracy and inclusiveness in the learning process. The loudness of collaborating partners is both an advantage and a hindrance during the knowledge co-production: An advantage as it helps to leverage strengths from the louder partners, and a disadvantage in that if left unchecked it could lead to delayed consensus garnering. To overcome this shortfall, all partners were given safe spaces to exploit the strengths from their domains of influence to the fullest and then the lessons were collated, discussed, and adopted in order of merit as representing a generally accepted, sound consensus. This made each partner feel that their worthiness was being recognized. Second, the plausibility of decisions can be ranked in terms of how the knowledge producers and users support them during the co-production process, as explained in Section 3.3.

2.5.2. Learning Labs and Seminar Series

In recent years, city governance systems have become more dynamic and complex than ever before due to growing social, political, and environmental pressures, thus cities have realized that the best way to increase their resilience and sustainability is by adopting an inclusive and experimental governance approach [45]. A range of literature, for example, [2], advocates that city governors in developing societies should push for innovative models of knowledge production and decision-making. In that context, richly structured Learning Lab seminar series were applied to answer research questions one and two.

As such, the FRACTAL project prioritized "City Learning Labs" as a key approach to facilitate a successful transdisciplinary climate knowledge co-production process [20] as it optimizes knowledge sharing based on the precept that it is not necessary to always harness more science, but to manage what is already in the complex and dynamic governance systems by managing the politics of knowledge and visions [2]. This approach is primarily designed to facilitate multi-disciplinary problem solving at the intersection of complex urban domains. The concept of City Learning Labs is based on the principles of social and adult learning. According to [19], this is described as the process of self-directed inquiry, which is primarily based on four key pillars. These pillars suggest that it is crucial for adults to be involved in the planning of actions, that experience provides the basis for learning;

that adults are most interested in subjects that have a direct relation to the impact on their lives, and that learning should be centered on a problem rather than content. He then advocated that a sustained knowledge-producer-knowledge-user relationship be based on the creation of an environment of mutual trust and expectation so that cooperation is effectively fostered.

Under this framing, a variety of stakeholders came together in Blantyre to find innovative solutions for specific questions or problems that they perceive as relevant and urgent. The process in Blantyre embraced the complexity of the city with all participants sharing views, needs, insights, and research. While sharing these insights, all participants listened and where possible revisited their own perspectives and understandings, thereby solving a complex challenge through exploring it from a variety of angles, and understanding climate science terminologies.

The City Learning Labs in Blantyre followed facilitated processes where the stakeholders shaped the engagement objectives and subsequent actions with the facilitator being key to ensuring a safe learning space. Each engagement then unpacked the relevant complexities and focused on particular aspects whilst deciding on areas for further exploration before and during the next City Learning Lab. The entire Learning Lab processes followed similar steps outlined by [20] but in particular, in Blantyre, the City Labs unpacked a variety of evolving burning questions and topics. These included:

(1) City-region decision pathways for the uptake of increasingly detailed climate information;
(2) City accountability for dealing with uncertainty, specifically relating to climate information, in its medium-term decision-making;
(3) Decision-making processes in relation to water and climate change;
(4) Governance response discourses of Blantyre City Council decision makers;
(5) Collaboration around climate change information and decision-making; and
(6) Principles for transformational climate change leadership.

This shared-learning process for urban decision-making in sub-Saharan Africa is relatively new [46], but through FRACTAL, it proved to be invaluable for leveraging learnings and discussions for climate resilience building and for supporting longer-term actions based on the generation of relevant knowledge and its ability for emergence of entry points for shifts in decision-making.

It was clear that this approach effectively supported the development of a systems perspective (see, e.g., Sections 1.1 and 2.1), supporting the transition from the disciplinary-comfort zone to the transdisciplinary-third-space, which is pivotal in sustained action interventions. This approach allowed research partners to better understand various climate-change scenarios to inform better planning and decision-making within the city. In addition, this approach was fundamental in developing networks between city leaders (decision makers) and technical staff (researchers).

2.5.3. Learning Labs and City Exchanges

FRACTAL's approach to learning was both experiential and structured, and involved multi-stakeholder engagements that encourage the building of trust and networks, which can then be leveraged when city level planning decisions need to be made. One key approach to support ongoing learning was the inclusion of city-to-city exchange visits into the project design of a Learning Lab that answered research question three. Blantyre engaged in learning exchanges with the Cities of Harare, Lusaka, and Cape Town and in the mentorship of Early Career Researchers (ECRs) to enhance sustainability of the knowledge coproduced. Specific parallels were drawn between Blantyre and Harare, whereby policy briefs were developed for each city and then a comparative piece was produced focusing on how to alleviate challenges in the management of water supply and quality in the two cities. The context of this comparative study was that both cities are in Southern Africa and face very similar challenges and can therefore learn from each other through sharing of experiences in order to foster climate resilience decision-making. Decision-making pathways in the water sector in the two cities were unpacked and opportunities and barriers to decision-making were identified.

In a bid to strengthen sustainability drives, a concept of Embedded Researchers (ERs) was borrowed from sister FRACTAL cities (Maputo, Harare, and Lusaka), whereby young researchers were employed by FRACTAL and attached to the City Council as part of their staff complement as a link between researchers and knowledge users (city decision makers) to enhance collaborations on a day-to-day basis.

It was clear that this learning design created an opportunity to share good practices for addressing problems and challenges that arise in urban areas and that are exacerbated by climate variability. In addition, city exchanges support networking through facilitating a flow of knowledge between cities. This exposure is critical to helping city level decision makers consider successful approaches beyond their borders.

2.5.4. Seminar Series on Climate Risk Narratives

The purpose of Climate Risk Narratives (CRN) was to respond to research question four by co-developing knowledge that would inform climate sensitive decisions in cities in the Southern African region and to limit uncertainties, based on Tier 2 cities (Blantyre, Gaborone, and Harare). Blantyre is the main industrial and commercial hub in Malawi, and CRN activities proved to be instrumental in bringing about change in the operational culture of the city council, where sustainability targets developed were made more flexible than before. Various stakeholders from different disciplines in Blantyre were brought together in one room to engage in exercises that required them to imagine possible climate resilience futures for their city. Initially, the focus of these activities was on producing narratives as a main output. However, as time went on, it became clear that the approach itself was generating learnings and discussions that were far more valuable than a tangible end product.

The CRN for Blantyre were developed based on climate change predictions by the year 2040 for three climate change scenarios and their accompanying assumptions, namely: Hotter, slightly drier, and fewer rain-days; hotter, no change in total annual rainfall, heavier rainfall events, and fewer rain-days; and warmer, slightly wetter, heavier rainfall events, and fewer rain-days. Although there is a number of sectors such as energy and water supply, land and population, food security, health and flooding, which are climate sensitive and affect the city of Blantyre, the priority for coverage in the CRN was on the energy and water supply sector.

The first scenario was based on the assumption that the city population would grow at around 3% per year and urbanization increase at an average of 4% per year, which would translate into increased energy demand for household purposes and lead to depletion of alternative energy sources such as charcoal, in combination with increased ambient temperature and evaporation [47], which would lead to shrinkage of water in Lake Malawi and the Shire river, thereby reducing hydro-power generation and negatively affecting social, commercial, and industrial activities. Lake Malawi and the Shire River are critical to the energy-water nexus for the city of Blantyre. Lake levels affect the flow of the Shire River (see Figure 1). The Walkers Ferry in-take on the Shire supplies a bulk of water to the city of Blantyre. In addition, the city has a Mudi reservoir, which supplements water supply from the Walkers Ferry. This reservoir supplied less than 1% of the city's water demand in 2015 [48]. The Shire River is also the source of water for 98% of hydroelectric generation capacity for the country.

The second scenario was based on the assumption that Blantyre will still be supplied with hydro power by ESCOM, with other energy mixes consisting of diesel thermal and solar-PV systems at a small scale. Furthermore, it was envisioned that the total annual rainfall will be the same as in the first scenario. Therefore, the water level in the Lake will be reduced due to the increased evaporation due to hot conditions, but the heavy rainfall events cause floods that destroy hydropower generation equipment and power supply infrastructure as it happened in 2001, 2003 [49], and in 2009 [50].

The third scenario was founded on the assumption that the heavier rainfall would have resulted in the increase in Lake Malawi level, but that would unlikely change the level significantly due to the increase in evaporation. However, the heavy rainfall events cause floods that destroy hydropower generation equipment and power supply infrastructure and Blantyre and the rest of Malawi is suffering from power shortages which is, in turn, affecting social activities, commercial and industrial development.

While developing these scenarios, officials engaged in conversations that significantly broadened their perspectives on climate change decision-mechanisms. While some individuals' views of the future were fairly one-dimensional at the start of the exercise, they became more complex and layered as others shared their thoughts and flagged additional points that needed to be considered. Important areas of tension also emerged around the following: (1) Whether or not current policies, plans, and interventions were sufficient to positively alter the future, or whether a bigger change was necessary in order to make certain visions a reality; (2) dealing with uncertainties is so complex that it cannot be adequately dealt with by collaborating partners who have limited knowledge in climate science, hence it should be directed to boundary organizations (see, e.g., Figure 4); and (3) the narratives portrayed a gloomy picture, which seemed plausible without spelling out the appropriate future adaptation strategies. Such discussions served as key learning opportunities for many participants, who subsequently changed their views and outlook on what needs to be achieved going forward.

2.6. State-Space Transitional Matrix Formulation, Assumptions, and Parameters

2.6.1. Transitional Matrix Formulation Using Markov

For purposes of undertaking the Markov process for simulation and modelling of the learning behaviour introduced in Section 2.4 to respond to research question five, we insert rates of transition into Figures 6 and 7 as shown in Figures 8 and 9, respectively. From Figure 8, the rates of transitioning away from States 1, 2, and 3 to State 4 are shown, respectively, as λ_1, λ_2, and λ_3, whereas, transitioning back to those initial states as μ_1, μ_2, and μ_3.

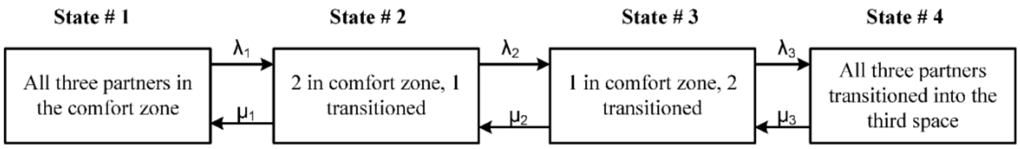

Figure 8. State-space transition rates in a four-state scenario.

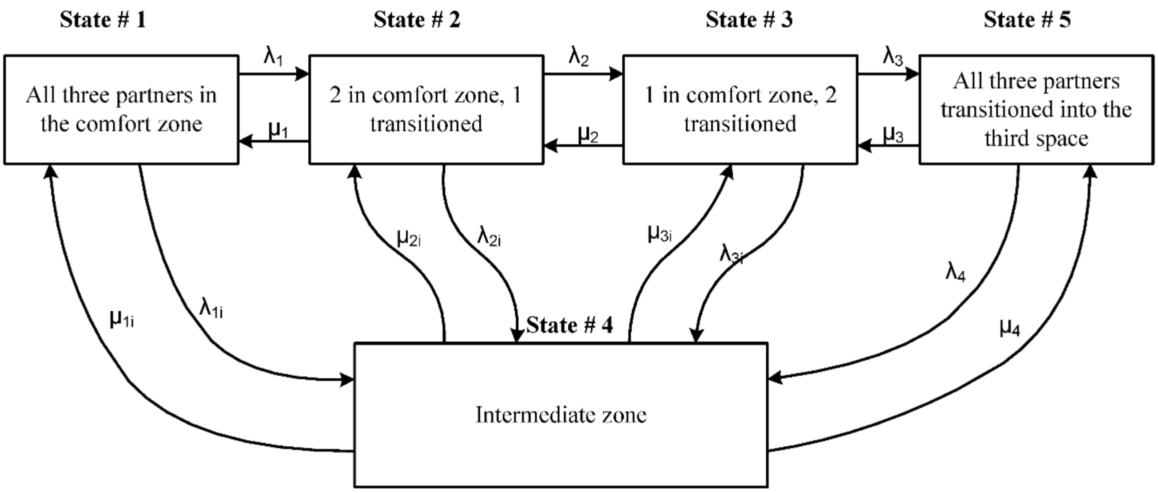

Figure 9. State-space transition rates in a five-state scenario.

From Figure 9, the rates of transition from States 1, 2, and 3 to State 5 are, respectively, λ_1, λ_2, and λ_3, whereas, rates of transitioning back to those states as μ_1, μ_2, and μ_3. The transition rate from State 1 to 4 is λ_{1i}, from State 2 to 4 is λ_{2i}, from State 3 to 4 is λ_{3i}, and from State 5 to 4 is λ_4, whereas, the transition rate back from State 4 to 1 is μ_{1i}, from State 4 to 2 is μ_{2i}, from State 4 to 3 is μ_{3i}, and from State 4 to 5 is μ_4. There are two ways of expressing the transitional stages, namely: Using Laplace Transforms and transitional probability matrices which are generated from block diagrams. In this study, the later method is used so as to eliminate complexity. In modelling state transitions with the Markov methodology, the probability of staying in a state is equal to the probability of the (initial) state (usually 100% or 1) minus the rates of departure from the state (see, e.g., Equations (2) and (3)), thus, transitional probability matrices can be constructed from those rates. Using this approach, from the application of Equations (1) to (3): A transitional matrix is constructed from Figure 8 as shown in Equation (5), and the one from Figure 9 is as shown in Equation (6). These equations are applied in the simulation, which is laid out in Section 3.4.

$$P = \begin{bmatrix} 1-\lambda_1 & \lambda_1 & 0 & 0 \\ \mu_1 & 1-\lambda_2-\mu_1 & \lambda_2 & 0 \\ 0 & \mu_2 & 1-\lambda_3-\mu_2 & \lambda_3 \\ 0 & 0 & \mu_3 & 1-\mu_3 \end{bmatrix} \quad (5)$$

$$P = \begin{bmatrix} 1-\lambda_1-\lambda_{1i} & \lambda_1 & 0 & \lambda_{1i} & 0 \\ \mu_1 & 1-\mu_1-\lambda_{2i}-\lambda_2 & \lambda_2 & \lambda_{2i} & 0 \\ 0 & \mu_2 & 1-\lambda_3-\lambda_{3i}-\mu_2 & \lambda_{3i} & \lambda_3 \\ \mu_{1i} & \mu_{2i} & \mu_{3i} & 1-\mu_{1i}-\mu_{2i}-\mu_{3i}-\mu_4 & \mu_4 \\ 0 & 0 & \mu_3 & \lambda_4 & 1-\mu_3-\lambda_4 \end{bmatrix} \quad (6)$$

2.6.2. Assumptions and Parameters

For the purpose of the simulation study, the following assumptions apply: (1) Collaborating partners do not transition into the third-space directly, but go through a number of stages prior to the third-space, one step at a time; (2) the probability of staying in a state is equal to one (p = 100%) and a complete learning transition is perceived to have taken place when the probability is greater than one (p > 100%); (3) the system is stochastic and the effort that collaborating partners put into the learning process can be operationalized (measured). The parameter used for the simulation is the effort, which can be measured by the number of learning engagements conducted and time spent on them, and number of networks created. In the future, when adequate primary data (e.g., level of trust, perceived value, and knowledge and attitude outcomes) have been collected, the transition into the third-space will be measured empirically using the Behaviour Change Theory as propounded by [51–53].

3. Results and Discussion

3.1. Crucial First Steps for the Success of Transdisciplinary Co-Production

Based on the research conducted in the Blantyre City and cross-city learning exchanges with the other eight cities mentioned in Section 1.2, certain aspects proved that they are so pivotal to the success of transdisciplinary knowledge co-production that they must be considered at the on-set of the learning process, and key among these are outlined in Figure 10.

Figure 10. Crucial first steps for the success of transdisciplinary collaborations.

It was observed that the establishment of the rapport at the onset of the co-production process was as important as the knowledge generation itself. This involves reaching out to the collaborating institutions or partners through their appropriate hierarchies and it consumes a considerable amount of time, hence it should be factored in the planning phase. This is where the objectives of the engagement are shared among the collaborating partners and the visions of the knowledge users are captured by the researchers in order to identify common grounds, and the institutional politics are understood. The success of this phase paves way for the context determination.

The research further revealed that in determining the context of the collaborating partners, it was necessary to determine the extent to which the partners are engaged in the thematic areas, such as building resilience to adverse climate change impacts. This can be explicit, where it is very clear from the partners' documentations, or implicit, where interviews with the partners indicate that although they may not be aware that they are contributing towards climate change mitigation and/or adaptation, they already have some decision-mechanisms that prove they are engaged in the climate change resilience building process. This approach proved to save time by preventing re-invention of the wheel as demonstrated by the categorization of nine FRACTAL partner cities into Tier 1 and 2 cities (refer to Sections 2.1 and 2.5.1) based on their contexts.

Finally, the establishment of city context and how it is positioned with respect to local and regional settings was possible through a situational analysis, and had the following major contributions to the learning processes: Helped shape research questions, pitch the research at appropriate levels, establish similarities and differences between the city in question and other cities in the region, so as to determine lessons and/or processes that could be replicated and focal points for learning exchanges. A comparison of four collaborative engagements showed that the two most successful, in terms of the speed at which deliverables were obtained and research questions formulated, were those which were preceded by situational analyses.

3.2. Trust and Relationship Building

Trust is a very important pillar of any lasting collaboration process for both the knowledge producers and users [3,54]. Team-building components that were embedded in the engagements (see Sections 2.1 and 2.5.1) helped the collaborating partners to bond and develop trust easily. The research showed that the more collaborating partners shared responsibilities within their domains of influence or mandates, the more they developed the trust between and among themselves in the learning engagements. In addition, the more transparent the facilitator or team-leader is, the more willing the partners are to participate in future undertakings—thus, buy-in and loyalty get propagated. This affirms what [54] advanced: Trust is the determinant of respect and loyalty, it is earned, while respect and loyalty are given and demonstrated, respectively. Furthermore, it was observed that the trust among the partners got stronger whenever the partners delivered what they had promised and when they consistently walked the talk, for example, sharing of information and meeting timelines for their respective deliverables in the collaboration.

Through focus group discussions, the consensus was reached at and networks were created spontaneously. The advantage of this approach is that it reduces the follow-up time for clarifications sought on research findings. The research further showed that trust and communication were inseparable, and it used some operational variables to measure how entrenched the trust and communication were, for example, the easiness with which the securing of appointments and scheduling of meetings is done later during the engagement relative to the early stages, the reduction in the number of conflicts where applicable, and the ease with which the consensus is reached.

3.3. Analysis and Ranking of Plausibility of Decisions

Evaluation of plausibility of decisions is one of the most difficult processes in the knowledge co-production. Therefore, from the think-tanks (see, e.g., Section 2.5.1) a four-step decision support tool was developed to solve this problem, as shown in Figure 11. It starts from the first step, where decisions are characterized to the fourth step, where they are rated quantitatively. In the figure, decisions are ranked on a scale of 1 to 10 as aggregates of X1 to X4, Y1 to Y4, and Z1 to Z4 scores (see e.g., the fourth step), respectively, for policy actors (A), evidence and knowledge (B) and context (C). If the score ranges from 7 to 10, the decision is very good and plausible for implementation; from 4 to 6, the decision is good and may be prospected for implementation after improving the weak areas; from 1 to 3 the decision is doubtful, may not be practicable; and if 0, the decision is very poor and other alternatives need to be strongly considered.

3.4. Simulation of the Third-Space Transitional Learning Behaviour

This section presents and discusses results from the approach that was followed to respond to research question five. Several scenarios were considered for modelling the transition of learning behaviour based on Figures 8 and 9, which correspond to Equations (5) and (6), respectively (see Section 2.6.1), whereby the two equations were processed according to Equations (1)–(4) by an algorithm that was developed in the MATLAB software to simulate the state probabilities after n time intervals. Only parametric data were used for the simulation, based on the assumptions laid out in Section 2.6.2 for three collaborating partners, and then transitional probabilities were plotted. Figures 12 and 13 are scenarios where the knowledge co-production partners invest little effort into the collaboration, where little learning takes place as signified by low probabilities of reaching the third-space stage. In these figures, probabilities and non-availabilities of states are plotted together in order to display some key patterns, which are only possible to detect when the two curves are plotted together, e.g., the cross-over points.

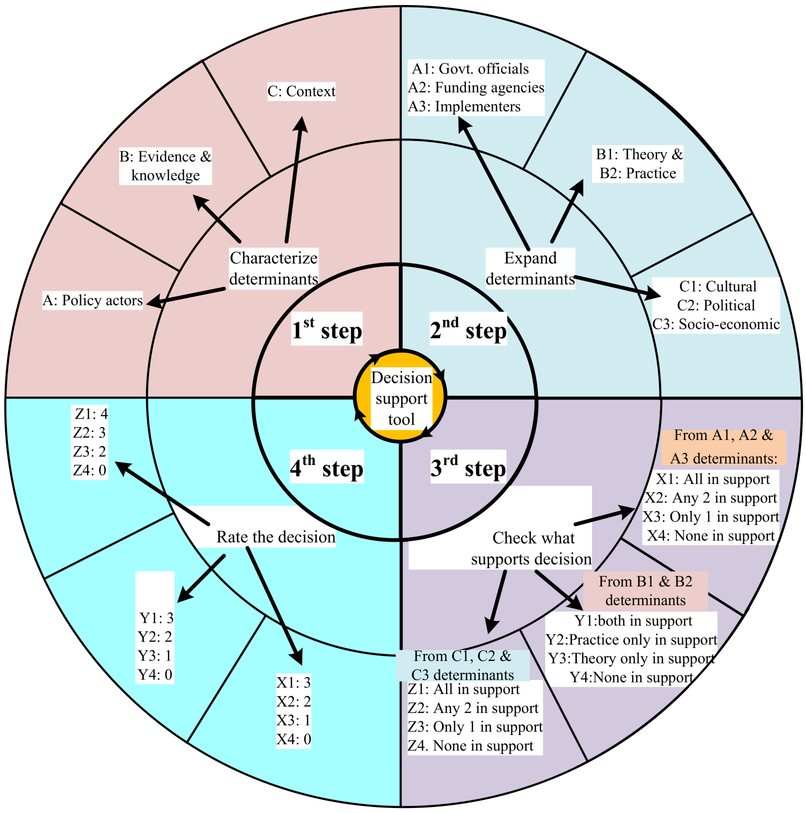

Figure 11. A decision support tool for ranking plausibility of decisions.

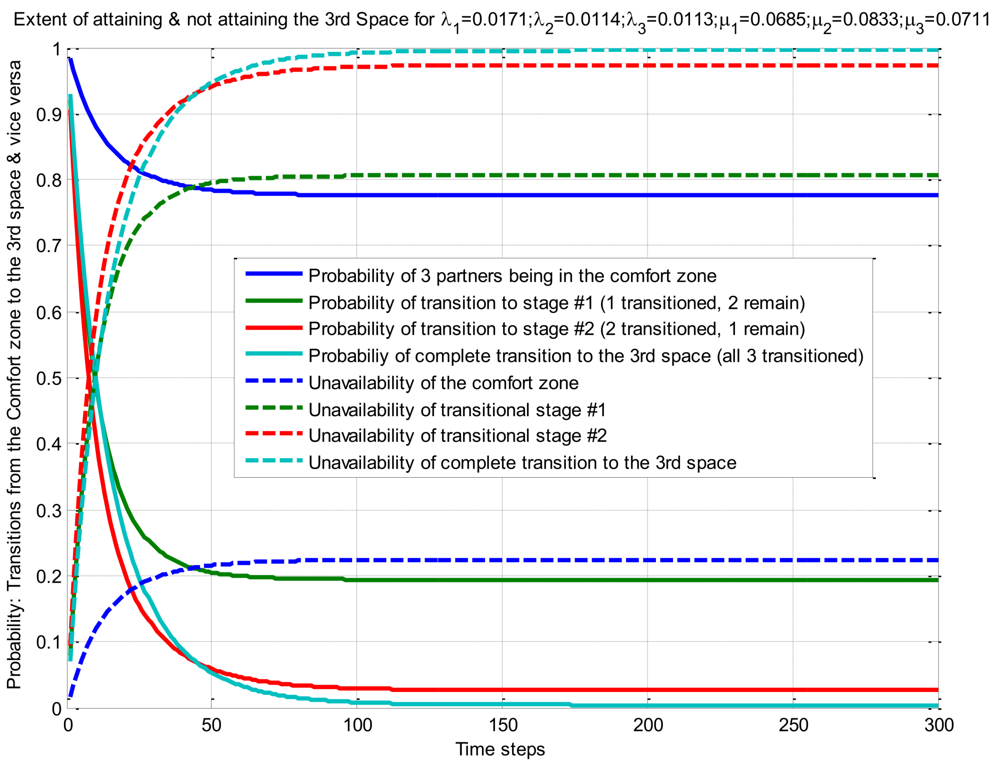

Figure 12. The extent to which collaborating-partners transition to the third-space in a four state system.

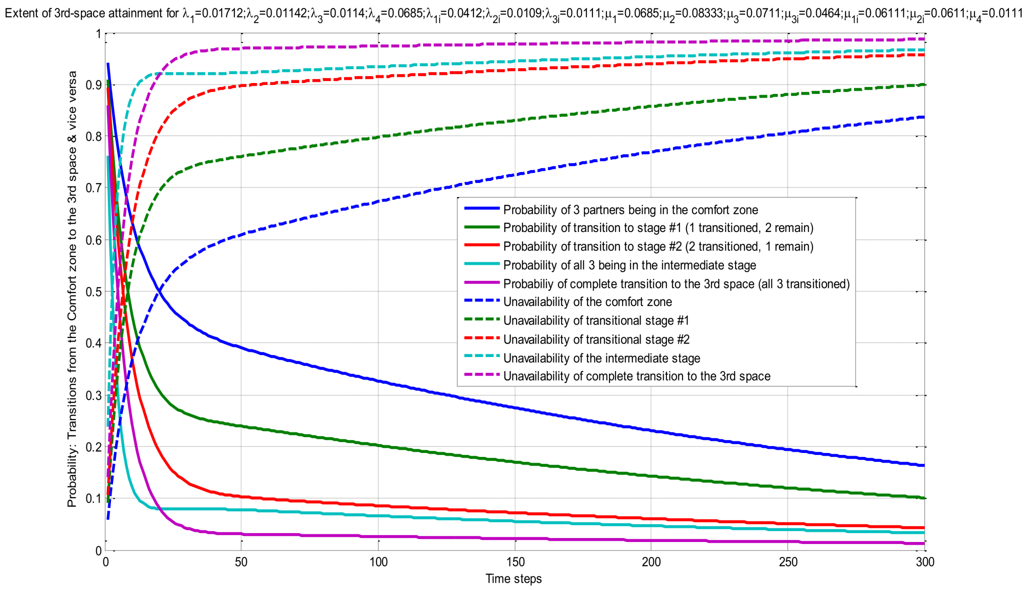

Figure 13. The extent to which collaborating-partners transition to the third-space in a five state system.

Figure 14 is a simulation of the case where the collaborating partners step-up their efforts to learn by approximately 3.4 times relative to the base scenario (Figure 13), and reduce their tendency to slump back to their comfort zones by almost half (0.44 times). Four phases of transition are evident from Figure 14, namely: Shock and resistance (where probability values start from one or 100% and are decreasing), experimenting and exploring (where probability values start increasing but are still below 100%), acceptance, and integration into the third-space (where probability values are above 100%). The shift into the third-space is characterized by an amplification effect where the probability is greater than one, after 420 time-steps which (in systems-thinking theory) signifies that the partners have not only learned but also increased in knowledge during the co-production. It is worth noting that different scenarios and graphical responses to change can emerge depending on the effort exerted by the partners in the learning process.

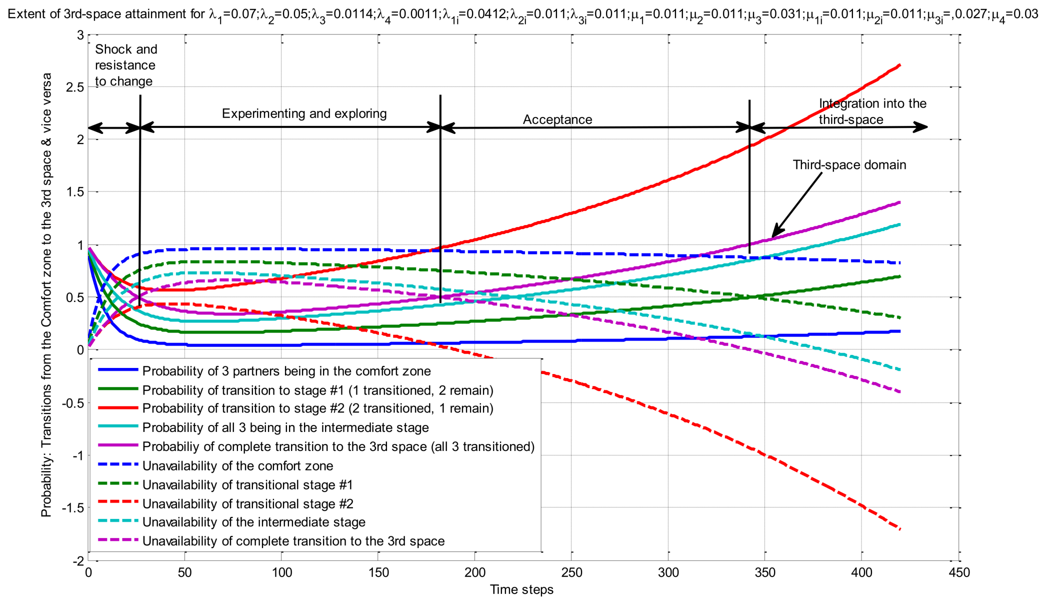

Figure 14. Transition into the third-space when partners in Figure 13 step-up their efforts to learn by 3.4 times and reduce the rate to revert to old ways by fifty percent.

This section has shown that the transition from the disciplinary-comfort zone into the third-space can be modelled and simulated stochastically, provided adequate parametric data are available. It is envisioned that, in the future, empirical data on the following attributes can be generated and used for sensitivity analysis in the simulation studies: Level of trust, perceived value, and knowledge and attitude outcomes. The Behaviour Change Theory, for example, as in [51–53], can be used to assign values to the attributes for simulation purposes.

3.5. The Third-Space Legacy: Challenges and Opportunities

This research has demonstrated that learning in a transdisciplinary knowledge co-production is not only a process of increasing knowledge but also a crucial cultural re-orientation approach that comes along with a number of challenges. The major challenges are two-fold, namely: How to get buy-in of decision makers and knowledge users so that they implement the recommendations (in the form of policy briefs, newspaper articles, journal articles, etc.) made during the knowledge co-production; and how to measure the level of trust, perceived value, and knowledge and attitude outcomes which can be used to quantify the various stages of transition from the disciplinary comfort-zone into the transdisciplinary third-space. Other challenges documented include: Lack of coordination and a communication strategy between the local and national government [1]; a general lack of monitoring systems to track the implementation of policies and policy-brief recommendations related to the mainstreaming of climate resilience strategies; difficulty to get facilitators with appropriate skills in creating safe work spaces for the collaborators during the engagements, where trust and consensus can flourish with ease; difficulty in maintaining institutional memory and subsequent continuity of cross-pollination of the knowledge co-produced (due to the high labour turnover in public institutions and NGOs involved in the collaborations); and lack of incentives for those involved in the knowledge co-production. These challenges are an opportunity for further dialogue between the climate knowledge producers and decision-makers (knowledge users) in general.

Notwithstanding the afore-stated challenges, the shift of paradigm from the disciplinary-comfort zone to the third-space enables collaborating partners to master the skills needed to make deliberate decisions to build relationships and communication mechanisms between scientists and knowledge users, namely: Listening, accommodating, humility (admitting ignorance where applicable), honesty, opening up to critique, balancing diplomacy with focusing on thematic areas and best practices, and motivating teams. In addition, living the third-space legacy requires a well-established information distillation mechanism, whereby important aspects of the knowledge co-produced are extracted and shared in a form that suits the users of that information. Furthermore, for the third-space legacy to be sustained, there must be a means of chronicling and propagating the findings through the following: A footprint of knowledge repository and sharing, a mechanism for keeping an institutional memory of the participants, as well as a mentorship programme in institutions that sponsored the participants. In addition, deliberate incentive schemes that encourage collaborators to yearn for more learning engagements, e.g., providing them with information on where to get funding for bankable climate resilience building projects.

3.6. Sustaining the Learnings

A comparative piece between Blantyre and Harare revealed that both cities experienced the following: Non-integrated environmental management approaches, political interference in varying degrees, limited linkages among the stakeholders which made networking difficult, conflicting statutory mandates, for example, multiple land ownership, and lack of up-to-date political and legal frameworks. Therefore, key examples of trans-

[1] The local government in Malawi consists of 28 administrative districts which are divided into 35 councils, whereas, the national government comprises the line ministry, the Ministry of Local Government. The Local Government Act 1998 (amended in 2017) provides the governance structure for both the local and national government.

ferable practices from these exchanges include: Integrated water catchment management, sharing of best practices through noting of similarities and differences in decision-making mechanisms, which leads to substantive environmental, social, and political governance in managing cities in the face of climate change, and identification of common themes in decision-making, as well as enablers and barriers in decision-making, which are pivotal in improving water and reticulation service delivery through the application of sound and well tested impact mechanisms. However, there were some layers of tension that existed between the knowledge producers and users that should be the focus of up-scaled research work, namely: Under-exploration of research on how gender and vulnerable groups are impacted by climate change in cities, lack of convincing data that link the increase in the development, reproduction and survival of insect pests in eucalyptus forests, and on the doubled presence of usipa (fish species) endemic to Malawi (in the past the species were seen only once a year).

From the 4 years that the FRACTAL research had been implemented in Blantyre, there is a wealth of evidence which suggests that successful climate knowledge co-production has occurred. However, as these co-production engagements are linked to a project funding period, the key question is: What can then be learned that showcases the sustainability of these processes and their respective learnings? This question unpacks research question six (see, e.g., Section 1.2), and it has been key in the FRACTAL design and through discussions, certain emergent areas of support were identified:

(1) Deepen and seek to institutionalize existing unearthed/engaged/initiated relationships and partnerships, so that they are not solely based on personal relationships;
(2) Expand to stakeholders not engaged with regularly, e.g., the private sector, communities/civil society;
(3) Enable better coordination and collaboration between local and national government; and
(4) Establish a regional footprint of knowledge sharing between cities.

In addition, the FRACTAL project was successful in extending the project period to include a bridge phase which aimed to scope the scalability and sustainability of the learning processes, as well as support the adaptation to best practices from the knowledge that was co-produced. Key outcomes of this phase include testing approaches in order to continue strengthening decisions so that they include climate information, strengthening the capacity to design and implement transdisciplinary processes, and strengthening networks that support the capacity development and learning within and across cities. Under the bridge funding phase, Blantyre has prioritized the following interventions that they see as key to sustaining processes and learnings. These include:

(1) City-specific dialogues on climate change relevant to Blantyre with regard to up-scaling the climate risk narratives (see, e.g., Section 2.5.4);
(2) City-specific dialogues on climate change relevant to Blantyre with respect to the waste-to-energy value chain; and
(3) Developing sustainable decision pathways for mainstreaming climate resilience strategies into policies.

As such, these emergent support areas and focus areas under the bridge funding phase paint a picture of what might be needed in terms of sustaining project learnings.

3.7. Synthesis of the Systems-Approach to Co-Production

This section synthesizes the general systems-approach (augmented by System Dynamics) to climate knowledge co-production that was highlighted in Sections 1.1 and 2.1–2.3, and it summarizes it as outlined in Figure 15. The numbers (1 to 13) in the figure show the sequence of stages in the methodology, whereas solid arrows are main flows and dotted arrows are feedback flows. Built-in sustainability drives in step 2b refer to ECRs and ERs discussed in Section 2.5.3. These ensure that institutional memory is retained and the bond between knowledge producers and users (city decision-makers) is reinforced. In the situational analysis (#4), research questions are formulated and then assumptions are developed and refined (4a), the context is established and reviewed (4b), and engagements for selected partners are designed (4c). It is envisioned that this approach has the capability for repeatability of the knowledge co-production processes. The final outputs of the research process are portrayed under #11, as policy briefs, decision support tools, and other modes of dissemination such as journal publications.

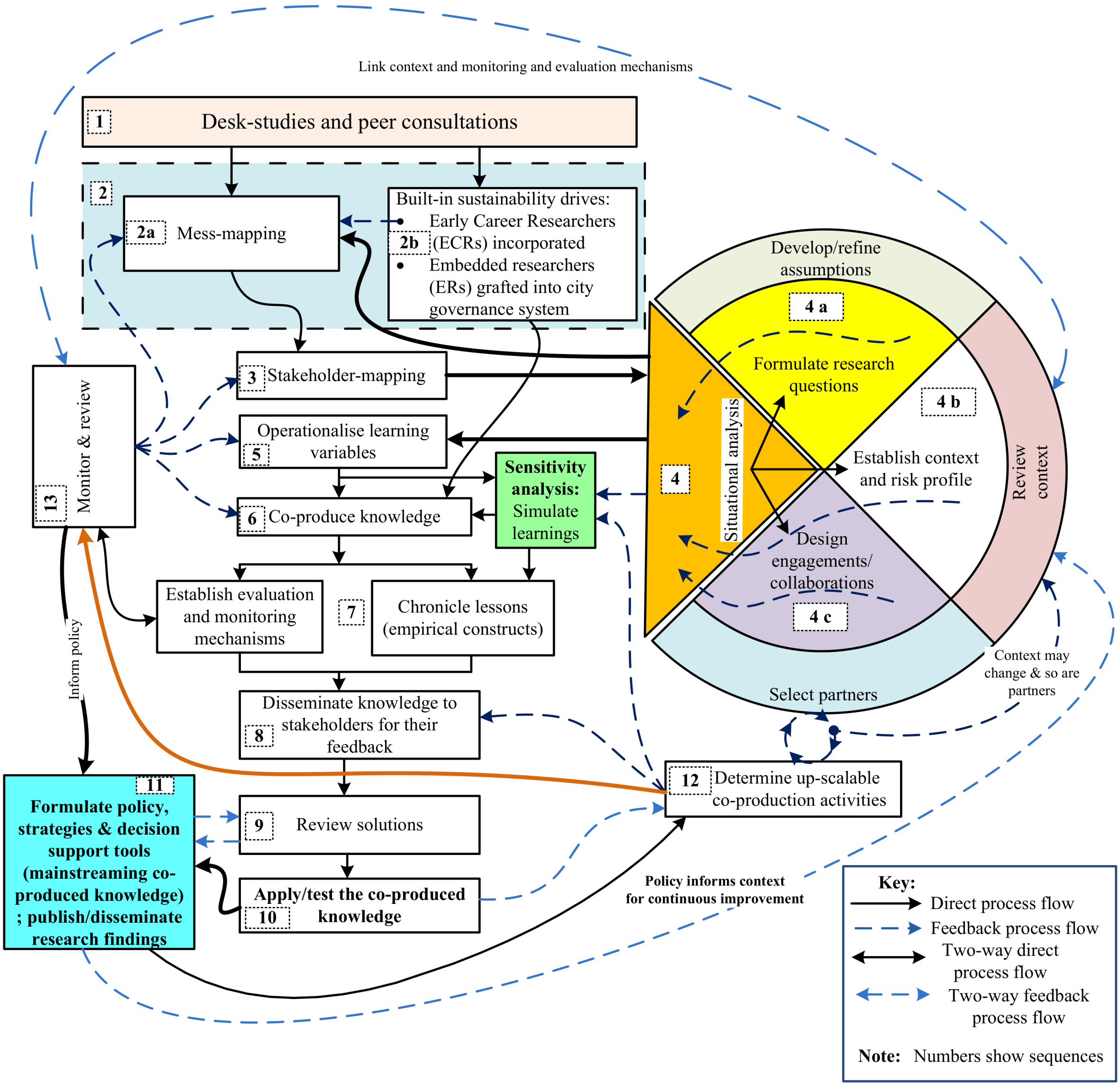

Figure 15. A synthesis of the systems method for transdisciplinary knowledge co-production.

Figure 15 depicts the characteristics of the systems-approach as presented in Sections 1.1 and 2.1–2.3; and summarizes the systems-model for replicating the knowledge co-production process. To put this depiction in context, the following highlights are made:

1. The situational analysis, mess-mapping, and stakeholder mapping ensure that emergent matters are flashed out and considered when developing and refining research questions, establishing the context and designing effective engagements, thereby making it holistic;
2. The co-production process is clearly illustrated, making it possible for other researchers to replicate the learning process, thus making it systematic;

3. The systemic nature of the co-production process is portrayed by how various aspects feed into the core knowledge production system, including feedback and feed forward.
4. The risk-based component is incorporated in the form of the process of identifying challenges, since these pose a risk to the success of the co-production process;
5. By advocating for tackling of issues that cut down on cost and time, namely: paying attention to the initial first steps at the study planning phase and taking a shared approach (through transdisciplinary co-production in Learning Labs), the method ensures that the process is optimal; and
6. Sustainability is guaranteed through the documentation of specific actions and transferable practices and networks developed for a possible up-scalability of learnings, as well as the incorporation of mentorship mechanisms in the form of the Early Career Researchers (ECRs) and Embedded Researchers (ERs).

4. Conclusions and Recommendations

The study showed that transdisciplinary climate knowledge co-production processes that were preceded by a thorough situational analysis had higher chances of success and possibilities of reducing the lead-time for the generation of deliverables. Therefore, the pre-engagement processes, such as context setting and choosing competent facilitators, are as important for collaborations as the actual engagements that lead to the knowledge co-production. The major contribution of the study is that it applies a parametric Markov process to simulate characteristics of learning stages from the disciplinary comfort-zone to the third-space, thereby establishing four distinct learning phases which are marked by respective probability values, namely: Shock and resistance to change, experimenting and exploring, acceptance, and integration into the third-space; and it ranks the plausibility of decisions in terms of how knowledge producers and users support them, using a four-step decision support tool. Other contributions to knowledge are in the form of system-archetypes which are 3-fold. First, salient features for successful co-production comprise: Establishing context, selecting suitable facilitators with skills to create safe and productive learning spaces, leveraging strengths of shared-learning experiences, and determining similarities and differences of cities in a region to establish transferable practices. Second, trust is the determinant of support from collaborators, which develops by delivering on promises and is a precursor for effective communication and networking, whereas, sustaining a third-space legacy calls for well-established information distillation structures and a methodical systems-approach. Third, knowledge co-production challenges comprise securing knowledge-users' buy-in, establishing monitoring systems, and coordination and communication strategies; assigning quantitative values to attributes that characterize the third-space, namely: Level of trust, perceived value, and knowledge and attitude outcomes; and retaining or sustaining institutional memory. It is envisioned that the findings and method propounded can be applied globally by academics, researchers, and policy makers to replicate the co-production process in a methodical and systemic way, while solving complex problems in dynamic socio-technical systems and environments, and to sustainably mainstream the knowledge co-produced in policies. In view of the discourse presented and findings from the research, it shows that there are a number of areas that the future research must focus on. Firstly, the simulation in this study treated the problem as a parametric rather than an empirical problem due to the lack of empirical data. Therefore, it is recommended that a set of parameters, namely: Level of trust, perceived value of the co-production process, attitude, and behaviour be used to simulate the probabilities of transitioning from the disciplinary comfort-zone to the third-space in both parametric and empirical terms. Secondly, knowledge co-production should be up-scaled so that innovative methods of garnering buy-in of knowledge-users are explored, and that more is investigated about gender, health, and climate change; as well as to whether the current increase in forest pests and double presence of some species of fish in Lake Malawi (which impact the livelihood in Blantyre City) are a result of anthropogenic climate forcing or of natural forcing. It is envisioned that the proposed systems-approach to knowledge co-production provides a holistic, repeatable, and methodical way of co-producing climate resilience mechanisms and solving complex city or urban development problems. Therefore, it is a useful tool for researchers and practitioners in urban planning and climate resilience development domains.

Author Contributions: Conceptualization, B.M.; methodology, B.M.; software, B.M.; validation, B.M. and B.T.; formal analysis, B.M., B.T. and D.M.; investigation, B.M., B.T., D.M., T.M., and J.K.; resources, A.M.; data curation, B.M.; writing—original draft preparation, B.M., J.K. and D.M.; writing—review and editing, B.M., A.M., T.M., C.J.; visualization, B.M.; supervision, B.M.; project administration, B.M. and B.T.; funding acquisition, A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the British Department for Foreign Investment and Development (DFID) through the Natural Environment Research Council (NERC) of the United Kingdom grant number NE/M020347/1.

Data Availability Statement: The data presented in this study are not publicly available because they are still being researched and there are some intellectual property issues like patenting that have not yet been finalized.

Conflicts of Interest: The authors declare no conflict of interest.

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