System Dynamics & Sustainability:
A Research Agenda for the Coming Decade(s)

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With detrimental effects of climate change already here, deteriorated natural habitats, increased pollution of soils, air, and water, and appropriate action still lagging behind, work on sustainability that applies system dynamics is more urgent than ever. In July 2018, a number of researchers - mainly active in Europe - commenced an open dialogue on system dynamics and sustainability at emlyon business school in Lyon. The aim of that meeting was to assess how to increase system dynamics and sustainability research output and impact. Since then a network has emerged and, some members of the group have begun working on a number of collaborative initiatives around research, teaching, and grants. More ambitiously, discussions also have evolved around the value of more coordinated avenues for future system dynamics research. At the 2020 SD Conference in Bergen, we, the "SD&Sus Lyon Group", would like to present some of our progress in our thinking so far.

In this essay bundle, we present some of the ideas that we have developed on near future avenues for system dynamics research and applications in the domain of sustainability. The aim of this essay bundle is to initiate a dialogue about how the system dynamics community may achieve impact through coordinated accumulation of policy-relevant knowledge in the area of sustainability and to make progress on identifying those critical avenues.

Content:

1 System Dynamics for Integrated Analysis of Sustainable Development Goals

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1.1 Abstract

The Sustainable Development Goals (SDGs) are at the heart of the United Nations' 2030 Agenda for Sustainable Development. The SDGs are meant to provide a holistic and integrated perspective on sustainable development challenges. This chapter analyzes how system dynamics can provide an analytical framework for representing the dynamic interdependencies among policy sectors, addressing the challenges and shortcomings of previous research. It describes two case studies and derives some general insights for SDG research. We conclude with reflections on the challenges ahead for research and for mainstreaming system dynamics in science diplomacy.

1.2 Introduction

In September 2015, all United Nations Member States adopted the 2030 Agenda for Sustainable Development (United Nations, 2015). At its heart are the 17 Sustainable Development Goals (SDGs). The SDGs succeeded the impactful Millennium Development Goals (MDGs), adopted from 2000 to 2015, as a concerted effort to address critical social issues. The MDGs helped mobilize action by developing nations in eight priority areas, such as poverty, hunger, and disease, among others (Sachs, 2012). However, as the challenges associated with environmental degradation, social inclusion, and climate change loomed large, the worlds' governments renewed their efforts with a set of reference goals that could steer the international community toward a sustainable trajectory over the following fifteen years until 2030. The SDGs are specified by 169 targets (about 10 per goal) and 232 indicators (about 1 or 2 per target, with some overlaps). While goals are broad and qualitative statements about objectives, indicators provide quantitative measures that assess the progress towards or away from a goal. Targets, in turn, use indicators to make goals specific with endpoints and timetables (Parris & Kates, 2003).

The SDGs cover a wide range of sustainable development dimensions such as well-being, economic prosperity and environmental protection as well as global partnerships for achieving the goals. And, while the MDGs were goals aimed mainly at developing nations, the SDGs are global in nature requiring the active involvement of all nations of the world. Previous policy approaches to sustainable development and especially the MDGs have suffered from lack of integration across sectors (policy domains) in terms of strategies, policies and implementation (e.g., Haddad, 2013 ; Waage et al., 2010). Lack of integration was manifested, for example, by insufficient accounting for the interlinkages across sectors, which resulted in unintended impacts of sector-specific development policies on other sectors, and ultimately in diverging trends across broad objectives for sustainable development (Le Blanc, 2015). Consider for example the challenging trade-off between eradicating extreme poverty and hunger (MDG1) and environmental sustainability (MDG7). Agricultural practices aimed at increasing agricultural yields and reducing poverty and hunger (e.g., widespread use of pesticides, synthetic fertilizers, intensive farming, and monocultures) contribute directly to environmental degradation (WHO, 2020).

The SDG framework was created as an “indivisible whole” (Weitz et al., 2014; Nilsson, 2016), adopting a more holistic and multidimensional view of development (Pradhan et al., 2017). This ambition is not without critique. Critique spans issues such as lack of measurability, attainability and actionability (Easterly, 2015), the large role that multinational enterprises had in the formulation of the SDGs, and the neo-liberal/capitalism values the SDGs imply (e.g. by emphasizing economic/GDP growth as a goal in itself; e.g., Hickel, 2015).

Going back to the integrated nature of SDGs, according to the International Council for Science (ICSU, 2017), “all SDGs interact with one another … [so] understanding the range of positive and negative interactions among SDGs is key to unlocking their full potential”. However, understanding such interactions and their effects is a challenging task, requiring the support of a variety of players: governments, academia, NGOs, industry, citizens (General, 2019). Since the SDGs were introduced in 2015, studies have adopted a variety of analytical approaches to explicitly identify and represent interlinkages among sustainable development goals and targets. The studies differed not only in terms of methodology used, but also with respect to geographical scope, and the number of goals and targets considered (Breuer, Janetschek, & Malerba, 2019).

In terms of types of analytical approaches, they include qualitative case studies (Donoghue & Khan, 2019; Machingura & Lally, 2017), correlation analysis between pairs of SDG indicators on global and country scales (e.g., Pradhan, et al., 2017), concept mapping (e.g., Lim et al., 2018), network analysis (e.g., Le Blanc, 2015; Zhou & Moinuddin, 2017), or SDG interaction scoring (e.g., Nilsson et al., 2016; Weitz et al., 2018), causal loop diagramming and system thinking (Ferri & Sedehi, 2018; Cernev & Fenner, 2020; Zhang, 2016), and system dynamics (iSDG model; Pedercini et al., 2018; Pedercini et al. (2019). Such analyses reveal, for example, gaps in the current SDG framework such as exclusion of key actors (e.g., corporations) and issues (e.g., intergenerational equity and population); inadequate reconciliation of economic growth with maintaining the Earth system; and deficient consideration of the relationship with international law (Lim, et al., 2018). The diversity of approaches employed also highlight the great disparity of possible insights.

Qualitative case studies on the trade-offs between SDGs, typically focus on the rich individual complexity of a particular country, and the specific challenges that may take place due to the interaction between two specific SDGs. (Machingura & Lally, 2017) focus mainly on SDGs that compete or conflict with each other, such as reconciling ending hunger (SDG target 2.3) with environmental sustainability (SDG target 15.2); or reconciling income inequality (SDG target 10.1) with economic growth (SDG target 8.1). (Donoghue & Khan, 2019) focus on both tradeoffs and synergies and develop a rich set of case studies for multiple countries (e.g., Ethiopia, Korea, Vietnam, Zimbabwe, Ghana, Ecuador, Sri Lanka). The first researchers to propose an approach for studying interactions between the SDGs were Weitz et al. (2014). Considering a subset of goals (e.g., water (SDG6), food (SDG2), and energy (SDG7)), their qualitative study created a map capturing the type of relation and the direction of influence between targets in the three goals.

Le Blanc, 2015) and Lim, et al., 2018) use network analysis to capture the static network of relationships between the 17 SDGs and their targets at a global level. Importantly, they employ the wording of the targets to establish a link between them. Because the network of interconnections between SDG goals and targets are based on the language used in the targets, capturing the result of political negotiations in an intergovernmental context, they at times ignore natural, biological, economic, and social systems relationships (Le Blanc, 2015; Lim, et al., 2018). Moreover, the relationships are qualitative, not establishing the quantitative impact between specific targets.

Still investigating SDG interconnections from a global perspective, Le Blanc et al. (2017) qualitatively explore the relationships of SDG 14 (Oceans)'s targets and the rest of SDGs' targets using, again based on their wording to establish interconnections. The authors conclude with the need for cross-sector collaborations for knowledge enhancement and sharing, and necessary policy discussions. In contrast to previous research, Zhou and Moinuddin (2017) identify and quantify the target interlinkages at national level, and use network analysis to present an integrated analytical framework on SDG target interlinkages for nine Asian countries. Nilsson et al. (2016) propose a 7-point scale for binary interactions, offering a way to quantify the strength of interconnections. The scale allows three types of positive interactions, three types of negative interactions, and a neutral interaction. The authors point out the need to collect evidence showing how particular interventions evolve. They also stress several considerations, regarding interactions: are they reversible?, are they bidirectional?, how strong are them?, how certain (or uncertain)?, can the relationships between targets and goals change over time? For example, some policies may have positive effects on goals in the short term, but could deplete resources and harm the environment in the long term, impairing the progress on the goal. In many ways, the considerations posed by Nilsson et al. (2016) preview the need for a methodological approach with the capabilities of system dynamics to investigate synergies and tradeoffs among SDGs.

The International Science Council (2017) apply the scale proposed by Nilsson et al. (2016) to four goals (Food (SDG 2), Health (SDG 3), Energy (SDG 7), and Oceans (SDG 14)) considering five key dimensions that shape interactions: directionality of the interactions, geographical context, governance, implementation technologies, and timeframe. Four possible directionalities of interactions between two goals or targets are presented: uni-directional, bi-directional (which can be symmetrical or asymmetrial), circular, and multiple (allowing them to form balancing and reinforcing feedback loops).

Modelling techniques, particularly when drawn from complexity science, provide complementary ways to evaluate the multidimensional and long-term impact pathways of interdependencies and policy interventions (Hammond & Dubé, 2012).

1.3 Overview of systems thinking work

More recently some studies have begun to employ Systems Thinking (ST) and Causal Loop Diagrams (CLDs) to study the SDG interactions. Ferri and Sedehi (2018) present a CLD capturing the interconnections among the 17 SDGs (only at the goal level). They propose the inclusion of three additional goals: Sustainable Migration (SDG 18), Sustainable Security (SDG 19), and Sustainable Population (SDG 20). From their CLD, they identify two important major loops: a reinforcing one – connecting SDG 4 (Education and Lifelong Learning), SDG 5 (Gender Equality), SDG 11 (Inclusive and Safe Cities), and SDG 19 (Sustainable Security); and a balancing one – connecting SDG 1 (Less Poverty Everywhere), SDG 3 (Healthy Lives at All Ages), SDG 20 (Sustainable Population), and SDG 6 (Water and Sanitation).

Zhang et al. (2016) also use ST and CLDs to investigate synergies and trade-offs between the SDGs. The authors use intermediate factors (in addition to the SDGs) to improve clarity and avoid inadequate or indirect links. They identify three system archetypes within their CLD: Reinforcing Growth, Limits to Growth, and Growth and Underinvestment, and propose leverage policies for each of them. Gender equality and sustainable management of water and sanitation are proposed as leverage policies for the Reinforcing Growth archetype. Limited available resources represent the leverage policy for the Limits to Growth archetype. And, the development of sustainable livelihood standards is suggested as the leverage policy for the Growth and Underinvestment archetype.

Finally, Cernev and Fenner (2020) develop a global CLD capturing the feedback mechanisms connecting the 17 SDGs. The authors categorize the SDGs into 4 categories: Outcomes/Foundational Goals, Enabling Goals, Human Inputs, and Physical Assets. Outcomes/Foundational Goals category have far-reaching effects on other goals, and can be seen as priority goals for policy initiatives. They include SDG 1 (No Poverty), SDG 3 (Good Health and Well-Being), SDG 14 (Life Below Water), and SDG 15 (Life on Land). The Enabling Goalscategory include SDG8 (Decent Work and Economic Growth) and SDG 17 (Partnerships for the Goals). The Human Inputs category include SDG 2 (Zero Hunger), SDG 4 (Quality Education), SDG 5 (Gender Equality), SDG 10 (Reduced Inequalities), SDG 13 (Climate Action), and SDG 16 (Peace, Justice and Strong Institutions). The Physical Assets category relates to infrastructure and includes SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible Consumption and Production). SDG 3 is determined as central to social goals, while SDGs 8 and 9 appear to play the role of facilitators of key services. Climate Action (SDG 13) affects a large part of the goals related to the environment. The authors go on to identify and analyze risks from failure to meet the goals and highlight the need of a longer timeframe, beyond the year 2030, for reaching the goals.

These studies offer policy makers an overview of the connections among SDGs and the possible trade-offs and synergies among them. Effective policies must take them into consideration. However, the methodological limitations prevent them from being applied in policy design and interventions. Since the ST and CLD studies adopt a global perspective they fail to address specific national and regional contextual differences identified by the International Science Council study (2017). More important, without the proper development of a formal dynamic simulation model, quantifying the relationships among different variables, it would be impossible to assess the impact of different policies over time. Nonetheless, the network and ST/CLD studies capturing the rich interconnections among different SDG targets at national or global level provide a good starting point for system dynamics.

1.4 Overview of existing system dynamics work

System dynamics (SD) has a long traditional of global modeling for policy design and policy analysis. World Dynamics (Forrester, 1971) and Limits to Growth (Meadows, 1972) were the first to adopt SD at a global level to study the impact of human activity on the long-term behavior of our world system. SD has also long been applied in policy analysis and design for sustainable development. It provides a synthesis framework and powerful tools for scenario-based analysis of critical societal challenges such as wellbeing and economic growth, climate change and natural resource management (Ford, 2010; Forrester, 1971b; Meadows et al., 2004; Sterman et al., 2012). Several authors have emphasized the analytical capabilities brought by systemic methods in face of the long-time frames, multiple values and holistic, integrated approach needed to address sustainability issues (Đula et al., 2019; Hjorth & Bagheri, 2006; Videira et al., 2017; (Kapmeier & Gonçalves, 2018). Moreover, the adaptive and stakeholder engagement requirements of sustainable development debates have led to experimentation with model-centered participatory system dynamics processes that foster a joint understanding of sustainable development pathways while nurturing stakeholder connections and knowledge co-creation (e.g.: Antunes et al., 2015; Stave, 2002; Videira, et al., 2017).

System dynamics diagramming tools can promote *structural* insights about the relationships among components in the system of SDGs (e.g., Bennich et al., 2018a; Bennich et al., 2018b; Macmillan et al., 2020; Videira et al., 2012; Videira et al., 2014). Controlling for undesired developments and ensuring progress towards targets and goals, however, requires formal simulation modelling (Kopainsky et al., 2018).

In the specific context of SDG analysis, a series of studies using the integrated Sustainable Development Goal model (iSDG model; Pedercini, et al., 2018) assess country-wide synergies and trade-offs between SDG targets. (Collste et al., 2017 study the interaction between SDGs 3 (health and well-being), 4 (education), and 7 (energy) and present the impact of five different policies on all three SDGs jointly considered. Pedercini, et al. (2019) identify and quantify synergistic interactions between ambitious interventions to achieve the SDGs for three African countries. Finally, Allen et al. (2019) assess synergies as well as trade-offs on target level resulting from different approaches to Australia's development (green, inclusive, neither or both). These examples show how quantitative system dynamics models provide policy makers with interactive tools to perform what-if analyses so that they can test the response of targets and indicators to unforeseen shocks and deliberate policy interventions and thus develop *dynamic* insights.

1.5 Two more detailed case studies

Cutting across structural as well as dynamic insights is the need for policy making and collaboration across policy sectors and sustainability domains. In this section, we describe one systems thinking and one system dynamics example in more detail.

1.5.1 Systems thinking case study

In a participatory qualitative system dynamics modeling approach, Macmillan et al. (2020) describe and demonstrate practically how integrated interventions for placemaking and active transport can contribute to a wide range of SDG targets. They base their analysis on a project in Auckland, NewZealand. To illustrate the interconnection between the SDGs, the found out that by addressing sustainable cities and communities (SDG11) primarily affects equity (SDG 10) and also affects eight of the other goals, in particular SDGs 1 (no poverty), 3 (zero hunger), 4 (quality education), 5 (gender equality), 8 (decent work and economic growth), 13 (climate action), 16 (peace, justice and strong institutions), and 17 (partnerships for goals). They identified one balancing and 12 reinforcing feedback loops, linking the interventions improvements to neighbourhoods with the SDGs (Figure 1). It is important for policy makers that policy interventions should engage the reinforcing loops in virtuous cycles – if set in a wrong direction, they would work as vicious cycles, worsening the situations.

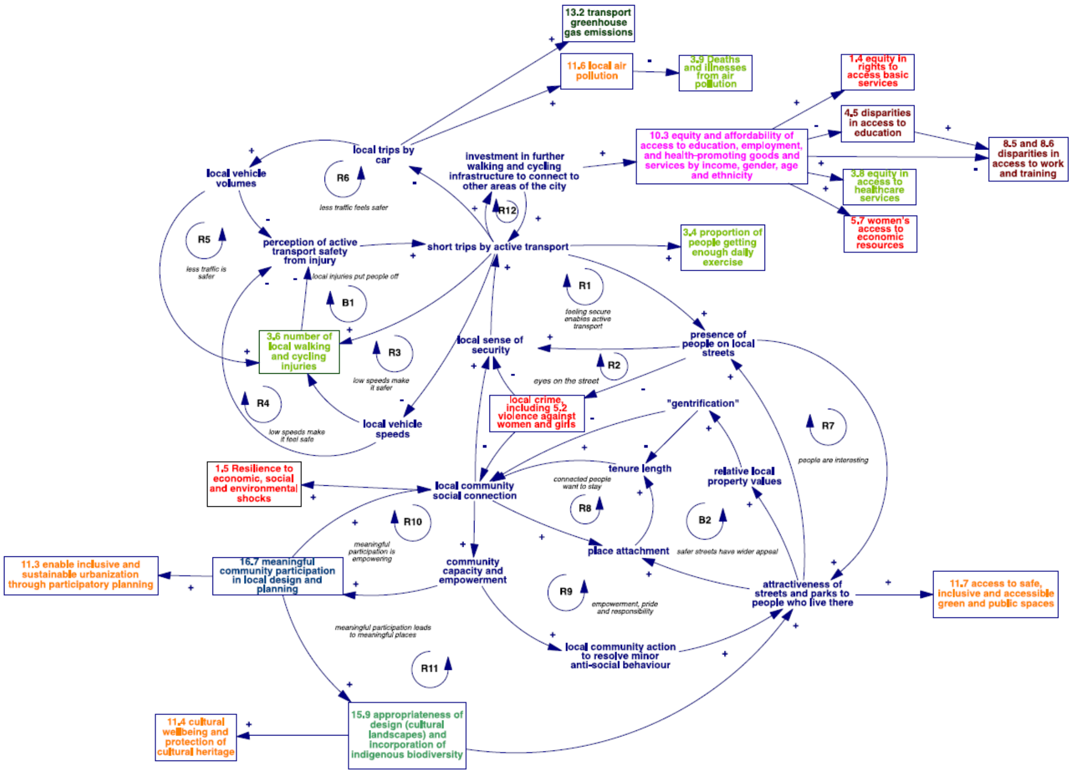

Fig. 1. Complex, dynamic causal theory for how equity-focused, participatory urban planning for walking and cycling contributes to specific SDG targets (SDG targets are shown in boxes, colour coded to match the goals. Arrows with positive signs (+) indicate that a change in the arrow-tail variable leads to a corresponding change in the arrow-head variable. Arrows with a negative sign (−) indicate that a change in the arrow-tail variable leads to an inverse change in the arrow-head variable. R – reinforcing loop, the result of which is an amplification of the initial pattern of behaviour. B – balancing loop, the result of which is a dampening of the initial pattern of behaviour).

Figure 1: Feedback diagram assessing the interplay of SDGs for urban planning for walking and cycling

1.5.2 System dynamics case study

Regarding quantitate modeling, Pedercini, et al. (2019), a study that discusses the nature of synergies between SDGs. As countries pursue policy goals across sectors as diverse as health, agriculture and infrastructure, sectoral policies interact and alter their effectiveness when implemented in isolation. The study identifies and quantitatively assesses synergies in three countries. The paper starts with introducing a typology of five classes of synergies (Figure 1):

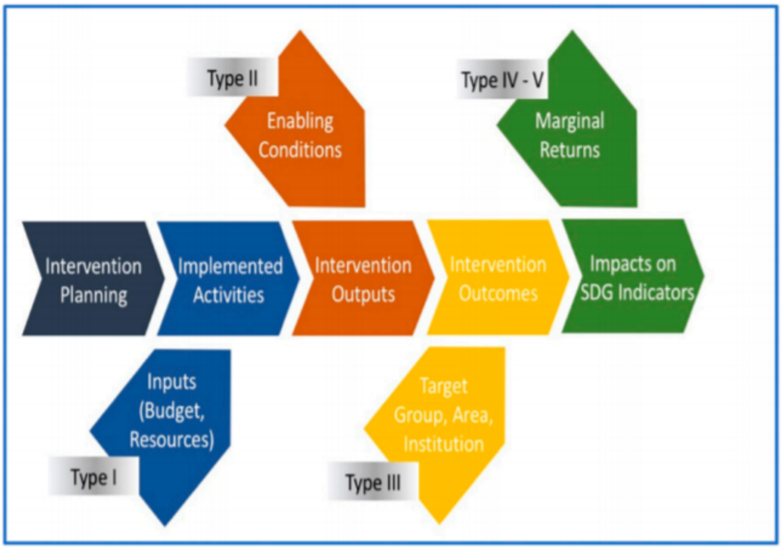

Fig. 1. Results chain for a single development intervention. There are 5 types of mechanisms at different stages of the chain that give rise to synergy. Type I synergies arise from interventions (e.g., financial investment) that increase the resources available for other interventions; type II synergies arise when an intervention creates enabling conditions for a second intervention; type III synergies arise when an intervention affects the target group of another intervention; type IV synergies arise when the cost-effectiveness of progressing on a target indicator changes as the level of the indicator improves; type V synergy occurs when progress on an indicator cannot, or should not, exceed a given target value.

Figure 1: Typology of synergies from policy interactions (Pedercini, et al., 2019: 23026)

1. Inputs; type I synergies result from interventions that increase the resources available for other interventions.
2. Enabling conditions; type II synergies result from interventions that create enabling conditions for other interventions.
3. Target group, area, and institution; type III synergies result from interventions that affect the target group of other interventions.
4. Marginal returns; type IV synergies arise when the cost-effectiveness of progressing on a target indicator changes as the level of the indicator improves.
5. Overshooting objectives; type V synergies – actually, trade-offs – occur when progress on an indicator cannot or should not exceed a given target value.

The paper operationalizes the typology in pilot studies of SDG strategies undertaken in Senegal, Côte d'Ivoire and Malawi. In the pilots, the integrated Sustainable Development Goal (iSDG) model was used to simulate the effects of policies over the SDG time horizon (2030) and to assess the contribution of synergies to progress towards goal achievement (Figure 2). In total, synergy contributions to overall SDG performance were 8% for Côte d'Ivoire, 0.7% for Malawi, and 2% for Senegal. The economic value of these contributions was estimated to be 2% of GDP for Côte d'Ivoire, 4% for Malawi, and 0.7% for Senegal.

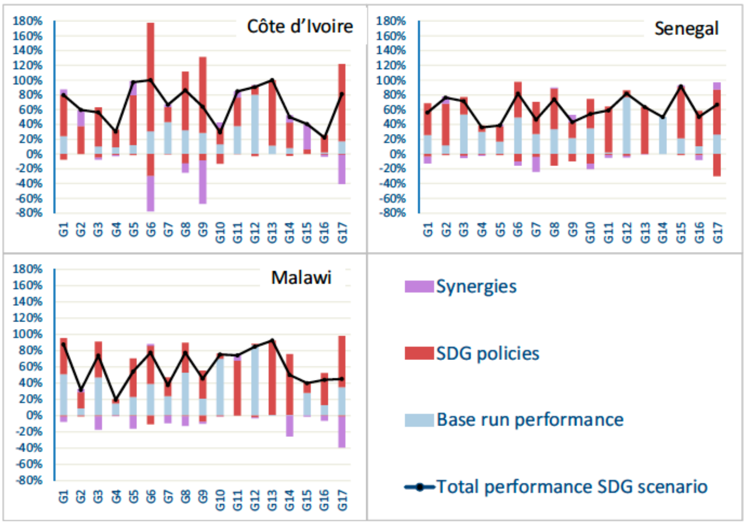

Fig. 3. Contributions to SDG attainment of BAU (base run performance), SDG policies, and synergies arising from policy interactions for Côte d'Ivoire, Senegal, and Malawi. The black line indicates the level of attainment of each SDG at year 2030. For simplification, the effects of the SDG policies are shown in aggregate. The SDG policy mix varies between the 3 countries. Note that SDG policies can sometimes exert a negative influence on some SDGs, e.g., expansion of irrigation for improvement of SDG2 could negatively impact water availability for human consumption (SDG6). The chart for Côte d'Ivoire exhibits instances of goal overshoot for SDGs 6, 8, 9, and 17, where the charts for Senegal and Malawi show all SDGs under 100% attainment. This is because the Senegal and Malawi cases have undergone several rounds of iterations to eliminate goal overshoot and redistribute resources to other SDG policies.

Figure 2: Synergies from policy interactions for three countries (Pedercini, et al., 2019: 23026)

The paper concludes by emphasizing that enhanced understanding of synergies in sustainable development planning can contribute to progress on the SDGs – and free substantial amounts of resources. A structural understanding of the synergies between interventions is fundamental to identifying those combinations of interventions that are particularly effective while alternative combinations may slow down progress towards goal and target achievement.

Opportunities for insights on policy design and impact

As the literature progressed in its attempt to inform and quantify synergies and trade-offs between SDGs, it has potentially focused too narrowly on its goal. At the heart of the matter, governments and policy makers need to understand the nature of such synergies and trade-offs. The question of ***how*** sectoral policies interact is just as important as ***how much*** synergy they can generate. Current, SD work quantifies the impact, identifies such synergies and trade-offs, and provides such information at a country level (as shown in Figure 2), it but does so using a black box approach.

Perhaps, the dynamic complexity of the system and the interconnectedness of its parts prevent a full grasp of its parts, however, an opaque system approach will likely generate drawbacks as well. Consider the five-class typology of synergies captured in figure 1. A critical cognitive aspect of such representation is the emphasis on a sequential path, open loop approach, for policy design. The policy design and implementation process has five stages: (1) intervention planning, (2) implemented activities, (3) intervention outputs, (4) intervention outcomes, and (5) impacts on SDG indicators. It is understandable that the authors have simplified complexity in such a way to facilitate understanding of the mechanisms that can bring the desired impact. At the same time, the sequential open loop approach misleads policy makers by obscuring the feedback perspective of the complex system. More important, the policies derived suffer from the same blindsight. Hence, it is unlikely that the generated policies identify the high leverage points in the system. Such policies potentially miss the opportunity associated with driving the system via dominant feedback processes.

Another aspect of the typology is that the types of mechanisms considered are narrowly influencing parts of the policy implementation “path”. While policy interventions must take place at a specific point in the system, policy makers may benefit significantly from policies that can be applied in a “distant” part of a system, but has the desired impact in another part. Hence, the explicit consideration of the intricate web of interconnections that led to such influence i s important for policy design. Naturally, this is automatically considered in research capturing interconnectedness among SDGs, however, it is not emphasized at the time of policy design. Flexibility in the locus of intervention matters.

In this sense, instead of a typology of mechanisms at different stages of a policy implementation “pathway”, a preferred system dynamics approach would create a library of feedback processes mapping the interconnection among different SDGs. Such a library would allow policy makers to recognize the key feedback processes driving the behaviour mong such SDGs. The feedback process library would map dyadic interactions between the SDG goals, but would capture specific targets. After all the natural, biological, economic, and social systems relationships between two SDGs are taken into consideration, it is very likely that both targets and indicators within such SDGs would change (i.e., some being added, and others removed) to such library. The library would allow for a more systematic and structured approach to the complexity associated with the SDGs of different parts of the world system.

1.6 Conclusions

The examples indicate that using a system dynamics approach in the analysis of the interconnections of the SDGs can help decision makers and policy designers to better understand complex systems. They also learn that policy interventions not only have single effects, but also co-benefits or multi-solving (https://www.climateinteractive.org/programs/multisolving/flower/). The examples also show that existing system dynamics work in the context of the SDGs serves several purposes (cf. de Gooyert & Größler, 2018; Harrison et al., 2007):

- Policy identification: what is the best policy (mix) to obtain SDGs efficiently?
- Goal (re)formulation: what kind of inconsistencies/ inaccuracies exist in the current formulation of goals/dimension/indicators, how could they be improved? This aspect, in particular, can be valuable for overcoming some of the shortcomings of the SDGs, such as the fact that they use economic/GDP growth as a goal itself.
- Empirical guidance: sensitivity analyses can reveal which future data collection appears to be crucial to fill knowledge gaps on how to obtain SDGs efficiently.
- Learning: interactive simulation models can help policy makers/ stakeholders to learn about SDGs and policy effects (and policy resistance).
- Implementation: participative simulation models can help foster smooth implementation of identified policies.

System dynamics interventions can be conducted on many organizational and societal levels. The analytical framework is useful for facilitating transformations towards sustainable development. This can be done by model experts or participatory modelling with community representatives of all organizational and societal levels.

1.7 Opportunities for future research

From the overview offered in this essay, three major opportunities arise for further exploration of system dynamics contributions to the implementation of Agenda 2030.

First, we suggest to advance the development and application of qualitative and quantitative simulation models that support an integrated analysis of SDGs achievement, at a macro or country level, such as illustrated by the iSDG tool. Extending application to other contexts and SDGs interactions is needed.

Second, transformations towards sustainable development on all levels and addressing many SDGs simultaneously requires embedding the analysis in broader processes of participation and stakeholder engagement. Also, building detailed, parameter-rich simulation models that represent the complex cross-scale and cross-level dynamics of sustainable development is time consuming to develop and calibrate, and may not be an easy task to achieve in resource constrained studies. On the other hand, SDG oriented simulation models should also be embedded in a wider assessment process that combines the use of quantitative and qualitative approaches and that thus integrates knowledge from various disciplines and various stakeholder groups in society (Engle et al., 2013; Ericksen et al., 2009; Janssen & Anderies, 2013; Ostrom, 2009). As argued by Videira et al. (2017) exploring multi-method approaches combining participatory modelling with other assessment tools (e.g., indicators, scenarios, cost-benefit analysis) in broader deliberative decision-making processes is an important area for future research.In these contexts, a careful consideration of political agency and negotiation of power relations will be needed (e.g. Avelino & Wittmayer, 2015; Geels, 2011; Jørgensen, 2012), with multiple process designs adjusted to different target groups.

1.8 Key resources

- Sustainable Development Goals, Knowledge platform: https://sustainabledevelopment.un.org/?menu=1300
- Integrated Sustainable Development Goal model: https://www.millennium-institute.org/isdg

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2 System Dynamics for Studying the Water Energy Food Nexus

Birgit Kopainsky

2.1 Introduction

The water-energy-food (WEF) nexus is an increasingly common framework for bridging science and policy (Yung et al., 2019). The nexus approach is based on the premise that improved water, energy and food security can be achieved through integrated management and governance across sectors and scales (Hoff, 2011). Water, energy and food security are necessary for human well-being, poverty reduction and sustainable development (FAO, 2014). The nexus approach constitutes a fundamental shift away from a pure sectoral approach to solutions that embrace the interdependencies between the sectors. It adopts a systems-based perspective that explicitly recognizes water, energy, and food systems as both interconnected and interdependent (Albrecht et al., 2018).

The water energy food nexus has only appeared relatively recently as an area of research (Figure 3). While the first studies were published in 1988, WEF research has expanded rapidly in recent years. A quantitative review of the literature on the WEF nexus (Newell et al., 2019) concluded that:

- Studies in the fields of environmental science predominate, while social science domains are underrepresented;
- Understanding of how actors and institutions shape resource access, distribution and use is underdeveloped;
- Methods for co-production of knowledge with stakeholders are lagging behind.

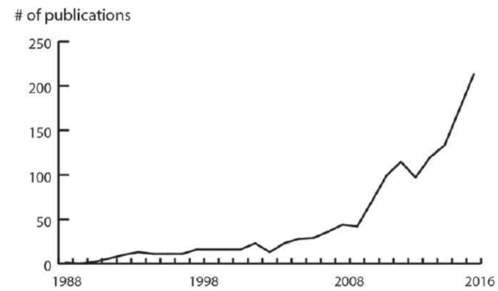

Figure 2. Academic publications on the food–energy–water nexus, 1988–2016.

Figure 3: Number of publications on the water energy food nexus (Newell, et al., 2019: 4)

In a systematic review of WEF nexus assessment methods, Albrecht, et al. (2018) identify a wide range of methods that are used to evaluate water, energy, and food interlinkages or support development of socially and politically relevant resource policies. The most important methods are, in decreasing frequency (total higher than 100% as many studies used more than one method):

- Environmental management (60%) includes methods such as scenario analysis, foot printing, life cycle assessment, stakeholder engagement, decision support and benefit analysis.

- Economic methods (45%) include input-output analysis, cost-benefit analysis, trade-off analysis, social accounting matrix, economic modeling incl. econometric modeling, value chain analysis, and supply chain analysis.
- Indicators (25%)
- Statistics (8%), e.g. principal component analysis, regression statistics, and trend analysis.
- Social science (26%), e.g. institutional analysis; questionnaires, surveys, interviews; historical analysis, agent-based modeling; Delphi technique; critical discourse analysis; ontology engineering; stakeholder analysis; participatory workshops / focus groups; policy analysis.
- Integrated modeling (16%), including environmental management, integrated assessment models, CLEWS model, and hydro-economic modeling.
- Systems analysis (16%), e.g. multi-sectorial systems analysis, material flows analysis, systems informatics and analytics, causal loop diagrams and system feedbacks, mathematical/engineering modeling, resource flows, and network analysis.
- Geospatial (16%) methods such as spatial analysis and remote sensing.
- Hydrological modeling (12%).
- Energy modeling (3%).
- Food systems (3%) methods such as caloric-demand analysis and source-to-service resource modeling.

This list illustrates that while the WEF nexus approach explicitly calls for a systems perspective, the most common methods used for nexus assessment do not reflect this.

2.2 Overview of existing system dynamics work

Elsayed et al. (2018) describe a water resources model for the entire Nile basin that provides the basics for integration with food, energy and socio-economic drivers in the basin. Feng et al. (2016) develop a WEF model that differentiates water storage, water supply, power generation, population, biomass, and environmental awareness. The model is calibrated for a case study region in China and used to study the co-evolution between the model components over an extended time period (2200). The co-evolution process seems to consist of four stages: exploitation, deterioration, depression and recovery. Of all the parameters in the model, critical biomass and the population growth rate have the highest influence on the trajectories of the stock variables over time.

Ravar et al. (2020)’s WEF model contains population, water, agriculture, and energy modules. It is calibrated for the Gavkhuni Basin in central Iran. The model was used to evaluate the relative effectiveness of sectoral municipal, industrial, and agricultural water and energy consumption management and environmental protection policies in improving ecosystem provisioning services during a 10-year period. The results indicated that a combination of agricultural policies (changing crop pattern and enhancing crop productivity) and controlling groundwater withdrawal was most effective in improving WEF outcomes while at the same time meeting the Gavkhuni wetland environmental demand. Energy-related policies, on the other hand, proved to be less effective in improving the ecosystem provisioning services. Overall, the results showed that the security of water supply and status of energy subsystem in the basin were highly dependent on the food sector.

Bassi and Gallagher (2016) describe a pilot version of a system dynamics model that evaluates the direct, indirect and induced effects of hydropower investment on economic, social and environmental indicators in a case study of the Mekong Flooded Forest landscape in Cambodia. This case study site is an area that depends critically on the Mekong river for water, food and energy. The model results show that the construction and subsequent operation of hydropower dams leads to positive impacts for energy access and economic growth, but it also has negative consequences on the environment. These impacts are both direct, because of the physical presence of the dam, and indirect, because of the increased use of natural resources (fish and land) when population, GDP and income grow. Further developments of the model underlying the Bassi and Gallagher (2016) study are described in more detail in the two case studies in the next section.

2.3 Two more detailed case studies

Both case studies in this section are situated within the LIVES project. LIVES is the acronym for Linked Indicators for Vital Ecosystem Services. The project explores actionable knowledge for governing the food, energy and water nexus under the UNESCO Chair in Hydropolitics at the University of Geneva's Institute for Environmental Sciences. The overall goal is to improve the approaches available to policy experts and local communities for visualizing and governing the dynamic interdependencies between food, energy and water. The LIVES approach is continuously tested in conservation landscapes in Cambodia and Colombia. Here, we focus on Cambodia, and more specifically, Kratie and Stung Treng provinces in the northeastern part of the country. These two provinces are currently experiencing rapid change through new hydropower development, forest clearance for rubber plantation, river bed sediment mining, road network infrastructure and climate change impacts. The provinces co-manage parts of the Mekong Flooded Forest (MFF), a transboundary biodiversity conservation landscape.

2.3.1 Model-based analysis of WEF risks in Cambodia

The model underlying the analysis of water-energy-food risks as used in Gallagher et al. (accepted) is a further development of the Bassi and Gallagher (2016) model described earlier. The model was developed in an iterative way including stakeholders from diverse policy sectors and provincial as well as national administrations.

Figure 4 shows a simplified version of the model. Development trajectories of key indicators in the landscape (food security, water security, energy security, per capita income) seem to be driven by the natural capital (fish stock, forest land, agriculture land) that has supported economic growth, but also by physical infrastructure investments such as hydropower dams and supporting roads.

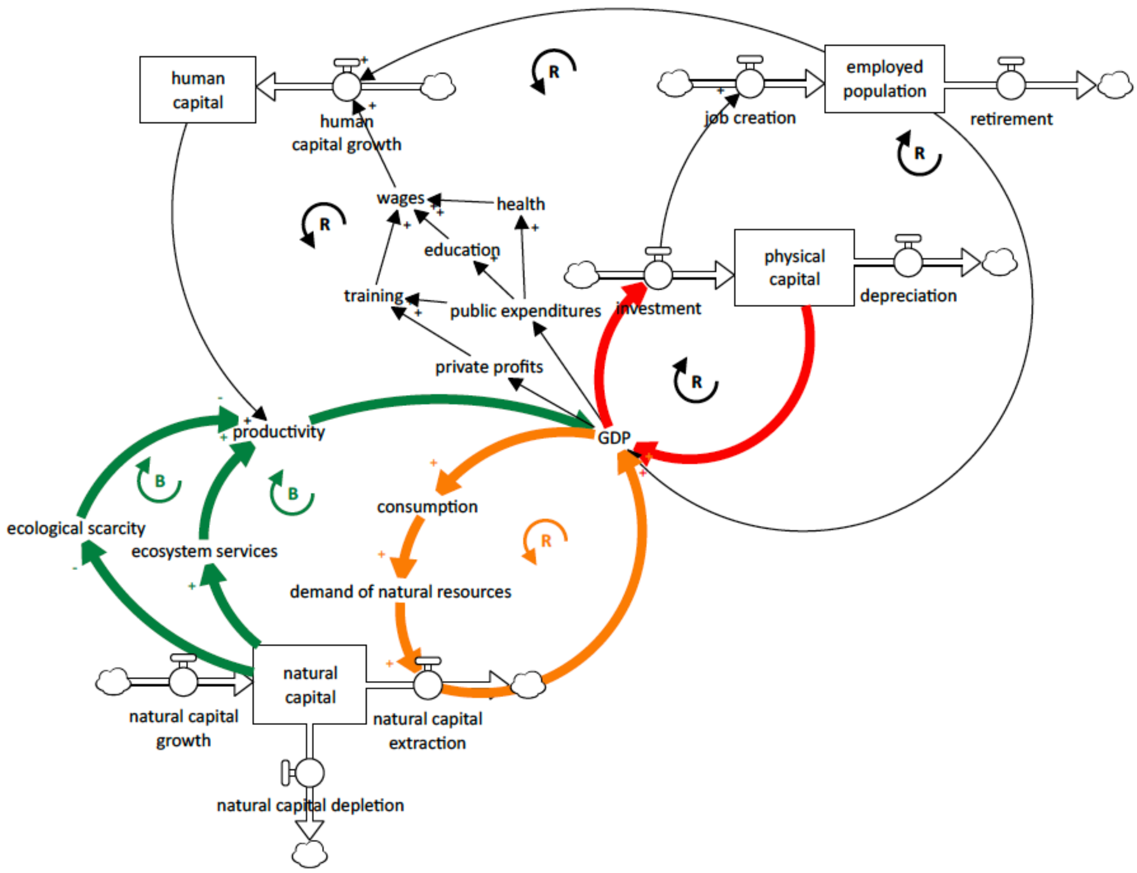

Figure 4: Simplified aggregated representation of the stakeholder-produced Mekong Flooded Forest model (Gallagher, et al., accepted).

Model analysis includes identification of policies and scenarios (Figure 5) as well as quantification of resilience metrics such as hardness (the ability of a system to withstand a disturbance without changing performance of the outcome function) and elasticity (the ability of a system to withstand a disturbance without changing to a different steady state) (Herrera, 2017) to estimate vulnerability of the landscape to climatic, demographic and economic shocks.

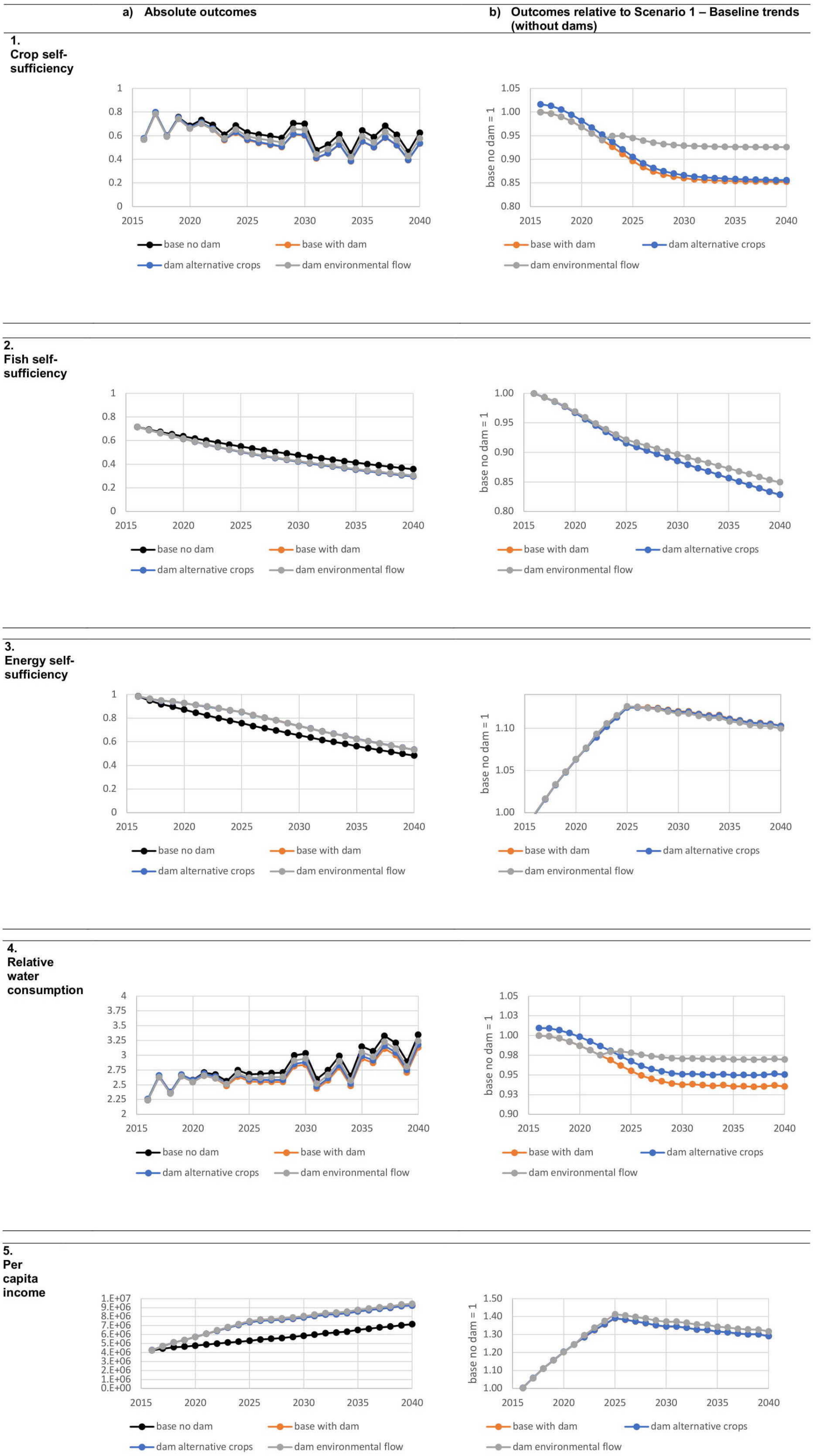

Figure 5: Nexus risk indicator outcomes for the different scenarios (Gallagher, et al., accepted)

Figure 5 shows some expected nexus trade-offs in crop self-sufficiency, fish self-sufficiency and energy self-sufficiency, however this occurs in all scenarios and not just those with dam development. Per capita income increases in the short run for all scenarios but experiences a marked increase with construction of the already planned hydropower dam because stakeholders assume local employment increases in dam construction phases. The growth rate drops as soon as the dam is completed, however. Even when local employment increases are assumed for the years of dam construction, model analysis also shows that national economic growth gains (proxied by increasing electricity supply and export) imposes costs on local economic growth and creates trade-offs for climate change preparedness.

Even though climate change is a major concern for national and local stakeholders, the two case study provinces may be more resilient to disturbances in climatic variability than to disturbances from population growth or additional dam investments (not shown in Figure 5).

2.3.2 Role of participatory modeling in the analysis of WEF risks in Cambodia

Also within the LIVES project, Kimmich et al. (2019) describe an experimental study that tested two assumptions in the participatory sustainability research: that participatory modeling improves self-efficacy when it comes to behavior change and that it reduces perceived uncertainties in addressing collective action challenges. The experiment centered around a participatory modeling intervention in the Mekong Flooded Forest area where stakeholders selected key variables and mapped relationships and pathways between them in the form of a causal loop diagram. They then simulated the development over time of the relationships postulated in the diagram using glasses of water to depict stock levels (Kopainsky et al., 2017). The simulations included the current situation as well as potential future actions on individual as well as commune level.

Before and after the modeling intervention, participants' subjective expectations about a variety of future events and situations were elicited. The difference between pre-treatment and post-treatment measurement of expectations served as a proxy for prospective behavioral change. The learning enabled by participatory modeling is hypothesized to reduce uncertainty by updating participant expectation about the future and increasing their agency to respond to future change.

Figure 6 summarizes the changes in key variables between pre- and post-treatment. Key variables refer to a variety of concepts: whether participants understood the concept of the questions about expectations; to demographic and household characteristics; and finally, more qualitative expectation dimensions that would be influenced more by communication effects or information sharing during the modeling intervention rather than the specific model itself. Overall, the results suggest that participants became significantly more optimistic about their individual agency to increase agricultural and fishing income but less likely to participate in local government development planning procedures. Some uncertainties for multiple variables were reduced within and across the different experimental groups. Such converging expectations suggest that participatory modelling could contribute to making collective solutions and institutionalized agreements more likely.

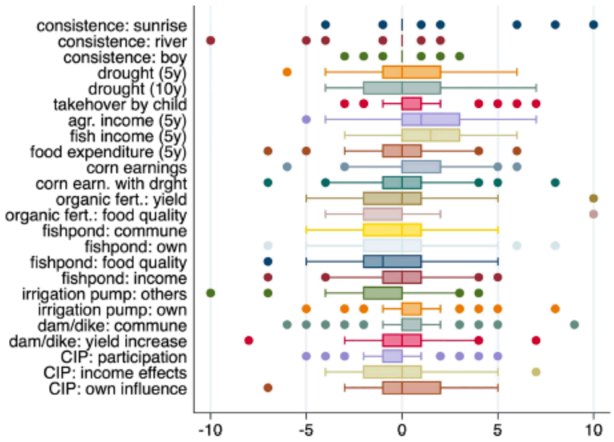

Figure 2. Box plots of the changes in expectations for our key variables. “Drought”: likelihood of a drought like in 2015/2016 reoccurring; “Take over by child”: likelihood that the family farm or fishing activity will be taken over by someone from the family; “Agr. Income”: likelihood that household income earned through agricultural activities will increase; “Fish income”: likelihood that household income earned through fishing activities will increase; “Food expenditure”: likelihood that the share of food bought rather than produced by the household will increase in the next 5 years; “Corn”: likelihood the household would earn more from planting corn than from rice in the next season, and then under drought conditions; “Organic fert.”: likelihood that yields would be higher with organic fertilizers than with conventional (chemical) fertilizers, and expected effects on food quality; “Fishpond”: likelihood that a new fishpond will be constructed in the commune within the next 5 years, by the respondent or someone else, and the anticipated implications for food quality and household income; “Irrigation pump”: likelihood that someone else or the respondent would purchase a water pump in the next 5 years; “Dam/dike”: small dikes or dams will be constructed by respondent's commune within the next 5 years and anticipated implications for agricultural production; “CIP”: likelihood that the respondent will participate in the CIP process within the next 5 years, that CIP decisions will have a positive effect on household income of the respondent, and that the respondent could influence a CIP decision.

Figure 6: Changes in expectations about key variables before and after the participatory modeling intervention (Kimmich, et al., 2019: 1344)

2.4 Implications for future research

Sustainability-related issues such as those characteristic for the water energy food nexus require transdisciplinary science and novel ways for improving the science-policy interface (Smajgl & Ward, 2013). System dynamics can mediate between scientific knowledge generation and integration on the one hand and informational and cognitive attributes of policy makers on the other hand. However, when focusing on identifying unanticipated consequences of policies, increasing resource use efficiency, and promoting adaptive governance, the social dimensions of resource linkages remain thinly described and under-theorized (Foran, 2015).

Foran (2015) provides a complementary approach to thinking about the nexus. This approach integrates critical social science theories that focus on the political economy of energy, water, and food linkages. Table 1 compares recommendations for WEF management in the Mekong area resulting, on the one hand, from complex systems thinking (as described in Smajgl & Ward, 2013 and comparable to a participatory system dynamics approach), and from critical social sciences on the other hand.

Table 1: Comparison of recommendations based on complex systems thinking versus critical social sciences (Foran, 2015: 662)

Node	Recommendations based on complex systems thinking (Smajgl and Ward 2013a)	Critical social sciences	
		Influential regime processes	Recommendations
Fish stocks	Effective regional monitoring and governance system for fishing and fish migration	Framing of wild-capture fisheries as inevitably doomed, backward leads to investment in culture and stocked reservoir fisheries (Friend et al., 2009)	A counter-narrative: Capture fisheries as an integral part of a diversified livelihoods portfolio; a resource with multidimensional benefits; with multiple examples of sustainable and equitable management by local communities (Arthur and Friend, 2011)
Energy demand	Building and construction ordinances Consumer choice	Financial regulation of utilities Engineers' mental models of reliability (energy efficiency vs. new power plants) Labour movement against utility restructuring, NGO advocacy to reform electricity planning processes (Greacen and Palettu, 2007; Foran, 2006, 2013a; Greacen and Greacen, 2004)	Strengthening existing, successful appliance standards and labelling programmes Treating energy efficiency as a resource on par with the supply side, through integrated electricity resource planning More authentic participation in power planning and approval (Foran et al., 2010a; Foran, 2013a)
Land use change and irrigation	Minimise extensive monoculture development Investment to improve productivity of smallholders Regulate foreign direct investment to protect existing tenure	Alignment between large-scale agriculture and state developmental interests (controlling and accessing budgets) (Blake et al., 2009) Populist regional development planning (e.g. greening *Isan)* (Molle et al., 2009a)	Multi-stakeholder debate and dialogue Civil society advocacy (Molle et al., 2009c) Regulation of land markets to prevent inequality in land distribution (Akram-Lodhi, 2013)

2.5 Key resources

- https://www.water-energy-food.org/nexus-platform-the-water-energy-food-nexus/ The Water, Energy and Food Security Resource Platform

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3 Sustainable housing and transformed cities: Places we like to live in

Nici Zimmermann

Abstract

With regards to housing, cities face two interconnected challenges: the need to reduce greenhouse gas (GHG) emissions and the need to react to rapid urban growth. Transformative changes are required in this complex context. This chapter summarises past and current approaches in system dynamics research on housing and cities and it discusses the challenges ahead in the areas of GHG emissions of housing and climate proofing of cities, housing affordability, and how we tackle such complex problems via organisational decision-making and transdisciplinary collaboration.

3.1 Introduction

It is estimated that by 2050, 68% of the world's population will live in cities (United Nations, 2018). This means, cities will continue to grow substantially and their design, services and neighbourhoods will strongly affect people's wellbeing. Many cities have an old and inefficient housing stock of which, in some cases, 80% will still be in place by 2050. 36% of global energy use and 39% of CO_2 emissions alone come from the construction and operation of buildings (UN Environment and International Energy Agency, 2017, relating to IEA, 2017). Cities thus need to simultaneously cope with inefficient existing buildings and the challenge to provide sufficient housing for their growing populations. How they tackle these challenges will substantially affect people's wellbeing, people's and planetary health.

To meet these demands, incremental changes will not be sufficient. We need drastic GHG reductions starting immediately. Transformative changes are required to turn the challenges of inefficient building stocks and growing populations into opportunities for cities, housing and people's wellbeing.

However, transforming housing is a complex problem. While it is a huge challenge already to retrofit buildings to higher levels of energy efficiency, retrofitting – i.e. the practice of making buildings more energy efficient – consumes a lot of energy. Retrofitted buildings are by definition more airtight, which can cause higher humidity and lead to mould growth and illness such as asthma unless proper ventilation strategies have been factored in (Maidment et al., 2014; Sharpe et al., 2015). In addition, energy efficiency improvements often fail to translate to reductions in energy consumption, called the rebound effect (Greening et al., 2000; Khazzoom, 1980). This is because occupants may appreciate greater warmth or may heat more rooms (Herring, 2006; Kuijer & Watson, 2017). Beyond the issue of GHG emissions from housing, cities directly affect people's wellbeing because they are becoming less and less affordable to live in. This is because of a lack of space due to increasing population numbers. Plus, social housing diminishes in city centres or does not exist at all, especially in poorer countries. In addition, there has been a growing focus on property as a financial asset such that housing prices grew overproportionally in comparison to the increasing density of the population.

There are thus multiple interconnected problems related to transforming cities towards sustainable houses and places to live in. These changes need to occur at the technical and technoeconomic scale, e.g. providing affordable retrofit solutions to historic buildings or apartment block towers such as Grenfell. In addition, solutions need to be integrated with behavioural adaptations of people. We need different political, organisational and individual decision-making. And last but not least, we need integrative and transdisciplinary approaches able to look at cross-boundary effects and co-create instead of impose solutions for better sustainability.

3.2 How does system dynamics contribute to addressing the topic

System dynamics is not only suited to address complex issues in general, but it has been applied to urban planning and housing questions for 50 years. The first study, **Urban Dynamics**, addressed dynamics between the population, housing and industry in a city life cycle (Forrester, 1969). It showed how the provision of social housing can have very unintended social effects. It still informs the most recent models today, e.g. the London Simulator, a system dynamics model for the evaluation of major infrastructure investments and policy (https://www.london.gov.uk/what-we-do/business-and-economy/better-infrastructure/london-simulator).

In the area of **urban studies**, system dynamics models often address the interactions of different sub-sectors such as the economy-resource-environment system (Fang et al., 2017; Guan et al., 2011) or the interactions between the land and construction, housing, non-residential, transport, labour and population sectors (Duran-Encalada & Paucar-Caceres, 2009) and their effects on sustainable urban development. There also exist studies of urban growth (Han et al., 2009).

A further theme addresses **housing market dynamics** from the **supply chain perspective** (Eskinasi, 2014; Hong-Minh, 2002). It focuses on price oscillations typical for housing markets. System dynamics models are often built around the construction supply chain; they focus on the delay between planning permissions and construction finishes and the additional delay if people do not directly move in (e.g. Barlas et al., 2007; Eskinasi et al., 2011; Mashayekhi et al., 2009; Özbaş et al., 2014).

It became more and more apparent that **housing finance** also strongly contributes to **housing market dynamics**. Researchers added speculation (Chen, 2005; Zhang et al., 2018) and mortgage credit (Mukerji & Saeed, 2011) to supply chain models or focus more exclusively on housing finance (Dianati et al., 2017; 2018).

The topic of **energy efficient housing** has received recognition with system dynamics studies focusing on diffusion and the effects of energy efficiency retrofit on energy consumption and GHG emissions (Blumberga et al., 2014; Müller, 2012; Onat et al., 2014). They also focused on household energy demand (Dyner et al., 1995). Motivations for energy efficiency and the behaviour of householders have so far largely been excluded (for an exception see Elias, 2008 and to some extent Yücel & Pruyt, 2011).

Participatory studies cluster around business models of housing associations and the success and difficulties of their implementation (Eskinasi, 2014; Eskinasi & Fokkema, 2006; Vennix, 1996). Others reflect on using participatory modelling in public policy, e.g. based on workshops on neighbourhood safety (Rouwette et al., 2016). Studies also address the wellbeing consequences of energy efficiency (Eker et al., 2018; Macmillan et al., 2016) and the need for systems approaches to improve building performance (Shrubsole et al., 2019). The following section will describe two case studies with a strong participatory element.

3.3 Two case studies

The two case studies described here are subsequent studies led by the same institute. The first one focuses on housing and the second one on urban transformation. Both have a joint focus on sustainability and health.

3.3.1 Integrated decision-making about housing, energy and wellbeing

The 'Integrated decision-making about Housing, Energy and Wellbeing (HEW)' project aimed to change people's thinking around housing energy efficiency. It explored the interactions between a policy focus *on* and the implementation *of* energy efficient housing, the positive and negative unintended consequences of energy efficiency measures, as well as physical health and mental wellbeing effects. Throughout the project, researchers worked directly with a large group of well over 50 stakeholders from policy, industry, non-governmental organisations (NGOs) and community groups. The project evolved through different phases.

First, a team member conducted 32 interviews with members of the above-mentioned groups, asking about the connections they saw between housing and wellbeing. An analysis of causal sketches drawn during the interviews resulted in seven themes, each with an underlying causal loop diagram (CLD). These themes are land, community connection, housing affordability, fuel poverty, energy efficiency and indoor air quality (see Figure 7). The interviews also provided a set of nine policy criteria to measure success of housing policies such as health, wellbeing, affordability, equity and policy coherence (Macmillan et al., 2016).

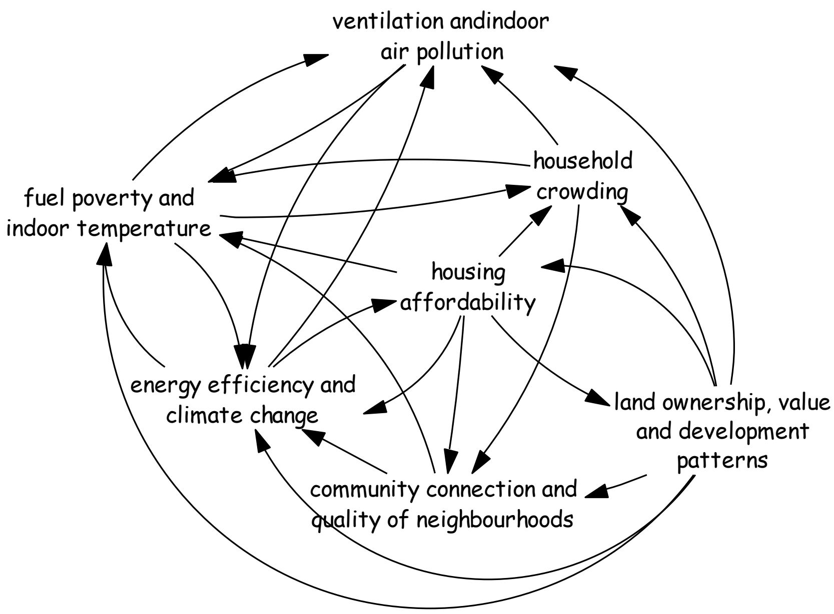

Figure 7: HEW project sector diagram (re-drawn from Macmillan et al., 2016)

Second, a series of three large workshops served to assess the CLDs, discuss potential dynamics and unintended consequences. The presentation of a stylised model and simulation results on the failure of the then flagship UK residential retrofit policy, the Green Deal, helped discuss the importance of model boundaries for inclusive policies (Zimmermann et al., 2015). The team also used the workshop to narrow down the area for future quantitative modelling to the issue of fragmentation in housing.

Third, a second round of interviews with 18 stakeholders followed. They were coded and used to build model structures and seed models in three areas where fragmentation occurs: at the policy level, in the housing industry and as a result in buildings and city neighbourhoods.

Fourth, the team used the seed models in three small group model building (GMB) workshops that had diverse stakeholder participation but a thematic focus each: policy, industry and community dynamics concerning fragmentation in housing. These workshops resulted in CLDs on their specific themes and links to the respective other themes.

Fifth, the interview and workshop data served to build a quantitative system dynamics model on housing fragmentation (Eker & Zimmermann, 2016). This model was subsequently used for policy analysis to identify how policy investments in energy efficiency, monitoring and communal spaces affect housing, energy and wellbeing (Eker et al., 2018).

Sixth, the team created a simplified version of this model as a web-enabled interactive simulation environment (http://www.systo.org/hew_wise.html). It used it at a final stakeholder workshop to which it invited previous interviewees and participants. Attendants were able to first anticipate and then interactively test how their energy efficiency, monitoring and communal space investments affect housing and wellbeing outcomes. This led to surprises and discussions on the validity of the tool and the majority of participants evaluated the use of the simulation environment as a positive learning experience (Eker et al., 2018).

The project revealed a higher importance of monitoring for the energy efficiency of buildings than participants expected. It also demonstrated that investments into communal spaces can largely enhance people's wellbeing, that increased community connection can provide the necessary word of mouth for energy efficiency measures, but that it can also delay the implementation of building work that does not fully suit the community (Eker et al., 2018).

It also showed more generally the usefulness of a system dynamics and systems thinking for improved decision-making on housing. It showed an unusually wide systems perspective on housing and allowed policy-makers for the first time to move beyond a narrow perspective in policy-making.

It resulted in several subsequent research projects that used a participatory system dynamics approach. In practice, it generated interest and a consultancy project with members of the UK Government department responsible for the Green Deal. It used quantitative system dynamics modelling to investigate what incentivises home owners to take up energy efficiency measures. The HEW project thus had research and real-world impact on developing a systems perspective on housing.

3.3.2 Complex urban systems for sustainability and health

One of the subsequent projects that was informed by HEW is the 'Complex Urban Systems for Sustainability and Health (CUSSH)' project. It collaborates with six cities to support major improvements in their GHG emissions and population health. These cities differ in size and have faced fundamentally different local challenges. In Europe, London and Rennes are at the forefront of sustainability and health. The Chinese cities Beijing and Ning-Bo are in the process of transforming air pollution, and Kenyan Nairobi and Kisumu face such health challenges in most of their sectors that GHG emissions have not been their primary concern.

The project builds on three principles for achieving transformative change: First, it provides cutting-edge scientific evidence. Second, it uses a participatory approach to co-create solutions together with city governments and their populations. Third, it uses a systems thinking approach to develop holistic solutions, informed compromises and to avoid negative unintended consequences for sub-groups of the population or in future.

CUSSH started with a pilot project focused on household air pollution in Nairobi slums. About 65% of Nairobi's population live in about 160 slums because other housing not affordable. They often live in a windowless room in which they cook with kerosene and charcoal. This generates high amounts of GHG emissions and has severe health consequences. Our work revealed the difficulty of quantitative modelling in a data-sparse environment, but it also demonstrated that it was still possible and worthwhile. It showed a likely trend shift and future stagnation of improvements to air quality and potential leverage points for real-world improvement (Dianati et al., 2019). These include fuelling a powerful reinforcing loop of monitoring and attention among researchers, the public and policy makers (see Figure 8).

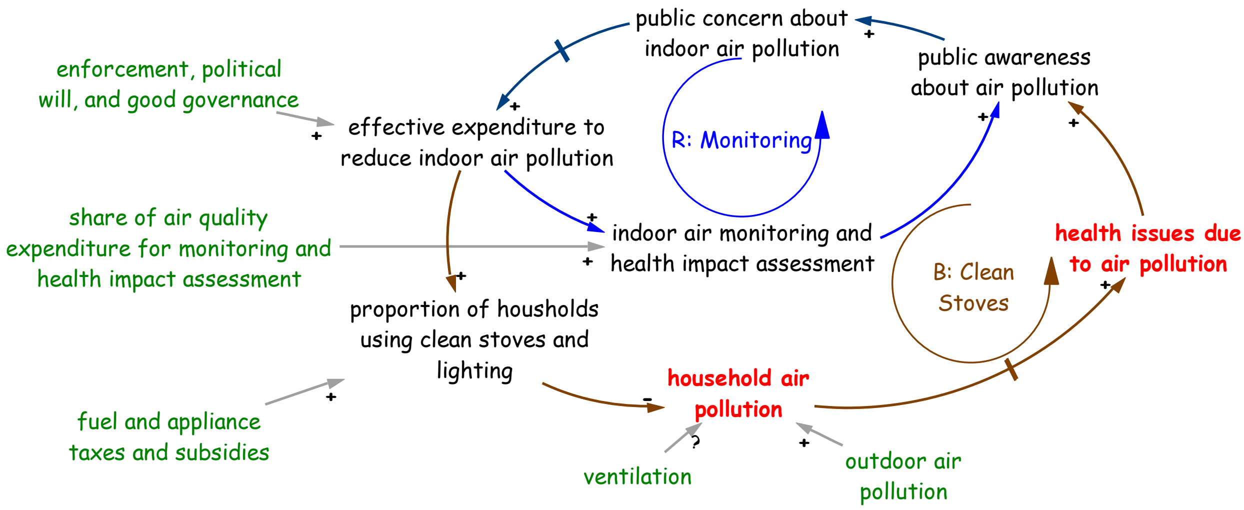

Figure 8: CLD of household air pollution in Nairobi slums (adapted from Dianati et al., 2019 and Zimmermann et al., 2017)

In London, the project initially focused on green infrastructure, such as parks and gardens. Starting with the Greater London Authority's, i.e. the municipality's desire to explore effects of different types of green infrastructure on GHG emissions and health, a GMB workshop broadened the focus to the maintenance and use of green infrastructure and their interaction with local attractiveness (see Figure 9, Zimmermann et al., 2018; Zimmermann et al., 2020). It thus provided a useful means for discussing the Greater London Authority's areas of interest and disinterest for in collaborating with the CUSSH project (see also Black, 2013; Black & Andersen, 2012; Luna-Reyes et al., 2019).

It led to subsequent case study work on the area of Thamesmead. Thamesmead, is a 1960s/1970s mainly social housing area of brutalist style, south-east of London. It was supposed to alleviate social problems then and now. Its rather extensive green spaces are underused and are competing with the provision of about 20,000 new homes. There are opportunities for creating amazing places, and system dynamics can potentially help to introduce a systems perspective and balance between competing goals.

The work with London also provided a useful first sketch for interdisciplinary work. A non-SD rapid policy assessment demonstrated, first, the importance of active transport policies for sustainability and health, and second, the need for very carefully designing housing retrofit policies because a climate-friendly policy could have negative effects on people's health if industry practice does not improve (Milner, 2019). In addition, the combination of system dynamics modelling with behaviour change frameworks can provide a structured approach to tackling transformative behaviour change.

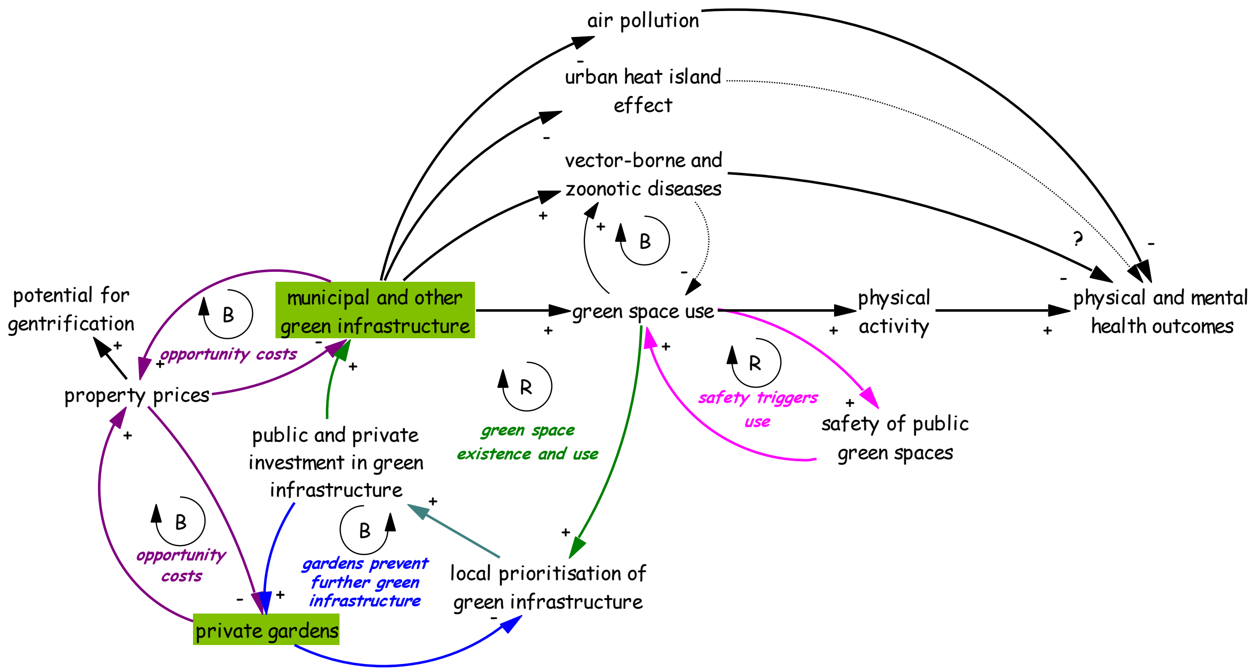

Figure 9: CLD of green infrastructure
(adapted from Zimmermann et al., 2018; Zimmermann et al., 2020)

3.4 Challenges ahead

The examples illustrated the differences in local settings for achieving sustainable solutions, but they also demonstrated the usefulness of a systems approach for creating sustainable houses and transforming cities into places that foster wellbeing. In going forward, system dynamics modelling can help address number of challenges. This includes the sustainable development goal of sustainable cities and communities (SDG 11), but it interlinks to other sustainable development goals of poverty and affordability (SDG 1), good health and wellbeing (SDG 3), affordable and clean energy (SDG 7), and climate action (SDG 13).

The two examples presented in the previous section as well as large parts of the literature section evidenced the pressure on space and an affordability crisis of homes in cities. While the area of spatial planning has been well explored (Forrester, 1969 and subsequent research), exploration of interconnections with the financialisation of housing is only just beginning (Dianati et al., 2017; 2018). Research that goes beyond the question of how land should best be used and that instead questions the very system that provides the funding for land use will thus be an important area to engage in. It will also be a prime example to explore the integration of two historically rather opposed lines of thought: that of economics vs. that of feedback and systems thinking.

The currently high levels of GHG emissions from housing as well as from cities provide a further challenge that needs to be addressed. There is potential for participatory studies following existing examples (Cappuccio et al., 2017; Eker et al., 2018; Eskinasi, 2014; Vennix, 1996). There is also potential to better address household decision-making through system dynamics to address the individual and behavioural side of climate change. In addition, fundamentally rethinking the housing as well as other sectors in cities that substantially contribute to GHG emissions allows to look for synergies with also substantially improving residents' physical health and mental wellbeing. The relations between urban transformation, housing and health should thus receive sufficient attention.

All of this will hardly get implemented unless important organisations adopt decisions very different from those in the past. There are city networks such as C40 Cities (https://www.c40.org/) that lead the way to sustainability and take bolder actions than national governments may require. These forerunners as well as those that follow suit will require guidance on how to overcome their own inertia, how to balance competing claims and adopt a long-term perspective beyond policy cycles. This means that many organisations such as city administrations, social and for profit housing providers and other infrastructure providers need to adopt a more holistic perspective. For all this, research on organisational decision-making will be valuable and system dynamics is well suited to delve into complex organisational-transformative-sustainable dynamics.

However, this will not be far-reaching unless we also cross disciplinary boundaries and cut across interactions among e.g. housing, transport, food, routines and behaviours, sustainability, health and wellbeing. Cutting across sectors has been a benefit of system dynamics modelling from the beginning (e.g. Meadows et al., 1972). In addition, there is ample opportunity to build on existing work on how to best manage research that cuts across (Black, 2013; Black & Andersen, 2012; Hovmand, 2014; Luna-Reyes et al., 2019). The option for transdisciplinary research also offers integration beyond sectors with practitioners, users and the public in participatory research (Black et al., 2014; Zimmermann, 2017). Researchers argue for a radical shift towards transdisciplinary research that uses systems thinking and integrates knowledge of multiple stakeholders (Lawrence, 2017). This can be for better models or for achieving consensus, commitment to action and implementation (Scott et al., 2016). The topic of sustainable housing and city transformation thus also provides a fruitful basis for research on participatory system dynamics that goes beyond the provision of evidence and makes first steps into why we do the research: achieving real world change.

3.5 Key resources

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4 Growth and waste management

Florian Kapmeier, Paulo Goncalvez

Abstract

Population and economic growth are desirable norms in (most of) the world's societies. Especially economic growth has many desirable benefits. Yet, this growth occurs in a finite world, leading to unintended side-effects. Growth requires both, renewable and nonrenewable resources and creates waste. Ecosystems seek to regenerate renewable resources and degrade waste. However, consumption of renewable resources has grown faster than ecosystems' ability to restore them, and generation of waste has grown beyond the ability of ecosystems to render them harmless. In addition, human activity depletes nonrenewable resources – which can only be used once. This has tremendous effects on the living conditions on the planet Earth. The production and management of waste lies in the center of our analyses. Building on insights from research on limits to growth, we focus on assessing how to better recognize the dynamic interplay between growth, consumption of renewable and nonrenewable resources and the production and management of waste. We highlight key focus areas of research on global and local levels that may support a better understanding of the dynamic interplay between growth and waste.

4.1 Problem statement

Growth both in population and economic activity is not only envisioned, actively sought after, and entrenched as a desirable societal norm (Sterman, 2012). As innovations enabled better living conditions from decreased mortality rates to increased crop productivity, the world population has soared (Figure 10a). Population growth has been the main driver of increased human activity. In modern societies, the growth in economic activity is often referred to as the "virtuous circle of industrial development" (UNIDO, 2017). According to the virtuous circle, industrial activity allows job creation, which leads to greater income generation, the diversification of demand and massification of consumption, leading to further industrial activity. Since the ascent of industrialization (from 1760), this reinforcing loop has effectively ensured economic growth at an aggregate world level. Figure 10b shows the growth in the World Gross Development Product (GDP) from 1820 until 2015.

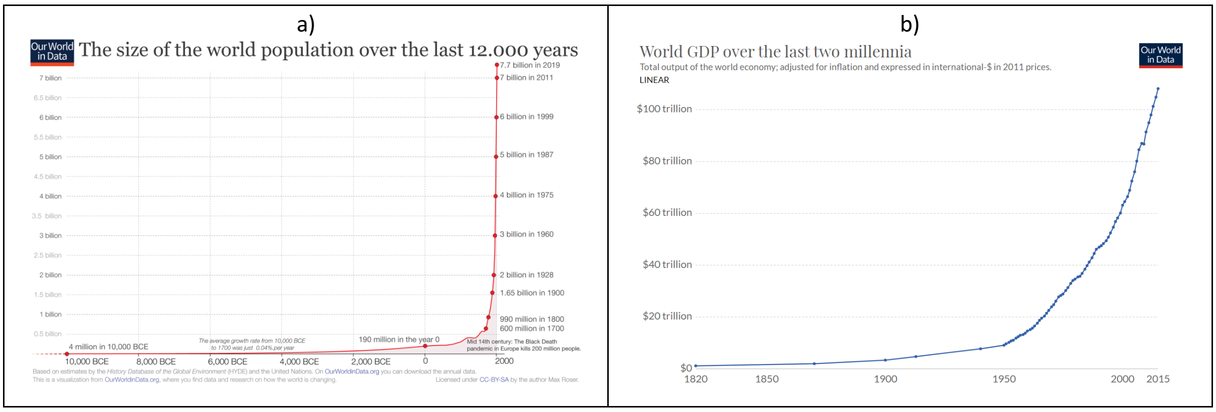


Figure 10a) World Population over the last 12,000 years Source: Roser et al. (2020); b) World GDP (1820-2015). Source: (Roser, 2020)

But growth has also taken place at a more disaggregate level. While different countries have experienced significant economic growth, measured by growth in their GDP, the ratio given by GDP per capita has still grown (Figure 11). That is, despite the fact that population in different parts of the world grew dramatically, the growth in the economy of the developed countries was even more spectacular, captured by the growth in their ratio (GDP/population). From the perspective of an individual country, this growth trend is highly desirable as it translates in the virtuous circle of industrial development and the wealth of the country's natives.

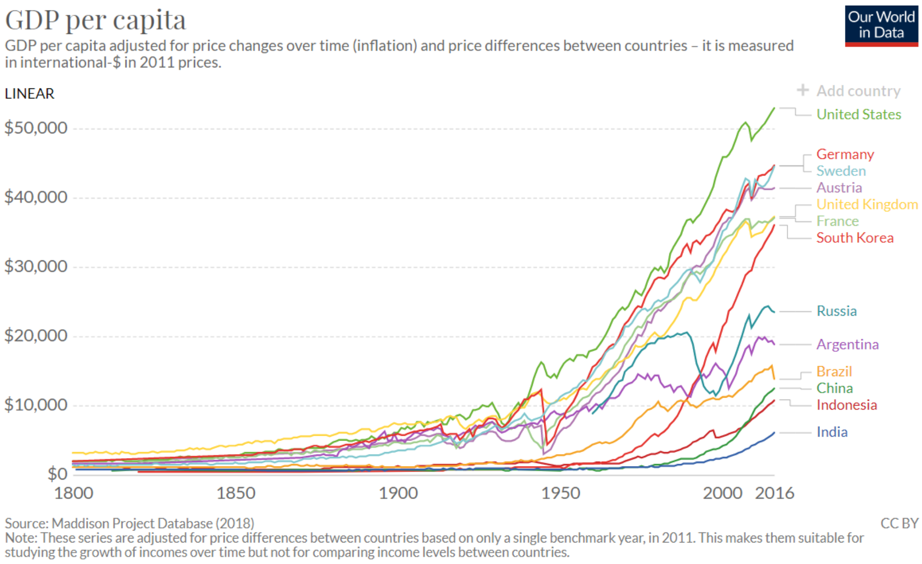
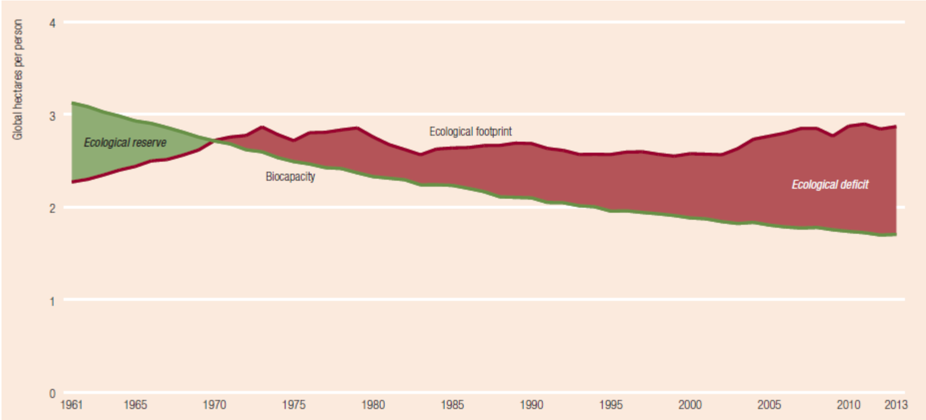


Figure 11: . GDP per capita for different countries (1800-2016). Source: (Roser, 2020)

Despite the benefits of increased economic activity (e.g., better living standards, diversity of goods, increased income, better infrastructure, etc.), this industrialization process also generates significant negative outcomes. The unequal distribution of the benefits between developed and developing countries is one of them (Figure 12). Also, industrialization and growth in human activity requires consumption of renewable and nonrenewable resources for producing goods. In turn, production fuels further growth, since it requires equipment, factories, and other production assets for which other resources are required. Considering renewable resources, to ensure sustainable growth, industrialization processes should not consume more renewable resources than the rate by which such resources can regenerate. Considering nonrenewable resources, sustainable growth should not consume such resources faster than the rate by which alternative substitutes can be found (Daly, 1991; Goodland and Daly, 1996; Sterman, 2012).

While these boundaries are well understood, for decades industrialized process have consumed renewable and nonrenewable resources much faster than their renewal or substitution rates. Figure 12 captures the global footprint as it overshoots the biocapacity of the planet.



Note: Global Footprint Network refers to global biocapacity as "the ecosystems' capacity to produce biological materials used by people and to absorb waste material generated by humans, under current management schemes and extraction technologies." The ecological footprint is defined as the amount of biologically productive land and water needed by an entity—individual, population or activity—to facilitate the production of all consumed resources and to absorb the waste generated in this process. An entity's footprint is measured in global hectares and given the global nature of trade, the footprint takes into account land and sea from all over the world. Read more definitions related to the National Footprint Accounts at: http://data.footprintnetwork.org.
Source: Global Footprint Network National Footprint Accounts, 2017 Edition (Global Footprint Network 2017a).

Figure 12: . Global ecological footprint. Source: (UNIDO, 2017)

In addition to the overconsumption of renewable and non-renewable resources, production creates waste. Waste accrues in all industries, including the chemical and paper industries, agriculture, life stock, construction, and tourism, etc., and affects the world's ecosystems, incl. pollution of soil, water, and air (CO2, CH4, small particles, etc.) through industrial and chemical (plastics) waste, fertilizers, etc. Such waste can have significant negative health effects in the population and must be handled accordingly.

Here, we focus on the interplay of managing growth and managing waste. Both resource (renewable and nonrenewable) stocks and waste stocks need to be well managed on a finite planet (Forrester, 1971): (1) the consumption of renewable resources cannot be faster than their renewal rate, (2) the consumption of nonrenewable resources cannot be faster than their substitution rate, and (3) the generation of wastes can be no greater than the capacity of ecosystems to render them harmless (Daly, 1991; Goodland and Daly, 1996; Sterman, 2012).

4.2 System dynamics for economic growth and waste

Previous studies (Forrester, 1968) suggests that rapid growth in complex systems can lead to significant challenges. System dynamics has been used since then to analyze the impacts of growth on the environment. Yet, research is diverse and nuanced. A study which is widely cited is Forrester's (1971) study on World Dynamics, using the World3 model. We describe the model and the main insights in the following section. The study has been widely cited and analyzed further (Acharya and Saeed, 1996; Meadows *et al.*, 1972; Randers, 2000). It is a key resource for illustrating the impact of human activity on the ecosystems. Environmental pollution plays a major role in the analysis. This study has initiated many other studies in the field, for example, the analysis of the impact of human activity including burning fossil fuels emitting greenhouse gases on the average global temperature (Fiddaman, 2007; Fiddaman, 2002; Sterman and Sweeney, 2002), Ford's (2009) analysis of managing water or analyzing pesticide flows in soil, air, and water or Mashayekhi's (1990) study on how population growth in Iran leads to more meat consumption, and consequently, demand for fodder, rangelands, and farmlands. Specifically with respect to waste management, there is a wide range of studies (Dyson and Chang, 2005; Estay-Ossandon and Mena-Nieto, 2018; Hénault-Ethier, Martin, and Housset, 2017; Kapmeier and Gonçalves, 2018; Karavezyris, Timpe, and Marzi, 2002; Mashayekhi, 1993; Randers and Meadows, 1973; Sudhir, Srinivasan, and Muraleedharan, 1997; Tan *et al.*, 2018; Zhang, Ji, and Zhang, 2015). See Kapmeier & Gonçalves (2018) for a more detailed overview.

In the following chapters we highlight two studies in more detail, first, the limits to growth to embrace a world-view and large-scale pollution and then the a view on the national level and small scale pollution at the example of the Republic of the Maldives.

4.3 Applications of system dynamics for economic growth and waste management analysis

4.3.1 World-view and large scale pollution: World Dynamics and Limits to growth

In 1970, Forrester was asked to join a meeting of the Club of Rome, a group interested in the "world problematique", that is, the broad global implications of growth of population and industrialization. The discussion with the Club of Rome became the basis for the model in Forrester's World Dynamics (Figure 13) (Forrester, 1971). Three weeks after the meeting, Forrester presented his insights from the World Dynamics model in a two-week meeting with the executive committee of the Club of Rome at MIT. The executive committee was excited about the insights and the potential of the system dynamics approach. This initiated the first phase of the limits to growth project at the MIT Sloan School of Management, funded by the Volkswagen Foundation, leading to the Limits to Growth book (Meadows *et al.*, 1972).Objective of the project was to assess the possibility of a sustainable world achieved by altering growth trends. At the MIT System Dynamics Group, a team of thirteen scholars under the guidance of Dennis Meadows starting with Forrester's World3 model, disaggregated and detailed the model, collected further data, calibrated the model, and analyzed further simulations to explore the consequences of continued growth in population and industrialization (Forrester, 1971; Meadows, 2007; Meadows *et al.*, 1974). World3 consists of several intertwined sub-models, including food (dealing with agriculture and food production), industry, population, non-renewable resources system, and pollution.

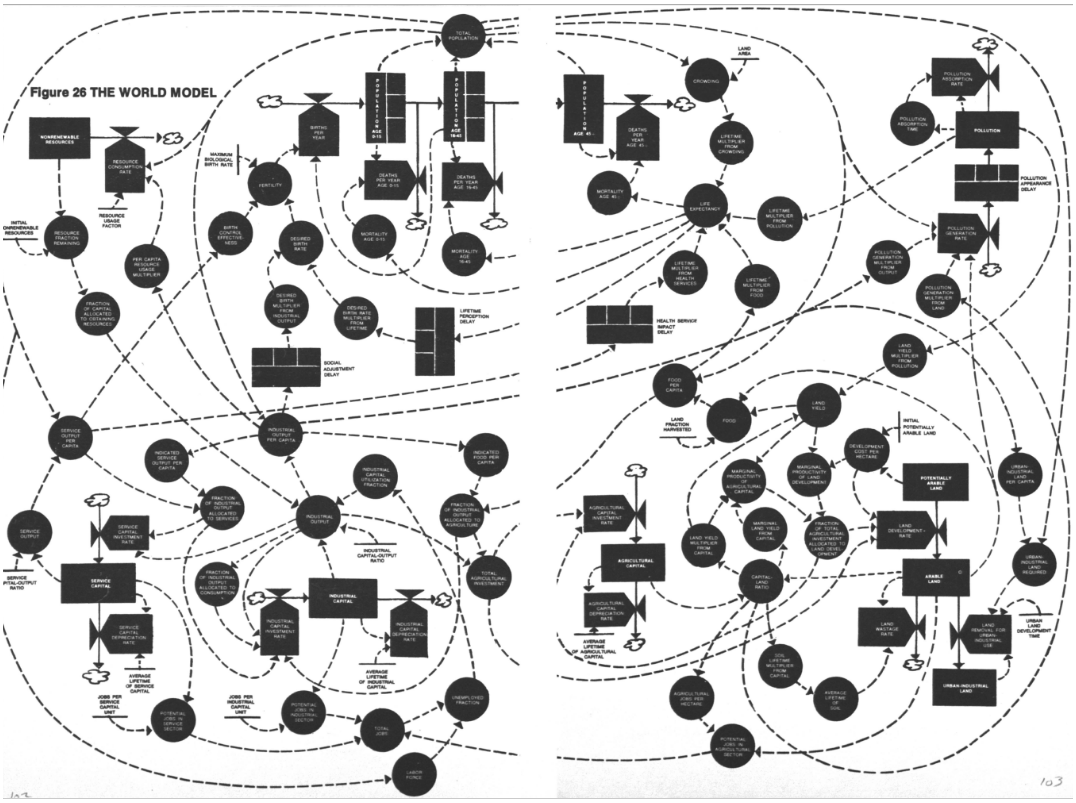


Figure 13 : World3 model (Meadows *et al.*, 1972: 102)

The team analyzed different future scenarios. The base case describes that with growing population and industrial output, resources are deployed and environmental pollution increases as well. This goes in line with over-exploitation of natural resources and consequent increase in pollution. Pollution only decreases after population had reached its peak and declines (Figure 14).

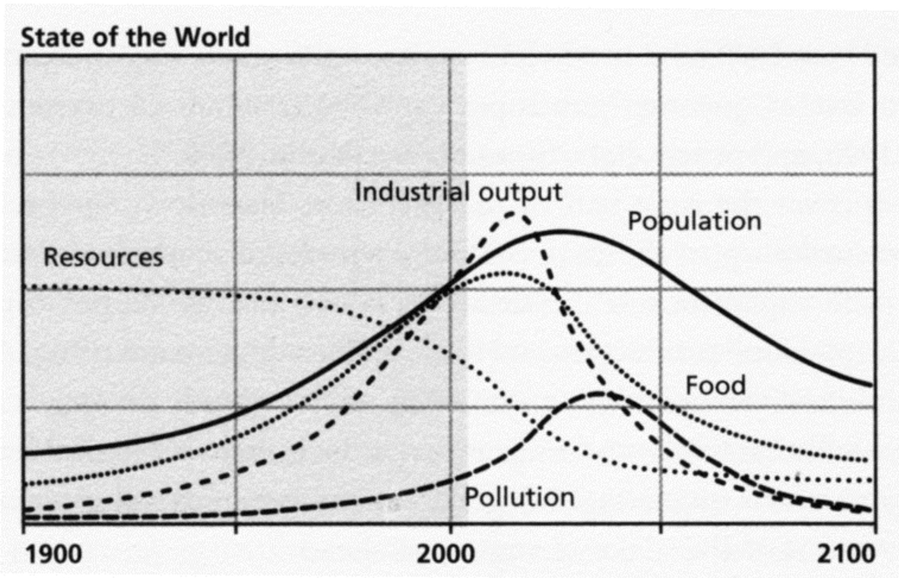


Figure 14 : Scenario 1 of Limits to Growth. Source: (Meadows, Randers, and Meadows, 2004 : 169)

The team conducted and analyzed ten scenarios, from the "reference point" (scenario 1) to "sustainability policies … introduced 20 years earlier" (scenario 10). Findings included that the way humans consume resources will overshoot the carrying capacity of the planet. The basic insight derived from World Dynamics is that exponential growth of population and industrialization cannot continue forever. Countries have a very difficult time entertaining such impossibility, as well as its consequences. Forrester posed that avid pursuit of growth was the main culprit behind a number of social challenges and stresses, such as income inequality, water shortages, and the impact of pollution.

World Dynamics also emphasized the existence of multiple limits to growth. When discussing the impossibility of continual growth of population and industrialization, Forrester did not specify ***which*** limit would be responsible for the stop in growth. Instead, the different simulations presented possible scenarios and different limit conditions. This succession of limits suggested that even if one of the possible limits could be evaded (e.g., by technology, higher agricultural yields, etc.) some other would eventually be reached. That is, regardless of the particular nature of the limiting mechanism, growth would have to come to an end.

Acceptance of the impossibility of growth could potentially turn our attention to a discussion about when and how growth should stop. However, this has been a very difficult discussion to entertain even today.

4.3.2 National level view and small scale pollution: managing growth and waste on the Maldives

For Small Island States, growth in tourism is seen as the engine driving economic growth (Schubert, Brida, and Risso, 2011): it is a significant source of foreign exchange, allowing the government to pay for imported capital goods and basic inputs. It also plays an important role in encouraging investment in new infrastructure, in stimulating other industries directly or indirectly, and in contributing to higher employment and increased income (Tang and Tan, 2015; Webster and Ivanov, 2014). The underlying rationale for economic growth through tourism rests on the goal of attracting ever more tourists by increasing the attractiveness of the tourist destination.

We developed a generic system dynamics model of the tension between tourism-driven economic growth and environmental degradation, calibrating it to 38 years of data from the Republic of the Maldives. It is a country-wide model, considering the different drivers of the Maldives' attractiveness, including demand-supply balance, price of tourist stays, tourist awareness of pollution, word-of-mouth, and crowding (Kapmeier and Gonçalves, 2018). Data show that tourism soared over the past four decades, accounting for about one-third of the country's GDP today. The government's current plan is to double bed-capacity in only 6 years – the same amount of beds for which they needed 40 years to build up. This policy of high economic growth will have a large impact on the environment.

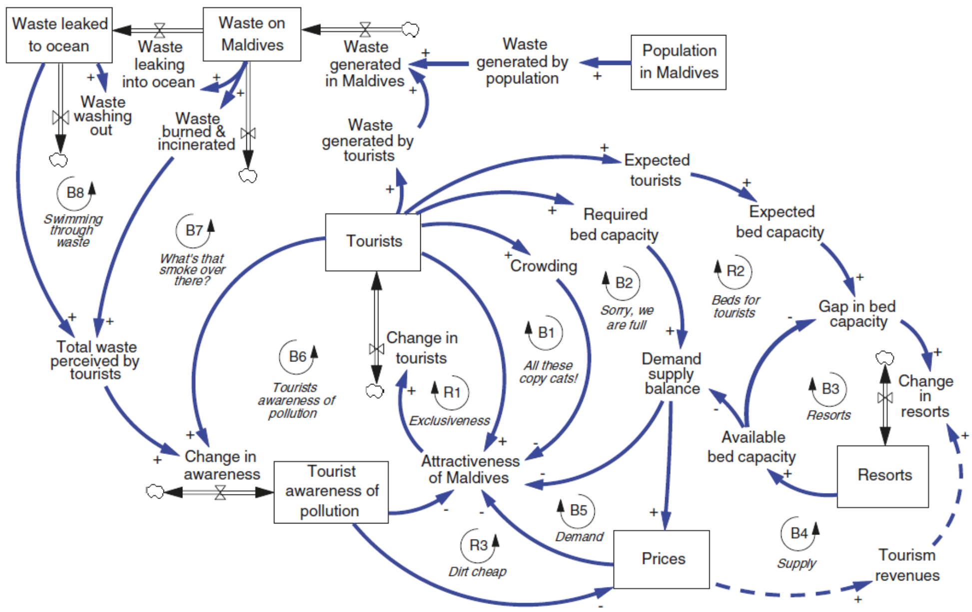


Figure 15 : Trade-off between economic growth and environmental pollution in the Maldives. Source: (Kapmeier and Gonçalves, 2018)

We tested different sets of policies, including growth stimulating policies, policies managing attractiveness, and waste management policies. We found out that the growth policy (increased bed capacity and access, lower prices) is tempting in the short-run as it generates much economic growth. But in the long-run, so much waste is created, that the island's attractiveness suffers, which leads to a large and significant drop of tourists (and revenues), likely to having disastrous impacts on the Maldives' economy.

Interestingly, policies focusing on waste management only temporarily eases the situation as waste grows back because the increased attractiveness increases the total number of tourists.

By contrast, the regulatory policies (decreasing capacity growth, increasing price, decreasing access, increasing awareness of pollution) produce a completely different outcome. The limited number of tourists creates much less waste than in the base case and the growth stimulating policies. Furthermore, because the high-paying tourists do not mind paying a higher price, the government generates higher revenues from tourism. Interestingly, accumulated government revenues until 2050 are the highest of all policies. Actual benefits could be even higher because of greater environmental quality, biodiversity, and other natural amenities. This outcome is counterintuitive, which might be the reason why it may be difficult to implement, since both the government and resorts may be concerned about the policy's impact on revenue and its possibly ambiguous results. Nonetheless, an increase in price (if planned properly) could generate more revenue for resorts, bringing them more money to invest in proper waste management technologies and training.

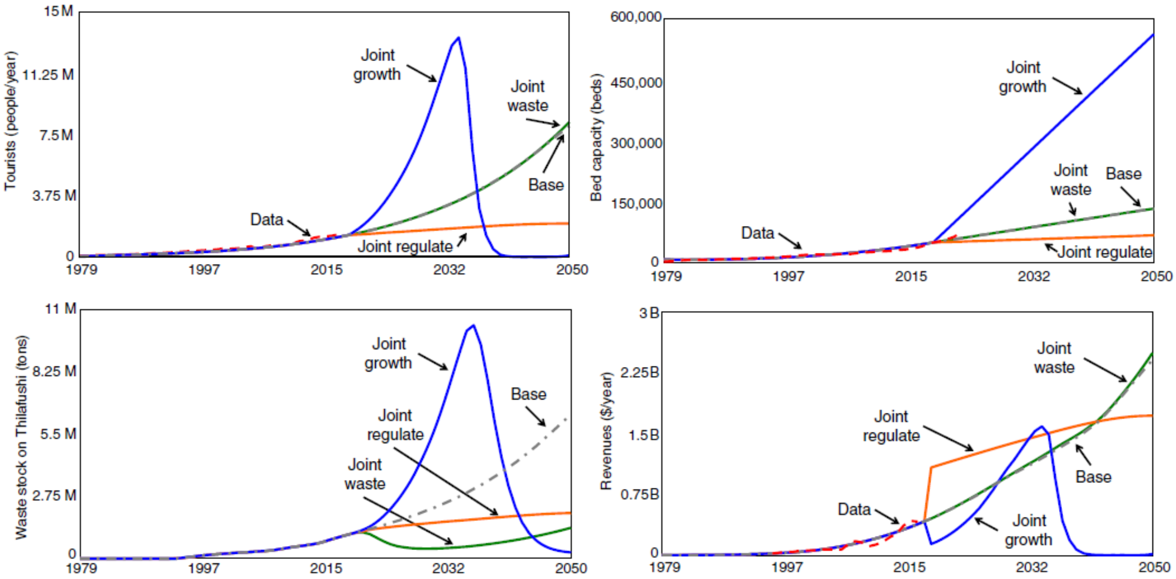


Figure 16 : Policy sets (compared to base run): growth, regulatory, waste policies and their effects on tourists, bed capacity, waste stock on Thilafushi, and government revenues from tourism. Source: (Kapmeier and Gonçalves, 2018)

4.4 Conclusions

Increasing awareness of the dynamic interplay between aimed-for growth and the production and management of waste is an imperative. In this essay, we laid out the dilemma of this interplay. Despite increasing insight, policy making, and scientific publications on this issue, the dynamic interplay of growth and waste management, including non-intended side-effects are often still neglected in real-world decision-making. Here, we used two examples of this dilemma. First, from a global perspective, we turn to the basic insights of World Dynamics and Limits to Growth. That is, growth of population and industrialization cannot continue forever. Acceptance of such impossibility should turn our attention to a meaningful discussion about when and how growth should stop. Countries have had a difficult time entertaining this difficult discussion. Second, from a local perspective, we used the case of waste management in the Maldives, a developing country which aims to generate more GDP for a wealthier local population. But we were able to show that more effective waste management could lead to a better-before-worse behavior, leading to a possible collapse of the tourist sector in the long-term because of environmental degradation. Also, at the national level, tourism growth cannot continue forever. The Maldives aspiration to fuel economic growth with tourism growth will lead not only to environmental degradation but also other societal challenges. In future research, we seek to explore avenues supporting decision-makers in learning to design more effective waste management policies which are able to combine both, growth and effective waste management.

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5 Circular Economy – thinking in systems for sustainable production and consumption

Nuno Videira, Etienne Rouwette

Abstract

The Circular Economy is a systemic concept aiming at maintenance of the value of products, materials and resources in the economy for as long as possible, which is currently viewed as a promising pathway to support sustainable consumption and production systems. This essay explores the role of systems thinking and system dynamics methods and tools in supporting the transition from linear to circular economy models. We start by presenting the problematic trends in materials extraction in the global economy, arguing for the need to adopt dynamic modelling approaches in sustainability analyses of products and materials life cycles. We subsequently draw the conceptual linkages between circular economy and system dynamics modelling approaches. We illustrate the potential of using systems thinking and simulation modelling tools to a selected diverse set of circular economy case studies, concluding with the identification of three challenging topics for further research in this field.

5.1 Introduction

All production and consumption activities depend upon material resources – such as, biomass, fossil fuels and minerals – harvested from natural systems. This generates a permanent throughput of materials extracted and transformed into goods or used to enable services in the economy (IRP, 2019). Global trends in material extraction and use in the past five decades show that annual global extraction of materials grew at an annual average rate of 2.6 per cent, from 27.1 billion tons in 1970 to 92.1 billion tons in 2017 (Figure 1). Global data depicts a very problematic trend since material demand has not stabilized or declined along with rising GDP worldwide. This implies that decoupling of economic growth from the demand of material resources – a necessary condition for sustainability if we acknowledge that infinite growth is not possible in a finite planet – is not happening across the globe, although some regions/countries may be experiencing some decoupling (IRP, 2019).

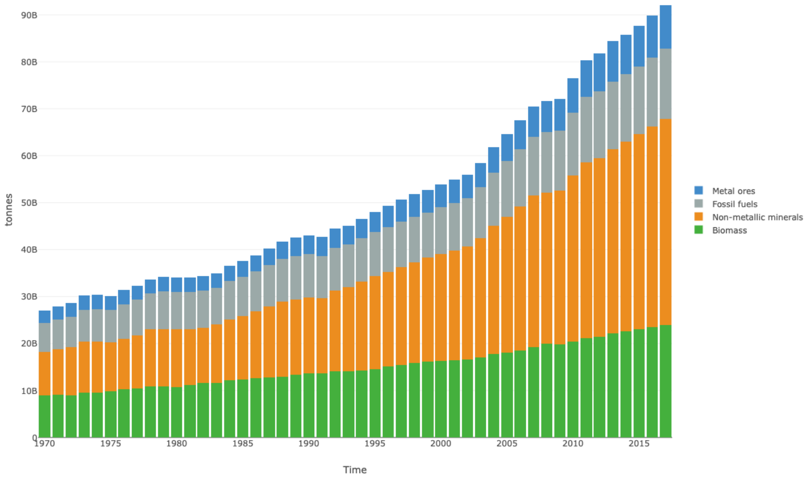

Figure 1 – Global material extraction, four main material categories, 1970 - 2017 (Source: WU Vienna, 2019)

To tackle the negative impacts on ecosystems and human health accruing from increasing material demand, wastes and emissions generated throughout supply chains, several solutions have been brought forward under the umbrella of Sustainable Production and Consumption (SPC). SPC is hereby understood as “the use of services and related products that respond to basic needs and bring a better quality of life while minimizing the use of natural resources and toxic materials as well as the emissions of waste and pollutants over the life cycle of the service or product (so as not to jeopardize the needs of future generations)”(NME, 1994). SPC encompasses multiple strategies and initiatives, including, using less resource intensive products, enhancing durability of products, moving from material products to immaterial services, promoting energy conservation, and sharing the use of products (Lebel and Lorek, 2010). As debates evolved over the years in policy, society, and science arenas, national governments and international organisations adopted SPC policies and programmes (c.f., “10-year framework of programmes on sustainable consumption and production patterns”, UN, 2012), while companies implemented sustainability strategies and researchers developed theories, methods and tools to tackle impacts of production and consumption processes (Almeida et al., 2013; Barber, 2007). More recently, SPC was explicitly adopted as one of UN’s Sustainable Development Goals (SDG 12), with a specific target of achieving sustainable management and efficient use of natural resources by 2030. Despite being part of the international discourse for more than four decades, the uptake of SPC policies has tended toward relatively weak measures focusing on technological improvements on the production side, favouring efficiency-oriented approaches to the detriment of broader, systemic approaches (Bengtsson et al., 2018).

Within this landscape, the concept of Circular Economy (CE) has recently been gaining traction as a promising solution to curb the impacts of linear ‘take-make-waste’ production and consumption models. The Ellen MacArthur Foundation defines the CE concept as “an industrial system that is restorative or regenerative by intention and design. It replaces the “end-of-life” concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models” (EMF, 2013). CE thus aims at maintaining the value of products, materials and resources in the economy for as long as possible, while minimizing the generation of waste (CE, 2015) (Figure 2).

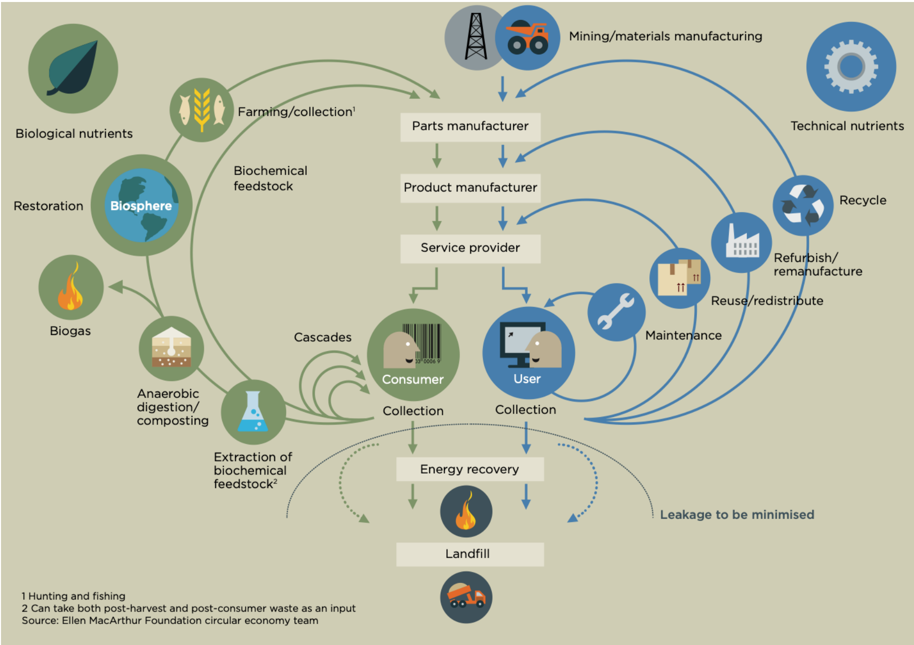

Figure 2 – The so-called "butterfly diagram" of the Circular Economy, with technological and biological nutrients cycling through the economic system (Source: EMF, 2013)

The goal of this essay is to explore the role of system dynamics approaches in providing a contribution to the analysis and implementation of CE strategies, weighing in arguments and offering illustrative examples on how systems thinking principles and modelling tools may be applied to support the analysis of circular models of production and consumption.

5.2 Applying systems thinking and modelling in a circular economy context

System dynamics (SD) fundamentally constitutes an interdisciplinary method to support learning, policy design and analysis to solve important real-world problems (Sterman, 2000). Grounded in the theory of nonlinear dynamics and feedback control, SD promotes the development of systems thinking skills and tools that offer the kind of analytical platforms often deemed necessary in the CE literature. SD and CE share, by design, an holistic perspective in the analysis of complex dynamics systems.

In Table 1 we elaborate on the features of the SD approach that make it suited to address CE concepts and the analysis of circularity policies.

Table 1 – How do elements of the system dynamics modelling approach align with the circular economy?

Elements of the circular economy approach	Elements of the system dynamics approach

Adapted from: EMF, 2013; Stahel, 2016	**Adapted from: Sterman, 2000**
Closing material loops: The goal of a circular economy is to close material loops and maintain value, as opposed to the linear economy model of "take-make-waste".	**Closed loop thinking and non-linearities:** This is a central tenet of ST and SD, looking for the feedback causal-chain structure in physical and information cycles responsible for a dynamic behaviour of concern.
Caring for stocks: Focus on managing stocks of manufactured and natural assets by increasing the efficiency of *using* (and not just producing) goods and services.	**Stock-and-flow structures:** SD sees the world as a collection of stocks and tries to test resilient, robust and antifragile management policies by gauging in- and outflows of those stocks. System dynamics favours a circular economy mindset wherein the focus is on stock-maintaining policies, through analysis of different inflow and outflow management interventions.
Maintaining product and material value over time: Circularity policies emphasize the need for a dynamic perspective, for instance, through analysis of material delays created by reuse, remanufacture and recycling processes. CE adopts long-term thinking as an important principle, for example through strategies that increase durability and extend products' life cycles.	**Dynamics and consideration of time delays:** SD recognises that changes in systems occur at different and often interacting time scales. By acknowledging time delays as a structural element of the method, SD accommodates a mind-set wherein long-term policy responses are seamlessly integrated with the analysis of short-term transitory changes.
Collaboration and stakeholder engagement along product and service chains and loops is required for the implementation of circularity strategies. CE raises awareness and prompts collaboration among manufacturers, retailers, users, service providers and administrative agencies for designing effective policies ensuring that responsibility for products and materials is maintained throughout their service lives.	**Participatory system dynamics:** SD recognises the importance of modelling with "problem-owners" and offers participatory modelling approaches for engaging intra and inter-organisational stakeholder groups in the modelling processes (see Essay 7 on group model building and participatory approaches).

The CE envisages strategies for closing material loops and maintaining value of products in production and consumption chains, emphasizing the need for paying attention to stocks of materials, as opposed to the focus on maximizing (economic) return from flows which guides the linear economy worldview (Stahel, 2016). As illustrated in Table 1, these features closely match the mindset underlying application of ST and SD approaches. Not surprisingly, a systems perspective is an integral part of many definitions of CE. Kirchherr et al. (2017) find 95 different definitions of CE in 114 studies. Of these 95 definitions, 42% refer to a systems perspective.

Deploying SD in a CE context complements the toolbox of approaches that have been applied a long time to the study of sustainable production and consumption topics. The most commonly used methods and tools applied to evaluate and develop circularity analyses include life-cycle assessment methods, material flow analysis and CE indicators (Merli et al., 2018). Adding to the analytical and environmental accounting power of these methodological options, ST and ST approaches allow modelling circularity in systems explicitly embedding a dynamic perspective, facilitating identification of critical feedback loops, as well as designing, assessing and supporting decisions regarding alternative short to long-term CE scenarios.

5.3 Illustrative applications emerging from the field

Although there are still few examples of ST and SD applications directly referring to the CE in the literature, the selection presented in Table 2 elucidates the diversity of areas and purposes of application.

Table 2 – Examples of systems thinking and system dynamics applications to study the circular economy

Reference	Objectives of the study	Circular economy focus	Applied systems approach
Franco, 2019	• Analysing the systemic effects of combining multiple product design and business model strategies	• Study focused on the assessment and comparison of product design and business model strategies • Manufacturing industry, considering both short-life and long-life groups and different product categories (e.g. cars, clothes,	• SD was used to assess innovative strategies for the circular economy • SD model offers a decision-support tool for industrial stakeholders • Time delays and reinforcing feedback loops explicitly modelled

		furniture, appliances, IT and industrial products)	
Gloser-Chahoud et al., 2019	• Exploring the dynamics of technical durability of products together with storage behaviour of consumers in the context of circular economy strategies • Demonstrate the potential of material savings and other environmental benefits through the implementation of functioning cascade systems.	• Durability of products and lifetime extension strategies (and discussion of associated business models) • Consumer electronics sector (phones, tablets, laptops)	• Simulation model depicting the stock and flow cascade in different use and storage phases of consumer electronics (modelled through an aging chain structure) • SD supported scenario analysis for service lifetime extension and storage time reduction of unused consumer electronics in typical households in Europe
Pinto and Diemer, 2020	• Supply chain integration strategies and circularity	• Study focused on the Steel industry • European-wide industry level focus (not individual firms)	• SD was used to simulate and test supply chain integration strategies to close material loops • SD integrated with lifecycle thinking and analysis tools, reflected in the model's structure and data used
Soo et al., 2019	• Life cycle modelling of end-of-life products • Model-based assessment of the characteristics of product design and recovery systems that realize near	• Material recovery efficiency • Closed-loop recycling of aluminium cans – analysis at the product life-cycle level	• Simulation model of a product's life cycle to investigate the dynamics of material flows • Simulates behaviour over time of strategies for product design and recycling to

	circular material recovery		understand the critical factors for success towards circularity
Videira et al., 2015	• Developing an integrated life cycle and systems thinking framework to define archetypes that support holistic assessments of the environmental consequences of CE business models	• Conceptual analysis of different collaborative consumption schemes, associated with product-service systems and redistribution markets • Developing criteria for achieving net benefits with product-service systems at a macro-level of analysis	• Causal loop diagrams representing generic structures where dominant feedback loops are portrayed • Identification of policy resistance factors and leverage points of intervention

The applications presented in Table 2 provide an overview of the range of modelling approaches (e.g. qualitative systems mapping, quantitative simulation modelling), scales of analysis (e.g. macroeconomic level, meso or industry level, company or product life-cycle level), and types of products and economic activity sectors (e.g. manufacturing industry, consumer electronics, steel industry, beverage packaging materials) applying systems methods to CE studies.

The results of these studies fall into two categories. On one hand, the development of formal modelling approaches, as in the study of Franco (2019), lead to the construction of stock-and-flow models depicting products' life-cycle stages and the decision-making structures responsible for the different circularity policies being studied (Figure 3). Model simulations then allow researchers to compare and assess the dynamic performance of the alternative scenarios and support the choices regarding product design strategies for slowing and closing loops in business-as-usual production and consumption chains.

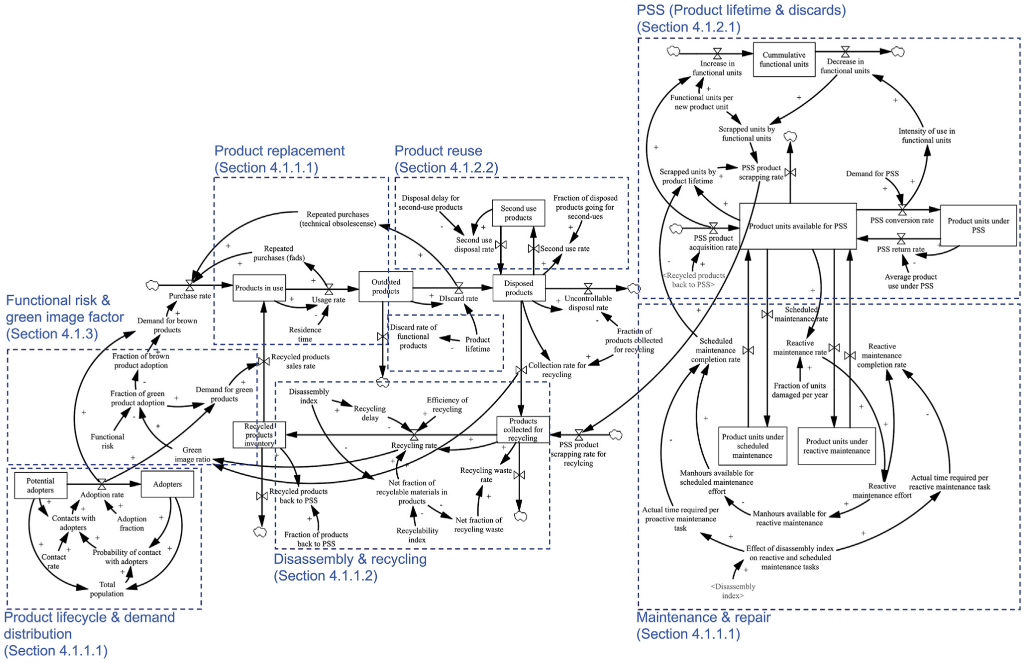

Figure 3 – Overview of the system dynamics model structure developed in the circular economy study conducted by Franco (2019)

On the other hand, conceptual systems thinking approaches are useful to map critical feedback loops associated with circularity strategies and identifying leverage points for achieving significant sustainability outcomes. In the study by Videira et al. (2015) causal-loop diagrams were used to represent conceptual structures (archetypes) of use-oriented product-service systems (Figure 4).

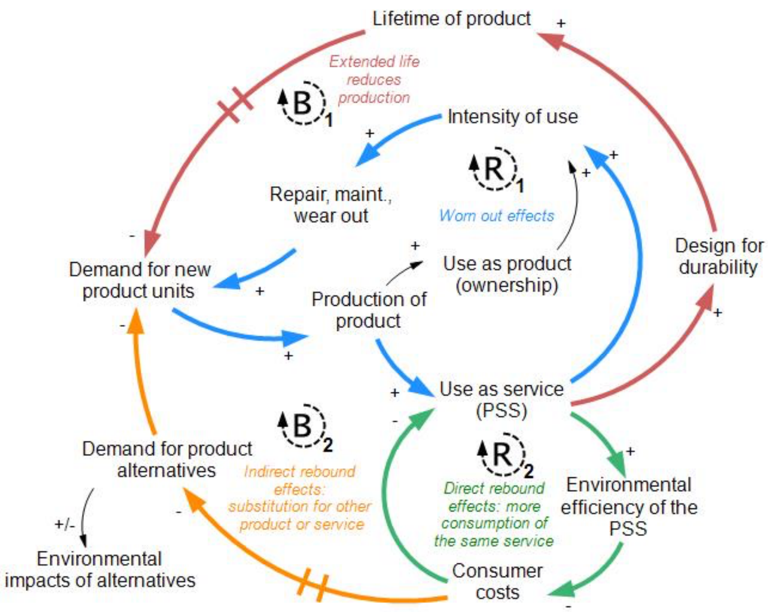

Figure 4 – Causal loop diagram depicting the feedback loops in product-service systems developed in the study conducted by Videira et al. (2015).

Systemic representations, such as the one depicted in Figure 4, allow for discovering and visualizing potential unintended consequences of CE strategies. In this case, the CLD reveals the importance of accounting for rebound effects, which then supports the development of criteria and rules for measuring net impacts of product-service systems (Videira et al., 2015). For example, a more intensive use of products in this scheme is expected, prolonging the lifetime of capital goods. As usage is maximized, incentives to design for durability are created, which will decrease end-of-life impacts and avoid waste as the product lifespan increases (loop B1). However, for a given population of potential users (with a total demand for service-units), total environmental impacts of the product-service system itself should be lower than those of the reference system (standard product ownership), thus tackling possible direct rebound effects (loop R2) of this circularity strategy.

5.4 Challenges ahead

As argued in this essay, ST and SD approaches have a lot to offer in CE studies by providing systemic methods and tools for holistic and dynamic analysis of sustainable production and consumption policies. Building on the conceptual linkages and empirical studies discussed above, we identify four challenging topics for further research and development:

1. Modelling circularity strategies focusing on different sectors and priority materials

Examples of ST and SD studies addressing CE issues are still very scarce. There is a great potential for expanding modelling applications given the wide range of circularity strategies, economic sectors, and specific materials relevant for CE policies. Such experiences would be particularly relevant to support priorities established by CE policy frameworks, such as the "EU Action Plan for the Circular Economy" and the "2018 Circular Economy Package";

2. Modelling circularity strategies at a macro-level in 'world' models

Building on the tradition of integrated 'World' models using system dynamics to portray dynamic interactions at a macroeconomic scale (e.g. from Jay Forrester's initial World model, to 'World 6', 'Earth 3' and others), there is a challenge in exploring the role of CE policies at a macro level of analysis. This could entail, for instance, an explicit incorporation of circularity strategies when using world models to support sustainability assessment of alternative material consumption pathways (cf. Svedrup et al., 2017);

3. Issues of data access and fragmentation, model parameterization

Building simulation models of products and materials life cycles, from micro to macroeconomic scales, encompasses issues of accessing data throughout value chains. These data are often fragmented, dispersed over different actors and stages of production and consumption systems. This poses a challenge for the parameterization of SD models and opens up avenues for further research on building CE indicators and databases that are suitable for supporting simulation model-based analysis of circularity policies;

4. Engaging supply chain actors in model-building processes

Given the diversity of actors involved throughout a product's life cycle, from raw material extraction, through production to consumption and end-of-life management, adopting a participatory modelling approach is critical for modelling CE strategies. Stakeholder engagement would not only contribute to sharing and co-production of knowledge but would also facilitate the establishment of the necessary governance arrangements for implementing collaborative circularity policies.

5.5 Key resources

European Commission

https://ec.europa.eu/commission/priorities/jobs-growth-and-investment/towards-circular-economy_en

Ellen Macarthur Foundation

https://www.ellenmacarthurfoundation.org

United Nations One Planet Network

https://www.oneplanetnetwork.org

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6 Patterns in transition governance: Towards a library of policy-relevant reference structures for sustainability transitions

Vincent de Gooyert, Jeroen Struben

6.1 Introduction

Sustainability transitions - structural changes towards more sustainable modes of production and consumption - are critical for achieving a sustainable society (Loorbach et al., 2017; Markard et al., 2012). Yet, they are notoriously hard to achieve and manage because of the multiple interactions over time between social and technological elements (Geels, 2004), the power differences between niche players and vested interests (Shove and Walker, 2007), and the long time horizon and global scale of sustainability challenges (Sterman, 2012). This essay argues for development of meso-level theories of sustainability transitions and proposes a direction for doing this. Theorizing in the context of sustainability transitions is not always helpful when there is urgent need for real-world high leverage interventions. Theories are often too general and too abstract (macro-level theories), therefore lacking policy relevance (Genus and Coles, 2008), or they are too specific and too context dependent (micro-level theories), lacking policy relevance because of a lack of generalizability (Geels, 2011). Another, perhaps more fundamental, problem is that both macro and micro theories for different reasons miss the side effects that often arise within such dynamically complex contexts (Sterman, 2012). This latter problem makes it critical to develop a more fundamental understanding of dynamic challenges involving both social and technical complexity, to transfer understanding across cases, and avoid unintended perforce behaviour. System dynamics is uniquely suited for such policy-relevant theorizing at the meso-level, with enough specificity to allow policy makers to draw from theories when designing policies for specific contexts, and also with enough generalizability to allow carrying over insights from one context to the other (Papachristos and Struben, 2019).

To guide policy-relevant theorizing in the context of sustainability transitions, this essay argues the need for a library of reference structures of sustainability transition problems. The reference structures we refer to here are in some way akin to the system archetypes developed by Senge (1995), Wolstenholme (2003; 2004), and Meadows (2008), amongst others. Yet, our conception of reference structures differs in important ways. While previous work addressed patterns in systems in general, we suggest developing a library focused on policy interventions around sustainability transitions in particular. Moreoever, because of the policy orientation, we need to pay attention to the different dynamic patterns they may produce as well as the particular conditions under which an associated policy works/does not work. Thus, a discussion of a policy exemplar will often include both simulated behaviour (as in Meadows, 2008), and attention to different parameterizations. To develop a library of such structures, our research questions are first, what are recurring meso-level feedback mechanisms in the context of sustainability transitions, and second, what are the accompanying policy implications? By identifying sustainability transition reference structures and by providing policy recommendations specific for each structure, we allow policy makers to learn from earlier transformations and draw on a coherent body of knowledge when embarking on new transformations.

6.2 System archetypes

System archetypes are “common structures that produce characteristic behaviours” (Meadows, 2008, p. 6). For example, the “policy resistance” archetype captures situations in which narrowly conceived policy interventions aimed to achieving a goal result in other actors responding so to pull the system away from that goal. Introduction to such overarching concepts helps one see common patterns of behavior that transcent specific situations and how these behaviours are produced from within – rather than outside- the systems in which we operate. By providing a system’s lens, such archetypes may then serve to sharpen one‘s ability to see parts of a system, to see interconnections, to ask “what if” questions about future behaviour, and to stimulate system redesign (Meadows 2008). These generic structures have been developed by many people in the system dynamics field (Senge, 1990, p. 401). Senge (1990) describes ten such archetypes, including ‘limits to growth’, ‘shifting the burden’, ‘escalation’, and ‘tragedy of the commons’ (Appendix 2 in Senge, 1990). Meadows (2008) provides a similar description of these archetypes, while elaborating more on general principles to address recurring problems they entail (Meadows, 2008). The recurring patterns of problematic behaviour are so abundant that illustrations of each of the archetypes can be found in one week of daily newspapers (Meadows, 2008, p. 112). While powerful to stimulate conversation, reflection, and learning, we argue that for policy relevance in sustainability transformations such level of conceptualization is not specific enough.

6.3 Initiating a library of policy-relevant reference structures for sustainability transitions

To initiate a library of policy-relevant **reference structures for sustainability transitions**, we begin cataloguing some of the fundamental common problems across a number of sustainability transition situations. In doing this we capture the human behaviour (‘the policy’) that has the intention to control a certain outcome, and the response of the system to either that behaviour or its outcome. Policies may intend to influence outcomes of different nature - influencing greenhouse gases, enhance the development of a specific technology, etc. - , involve different action contexts – mobility, stationary applications, etc.- and may cover different gegraphies and scales - local, regional, global, etc. The basis for classification of different reference structures is the structural similarity across various settings. Such structures are complex that they may produce different outcomes. Hene, subsequent simulation modelling and analysis must be performed to understand implications for specific contexts. To illustrate the idea of such a s a library of transition policy reference structures, this essay presents two initial contours of such sustainability transition strucctures with policies aimed at reducing greenhouse gas emissions (one with diagrams, one without). We suggest their applications acorss contexts but also point to different – context specific – outcomes. For the sake of brevity no detailed analysis is performed here.

6.3.1 Reference Structure 1: Sustainability policy resistance

Figure 1 shows a first transition reference structure – sustainability policy resistance – with, as part of that class, three sub-structures in the context of policies aimed at controlling greenhouse gas emissions. Policies aimed at controlling greenhouse gas emissions tend to involve a balancing feedback loop: the greenhouse gas emissions incline policy makers to act, and the resulting policy reduces greenhouse gas emissions. In addition, most policy implplementations involve long delays, as is the case for the time between greenhouse gases being emitted and policy being formulated as a response. *Rebound* is the mechanism where efficiency gains are partly undone because the increased efficiency makes it more attractive to consume (Berkhout et al., 2000). An example: if a car has a better mileage this could lead to lower fuel consumption. However, because of the increased fuel efficiency, it becomes more attractive to drive larger distances, increasing fuel consumption again, partly undoing the desired effect of lowering fuel consumption (de Gooyert et al., 2016). In the context of transition governance, a similar effect can be seen with subsidies on electricity production with relatively lower greenhouse gas emissions (compared to e.g. coal). If no additional measures are taken subsidies may lower the market price of electricity, thereby increasing electricity consumption. *Carbon leakage* is the mechanism where implementing a solution for carbon emissions in one place, results in more emissions in other places (Babiker, 2005). Carbon leakage is a specific form of the 'fixes that fail' archetype (Meadows, 2008). Carbon leakage can occur on the level of industries. For example, if one country adopts policies which have as an effect that steel manufacturers decide to stop the production of steel in that country, this may increase steel prices, which may increase the production of steel in other countries. *Crowd-out* is the mechanism where subsidies in a green technology come at the cost of subsidies in an even 'darker green' technology. For example, without appropriate policy measures, subsidies for carbon capture and sequestration may crowd-out subsidies in renewable technologies (de Coninck, 2008).

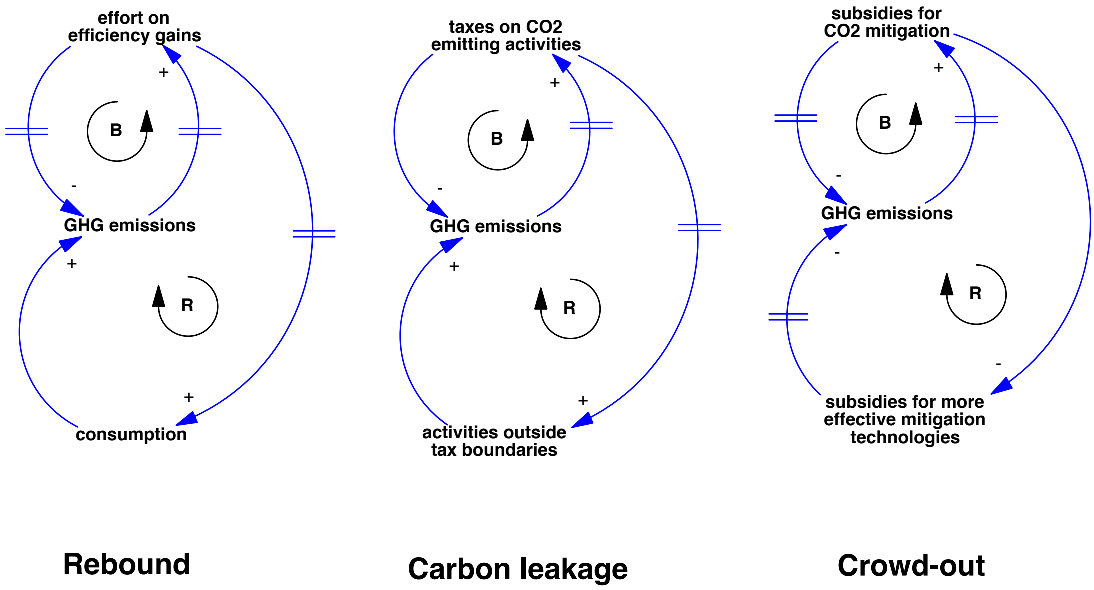

Figure 1: Reference struccture illustration of "Sustainability policy resistance"

behaviour, with three specific examples from different contexts on policies aimed to control greenhouse gas emissions[1]

6.3.2 Reference Structure 2: Sticky stepping stone

Another reference struture evolves around the reliance on hybrid technology with the aim to speed up a transition, which we call the “sticky stepping stone”. Many countries consider how to structurally transform one’s energy systems towards low carbon dependence, for example by replacing fossil-based electricity generation (e.g. coal) with renewables (e.g. wind, water, solar). A fundamental challenge is that these alternatives take time to develop, gain acceptance, and scale-up, and require huge investments including in requisite infrastructure needed. A central question therefore is whether to invest, in the short-medium run, in moderately carbon intensive resources such as natural gas to bridge towards the low carbon resources (Hausfather, 2015; Levi, 2013; Stephenson et al., 2012). That is can a “hybrid” alternative benefit the transition by not only speeding up change, but also by offering social and technical spillovers towards the more radical alternatives? This stepping stone question is relevant in many other sustainability systems – from the macro- to micro-level. For example, can hybrids help replacing the conventional vehicles (e.g. petroleum based internal combustion engines) with low carbon alternatives (e.g. renewable-based electric or hydrogen fuel cell vehicles)? Should the agricultural sector radically renew or should it go step-wise through intermediate solutions? Should one radically stop eating meat, or is it better to change nutritional practices incrementally?

Understanding the integrated dynamics of bridging technologies or practices is critical for improving sustainability transformations. However, dynamics are more complex than we tend to consider. For example, such hybrid technologies not only help spur spillovers, but also compete with the alternatives. Precisely because of their more rapid deployment, there is a crowding out effect. While some research considers such factor, their role is often examined in isolation - impact of bridging technologies for other technologies (Pistorius and Utterback, 1997; Sandén and Hillman, 2011), i.e. will investments in natural gas come at the expense of investments in fossil or at the expense of investments in renewables? Instead the hybrid technology reference structure helps consider the full integrated dynamics focusing on the interaction over time across the multiple technologies or practices. Further, while much of the underlying structures are common across different problem-contexts, specifics will differ. By operationalizing common and different features across systems, one may understand why and how outcomes and high leverage policy solutions differ across contexts.

6.4 Discussion

The two policy relevant sustainability transition reference structures disucssed in this essay are presented as illustrations of what direction a library of transition governance reference structures may take. The widespread knowledge and understanding of such and other reference structures allow leveraging insights dynamic across settings. These were just examples and

[1] Note that each structure has been simplified to its most abstract form for the sake of simplicity. As a consequence, many cause-effect relationships remain implicit (for example, the perception delay after the emission of greenhouse gas emissions, and the delay of agreeing on and the implementation of policies). We acknowledge that the many implicit relationships decrease the self-explanatory power of the visualization of the archetypes.

many more reference structures can be formulated, and hope that this essay serves as a motivation to contribute to the idea of forming a comprehensive library. Attention for operational implications within each family of reference structures will help ensure that the reference structures are policy relevant, avoiding the situation where they would allow policy makers understand the problems they face without giving actionable knowledge on how to address these problems.

A major strength of transition governance reference structures is their ability to increase theorizing sustainability transitions on the meso-level, and their potential to increase the policy relevance of social scientific studies. Despite the central role of human behaviour in sustainability transitions, the social sciences have had only limited impact on the climate policy discourse (Shove, 2010). Taking the meso-level systems approach allows identifying efforts that are repeatedly undertaken or solutions that are sought, or why an alternative solution may work, or why coordination is needed. As such, the reference structures fill the gap between case narratives that focus more on context than on generalizations, and frameworks that are so abstract that they have little policy relevance (Geels, 2011; Genus and Coles, 2008). Yet, wheras current policies are often implemented without the bigger picture the policy relevant reference structures have the power to transfer knowledge across contexts relating to the nature of dynamic systems and long-term behaviour. To this end, we see sustainability transition reference structures as a tool for knowledge management: they help synthesize studies across related transition challenges and guide the process of developing theory from specific cases to general patterns (Loorbach et al., 2017; Markard et al., 2012). In addition, they help convey the knowledge that has been gained through more specific studies. For researchers, they provide an overview of current thinking on recurring problems, and therefore also guide future research.

In fundamentally complex / uncertainty environments, a course of action should be based on the best available understanding. Developing the causal structure responsible for recurring sustainability transformation problems should help answering questions like: under what conditions can we reduce carbon emissions while avoiding typical system traps? While to some degree inspired by the classic archetypes, our operational approach can limit usual pitfalls of qualitative system diagrams by providing a false sense of secturity and suppressing empirical work where it is most needed (Homer, 1996; Forrester, 1994, Richardson, 1996). IFurther, we would like the reference structures to motivate more empirical and context-specific research, by helping the directed accumulation of knowledge in a currently scattered field (Markard et al., 2012). We hypothesize that their further devepment by, first, simulation-based illustrations will provide a deeper understanding of the potential behaviour modes. Second, by drawing from acoss existing empirical and theory work across various sectors will further provide appropriate confidence in their use. While reference structures should never be a direct driver of policy decisions, a library of such operational transition policy reference structures may contribute to climate policy research through learning across cases ansd so deepen our understanding of transition dynamics and helping avoid transition failures (Weber and Rohracher, 2012). Embedding empirical research within reference structures further helps ensure that the reference structures do in fact form a synthesis of insights that have been accumulated in earlier studies.

For us, sustainability transition reference structures are not “free standing devices” (Wolstenholme, 2003, p. 7) that provide silver bullets for recurring problems. We believe that reference structures can complement other system dynamics approaches such as more detailed simulation studies and interactive learning environments by fostering *dynamic* insights where (interactive) simulations typically foster *policy* insights (Stave, 2019). An interactive learning environment often primarily presents inputs (policies, exogenous factors) chosen by the user, and outcomes over time that those choices have as a result. This is likely to help policy makers develop policy insights: understanding of the consequences of interventions (Stave, 2019). However, by complementing this with prominent visualizations of (simplified) model structure transferrable across settings, such environments are more likely to build deep systems and dynamic insights: understanding the link between structure and behaviour (Stave, 2019). These deeper dynamic insights are crucial for developing transferrable knowledge. If policy makers understand *why* certain inputs lead to certain outcomes, for example through the use of sustainability transition reference structures, the experience in one situation may help address other resembling situations. Perhaps the bests results may be expected from combinations of interactive simulations and transition governance reference structures, although we do realize that we rarely have to luxury to spend enough time with policy makers that this combination would require.

We realize that our reference structure illustrations in this essays do not yet meet the criteria we set out above, and are purely meant as an illustration of the idea of transition governance reference structures. Hence, our next goal is to both develop individual reference structures including their empirical and simulation-based analysis, and a library as a whole.

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7 Group model building and participatory approaches in sustainability issues

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Abstract

Sustainable development goals link three domains: the ecological, economic and social. Decisions by consumers, managers or policy makers often have effects across all domains. In several European countries, for instance, proposed climate mitigation policies have led to protests by labour unions, farmers and others who feel they bear a disproportionate part of the costs of these measures. The different and sometimes conflicting stakeholder goals, complex interconnections between ecology, economy and the social domain, and scientific uncertainties make it difficult to arrive at decisions that are both grounded in evidence as well as supported by affected parties. To support stakeholder decision making, a variety of decision support methods have been developed and tested. These can be broadly categorised into participative modelling and gaming simulation approaches. Gaming puts participants in the role of a decision maker in a simulated sustainable development issue. Decisions are entered in a readymade model, participants receive and evaluate results and use these as a base for their decisions in the next round. Participative modelling, on the other hand, engages stakeholders in building the qualitative or quantitative structure of a simulation model. We show how gaming simulation and participative modelling has been used to build participants' insight into interactions between sustainability domains. We then focus on participatory modelling and how it complements approaches traditionally used in sustainability analysis. We end with challenges for future use of participatory System Dynamics for addressing sustainability issues.

7.1 Introduction

The central objective in sustainability science is to address the complexity of sustainability challenges, by creating and applying knowledge, recognising that for knowledge to be useful it needs to be coproduced in a close collaboration between scholars and practitioners (Clark & Dickson, 2003; Olsson & Ness, 2019). In these collaboration efforts scientists learn how their theories and methods are relevant to the particular challenge addressed, while practitioners contribute local knowledge and experience. The integration of both types of knowledge is the basis for formulating actions that both address the issue at stake and are supported by stakeholders. The difficulties in collaborative analysis of sustainability issues are vividly sketched by Randers (2018). In the 1970s the work around limits to growth (Meadows, Meadows, Randers, & Behrens III, 1972) presented an early warning against growth beyond the limited capacity of planet earth. This modelling work challenged many people's preconceived ideas, was widely discussed but the controversy it created is also an indication of the resistance it generated with some members of the academic community, policymakers and the public. In an attempt to increase understanding and acceptance of conclusions, Randers proposed to involve a cross-section of stakeholders in creating a joint understanding of the issues faced. He put this in practice in an early project on climate mitigation in Norway in which he involved stakeholders representing industry, NGOs and citizens. The effort was successful in the sense that participants in the process unanimously backed conclusions but failed in gathering support from important external stakeholders, such as the Norwegian parliament.

Collaborative analysis of sustainability issues seems a promising approach to supporting increased understanding and action, but Randers' experiences show it is fraught with difficulties. What are the main reasons for this partial success? An important part of the explanation is the analytical and social complexity surrounding sustainability. Analytical complexity follows from the close interaction between the ecological, economic and social domain. Coming to grips with this complexity first requires a specification of what needs to be sustained and for how long (Stave, 2010: 2765). Next is to identify and understand relevant factors and their (possibly delayed and nonlinear) relations. However, at the heart of many sustainability challenges is human activity and its adverse effects on ecosystems. Human activity typically involves many stakeholders with diverging views and interests. Some of Randers' (2018) reflections on nearly 50 years of working on sustainability clearly point to value conflicts: what society needs most (e.g., reduced emissions), is not what is most profitable in the regular investor perspective; most people are not willing to spend money today in order to obtain an uncertain benefit for their children or grand-children in 30 years. Stave (2010: 2764) notes that: '*A growing number of experts in environmental decision-making argue that because environmental decisions often require subjective judgment—involving tradeoffs, conflicting values, and decisions that have to be made with incomplete or uncertain information—deliberation among stakeholders should be central to environmental decisions, with scientific analysis directed by and in support of deliberation.'*

This assertion underlines the need for designing deliberative methods and processes that speak directly to the requirements of most sustainability issues – i.e., the recognition of complexity, uncertainty and non-linearities in system interactions and deployment of interdisciplinary approaches to tackle diffused responsibilities and plural values among stakeholders (Videira et al., 2017).

In the last years evidence-based deliberation has been discussed both from a theoretic and instrumental perspective. On a theoretical level, transition researchers look into requirements for promoting sustainability and building resilience. Geels et al. (2017) see transformation as a process in which a sociotechnical system which is stabilised by lock-in mechanisms, is perturbed by niche innovations interacting with exogenous 'landscape' developments (e.g. demographics or ideologies). For the specific transition of decarbonisation, they call for supplementing model-based studies on technically feasible least-cost pathways with research addressing *'innovation processes, business strategies, social acceptance, cultural discourses, and political struggles'* (2017: 1244). Similarly, according to Markard, Raven and Truffer (2012) conceptual frameworks on transition have 'somewhat neglected' power and politics. Transition research calls for more attention to instrumental support for making local, regional national and international transition initiatives more effective.

The instrumental perspective concerns the approaches to support decision making on sustainability issues. In a review of methodologies for sustainability assessment, Sala, Farioli and Zamagni (2013) conclude that dominant analytical methods at the product level, such as Life Cycle Assessment or cost benefit analysis, when used in isolation might fail to achieve a comprehensive overview of the challenge at hand, in the sense that they may not cover all relevant and interdependent socio-ecological factors in the wider context. In order to be comprehensive, methodologies should take a holistic view, clearly define the decision context, consider visions and objectives as well as alternative options, be proactive, support scenario development and assessment and promote consensus building. Purely (environmental) accounting tools are usually less efficient in considering visions and objectives, in proactive use and in its support for scenario development and the creation of consensus. In a more general sense, according to Sala Farioli and Zamagni (2013: 1667), sustainability assessment (SA) lacks approaches that support stakeholder participation: *'Almost all the reviewed papers identify the involvement of stakeholders as a crucial issue in SA methods development and application, but rarely is a proposal put forward on how to actually involve them.'* The importance of communicating with stakeholders is underlined in the study by Howarth and Monasterolo (2016) on building resilience in the face of climate change. On the basis of five workshops with a total of 80 stakeholders, they conclude that improving communication and collaboration is crucial to building resilience. This in turn means dealing with social and cultural differences, and the complex nature of responses to shocks and associated decision making mechanisms. There is evidence on the benefits of stakeholder participation in ecological issues, which seems relevant to sustainability as well. Reed (2008) identifies normative and pragmatic claims for benefits of stakeholder involvement in environmental management and surveys the evidence on the claims. Overall, his conclusion is that *'these studies suggest that stakeholder participation may improve the quality of environmental decisions'* (2008: 2421) but warns that the quality of the decision is strongly dependent on the process that leads to it. Best practices have emerged over the years and are condensed in eight recommendations (Norström et al., 2020, pp. describe four principles for knowledge co-production that are based on similar ideas). A first set of recommendations applies before the project start: found participation on equity and trust, encourage participation from the start and throughout the process, analyse systematically which stakeholder to represent and jointly agree on objectives for the process. Within the project it is recommended to select methods in line with the decision-making context, employ facilitation, integrate local and scientific knowledge and institutionalise participation. These guidelines ensure that the focus remains on the overall process of participation instead of on the tools, and thereby prevent some of the failures observed in the past.

In conclusion, there is a need for approaches that support collaboration between scholars and practitioners in analysing sustainability issues. Collaborative analysis is hampered by analytical and social complexity of the problems at stake. Theoretical analyses of transitions in this field have tended to focus on the first perspective and somewhat neglected social and cultural aspects, power and politics. Existing methods and tools may not achieve a comprehensive view of relevant factors. In addition, although these methods recognise the importance of supporting stakeholder involvement they often do not offer guidelines for doing so. Evidence is available that stakeholder participation improves environmental decisions, provided that best practices in process management are followed. In the next section we turn to experiences with stakeholder approaches in system dynamics: participative modelling and gaming simulation.

7.2 Using System Dynamics for modelling with stakeholders

System Dynamics has a long tradition of working with stakeholders. The crucial role of the mental database of managers as an information source for modelling was recognised in the early days of the field (Forrester, 1961). From the second half of the 1970s onwards, different approaches to involving clients in model construction were designed and tested (Andersen, Vennix, Richardson, & Rouwette, 2007). Participatory modelling approaches tend to involve a small group in model construction. This may span the full development process from problem selection, via conceptual and formal modelling to policy analysis or be concentrated on conceptual modelling only. Gaming simulation has a distinct history of its own (Lane, 1995) and is applied in the System Dynamics field at least since the 1980s. Gaming simulations allow decision makers to interact with a simulated scenario. Players take on the role of decision makers by choosing the value of decision variables. The underlying computer model calculates the results of decisions which are then available to the user in the form of graphs or reports. On the basis of this information, the user makes decisions for the next round. Compared to participation in model building, gaming simulation does not give users a role in constructing model structure, but on the other hand allows for involving larger groups of participants who may also compete with one another, contributing to a wider dissemination of model insights.

Both forms of stakeholder involvement in System Dynamics have been evaluated as to their impact on (among others) learning and consensus formation, and have been applied to sustainability issues (Antunes et al., 2015). Evaluation studies on participatory modelling have brought together over 130 studies describing single applications, analysed in two review papers (Rouwette, Vennix, & Van Mullekom, 2002; Scott, Cavana, & Cameron, 2015). The mechanisms leading to learning and consensus are increasingly becoming clear, although research in a controlled setting has not yielded consistent results (Rouwette, 2016). Research on gaming simulation is also reviewed in several papers (Aramburo, Acevedo, & Morales, 2012; Rouwette, Größler, & Vennix, 2004). Essay 8 provides more information on the results of using simulation gaming in sustainability issues.

Moon (2017) reviews the use of simulation modelling for sustainability. Of the 192 papers found between 2000 and 2015, 66 (36%) System Dynamics is the only approach used and in another eight (5%) System Dynamics is used in combination with another simulation approach. These applications include participatory as well as expert-based modelling. Whereas the early work on limits to growth concerned modelling on the macro level, recent applications also cover sustainable business models (Abdelkafi & Täuscher, 2016) and agriculture and natural resources (Turner, Menendez, Gates, Tedeschi, & Atzori, 2016).

Thus, it seems that stakeholder involvement has been extensively used in System Dynamics modelling, and both the expert-based as well as participatory approaches have been in issues of sustainability. How does participatory modelling align with the characteristics of sustainability issues? Table 1 below addresses this question.

Table 1 – How do characteristics of sustainability issues align with elements of participatory System Dynamics?

Characteristics of sustainability issues **Adapted from: Sala, Farioli and Zamagni (2008):, Reed (2008)**		**Elements of the participatory System Dynamics (SD)** **Adapted from: Vennix (1996)**
Take a holistic view	⟷	A central aim of SD is to explain observed behaviour over time on the basis of structure. Structure includes all variables, their (delayed or nonlinear) relations and the resulting feedback loops. This approach is holistic in the sense that it attempts to make a comprehensive analysis of the

	causal structure underlying the issue at hand.
Consider visions, objectives and alternative options	SD emphasises analysing the causes of observed behaviour. The resulting model then allows for testing policies and the extent to which (combinations of) these help to realise the vision or objectives.
Be proactive	SD models enable the proactive testing of proposed policies against different scenarios.
Clearly define the decision context in terms of actors involved	Several group model building scripts (see resources at end) support selection of stakeholders. An example is the power-interest graph.
Support scenario development and assessment	SD models are transparent which allows for causal analysis of how changes in exogenous parameters, via their impact on model variables, influence indicators of interest.
Promote consensus building	Evaluation studies (e.g. Rouwette, Vennix and Van Mullekom, 2002; Scott, Cavana, and Cameron 2015) show consensus on problem causes is a common outcome of participatory SD. Increased consensus on joint actions is also frequently observed but less common.
Found participation on equity and trust	Participatory SD strives to give all participants equal status and chance to contribute to the discussion.
Encourage participation from the start and throughout the (decision-making) process	The aim of participatory SD is to check and if needed adjust the central issue to be modelled with the participant group, and then to involve the group throughout the modelling process.
Analyse systematically which stakeholder to represent and jointly agree on objectives for the process	Selection of stakeholder is supported (see above). Emphasis is placed on explaining observed behaviour on the basis of model structure, which necessitates making available knowledge explicit, confronting and testing it. A joint learning process is an explicit goal of the process.
Select methods in line with the decision-making context	Of the levels of engagement (communicate, consult, participate) participatory SD

		is most suited for the latter level as participants co-create model structure. Gaming simulation can be employed at the other levels as well.
Employ facilitation	⟷	Participatory SD is a facilitated form of modelling which means that central facilitation notions such as neutrality are core to the approach.
Integrate local and scientific knowledge	⟷	Several participatory modelling projects (e.g. Vugteveen, Rouwette, Stouten, Van Katwijk, & Hanssen, 2015) involve local and academic participants, assigning each an equal role in model construction.
Institutionalise participation	⟷	Although studies are beginning to appear (e.g. Eckert, Wieck, Rouwette, & Pedercini, 2019), institutionalised use of SD is not common.

7.3 Challenges ahead

As sketched above, System Dynamics has a distinct tradition in addressing sustainability challenges by coproducing knowledge in a close collaboration between scholars and practitioners. System Dynamics based participatory modelling emerged in the mid-1970s and simulation gaming in the 1980s. these approaches offer a way to deal with analytic and social complexity and complement methods more commonly used in sustainability studies. Some technology-oriented sustainability analysis have been criticised for neglecting stakeholders, although studies show that involving stakeholders improves decision making quality. Table 1 above provides more clarity on how participatory modelling addresses characteristics of sustainability issues and an example on its application was provided. What then are the challenges ahead for addressing issues in sustainability, using the participatory tools that System Dynamics has to offer?

1. Addressing problems without a clear owner

Participatory modelling projects are typically started at the initiative of a client in a for-profit organisation, public body or NGO. Most urgent sustainability challenges have no single owner. Simulation games have been developed as academic initiatives and then sought to influence decision makers. Essay 8 describes the aim and results achieved by for instance the Climate interactive initiative. Involving stakeholders not just in playing fully developed models, but in building model structure, means that the researcher takes the initiative of selecting and inviting participants. Here we meet a sort of Catch 22 situation since when the issue is not perceived to be important enough, participants may be unwilling to spend time. Without spending time, participatory modelling cannot commence and no model (showing the importance of the issue) is generated. Examples of researcher-initiated projects are appearing (Guariguata et al., 2020) but the question of how to disseminate results beyond the small group of participants involved in building the model remains (e.g. Randers, 2018). Institutionalized use of System Dynamics models, for instance in national planning, is a clear avenue to increasing dissemination but remains in its infancy (e.g. Eckert, Wieck, Rouwette and Pedercini, 2019).

2. Tailor participatory System Dynamics to sustainability issues

The participatory modelling approaches described in the foregoing are generic, in the sense that proposed steps, techniques and scripts can be used across domains. Other participatory modelling approaches, in System Dynamics (Van den Belt, 2004) and the broader Operational Research domain (Gregory, Atkins, Burdon, & Elliott 2012) are tailored to environmental or ecosystem issues. Gregory et al., for instance, use the DPSIR (drivers, pressures, state changes, impacts and responses) framework as a starting point and boundary critique for selecting stakeholders. A relevant question for future applications of participatory modelling, is to investigate the particular conditions calling for development of fully customized versions of the generic group modelling approach to specific sustainability domains. A middle ground may be to adapt the standard set of availble scripts and tailor some of these to the context and specificities of different sustainability issues. An example is the concept model script (Richardson, 2013), which describes one way to start a participatory modelling project. Using the DPISR framework as a starting point for the ecological dimension, essential elements of the economic and social dimension can also be brought into a concept model fit for modelling with an integrated sustainability assessment lenses.

7.4 Key Resources

Scriptapedia, a collection of scripts for participatory modelling https://en.wikibooks.org/wiki/Scriptapedia

7.5 Literature

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8 Overcoming transition challenges: Developing organizational and market-level sustainability-oriented capabilities.

Jeroen Struben, Florian Kapmeier

Abstract

Why do we see so few high impact actions that transform markets and organizations towards sustainability, despite evidence of successful efforts? Potential explanations include organizational "greenwashing" or limited opportunities of creating long-term value within or across organizations. But these at-hand explanations of intra- and inter-organizational challenges fall short. Here, building on insights from research on process improvement and on collective action during market formation, we shift focus to dynamic challenges that constrain action for intra- and inter-organizational (within market-level) transformations. In either case, central to our explanations are the dynamics around building up capabilities for sustainability to replace established, unsustainable, practices and associated worse-before-better dynamics. While organizations tend to focus on low hanging fruit with easy and fast pay back, these efforts still build on conventional approaches, routines, technologies, etc. Instead, scaling up or expanding ambitious efforts with real impact affects the entire organization, or involves multiple organizations, and requires actual transformational efforts that organizations find difficult to recognize and undertake. We highlight key focus areas for research that may identify individual and collective success for large-scale transformation.

8.1 Problem statement

Scientific evidence supporting an urgent need to mitigate anthropogenic climate change is clear (IPCC, 2018). The Paris agreement was crucial to agreements on limiting global warming to well below 2 °C above pre-industrial levels (UNFCCC, 2015). Organizations are responsible for a large fraction of greenhouse gas emissions: consumption and production contributes to the human global footprint, and the access to limited resources to achieve change. Therefore, ambitious organizational efforts are critical to meet the climate target and improve ecological sustainability. Businesses increasingly realize the advantages towards environmental sustainability, such as reduced costs and risk, increased employer attractiveness and reputation, and higher competitiveness (Haanaes *et al.*, 2011; United Nations Global Compact and Strategy, 2015).

Yet current efforts by industry fall short (right.based on science, 2019). While we see increasing examples of corporate sustainability programs, the overall state is worsening: CO_2 emissions from energy as well as methane and N_2O emissions from land-use, and other environmental pollution are still increasing, rather than strongly decreasing, required for a sustainable living habitat (Holz *et al.*, 2018). This lack of action cannot be attributed to a lack of awareness or willingness to act. For example, while 43% of business leaders think they should act in line with science on reducing emission targets, only 27% have done so (United Nations Global Compact and Strategy, 2015). To address this problem, while regulation could play an important role, overly relying on this outside force is unrealistic for at least two reasons. First, at the moment there is limited support for this option to achieve cross-sectoral industry transformation at scale necessary for sustainability. Second, policy change itself is too inert. Thus, successful implementation of sustainability initiatives driven from within and across organizations is more important than ever. It is critical to better understand what drives successful transformational efforts, and what limits these?

One hurdle to achieving larger-scale transformation is the perceived trade-off between doing well (increasing financial performance) and doing good (reducing environmental impact) stands. Despite much evidence that firms may economically benefit from sustainability initiatives many companies still do not consider the potential of sustainability initiatives as win-win situations (Slawinski and Bansal, 2009). To understand this better it is instructive to view the challenge to achieve change within and across organizations, and within and across industry sectors over time. Many sustainability efforts require considerable upfront investment and resource commitments. When reducing emissions, for example, the short-term financial performance will suffer (lower return on assets), while investors will realize the benefits of reduced emissions in the long term (Delmas, Nairn-Birch, and Lim, 2015). Greater corporate social responsibility can lead to better access to finance in the longer run, a higher level of transparency, more stakeholder engagement, increased trust, and reduced risk (Cheng, Ioannou, and Serafeim, 2014; Flammer, Hong, and Minor, 2019; United Nations Global Compact and Strategy, 2015). However, generally, environmental efforts require a firm to in endure a worse financial performance the short term before reaching this win-win situation in the long term (Hart and Ahuja, 1996), known as worse-before-better behavior (Repenning and Sterman, 2002).

During this worse-before-better behavior management support is severely challenged to maintain support for such sustainability initiatives with financial and, potentially, environmental performance initially worsening. In fact, decision-makers may come to believe they can only achieve either, social benefits or financial benefits through implementing sustainability initiatives but not both (Nidumolu, Prahalad, and Rangaswami, 2009). Underlying these worse-before-better dynamics is a different set of capabilities that organizations need to develop in order to achieve this long-term performance. Importantly, the extent to which there is such an over-time tradeoff depends on social technical complexity of the problem. Sterman (2015) uses the half-life analogy to illustrate this point (Figure 1).

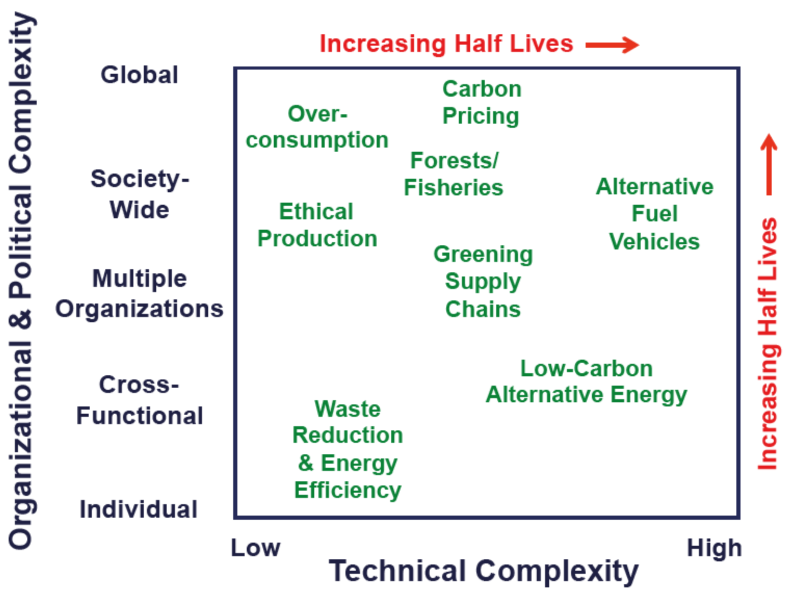

Figure 17: Process improvement half-lives depend on the technical and organizational/political complexity of the process. The complexity of illustrative sustainability issues is shown. Source: Sterman (2015)

Initiatives on the bottom left of Figure 1 can be characterized as being rather simple and are more readily achieved. Future benefits can be easily imagined, take little time to achieve, and doing so requires little coordination. As projects become more complex, either technically (right), requiring novel technology and organizational capabilities, or organizationally (top), requiring involvement of actors from within or across organizations coordination between them, uncertainty about duration, payback, and achievability increase. Initiatives towards the top right can be described as market transformations requiring both large technological and organizational and political shifts. In such situations, capabilities need to be developed that not only lie within individual organizations but also across organizations. That is, self-sustaining exchange of environmentally benign practices and services requires a new "market infrastructure" - consumers willing to consider the product categories, standards, infrastructure, established firm roles, favorable regulation etc. - (Lee, Struben, and Bingham, 2018). Because the development of this market infrastructure tends to require investment beyond the capability of individual firms, cross-organizational coordination is required, often leading to collective action problems (Lee *et al.*, 2018).

Problematically, generally, those that offer the highest leverage for environmental improvement involve increasing technical and organizational complexity. As the short-term sacrifices of the worse-before-better behavior can be avoided when undertaking sustainability initiatives with projects in the bottom-left, corporate decision-makers tend to focus on these "low-hanging fruits". This observation has important implications. Without fundamental technological or organizational efforts, required to achieve the more complex projects, organizations do not build capabilities for those higher leverage but technically and organizationally more complex projects (upper right), and they remain out of reach. Consequently, what is needed is a better understanding of these dynamics and how larger scale transformation is achieved.

8.2 Illustrations for sustainability initiatives within and across organizations

8.2.1 Sustainability initiatives within organizations

Organizational failure to overcome a win-win challenge of sustainability transformations can be seen as a form of "capability trap" – the problem that companies fail implementing promising but ambitious improvements (Repenning and Sterman, 2001). The capability results from self-reinforcing pressures to increase firm performance, leading actors to favour short-term solutions with more salient payback – overtime work, less maintenance and training – over long-term ones, such as process improvement and capabilities development (Repenning and Sterman, 2002).

Figure 18 (adapted from Repenning and Sterman 2001 to make it applicable to sustainability-oriented innovation) depicts the core structure of sustainability capability development with the feedback processes affecting the intensity and effectiveness of environmental efforts.

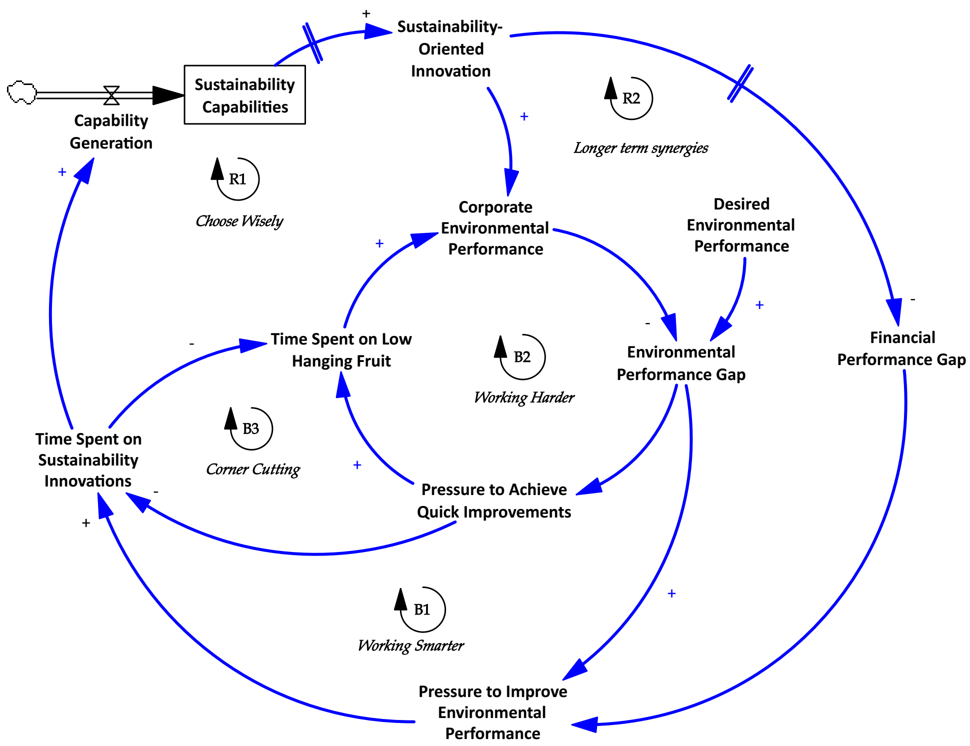

Figure 18: Feedback structure for the implementation of sustainability initiatives. Adapted from Repenning & Sterman (2001)

Organizational leaders and operational (sustainability) managers need to achieve organizational performance in a way that is consistent with sustainability targets. Two key loops highlight two ways by which organizations can respond to performance pressures. First, managers could consider their performance shortfall as having insufficient capabilities for achieving longer-term prosperity in line with sustainability needs. Managers can dedicate improvement activity designed to eliminate the root causes of poor performance. In this case, they retrain the workforce, replace plant and equipment, develop alternative products, and, more generally, invest in capabilities to make improvement effort effective that build people's skills and knowledge of best practices, enhance adherence to those practices, and build cooperation and trust. Investing in capability improvement on sustainability forms the balancing Working Smarter feedback, B1.

Alternatively, firms could interpret the performance gap as a sign of falling behind in the day to day operation. Sustainability managers – just like process managers – are responsible for the performance of processes against target or required performance. To close aspiration and performance gaps of sustainability, organizations may therefore be enticed to better exploit existing resources, by trying to improve process and energy efficiencies, eliminate waste etc. (Balancing Work Harder feedback, B2). Such efforts are cheaper, more tangible and, in the short run, provide greater returns, thus helping to close the gap relatively quickly.

Importantly, however, the two working harder and working smarter loops interact because organizations work under pressure and nearly always act below their goals. When organizations are heavily loaded, efforts aimed at achieving more direct returns come at the expense of transformative efforts, learning, training, and other activities needed to enhance sustainability capabilities (Choose Wisely feedback, R1) and in the long run leads to reduced financial performance (Longer Term Synergies feedback, R2). These feedbacks can operate either as virtuous cycles that cumulatively build capabilities and performance, or as vicious cycles that degrade both. An organization that increases the time and resources devoted to improvement will, after a lag, augment its sustainability capabilities and performance, easing the performance gap and yielding still more time and resources for further improvement in a virtuous cycle. By contrast, if managers respond to a performance gap by increasing pressure to improve efficiency and achieve a number of lower leverage but tangible results, the time spent on developing sustainability capabilities falls, and the organization's sustainability capabilities erode. Note further that because such erosion takes time, managers can easily take away resources at the cost of capability improvement, so to boost short-term performance, without being penalized – at least in the short run, creating a balancing "Short-cut" feedback (B3).

Altogether these dynamics depicted in Figure 1 explain the worse-before-better dynamics that organizations need to go through to transform on their way to sustainability. The capability trap shows that intentionally rational responses to problems in complex systems often do not help and can make the situation worse. Instead, identification of high leverage interventions requires actors to understand the system-level interactions. Further, interventions to improve system performance must often be sustained longer and with stronger commitment in contrast to the short-term solutions that than actors tend to favour. Sustainability initiatives involving technically and organizationally complex processes are particularly vulnerable to the capability trap because they involve longer, deeper periods during which performance falls and/or costs rise before the benefits of improvement will manifest. The capabilities required for addressing complex sustainability challenges will not develop if organizations do not believe that they can sustain the investments needed to succeed. A history of failed efforts can lead to a vicious cycle of eroding goals and low ambition seen today in widespread cynicism about the prospects to mitigate GHG emissions. In taking sustainability pathways organizations must not only communicate within but also to the outside. High work pressure, intense competition and pressure from financial markets mean initial improvements are often harvested through cost cutting, weakening the reinvestment feedbacks so essential in building the capabilities and resources for continuous improvement. For example, Unilever's share price was so reduced during its efforts towards sustainability transformation that they were nearly bought by a competitor – to whom such initiatives was not a priority (Financial Times, 2017).

8.2.2 Sustainability initiatives across organizations

Self-sustaining exchange of environmentally benign practices and services at the market level often requires efforts from multiple organizations. In such technically and organizationally complex cases, the worse-before-better dynamics do not only play out within individual organizations but take hold across the market as a whole. For example, consumers willing to consider the product categories, standards, infrastructure, established firm roles, favorable regulation etc. In this case, often a particular combination and sequence of contributions are necessary to form a market. Specific contributions may be required from numerous companies, i.e. distinct producers and retailers, state agencies, educational organizations, producers of complementary goods. The different actors involved all possess unique capabilities or resources that other companies do not. When such distinct resource commitments are required, actors may be hesitant to make a large initial commitment because the overall market infrastructure remains underdeveloped relative to their large commitment. Figure 3 shows the feedback structure around the building of such market infrastructure for new product categories, involving (at least) three dimensions: consumer consideration, industry capabilities, and systems and institutions. The figure highlights the process of building of such market infrastructure – comprising industry capabilities, category consideration, and systems & institutions. Distinct firms (f) need to jointly overcome dynamics governed by a number of positive feedback loops for multiple competing product categories (c), addressing different population segments (s).

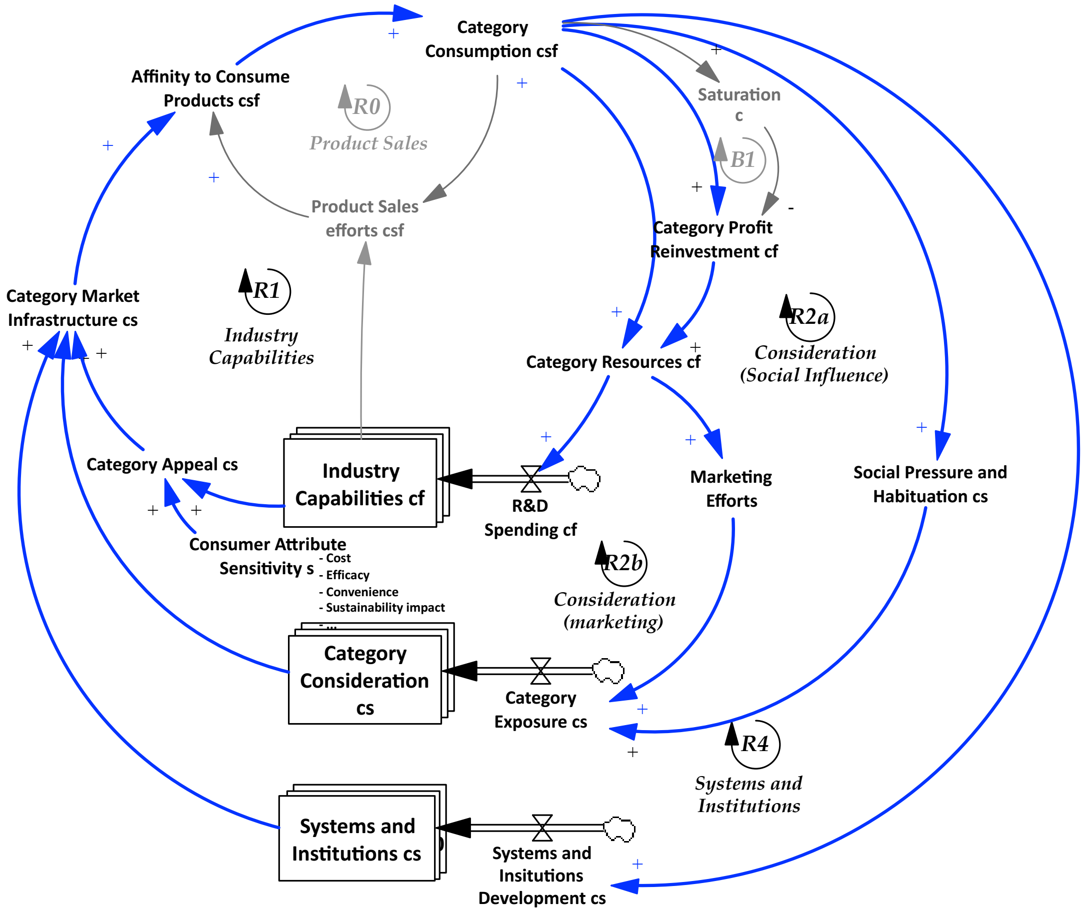

Figure 3: Feedback structure for market transformation efforts for sustainability initiatives. Indices: c=product category; f=firm: s=socio-/demographic population segment.

This was the situation the company BetterPlace found itself in (Etzion and Struben, 2014; Struben and Lee, 2019). In 2007, led by its charismatic and experienced founder Shai Agassi, BetterPlace embarked on a mission to rid personal transportation of oil by 2020. Better Place proposed a revolutionary business model built around electric vehicles (EVs). With a professional team, a sophisticated charging infrastructure that swapped an empty EV battery in just two minutes, a vehicle developed by Renault-Nissan, media excitement, and 900 million dollars of venture capital, the company seemed destined for success. Yet after first roll-outs in 2012 in Denmark and Israel, quarterly demand never exceeded 100 vehicles. Having burned through all its cash, Better Place filed for bankruptcy in November 2013 (Kershner, 2013). This dramatic failure not only doomed Better Place, but was a major setback for the transition toward a future of sustainable transportation.

BetterPlace' success depended on the willingness of many other market and political players to help build the market. But few actors were willing to go along. For example, to be a viable electric vehicle provider in general, a company would need to build upon pre-existing efforts from automotive and battery producers, charging infrastructure providers, as well as internal combustion technology (ICT) developers. Without this, few consumers will consider EVs, and those who do, experience a low product value. Under such demand and supply uncertainty, most companies in the market face unclear opportunities and high risks, resulting in reluctance to commit resources critical to successful market formation. Thus, the collective action challenges across organizations put significant extra burden on the transition problems. Yet, the diagram also points us to high-leverage interventions that have along-time horizon and that cut across actors and market elements.

8.3 Conclusions

The shift towards more ecologically responsible acting is urgent. In this essay we explained the fundamental and central role that organizations play in sustainability transitions. Despite ongoing societal pressures, increasing stakeholder awareness, and business opportunities having been identified, organizational and market shifts have been slow and failure prone. In this essay we point to the requisite development of and dynamics around organizational- and market-level capabilities as a barrier to transformations towards sustainability. We highlight that research should focus on the coordination within and across organizations to overcome such dynamic challenges. For necessary long-term commitment, all actors involved need to understand the underlying complexity and interconnections between subsystems. In subsequent research we will be exploring real-world cases to better understand sustainability transformations and to help decision-makers learn device strategies for lasting change with large impact.

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9 Addressing environmental issues and impact through simulation models and interactive learning environments

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Abstract

Learning about complex systems is challenging. Because of long time delays from scientific insight until policy implementation, important decisions are oftentimes delayed, leading the environment to suffer more and longer under degradation than it should. An explanation might be embedded in the ancient saying "When I hear, I forget. When I see, I remember. When I do, I understand" (Meadows, 2007). There are different approaches to designing interactive learning environments, from board to role play games. Here, we focus on interactive learning environments that embed computer models. System dynamics models seem to be ideal for this purpose. They are (or, should be) transparent and oftentimes invite users to explore the models' behaviors and structures for themselves. When including them in a game, this might trigger emotional aspects, which could leading to more interest in learning more about the subject: scientific assessments of interactive learning environments provide promising results on learning opportunities for participants. But it seems as if the design of attractive interactive learning environments and the underlying computer models is difficult and dissemination of these interactive tools is challenging. Here, we highlight key aspects of serious games and interactive learning environments, lay out three examples and develop areas for research that may support the development of more impactful interactive learning environments addressing environmental issues.

9.1 Problem statement

Humans tend to overexploit the natural systems, i.e., fisheries (Rousseau *et al.*, 2019) or the atmosphere (IPCC, 2018). The scientific community has long been signaling the need for more ambitious action against overexploitation of these natural resources. In the meantime, there is a dramatic need for sustainable management of resources. The necessary conditions for sustainability are clear (Daly, 1991; Sterman, 2012): humans should not harvest renewable resources faster than the ecosystem can regenerate and should not generate more waste than the ecosystem can recycle or decay. Nonrenewable resources should not be extracted at all (Figure 19).

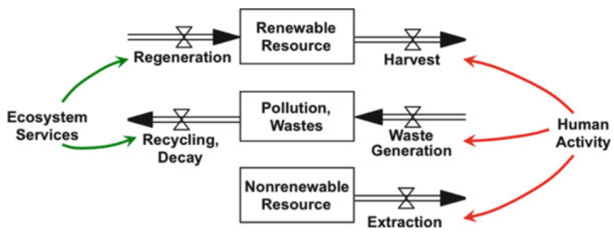

Figure 19: Three necessary conditions for sustainability shown in stock and flow notation. Source: Daly (1991) and Sterman (2012).

All complex, dynamic systems, such as natural systems include many stocks, flows, time delays, and feedback processes (Sterman, 2000). But humans can only process the dynamic interactions of two to three variables at a time (Halford *et al.*, 2005), a limitation clearly exceeded by the complexity of natural systems. While dynamics of natural systems like the climate are strongly conditioned by feedbacks, accumulations, nonlinearities, and time delays, even highly educated adults are unable to infer the behavior of even the simplest dynamic systems (Cronin, Gonzalez, and Sterman, 2009).

Appropriate action towards a more sustainable world depends on human action; and humans only act (differently) when they learn. Learning relies on experience and experimentation. Both do not work for managing natural systems as time delays are too long and experimentation is too dangerous if the original state cannot be restated. Because of the time delays, building up insights on the behavior of natural systems may take decades, or even centuries to emerge. Long time delays even mean humans never experience the full consequences of actions (Sterman, 2015). It took, for example, more than 250 years from the first scientific findings that vitamin C deficiency leads to the biggest reason for the death of seafarers until the British Board of Trade mandated citrus use (Mosteller, 1981; Sterman, 2000). The first scientific publication on greenhouse gas emissions affecting the atmosphere and the temperature was published in 1897 (Arrhenius, 1897) – and still more than 120 years later, the world's nations have not found an effective and binding way to limit global warming.

9.2 System dynamics for action learning

As in natural systems time delays are long and experimentation is dangerous, simulation might become the main, and perhaps the only way humans can discover for themselves how complex systems work. System dynamics has a long tradition of involving participants in interactive simulations, with the aim to build understanding of the system that is managed and improve decision effectiveness. Intuitively, there seems to be a link between learning and decision-making. Learning is a feedback process in which decisions alter the real world, users receive information feedback about the world and revise the decisions they make and possibly the mental models that motivate those decisions (Sterman, 1994, 2000). The assumption that when experimenting in interactive simulations, people learn and improve decision-making has been studied in a number of experiments. Early studies lead to disappointing results and the conclusion that humans suffer from a set of biases that are difficult to change, even when offered excellent learning conditions. For example, Paich and Sterman (1993) show that the repeated use of a simulator to tackle a dynamic decision making task does not improve decision quality, measured by performance (in this case, cumulative profit compared to a benchmark). Reviews by Hsiao and Richardson (1999) and Rouwette, Größler and Vennix (2004) identify a number of task characteristics that decrease performance, such as duration of delay and feedback strength. They also show that game characteristics have a separate effect on learning and performance: model transparency, for instance, improves performance. Around the year 2000, simulator studies turned from complex designs to simpler, basic stimuli such as a single stock with inflow and outflow (Booth Sweeney and Sterman, 2000). Even in such simple systems, participants show consistent failures. A review by Aramburo et al. (2012), in line with previous research, points to two important explanations for poor performance with reference to the Beer Game (Sterman, 1989): people tend to ignore delays and previous orders (the inflow, or in the case of a production chain, the supply line). Aramburo et al. (2012) also review attempts to model participants' behaviour on the basis of experimental data gathered in simulator research.

A number of studies, not included in the reviews discussed above, shed more light on the relation between participating in a simulator, learning, and quality of decision-making. Two studies focus on understanding of structure and both find a positive result. Elsawah, McLucas and Mazanov (2017) conclude that a series of progressively more complex simulators improves understanding of the causal relationships in a model of water availability. Participants report on surprising insights, or Critical Learning Incidents (Thompson, Howick, and Belton, 2016), that coincide with major changes in their understanding. Kopainsky and Sawicka (2011) find that simulations allow participants to acquire more adequate mental representations of the task, increasing their performance. Another set of studies measure both structural learning and decision quality. Gary and Wood (2016) report on three experiments on structural understanding and performance. They conclude that better structural understanding leads to better decision rules and to higher performance, that model support can improve structural understanding, and that structural understanding fosters performance in a task in another domain (transfer). This last result is similar to the conclusions drawn by Kumar and Dutt (2018), who found that the use of a simulation on climate change improved performance on a second task on climate stabilization. In the experiments by Petersen et al. (2018) exposure to a visualization of city-wide use of water and electricity expands participants' causal extent (the length and complexity of causal paths) in scenarios in a different domain. This suggests that the impact of participating in a simulator transfers across domains.

Effective simulation experiences should not only be rigorously grounded in the best available science but also engage the often messy, imperfectly rational, socially conditioned emotions and behavior of participants (Rooney-Varga *et al.*, in press). A way to embed simulations in interactions with people are interactive learning environments (ILEs) (Sterman, 2014a, b)

9.3 Applications of system dynamics for action learning

Many ILEs exist in the area of sustainability, not all of them using system dynamics. Hallinger et al. (2020) reviewed 376 papers on serious games used in educating for environmental, economic, and social sustainability, including energy, climate change, and natural resource management, using different game set-ups like desktop computer simulations (Dieleman and Huisingh, 2006; Moratis, Hoff, and Reul, 2006), board games (Applegate and Sarno, 1997; Hirose, Sugiura, and Shimomoto, 2004; Meya and Eisenack, 2018), and role play games (Hertzog *et al.*, 2014). Table 1 depicts a non-exhaustive list of interactive learning environments that are embedded in system dynamics models.

Table 2: Overview over interactive learning environments in the area of sustainability, embedded in system dynamics models

Name of ILE	Content	Available through
CleanStart	Entrepreneurship; marketing, product development, financing; employee ownership	https://mitsloan.mit.edu/LearningEdge/simulations/cleanstart/Pages/default.aspx
Climate Action Simulation*	Climate policy; negotiations; assessing solutions to reach climate goal	https://www.climateinteractive.org/tools/climate-action-simulation/
Eclipsing the Competition	Strategy in the presence of learning curves and scale economies	https://mitsloan.mit.edu/LearningEdge/simulations/solar/Pages/default.aspx

FishBanks*	The Tragedy of the Commons; strategy for open-access renewable resources	https://mitsloan.mit.edu/LearningEdge/simulations/fishbanks/Pages/fish-banks.aspx
World Climate Simulation*	Climate policy; negotiations; collective action and the Tragedy of the Commons	https://www.climateinteractive.org/tools/world-climate-simulation/

* These ILEs are briefly described in section 4.

In the following we exemplarily describe three of the ILEs shown in Table 1: two more recent simulation models, C-ROADS and En-ROADS and their accompanying games and workshops and a more classic system-dynamics-based game, FishBanks.

9.4 Climate Interactive's models and learning environments

The interactive simulations C-ROADS and En-ROADS have been developed by the US-based NGO Climate Interactive (www.climateinteractive.org) together with MIT Sloan and UMass Lowell. Climate Interactive's objective is to develop user-friendly, intuitive, interactive simulation models based in best-available science for decision-makers. Users can learn for themselves what works to address climate change and related issues like energy, health, food security, and disaster risk reduction.

First, the simulation model C-ROADS (Climate Rapid Overview and Decision Support) helps users like policymakers, negotiators, educators, businesses, the media, and the public to build their understanding of the likely long term impacts of climate change action, reducing greenhouse gas emissions (Sterman *et al.*, 2012; Sterman *et al.*, 2013).

C-ROADS is used in the *World Climate Simulation*, an interactive simulation-based role play negotiation of the UN climate summits. It has been facilitated all over the world, with more than 62,000 participants in 93 countries around the world since its launch until January 2020 (see https://www.climateinteractive.org/tools/world-climate-simulation/). The *World Climate Simulation* is effective in increasing participants' knowledge of climate change science, and, even more importantly, their emotional engagement, including their sense of urgency and their desire to take action on climate in the real world. There is evidence that the simulation has a strong positive impact even among those who oppose government regulation of the free market.

In the *World Climate Simulation*, participants take on the roles of delegates to the UN climate change negotiations. The facilitator, in the role of the UN Secretary General, welcomes them and asks them to create an international agreement that limits global warming by 2100 to well below 2 °C above preindustrial levels. Participants specify the Nationally Determined Contributions (NDCs) for the party they represent, while pursuing to influence the other parties through face-to-face negotiations. The facilitator enters the proposals into C-ROADS, which provides immediate feedback about the expected climate outcomes of those decisions. Usually, first round results fall short, illustrating to everyone the likely harm to prosperity, health and welfare. Participants then negotiate in a second (and, possibly, a third) round, using C-ROADS again to explore the consequences of more ambitious emission cuts.

Eighty-one percent of *World Climate* participants showed increased motivation to combat climate change, with statistically significant gains in (i) knowledge of climate change causes, dynamics and impacts, (ii) affective engagement including greater feelings of urgency and hope, and (iii) a desire to learn and do more about climate change (Rooney-Varga *et al.*, 2018).

Second, the climate-energy simulation model En-ROADS (Energy Rapid Overview and Decision Support) embeds the physical structure of the carbon cycle and the climate system modeled in C-ROADS in an explicit model of the energy system and economy. It is designed for decision-makers to explore how to achieve the climate goals through changes in energy, land use, consumption, agriculture, and other policies. It focuses on climate solutions.

En-ROADS is used in two interactive settings, (i) the simulation-based roleplay *Climate Action Simulation* (formerly known as *World Energy*) and (ii) the En-ROADS Workshop. Participants in the *Climate Action Simulation* take on roles of political, business, NGO, and society leaders, all invited by the UN Secretary General to an emergency summit to negotiate an agreement *how* to reach the climate goals and limit global warming to below 2 °C. Participants explore the impacts of carbon prices, energy efficiency, consumption, oil subsidies, electrification, methane from cattle, and other factors, and need to negotiate on meeting the climate goals, while better understanding their own as well as other participants' positions. First findings confirm the first two learnings occurring in the *World Climate Simulation*, with creating an immersive, social learning experience (Rooney-Varga *et al.*, 2019).

Both the *World Climate Simulation* and the *Climate Action Simulation* are suited for 15 to 500 participants. In the En-ROADS workshop, a facilitator guides a smaller number of participants through a more dialogue-style workshop, in which participants explore the impacts of policies and actions on the climate in more depth. Similar to the above, the workshop design puts the learner center stage and supports participants in learning for themselves about the dynamics of the natural system and the interactions of policies. The simulation models and all materials for both games and the workshop are freely available through Climate Interactive's website.

9.5 FishBanks

FishBanks is a multi-player game in which participants manage fishing companies, seeking to maximize their company's net worth at the end of the game. It exposes them to the tragedy of the commons (Hardin, 1968) in the context of renewable resource management (Sterman, 2014a, b).

The game provides participants with the opportunity to learn about the challenges of managing resources sustainably in a common pool resource setting, with realistic resource dynamics. Participants learn about (i) resource dynamics, (ii) the Tragedy of the Commons, (iii) misperceptions of feedback, and they learn that (iv) successful governance of the commons is possible. Summarizing, it offers participants an opportunity to experience the self-inflicted destruction of the resource, and the chance to negotiate and enforce self-regulation to preserve the resource and yield sustainable business success (Sterman, 2014a). Fishbanks has been played by thousands of people worldwide, from high-school students to managers of fishing companies. All materials are freely available through the MIT Sloan LearningEdge portal (https://mitsloan.mit.edu/LearningEdge/simulations/fishbanks/Pages/fish-banks.aspx).

Despite FishBanks having been developed at the end of the 1980s and many teachers having been trained in facilitating it (Meadows, 2007), its effectiveness on motivation to act has to the best of our knowledge not yet been measured. But scholars have assessed other aspects of FishBanks. Ruiz-Pérez et al. (2011), for example, used FishBanks to analyze institutional effects of sustainability. Their study with about 1,100 participants confirm that institutional regimes improve the performance of fisheries. They showed that introducing fisheries management institutional regimes reduces the pressure on the renewable resource. In terms of equal justice, institutional regimes tends to produce higher and better distributed economic returns. Yet, when the participants find themselves in a race for increasing their fleet sizes, an institutional regime is not able to prevent a collapse of the fisheries. Do Amaral & Hess (2018) assess dissemination effects of a FishBanks event with more than 100 people in South America. In a preliminary study, they found that after having experienced FishBanks, (i) participants from universities and consultancies used FishBanks in their business environment and (ii) it increased systems thinking skills and environmental awareness. Kunc and Morecroft (2010) used FishBanks to shift the focus away from sustainability to managerial decision making in a competitive and dynamically complex industry. Specifically, they study how participants in FishBanks follow different decision making strategies and how they led to a different development of resource stocks (and eventually to different performance – measured in 'total assets' – results).

9.6 Challenges ahead and conclusions

System dynamics models embedded in ILEs provide powerful ways for players to test assumptions embedded in their mental models and to learn for oneself. Embedding simulation models in ILEs is also an attractive avenue to disseminate simulation models across societies. But there are challenges for dissemination, assessing effectiveness, and reaching out to policy makers.

First, some ILEs like FishBanks use stylized simulation models. They capture the basic interrelations of the problem at hand in a highly simplified way and are (fairly) easy to understand by the facilitators. Here, learning is happening and insights are discussed in the debriefing. Because (some) participants are motivated to facilitate a session themselves (do Amaral and Hess, 2018), these ILEs seem to have a large potential of dissemination. Other ILEs use more sophisticated simulation models, which are also used by policy makers, like in World Climate or the Climate Action Simulation. As they are used by policy makers, they need to be embedded in the best-available science and the modeling should follow rigorous system dynamics model design (Rahmandad and Sterman, 2012). Here, (potential) facilitators need to be better trained and prepared for their sessions. This requires a larger effort for the game developers, ensuring dissemination.

Second, Hallinger et al. (2020) highlight a variety of stronger research designs and methods that can be used as to design future research. This aligns with a key recommendation for scholars in this domain to undertake programmatic research aimed at substantiating the effects of simulations and serious games on learner attitudes, knowledge and behavior. In particular, assessing the effectiveness of ILEs is difficult. Rooney-Varga et al. (2018) assessed the learning impacts of the experience of the World Climate Simulation. They showed that World Climate increases the motivation to act. It is subject for further research whether they also lead to actual behavior change. This is challenging, as intentions can be measured in a straightforward manner using questionnaire items, but measurement of behavior may involve time intensive observation in relevant real-life conditions (Mintzberg, 1975). An easier route may be to capture a fuller set of antecedents of behavior. Theories on the impact of intention on behavior (Ajzen, 1991; Ajzen, 2001) for instance, point to the central role of perception of control. An interesting question for future research is to which extent games influence perceptions of control, and in which direction. Yet, even if it was possible to measure behavior change and its antecedents, it would still be difficult to show that the behavior change can be traced back to people having participated in an ILE intervention. Behavior change takes time – and until the behavior is changed, people may have gone through many other experiences.

Finally, while scholars understand to develop models and write scientific papers, it is challenging for many to reach out to decision makers to understand the their thinking, their mental models better so that these can be addressed in the ILE. This is crucial to ground the model in their decision-making in messy problem situations in simulations embedded in the best available science.

9.7 Key resources

Websites

- World Climate Simulation: https://www.climateinteractive.org/tools/world-climate-simulation/
- Climate Action Simulation: https://www.climateinteractive.org/tools/climate-action-simulation/
- FishBanks: https://mitsloan.mit.edu/LearningEdge/simulations/fishbanks/Pages/fish-banks.aspx

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