MAIN ARTICLE

Participatory modeling for high complexity, multi-system issues: challenges and recommendations for balancing qualitative understanding and quantitative questions

Arielle R. Deutsch,[a,b*] Leah Frerichs,[c] Madeleine Perry[c] and Mohammad S. Jalali[d,e]

Abstract

Community stakeholder participation can be incredibly valuable for the qualitative model development process. However, modelers often encounter challenges for participatory modeling projects focusing on high-complexity, synergistic interactions between multiple issues, systems, and granularity. The diverse stakeholder perspectives and volumes of information necessary for developing such models can yield qualitative models that are difficult to translate into quantitative simulation or clear insight for informed decision-making. There are few recommended best practices for developing high-complexity, participatory models. We use an ongoing project as a case study to highlight three practical challenges for tackling high-complexity, multi-system issues with system dynamics tools. These challenges include balanced and respectful stakeholder engagement, defining boundaries and levels of variable aggregation, and timing and processes for qualitative/quantitative model integration. Our five recommendations to address these challenges serve as a foundation for further research on methods for developing translatable qualitative multi-system models for informing actions for systemic change.

Syst. Dyn. Rev. (2024)

Additional Supporting Information may be found online in the supporting information tab for this article.

Introduction

Over the past decade, there have been calls for the use of systems science within fields tackling high-complexity issues such as public health (Luke and Stamatakis, 2012; Carey *et al.*, 2015). Here, we consider two broad aspects of "high-complexity." First, that issues of focus can involve interactions between multiple focal issues and the systems underlying them (e.g. comorbidities, syndemics, and cross-sector collaboration; Osgood, 2009; Batchelder *et al.*, 2015; Sydelko *et al.*, 2021). Second, that such issues are contextualized by nested system levels (e.g. socioecological systems paradigm; Bronfenbrenner and Morris, 2006; sociotechnical systems theory; Walker *et al.*, 2008), which involve multiple levels of granularity (for example, in understanding healthcare, considering client, provider, and institutional levels; Fallah-Fini *et al.*, 2013; Moustaid

[a] Avera Research Institute, Avera Health, Sioux Falls, South Dakota, USA
[b] Sanford School of Medicine, University of South Dakota, Vermillion, South Dakota, USA
[c] Gillings School of Global Public Health, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina, USA
[d] MGH Institute for Technology Assessment, Harvard Medical School, Boston, Massachusetts, USA
[e] Sloan School of Management, Massachusetts, Institute of Technology, Cambridge, Massachusetts, USA

* Correspondence to: Arielle Deutsch, Avera Research Institute, Avera Health, Sioux Falls, 6001 S Sharon Ave, Sioux Falls SD, 57108, USA. E-mail: arielle.deutsch@avera.org

Accepted by Krystyna Stave, Received 14 September 2022; Revised 16 July 2023; 30 October 2023 and 20 December 2023; Accepted 22 December 2023

System Dynamics Review
System Dynamics Review
Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/sdr.1765

et al., 2020). These calls have resulted in a growing body of qualitative and quantitative systems models that are intended to inform policy (Currie *et al.*, 2018; Darabi and Hosseinichimeh, 2020). However, there are concerns that many system modeling efforts fall short of their policy-informing goals. Multiple reviews have discussed this concern within the realm of participatory (e.g. community-engaged, stakeholder-developed) projects (Rutter *et al.*, 2017; Cilenti *et al.*, 2019; Felmingham *et al.*, 2023), which often focus on highly complex health-related concerns.

There is a wealth of high-complexity modeling efforts and guidance within city planning (Hennessy *et al.*, 2011), infrastructure planning (Stave, 2003; Stave, 2010), transportation (Shepherd, 2014; Suryani *et al.*, 2020), and public health (Moustaid *et al.*, 2019; Kontogiannis, 2021) literature. These examples contain valuable insights for addressing important, albeit discrete, modeling challenges, but often focus on individual aspects of the model building process. For example, high-complexity simulation models, such as those examining comorbidities between issues or multiple systems, often omit intensive participatory qualitative model building (Osgood, 2009; Cirone *et al.*, 2020). Further, although participatory qualitative model building has many important purposes, simulation is often desirable. Yet, examples focusing on stakeholder learning via participatory processes often do not discuss the process of developing qualitative models that are clear, actionable, and/or readily translatable to quantitative system dynamics models (Macmillan *et al.*, 2016; Sydelko *et al.*, 2021; Lutete *et al.*, 2022). Finally, examples of participatory-grounded qualitative-to-quantitative projects often focus on smaller model components (e.g. individual systems or levels of granularity; Freebairn *et al.*, 2019; Weeks *et al.*, 2020) without relating to broader system models.

Pitfalls and recommendations have been discussed in the literature for participatory, qualitative, and quantitative system dynamics model development (Luna-Reyes and Andersen, 2003; Laws and McLeod, 2004; Martinez-Moyano and Richardson, 2013; Hovmand, 2014; de Gooyert, 2019). Generally, qualitative models are recommended to serve as broad documentation of the system and the conceptual foundation for formulating the quantitative model. In turn, quantitative models discern key leverage points and potential strategies for systemic change (Sterman, 2000; Zock and Größler, 2007). However, although many research projects include a multiple-model/solution framework (Loyo *et al.*, 2013; Freebairn *et al.*, 2019), most guidance focuses on developing a single model (representing a single issue or system). There is little guidance on how to consider both individual models and their position within multiple interacting systems simultaneously.

Current recommendations can also be challenging for high-complexity issues that involve diverse and intense stakeholder participation (Király and Miskolczi, 2019). Complex problems require a wide range of stakeholders who reflect expertise in different system areas (Hovmand, 2014) and across spectrums of power (to enact system changes), urgency (those experiencing a need for change), and legitimacy (those who believe that change is appropriate) (Mitchell *et al.*, 1997; de Gooyert *et al.*, 2017). Engaging such a diverse set of stakeholders can result in overwhelming qualitative models (e.g. models with a large set of variables and multiple levels of granularity) that are difficult to use for informing

DOI: 10.1002/sdr

decision-making, or challenging to translate into simulation for quantitative policy testing (Boswell *et al.*, 2021; Lamont, 2021). Coordinating these multiple perspectives is a time-consuming and cumbersome process (Homer, 2014); thus participatory modeling approaches often emphasize quickly narrowing perspectives and the modeling problem. This can reduce the volume of knowledge and complexity of the model, making it easier to understand (and simulate). Unfortunately, this process can inhibit insights for systemic change and reinforce the "status quo" mental models of participants (Adams *et al.*, 2021). To that end, more work is needed to advance strategies that can respectfully engage diverse stakeholders and adequately document the many interacting systems and variables while balancing the need for "policy-informative" qualitative models with clear and purposeful quantitative model integration.

The purpose of the current study is to highlight three challenges (and potential strategies to address them) that limit the process of translation to simulation/and or clear stakeholder insight, which are encountered in participatory-engaged system dynamics projects involving highly complex qualitative models. We use an ongoing community-based system dynamics (CBSD) project that involves modeling multiple issues, systems, and levels of granularity as a case study to discuss these challenges. Challenges include (i) navigating a diverse set of potential stakeholders at the appropriate level; (ii) specifying clear research problem(s) and model boundary objects over levels of granularity across the timeline of a project; and (iii) identifying optimal timing of integration of qualitative and quantitative model structures. Finally, we provide recommendations based upon the challenges we encountered; we discuss strategies we found successful, the limitations of these strategies, and potential ways to address these limitations. Our goal is not to provide definitive best practices, but to contribute to the ongoing discussion within broader system dynamics research for best practices with high-complexity participatory models.

Case study: Alcohol and substance-exposed pregnancy within indigenous communities

Study premise

Project SYstems of Native Community Health (SYNCH, pronounced "sync") is an ongoing CBSD project focused on identifying strategies to reduce alcohol and substance-exposed pregnancy (ASEP) rates and disparities experienced by Northern Plains Indigenous women. Despite concerted efforts to address ASEP, it remains a leading preventable cause of long-term negative outcomes for offspring (England *et al.*, 2020; Gosdin *et al.*, 2022). The premise of Project SYNCH is to address ASEP by targeting the underlying synergistic relationships between alcohol/substance use, intimate partner violence, and unintended pregnancy/low contraceptive use noted within HIV risk literature (e.g. the SAVA syndemic) (Singer, 2000; Batchelder *et al.*, 2015). This synergy manifests in a reinforcing feedback loop that maintains ASEP over time (Figure 1). Briefly, intimate partner violence facilitates alcohol/substance use (as a coping mechanism for victims or control mechanism for perpetrators; Ogden *et al.*, 2022), and unintended pregnancy (e.g. reproductive coercion; Giacci *et al.*, 2022). In turn, intimate partner

DOI: 10.1002/sdr

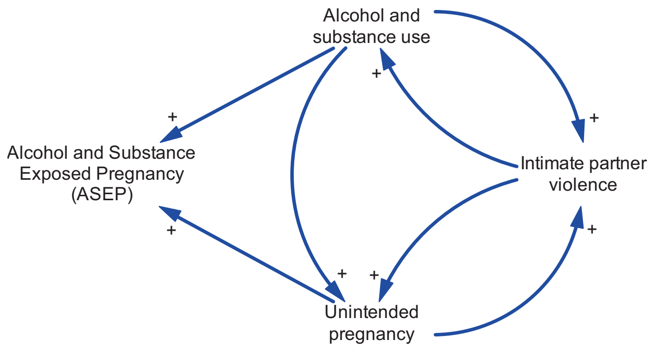

Fig. 1. System between alcohol/substance use, intimate partner violence, and unintended pregnancy underlying alcohol and substance-exposed pregnancy (ASEP)

violence is maintained by alcohol/substance use (in both discrete event-level cases and over time; Reingle *et al.*, 2014) and can be heightened over pregnancy (e.g. increasing vulnerability and dependency on partners and interpersonal relationship stress; Mojahed *et al.*, 2021). ASEP, which is linked to all three indicators (McDonald *et al.*, 2014; Deutsch, 2019), can be considered a symptom of this synergy. However, programs to reduce ASEP focus predominately on reducing alcohol/substance use or unintended pregnancy, ignoring interpersonal contexts of violence and trauma (Deutsch *et al.*, 2021; Reid *et al.*, 2021).

Intimate partner violence, unintended pregnancy, and (to a lesser extent) alcohol/substance use and ASEP are disproportionately experienced within Indigenous communities (Rosay, 2016; Giacci *et al.*, 2022). These disparities are entrenched in historical trauma and colonialism, and maintained through multilevel contexts of racial and socioeconomic inequity (Herron and Venner, 2022). Additionally, systems-level change for health equity within Indigenous communities requires accounting for contexts of disparity, inequity, and trauma, and cultural strength and resiliency (Blue Bird Jernigan *et al.*, 2020). Therefore, the goal of SYNCH is to identify key areas of intersection between alcohol/substance use, intimate partner violence, and unintended pregnancy that foster ASEP, as the most effective solutions are expected to involve areas that are shared between the systems that underlie each issue (not solely within one system). We also consider equity, such that the best policies should result in system changes that reduce negative health outcomes and reduce health disparities (Deutsch *et al.*, 2024), and therefore consider ways in which system structures may be unique for Indigenous, compared to non-Indigenous, community members (e.g. structural racism) (Bailey *et al.*, 2017). Project processes are grounded within best practices for community-based participatory research with Indigenous communities; these emphasize collaborative relationships based on trust and reciprocity, cultural humility, valuation of Indigenous knowledge, and honoring data sovereignty and community ownership of research (Brockie *et al.*, 2022).

Study methods

Project SYNCH started in 2018, based in a Northern Plains "small metropolitan" county (with a population of ~75,000 people, at the low end of the NCHS Urban–Rural classification range; Ingram and Franco, 2014). The area borders multiple

DOI: 10.1002/sdr

reservations, and Indigenous community members make up the largest non-white demographic. The area has a high underserved population and lack of resources, exacerbated by its status as an "urban hub" (it is the largest city within a 225 mile radius). To address longstanding conflict between Indigenous and non-Indigenous community members precipitated by a history of experienced and structural racism and enduring inequities, the city has invested in initiatives to improve relations and resources. Initiatives and their outcomes have received mixed reviews, as Indigenous communities often feel excluded from decision-making processes.

As further highlighted below, many of our strategies were tailored to accommodate the diverse participatory-related needs of community members. Table 1 provides an overview of the project steps to date. We are currently in the process of developing final, testable models for simulation for the ongoing study. Here, we focus on three project steps: qualitative conceptual model building, model consolidation/synthesis, and quantitative model structure development.

Challenges and recommendations

Table 2 provides a summary of challenges and recommendations. For each challenge, we provide an overview of literature and discuss our case study, following with recommendations to address the challenge.

Challenge 1: Navigating a diverse set of potential stakeholders at the appropriate level

Literature overview

Although qualitative diagramming and simulation modeling can be done solely by an expert or expert team, it is common to engage stakeholders during the model development process (Vennix, 1999; Király and Miskolczi, 2019). Literature emphasizes two main stakeholder selection criteria. The first criterion involves qualities relevant to policy and action such as decision-making power, need for change, and interest in change (de Gooyert *et al.*, 2017). The second criterion involves qualities relevant to subject expertise and experience (Hovmand, 2014), typically separating stakeholders by professional (e.g. individuals with knowledge in different domains relevant to the system) and "personal" (e.g. consumers/end users, community members, personal experience) statuses (Lee *et al.*, 2022). Stakeholders participate in a variety of ways, including informal discussions or more formal processes such as semi-structured interviews or group model building.

There are several issues with conventional participatory modeling approaches that are less adaptable for highly complex models. For example, in CBSD and group model building, relatively small groups (5–17 individuals) with diverse viewpoints are preferred, especially when models are developed by reaching group-level consensus through iterative model refinement (Vennix, 1999; Hovmand, 2014). This approach can be burdensome for both modelers and participants when developing highly complex models. High-complexity participatory

DOI: 10.1002/sdr

Table 1. Accomplished community-based participatory model building steps over the process of Project SYstems of Native Community Health (SYNCH)

Project Step	Description
Community Relationship-Building	Monthly conversations (over the first year) with community members involved with any and all areas of the project target issues. This included community member perspectives (feedback, recommendations, level of interest) on the project and method and recommendations for other stakeholders we should connect with. This also included development of our community advisory board.
Model-building protocol development	Iterative feedback and development of our group model building protocol, including critical stakeholders to include and strategies for recruitment feasibility of protocols based on appropriate amount of time and barriers for participation, and culturally-appropriate and trauma-informed strategies for implementing sessions.
Individual and Small Group Diagramming Sessions	Based on the adapted model building protocol, we engaged in over 20 participatory diagram short sessions spanning more than 90 participants prior to standardization and aggregation. More details on this process are discussed below.
Quantitative Model structure parameterization and calibration	Parallel to initial diagramming sessions (as discussed below), the modeling team identified critical stock-and-flow structures that would be part of the full models regardless of knowledge gathered in qualitative models (e.g. developing the quantitative model structure for alcohol and substance-exposed pregnancy [ASEP]). This included developing modeling structures, compiling a rigorous dataset based upon community and nationally available data and literature, and stock-and flow parameterization and calibration.
Causal Loop Diagram Standardization and Aggregation	After individual models representing knowledge from the target subsystem areas was collected, the modeling team used a synthesis approach to thematically aggregate variables from all models, connecting all aggregated variables based on individual model links. This resulted in a consolidated model that involved multiple sub-models that could be broken down at further levels of granularity. More details on this process are discussed below.
Refinement Focus Group Sessions	A series of five 3-hour model critiquing sessions were held 2 weeks apart with small groups of 8–10 participants (some participating once, some participating all five sessions), oversampling Indigenous stakeholders with personal experience. For the first three sessions, participants evaluated simplified versions of sub-models (healthcare and western treatment; family/community cycles of alcohol/substance use, violence, trauma and healing; justice/social systems) to provide critical feedback. Using the ideas and themes discussed over the first three sessions, the last two sessions involved "big picture" issues in which participants discussed the most important aspects of the systems, and potential solutions to address these aspects.
Rigorously Interpreted Quotation Analysis	After refinement sessions, we used a rigorously interpreted quotation analysis approach (Tomoaia-Cotisel *et al.*, 2022) to integrate the information developed from refinement sessions into a series of testable hypothesis models. We used transcriptions from the refinement sessions to clarify the key causal links that participants identified as critical leverage points.

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Table 2. Encountered challenges and recommended strategies for improving system dynamics modeling for highly complex, multi-system problems

Challenges	Recommendations
Navigating a larger and more diverse set of potential stakeholders at the appropriate level	• Be prepared to involve a greater number and diversity of stakeholders in creating and refining the systems model with multiple and adaptive techniques. • Use rigorous and systematic stakeholder assessment (e.g. checklists by content area and granularity level) methods to determine engagement strategies.
Specifying clear research problem(s), model boundary objects, and levels of granularity across the timeline ("system" vs. "problem")	• Develop engagement strategies and diagrams that focus on identifying and understanding the structure of the interrelated issues rather than the completeness of each system. • Iterate diagrams that zoom in and out of the syndemic, i.e. it is ok to create a larger "spaghetti" diagram, but create smaller, simplified diagrams to use when engaging with stakeholders to refine and identify areas for simulation.
Timing of qualitative and quantitative model structure integration	• Develop and integrate quantitative model structures in earlier stages of qualitative development (e.g. aggregation), starting with the clearest "problem" areas (e.g. highly granular target issues).

modeling efforts often require more stakeholders, and include a number of long-duration sessions (e.g. multiple hours or days) (Langellier *et al.*, 2019; Sydelko *et al.*, 2021; Tiller *et al.*, 2021), over longer periods of time for the overall project. However, there is little guidance on potential alternative processes that address the needs and burdens of participants and modelers both.

Furthermore, traditional group-modeling efforts, in an effort to meet timelines and coordinate information, often exclude or inhibit the contributions of "non-modelers" through emphasis on quick consensus-reaching (Adams *et al.*, 2021) and inequitable representation within modeling groups (Deutsch *et al.*, 2022b). Such "non-modelers" are often the low power, high urgency stakeholders that have routinely been ignored in decision-making processes, but are the "target population" for policy change (e.g. those experiencing health disparity via systemic inequities; Frerichs *et al.*, 2016). Excluding such stakeholders, or including them but failing to address power imbalances (between stakeholders, between stakeholders and modelers), can not only result in potential failure to identify critical leverage points, but also perpetuate systemic inequity itself (Wallerstein *et al.*, 2019). Projects focusing on divisive and/or stigmatized issues, especially within contexts of systemic inequity and inequality, will likely require situations in which group collaboration is not feasible (e.g. between high and low-power stakeholders) if decision-making and modeling is to be equitable (Adams *et al.*, 2021). Recently developed metrics for evaluating the quality of participatory engagement in modeling projects (Lee *et al.*, 2022) do include measures of power. However, there remains little guidance for how to accommodate the needs of diverse stakeholders to ensure that (i) participation is maximized for all, and (ii) information collection is structured to reduce model complexity.

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Case study experience

With Project SYNCH, we encountered a host of challenges in systematically identifying stakeholders and engagement strategies. A lack of communication between knowledgeable stakeholders (institutions, providers, policymakers, clients, and community members, and between Indigenous and non-Indigenous communities) indicated a need for a large and diverse participant sample. The potential for sessions to cultivate shared understanding of these issues (Voinov and Bousquet, 2010) within such a highly diverse group was appealing. However, our community members and our advisory board raised several barriers and concerns to this approach. Indigenous community members, in particular, discussed a history of conflict and negative experiences from past efforts to improve shared understanding across these stakeholder groups. They were concerned that many combinations of stakeholders (across professional and personal experience groups, between Indigenous and non-Indigenous stakeholders) would create untenable dynamics in a group session. Community members voiced concerns that mistrust and participant safety (social/legal consequences given community size and state-level laws) would be a barrier for participation and session/project success. Advisory board members also discussed barriers to participating in lengthy modeling sessions. The community's lack of resources and excessive workloads left little time for participation, regardless of whether they were high-power administrators, service-providing caseworkers, or grass-roots advocates. Finally, community members mentioned that critical "personal experience" stakeholders (those most at risk for or currently experiencing the issues of interest) would face the most barriers to lengthy sessions, including issues with transportation, childcare responsibilities, and inflexible work requirements (e.g. jobs that have little opportunities for taking time off).

In response to these barriers, we developed a protocol that maximized the amount of information needed (through a large number of stakeholders) and reduced participation burden. This protocol involved a high number of short-duration (1½ hour) small-group or individual qualitative diagramming sessions. Sessions focused on understanding the system from specific viewpoints or content areas, e.g. personal experiences of partner violence and ASEP, or police approaches to substance use or partner violence. Rather than setting the number of sessions a priori, we used a synthesis approach to indicate what information was missing and when saturation (or model "completeness") was reached (e.g. collecting information until sessions start to demonstrate repetitions). After collecting information via causal loop diagrams (CLDs) representing different aspects of the overarching system(s), consensus would be developed by aggregating the multiple CLDs (discussed below). Early exploratory sessions with small groups followed a script (please see supporting information Appendix S1 for a short facilitation guide) that included variable elicitation and causal loop diagramming. As we gained knowledge from different areas, we focused on what information was still needed, and created "starter" models for stakeholders that could provide this necessary information (e.g. asking "based on your experiences, what are the important things that are missing from this model?"). Many later sessions involved a hybrid interview/focus group and model-building approach, in which CLDs were iteratively developed in "real time." Specifically, modelers

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Table 3. Stakeholder engagement through targeted or indirect recruitment over short-session causal loop diagram building activities, categorized by content area and experience type

	Type of Experience/Knowledge			
Content Area	Personal Experience	Professional Experience	Indigenous Systemic Equity/Inequity	Syndemic Issue Areas
Alcohol/Substance Use in Pregnancy	Targeted	Targeted	Indirect	Alcohol/substance exposed pregnancy, alcohol/substance use, intimate partner violence, unintended pregnancy
Treatment, Services, and Resources	Targeted	Targeted	Targeted	Alcohol/substance exposed pregnancy, Alcohol/substance use, intimate partner violence, unintended pregnancy
Intimate Partner Violence Victimization	Targeted	Indirect	Targeted	Alcohol/substance use, intimate partner violence
Intimate Partner Violence Perpetration	Indirect	Targeted	Indirect	Alcohol/substance use, intimate partner violence
Justice System (Policing/ Court)	Indirect	Targeted	Targeted	Alcohol/substance use, intimate partner violence
Justice System (Re-entry)	Targeted	Targeted	Indirect	Alcohol/substance use, intimate partner violence
Reproductive and Perinatal Health	Indirect	Targeted	Indirect	Alcohol/substance exposed pregnancy, Alcohol/substance use, intimate partner violence, unintended pregnancy
Child Welfare Services (Child Protective Services/Department of Social Services)	Indirect	Targeted	Targeted	Alcohol/substance exposed pregnancy, Alcohol/substance use, intimate partner violence, unintended pregnancy

would diagram participant dialog, allowing participants to reflect on the drawn structure and add to or revise it, or the modeler would ask for elaboration on specific aspects of the diagram. Additional notetaking (and later, recorded transcripts of sessions), provided additional context to further refine and revise the models developed during all sessions.

We guided participant recruitment using a checklist developed by the research team and community advisory board of important content areas for understanding the multi-issue system, considering both professional and personal experience. This allowed us to cover broad aspects of the shared and unique system elements across multiple issues (Table 3). Importantly, this checklist changed over the course of the project as new content areas became relevant following initial modeling sessions. Some stakeholders had expertise or experiences in

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multiple areas and provided information on additional areas indirectly (e.g. content areas/perspectives that were not the reason for their targeted recruitment). A main goal was equitable representation of marginalized participants (Deutsch *et al.*, 2022b). Thus, we over-sampled underrepresented groups and recruited participants with diverse personal experiences (e.g. different methods of recovery, involvement with different institutions or resources).

Recommendation 1a. Be prepared for involving a greater number and diversity of stakeholders in creating and refining the systems model with multiple and adaptive techniques.

Our strategy to engage with distinct stakeholders who can provide separate pieces of information for unification into a holistic system was similar to a synthesis qualitative research approach (Pearson, 2004; Barnett-Page and Thomas, 2009), following previous suggestions for increasing participatory engagement (Wagle, 2014). This approach was useful for building initial understanding of the multi-system issue in a low-burden way for participants. In particular, it helped address logistical concerns and allowed for engagement at multiple time points and in ways that did not require high skill levels in system mapping. We consider this approach as a supportive complement to, but not supplement for, more intensive participatory modeling activities (e.g. our later refinement sessions) that provide the foundation for stakeholder-engaged modeling projects, especially CBSD studies requiring long-term, high-level community participation (Király and Miskolczi, 2019). However, a criticism of participatory modeling is that non-conventional stakeholder involvement has often been limited; thus, the predominant model structures, assumptions, and boundaries created by professionals and those with political, organizational, or positional power have not been adequately challenged (Adams *et al.*, 2021). Our approach included a broad range of stakeholders and strengthened our relationships (e.g. building trust) with stakeholders who typically have low decision-making (political, positional, institutional) power. These relationships, in turn, helped us identify key stakeholders for our more intensive modeling refinement sessions.

Many participatory modeling efforts include a mixture of participation activities, including interviews and model building efforts (Mahamoud *et al.*, 2013; Frerichs *et al.*, 2016). For the first phase of model conceptualization and diagramming, we wanted to provide the opportunity for all participants to engage in the qualitative model diagramming process (treating their information "equally"). However, early modeling sessions indicated that many participants, especially those who were "personal experience" participants preferred a low amount of structure in which they could freely talk. Therefore, we shifted to using CLDs as a way for participants to visually see the "story" they were telling, which allowed them periods of reflection and further model development. Modelers were initially conflicted by how this could stray from the more rigid model-building process outlined in group model building guides. However, reducing rigidity increased participants' comfort and engagement, creating a more intimate environment in which they could share their perspectives on highly stigmatizing and polarizing subjects.

A limitation of this approach is that, as a stand-alone method, it provided relatively short-term engagement for many stakeholders. The large amount of time

DOI: 10.1002/sdr

and effort taken to collect initial models, as well as the subsequent steps (aggregation, refinement), left little time, effort, and funding available for continued engagement opportunities for most participants. We had intentionally focused on providing environments that reduced power imbalances and experienced marginalization, but an unintentional trade-off was reduced potential for longer-term and intensive engagement across the model-building process. Below, we discuss addressing limitations through scheduling specific times across the initial data conceptualization process for aggregation and quantification. These activities could provide opportunities to follow up with participants and include them in these processes.

Recommendation 1b. Use rigorous and systematic stakeholder assessment (e.g. content area checklists) methods to determine engagement strategies. Our process illuminated areas that need further consideration for stakeholder engagement for highly complex multi-system modeling projects. By considering both content (area of the system) and positionality (professional vs. personal), we were able to represent a wide variety of voices that otherwise would have been excluded. This is particularly the case for representing diverse personal experiences, rather than considering "personal experience" as a homogenous domain of expertise (Deutsch *et al*., 2022b). Furthermore, by comprehensively considering the most important areas of knowledge and experience, we were able to include new stakeholder domains and areas of expertise/experience as information was gained. For example, child welfare was identified as playing a key role in personal experiences for a wide variety of community members, leading to sessions with protective service caseworkers and program managers. As another example, funding for resources was a prominent variable in multiple sessions, leading to a "funding-focused" session with nonprofit, public, and private funding experience stakeholders.

As a limitation, we would have benefited from more deliberate consideration of additional characteristics of stakeholders such as interests, alliances, and power (Schmeer, 2000). As sessions focused on understanding the system structures themselves, given the high level of complexity, this resulted in us ignoring the roles of individuals in facilitating change or action, which limited our ability to identify important dynamics and areas to focus on for further development. Incorporating additional prompts that focused on personal and community decision-making and action (Where do you see yourself within this system? What connections and pathways have you navigated? Where do you have leverage to make changes in the system?) would have strengthened the value of the stakeholder, and transformed their meaning in the project from simply a source of information (product modeling session) to a collaborative agent for change (process and product modeling session) (de Gooyert *et al*., 2017). Furthermore, identifying stakeholders more by positionality (e.g. decision-making power and personal impact metrics; Dhirasasna and Sahin, 2019) in addition to content area knowledge, provides critical information about stakeholder-level barriers for change, e.g. low-interest, high-power individuals (Boswell *et al*., 2021). This approach may be particularly useful when considering the most important stakeholders to include for refining the smaller "problem" systems for quantitative modeling (Brychkov *et al*., 2021).

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Challenge 2: Specifying clear research problem(s), model boundary objects, and levels of granularity across the timeline ("system" vs. "problem")

Literature overview

Testable quantitative system dynamics models are typically developed through an iterative process between understanding the system structure and defining the dynamic problem and hypotheses. This iterative process requires building towards a sufficiently comprehensive and "complete" model (Martinez-Moyano and Richardson, 2013). However, there is little guidance on how to determine when completeness is reached, especially for highly complex issues (Ryan *et al*., 2021). The most effective leverage points may lie in key areas of intersection shared by systems, and/or variables or loops unique to one system. Therefore, a considerable amount of exploration is necessary. Textbook guidance of the model process (Albin, 1997), while helpful, oversimplifies how complicated the model conceptualization (problem definition and boundary setting) and formulation phases (simulating a basic hypothesized structure to assess validity) can be with highly complex issues. Common strategies to discern completeness in qualitative models, such as reaching consensus or convergence in group model building (Vennix, 1999) or grounded theory approaches (Glaser and Strauss, 1967; Groesser and Schwaninger, 2012), may not provide the necessary balance between understanding the system and identifying problems that can specifically be tested (Sterman, 2000; Northridge and Metcalf, 2016). In our case, for example, reaching a consensus on specific problems to pursue with quantitative modeling would have risked leaving out important stakeholder especially the perspectives of stakeholders who desired documentation of the broader system.

Highly complex models can require sufficient understanding about areas of intersection: between issues, between systems, and between different levels of granularity. Ensuring "completeness" may continually expand the boundary object as more variables are identified within each system. This can be due in part to the common strategy of using endogeneity and exogeneity to determine variable or loop inclusion (Dhirasasna and Sahin, 2019) to maintain boundary objects. For models evaluating synergy between issues (e.g. issues that may have a strong reinforcing impact on each other), individual variables may be both endogenous and exogenous, in that they are central to the system underlying one issue but are peripheral to the system underlying another. Modelers must therefore balance between uncertainty that will result in a large and unwieldy model with the need for precision and parsimony to determine areas for simulation. Although a common strategy for breaking up large qualitative models is to partition them into multiple subsystems (Allender *et al*., 2015; Payne-Sturges *et al*., 2023), this strategy does not allow for identifying shared and unique systems that underlie different, but intersecting, issues. In our case study, focusing solely on a problem definition for alcohol or substance use, without considering how this intersects with the underlying system of violence, has been indicated as a clear oversight for addressing system change.

Relatedly, multi-system models provide additional concerns with variable granularity (e.g. depth of models and level of specificity in the de-aggregation of variables, population, and time). (Dis)aggregation typically focuses on the level of detail for stocks (e.g. using one stock for infected people versus multiple stocks

DOI: 10.1002/sdr

for incubation, illness, and convalescence stages of infection). Although the best approaches discuss considering a "macro to micro" strategy, selecting only key areas or variables to de-aggregate, such choices are typically discussed within the context of understanding a single concept of interest (Sterman, 2000). However, decisions regarding aggregation or disaggregation are often unclear when navigating multiple systems. For example, in our case study, there were parallel processes of navigating child welfare and justice systems, but the decision rules governing the processes could overlap and interact with each other. Thus, the levels of aggregation would vary depending on the specific modeling problem; meanwhile, unsurprisingly, different stakeholder groups often desired more (rather than less) detail (Roberts, 1977). Finally, there is little detailed information on practices for aggregation or disaggregation of variables or subsystems for qualitative models, or the broader meanings of granularity in relation to populations (e.g. modeling processes within individuals, groups of people, or whole populations or across different time spans) (Ryan *et al.*, 2021).

Case study experience

This challenge was quickly encountered in our work with Project SYNCH, as every additional discussion with community members provided information on a new system component to consider. Although there was little consensus between community members regarding the system structure, there was clear consensus that solutions to ASEP should include the intersection between intimate partner violence, alcohol and substance use, and unintended pregnancy. Thus, our initial plans included a focus on alcohol and substance use treatment, healthcare, and justice systems, but quickly additional systems such as family, child welfare, mental health, housing, and education were identified as important and interrelated. This would, in turn, require us to include new stakeholders who could represent additional different perspectives regarding focus areas and levels of granularity. For example, questions and differences of opinion would be raised whether we should include a variable for "level of mental health" or if it would require many separate variables to denote specific mental health issues (e.g. depression, anxiety, suicide, etc.).

We used multiple strategies to balance between system exploration and considering areas for model testing over the course of the project. Early in the project, we knew that many of our stakeholders valued the broader understanding of the system in its entirety. Modeling the "system" rather than the "problem" is at odds with best practices (Sterman, 2000), and would result in developing a model too large to simulate or test. However, to be responsive to what community members were interested in and incorporate these interests into the collaborative modeling process, we defined two types of models necessary for our project. "Story models" involved using CLDs as a storytelling approach to represent the broader system in which ASEP exists. "Problem models" were smaller stock-and-flow models that represented dynamic hypotheses for formal policy testing that directly evaluate system changes to reduce the "problem" of ASEP.

As an example, we used the CLDs to provide the "story" of how rates of ASEP are maintained over time (Figure 2). Short-term rates of ASEP are maintained by interactions between individual, intrapersonal, and community contexts

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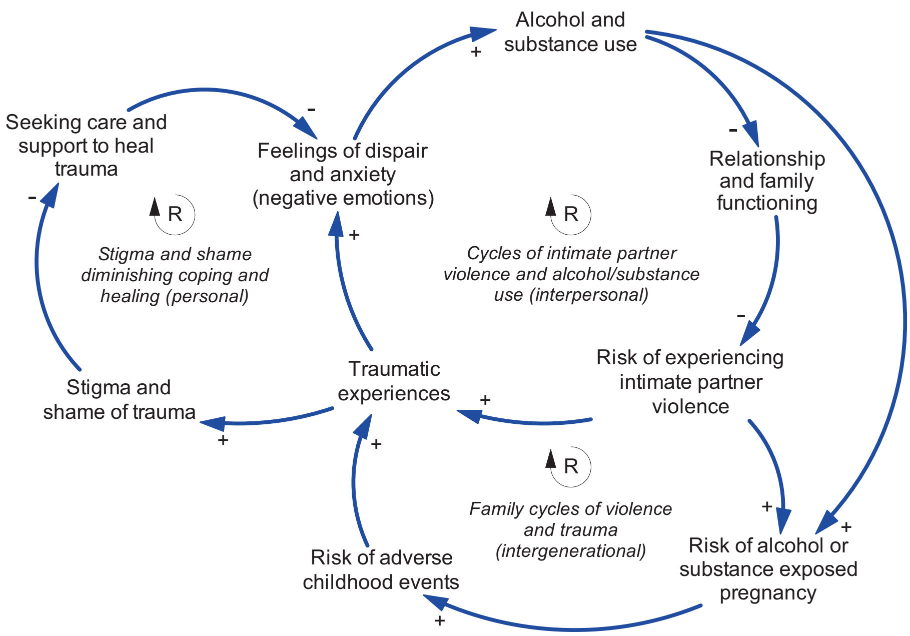

Fig. 2. Conceptual intergenerational model of alcohol and substance-exposed pregnancy, considering individuals nested within relationships and families over short-term (repeat pregnancies within people, pregnancies within community) and long-term (between generations) periods of time

(reinforcement of trauma, alcohol/substance use, and intimate partner violence within people and couples that persists through isolation from health-providing resources). Longer-term ASEP rates are maintained by the subsequent effects on offspring through poorer familial health and subsequent traumatic experiences across generations, which in turn maintain the short-term systems. Through models built from the perspectives of community members in a variety of different subsystems, we were able to develop CLDs that could detail different aspects of this "story" within the context of these subsystems (e.g. healthcare, justice) and at different levels of granularity (e.g. individual pathways to trauma or healing, interpersonal contexts of support or violence). Having a variety of different story models served as a useful strategy that helped both the modelers and community members understand the complexity of the model without becoming completely overwhelmed.

The story models have also served as a resource for further refining the "problem models" used for policy testing. The main components for reducing ASEP ultimately involve reducing the pregnancy rates for people who are using alcohol/substances, and/or reducing alcohol/substance use for people who are getting pregnant, which can easily be represented by stock-and-flow models in which policy testing involves changes to flows into and out of the alcohol/substance use and corresponding pregnancy stocks. However, in developing dynamic hypotheses, we needed to consider the best way to quantitatively model variables at multiple levels of granularity and as existing within different areas of the system. For example, Figure 3 provides an excerpt of a stock-and-flow diagram in which ASEP is represented within people, but the potential leverage points are represented within couples. Although not shown, the story model CLDs can be used to

DOI: 10.1002/sdr

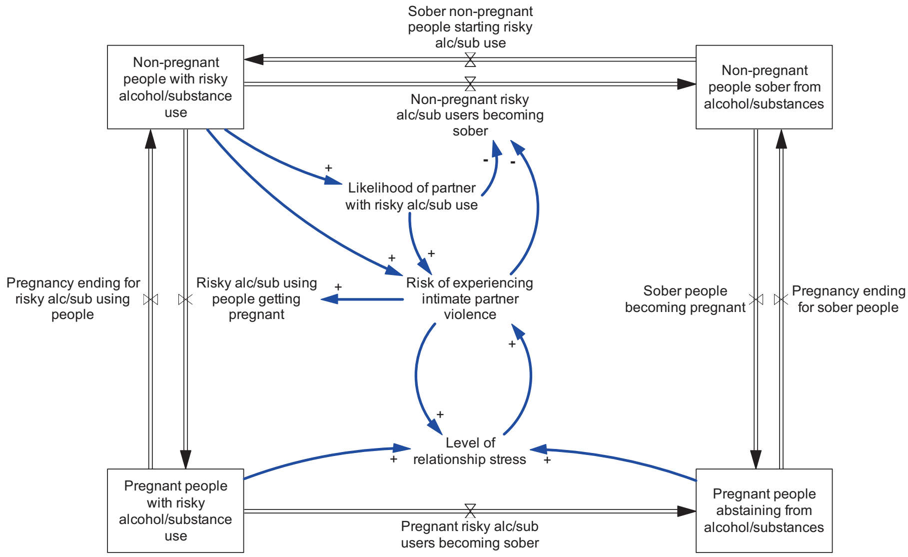

Fig. 3. Simple example "problem model" to incorporate tests for alcohol and substance-exposed pregnancy (ASEP)-prevention policies, focusing on romantic relationship level influences for an alcohol and substance use/pregnancy stock-and-flow structure

examine critical variables connecting to these leverage points, that will in turn provide a smaller, testable model for examining best strategies to reduce ASEP.

To develop the story model, we needed to gain enough information that explored the systems underlying each issue, but remained focused enough so that we did not completely change the main focus of our project. Therefore, our short-session CLD building scripts focused on understanding system intersections and their connections to ASEP (critical leverage points), rather than individual systems of alcohol/substance use, intimate partner violence, and unintended pregnancy themselves. This approach also helped during aggregation of CLDs and developing the larger cohesive model. Using a synthesis approach, we initially coded variables based on thematic similarity, and then considered their context within broader systems or subsystems, both specific to one issue, and generalizable to multiple issues. This allowed us to further refine aggregate variables, considering relevance to both ASEP and areas of intersection. Through this iterative process, we also defined and revised variables at multiple aggregation levels by examining how each connected to each other within and between CLDs (e.g. we examined if individual CLD variables included in one aggregate variable were connected to individual CLD variables included in a second aggregate variable).

Stakeholders participating in our refinement sessions held after CLD aggregation benefitted from using the consolidated diagram as a conversational springboard. Refinement sessions focused around the most important areas of intersection (those identified or those missed) to test as potential leverage points for change. Importantly, community participants and collaborators, especially Indigenous community members, appreciated how the consolidated diagram documented the complexity they experienced in a visual and tangible way. However, through this process, we also realized the need for multiple, simplified versions of the CLD with varying purposes. For refinement sessions, this included the ability to facilitate stakeholder discussion on specific areas of uncertainty,

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identify areas of intersection, and challenge some of the "status quo" concepts represented in the models (e.g. the utility of referrals in healthcare). We were also able to evaluate thematic causal loops that exist in multiple subsystems and between issues of ASEP, alcohol/substance use, violence, and unintended pregnancy during the rigorously interpreted quotation analysis (Tomoaia-Cotisel *et al.*, 2022) of the refinement sessions. For example a key reinforcing feedback loop seen in healthcare, psychosocial care, social welfare, and justice systems, which reinforced all issues, involves the relationship between personal trauma and isolation, and the inability to receive help from a fragmented and hostile institution that places the burden of help seeking and resource navigation on individuals in need. Such loops that repeat over multiple subsystems have been identified as dynamic hypotheses.

Challenge 2—recommendations

Recommendation 2a. Develop engagement strategies and diagrams that focus on identifying and understanding the structure of the interrelated issues rather than the completeness of each system. Understanding multi-system issues requires a dedicated amount of time and effort for qualitative exploratory research at highly granular levels to discern intersections. Areas of overlap may not be easily apparent, and may require probing the systems underlying individual issues to consider intersections. However, this time-consuming endeavor can be derailed quickly by efforts to model "everything" if the boundary is considered the system underlying each individual issue in full. We addressed this concern by focusing on the interactions between target issues for model development, understanding that "completeness" (Martinez-Moyano and Richardson, 2013) should focus on areas of intersection (e.g. variables or loops that overlap between the systems that underlie the individual issues). This required some exploration into the individual systems, as not all intersections were easily apparent. However, emphasis on intersections provided a broad, but clear "overarching" boundary that allowed us to explore multiple dynamic hypotheses without straying from the original project goal (Sterman, 2000). By starting this emphasis in the earliest stages of model development and data collection (e.g. exploratory CLD models), we were able to structure conversations around the intersection of issues (e.g. shared causes and effects). This also provided us guidance for model aggregation, as we could discern variable endogeneity and exogeneity by their position within causal loops related to the association between the central issues and outcome.

Recommendation 2b. Iterate diagrams at different levels of granularity and subsystems, i.e. it is OK to create a larger "spaghetti" diagram, but create smaller, simplified diagrams to use when engaging with stakeholders to refine and identify areas for simulation. Despite best efforts to have a simplified model, the need for highly granular information and the multiple subsystems led to a story model that was often overwhelming. The larger diagram has been valuable to help us identify key subsystems and how they intersect, but we found it challenging to communicate to our stakeholders in totality. As we focused on understanding the broader intersections between systems (shared variables, loops, and subsystems), we paid less attention to the individual areas of the model we were creating. There was little ground between developing an overarching "story" model and

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much more specified "problem" models. We instead observed that there was not a single "story" but rather many stories that are part of a larger anthology. Thus, our aggregation strategy was not completely sufficient to comprehensively cover the various qualitative models we were required to create (for refinement sessions) to highlight different issues or their interconnections at different times throughout the project.

For the refinement sessions, we experimented with creating simplified diagrams that focus on one identified "subsystem" (e.g. family and social systems, alcohol and substance abuse treatment) that are a part of the larger multiple system synergy and specific factors where it intersects with others. System dynamics scholars will often provide these types of simplified diagrams in peer-reviewed literature. For example, Macmillan *et al.* (2016) conducted a participatory system dynamics study of housing, energy, and wellbeing and documented a high-level causal map of seven interrelated "subsystems" (e.g. household crowding, energy efficiency, community connection) wherein each subsystem had a more granular respective causal loop diagram. Many other examples exist across a range of topics (e.g. cognitive function and dementia; Seifert *et al.*, 2022; social determinants of non-communicable disease; Sharma *et al.*, 2023; pandemic preparedness, Fredericks *et al.*, 2023) where authors identify and visualize domains or subsystems in simplified forms; however, it is not typically communicated that this type of simplification may be valuable in the modeling process. Thus, it may be valuable to consider more iteration in both depth and breadth of multiple aggregate models that balance granularity and inclusion of multiple subsystems. For example, macro-level models could provide the broader ways in which core variables from multiple subsystems (e.g. justice system, physical health/healthcare, psychological functioning, social environment) intersect. More granular models will comprehensively detail this intersection. A balance of both larger "spaghetti" diagrams and smaller, simplified ones have greatly enabled our current participatory sessions for stakeholder communication and identifying leverage points/solutions.

As a limitation of our aggregation approach, separation of "story" and "problem" models may have artificially kept us from more systematic integration of our qualitative diagramming and simulation modeling processes in a manner that would allow more flexible modeling versus rigid aggregation to achieve a single "multiple system" model. A potential solution could be to adapt and expand a framework such as the "ScriptsMap" tool (Ackermann *et al.*, 2011) to include activities, products, and deliverables that span the broader cycle of model development for providing the additional structure and guidance necessary for multi-system models, and to connect story and problem models. For example, aggregation could be guided by a "living" codebook for thematic variable analysis (that changes as new CLDs are created). This may provide a broader structure for more fine-grained aggregation after collecting sufficient data, within a manageable framework that can better guide this aggregation. This could also be paired with participatory model aggregation activities to examine the higher-level aggregate models. For example, when identifying more specified quantitative modeling problems for simulation, participants could discuss the key elements from the qualitative model that will be necessary to include. Similar to the core modeling team used to design scripts (Hovmand, 2014), a "core model building group" could provide feedback during intermediary periods of model aggregation.

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Challenge 3: Timing of qualitative and quantitative model structure integration

Literature overview

One may debate whether qualitative system maps are sufficiently informative (Coyle, 2000), while many others assert that quantitative simulations are essential, or always add value to the project (Homer and Oliva, 2001). Moving from qualitative, highly complex diagrams to quantitative modeling can create a tension during the iterative process between understanding the system structure and defining the dynamic problem. On one hand, qualitative diagrams emphasize documenting the constellation of factors that comprehensively affect issues. On the other hand, quantitative models represent a more defined dynamic hypothesis about why and how a system may produce certain outcomes.

Quantitative model components have the potential to change, refine, and enhance qualitative model structures; developing quantitative model components *after* a full qualitative model is a common practice that does not take full advantage of the power of model formulation. For instance, in CBSD model review sessions, structures are reviewed to ensure qualitative models represent the content from the sessions as much as possible. After review and integration, a simplified model is put together to represent a "road map" for building a formal, quantitative simulation model. The CBSD literature discusses quantification enhancement (e.g. quantification by a modeling team to increase the diversity of thoughts, reduce errors, and build model confidence) (Hovmand, 2014).

A lack of consideration to qualitative and quantitative co-development could result in a lengthy process of iterative refinement. For example, a common tendency to make high-complexity participatory qualitative models more understandable is to partition them into qualitative subsystems (that collectively make up a single system). Within health literature, subsystems often include individual (e.g. physical and mental health, behavior), intrapersonal (e.g. familial and social environments), institutional (e.g. health system, justice system), and community/societal (e.g. built or natural infrastructure, economy) components (Gerritsen *et al.*, 2019; Payne-Sturges *et al.*, 2023). However, these subsystems commonly differ in levels of granularity. Integrating quantitative structures early in the modeling process can help inform qualitative aggregation and conceptualization, as modelers will need to consider, for instance, how to integrate person-level stock-and-flow models within institutional-level qualitative subsystems.

Developing qualitative and quantitative models simultaneously is not a new construct; in the general system dynamics literature, modeling guidelines discuss such iterative processes (Sterman, 2000). However, it is not commonly documented in participatory modeling methods beyond inclusion of stock-and-flow models after early model conceptualization (e.g. during longer group model building workshops). For example, there is little guidance on the roles that strong quantitative modelers can play in modeling teams for participatory projects, or the process of iteration during the participatory modeling process.

Planning for this process is particularly important during the initial gathering of information about promising multi-system "areas of intersection." Common approaches to developing a dynamic hypothesis require understanding variable/loop endogeneity (Martinez-Moyano and Richardson, 2013), which may not be fully understood until late in the qualitative development phase. Furthermore,

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without sufficient information, dynamic hypotheses and quantitative models may be subject to bias (Homer, 2014). Although some researchers have highlighted strategies for integrating data collection and analysis for system dynamics models, such as grounded theory (Kopainsky and Luna-Reyes, 2008; Akcam *et al.*, 2011), qualitative models are still used to inform quantitative model development.

Case study experience

As the conceptual model diagramming and exploration was a time-intensive process, our process left little time available in modeling sessions to develop stock-and-flow models (which would have in turn required teaching participants about stock-and-flow models within short sessions). Therefore, we initiated quantitative modeling processes parallel to qualitative model development and aggregation, focusing on areas that we knew would require quantitative modeling (e.g. the interrelated issues), and those in which we had sufficient information to reduce potential bias (Homer, 2014). A critical area of consideration was how to best quantify the areas of focus themselves, as this involved multiple levels of nestedness (pregnancies within people within relationships). We first focused on alcohol use for the simulation model, as this would provide a foundation for alcohol-exposed pregnancy, and used theoretical and empirical alcohol use research as a basis for model structure. During development, we cross-checked the simulation model's stock-and-flow variables with the larger CLD structure and ensured that they aligned. Additionally, as early CLD models incorporated intergenerational transmission of the key issues of interest (e.g. intergenerational alcohol/substance use and violence), we used a developmental lifespan approach for developing our quantitative stock-and-flow alcohol use model (Deutsch *et al.*, 2022a). This further allowed us to consider how we could test different strategies for prevention (reduce inflows to critical stocks) versus intervention (increase outflows of critical stocks).

Developing initial stock-and-flow models also influenced our qualitative model aggregation process, as we more closely considered person-level granularity. When possible, we specified populations experiencing comorbidity of issues (e.g. pregnant women who are both using substances and are involved in relationships marked by intimate partner violence) rather than broader populations. This provided guidance for qualitative aggregation (e.g. reduced need to de-aggregate variables that were not relevant to these populations) and quantitative aggregation (e.g. discerning between Indigenous and non-Indigenous pregnant women who use substances and/or alcohol in intimate partner violence relationships to probe areas of inequity, compared to multiple categories for both race/ethnicity and combination of experiences).

Challenge 3—recommendations

Recommendation 3a. Develop and integrate quantitative model structures in earlier stages of qualitative development (e.g. aggregation), starting with the clearest "problem" areas (e.g. highly granular target issues). Developing dynamic hypotheses and subsequent testable models may not be easily accomplished at the earliest stages of understanding the multiple systems. However, we also wanted to

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introduce quantitative structures as early as possible. Focusing on variables that we knew would be part of the testable models, i.e. the problem areas such as alcohol and substance use and ASEP, was not only a strategy that helped conserve time, but also influenced the way in which we considered these variables in our qualitative models over the initial diagramming and aggregation processes. For instance, at the time of qualitative model building, one might not realize that some variables have widely different time units (e.g. hour vs. year), an issue quickly noticeable in quantification. After considering the painstaking process for creating multiple population-level subscripts based upon both race/ethnicity group and multiple combinations of alcohol/substance use and/or intimate partner violence experiences, we added clarifying information on qualitative variables to specify populations. This approach has also allowed us to flexibly consider the multiple ways in which higher-level constructs could directly impact the target focus areas from a prevention or intervention perspective (e.g. how we can include auxiliary parameters from multiple contexts to impact relevant inflows and outflows).

Extending this process could have involved integrating our stock-and-flow models into smaller "story" models (during but not after complete aggregation) and running preliminary "local" level simulations (e.g. the stock-and-flow variable in a smaller systems model). This could follow a similar process as partial-model testing, which is noted to help pin down uncertain formulations and parameter values (Homer, 2012). Preliminary simulations testing these stock-and-flow models can provide feedback on stock-and-flow model validity in parallel with more involved qualitative work (e.g. aggregation) and dynamic hypothesis formulation. Further, when a simulation model is developed and calibrated to quantitatively project the system's behavior, there will often be mismatches between model behavior and reference modes or historical data. Even if the model provides a good behavior match, through validation approaches (e.g. extreme testing), unreasonable behaviors may be identified (Barlas, 1996). Together, these offer the opportunity to identify errors or shortcomings in the model structure, e.g. a feedback loop, that were not initially considered in the system map. Such insight will be particularly important when considering areas of inequity, e.g. differences in system structures based upon systemic marginalization that can better explain group-level differences in variable behavior (Deutsch *et al.*, 2024).

One limitation of this approach was that, due to the intensive process of collecting qualitative information, we had little opportunity for integrating the models as they were developed in parallel. If they are not specifically part of a dynamic hypothesis and simulation model to be tested, stock-and-flow models are not often created and causal loop diagrams are solely relied upon (Schaffernicht, 2010). However, causal loop diagrams can hide important dynamics including feedback loops and accumulations, and thus integrating stock-and-flow structures (even without simulation) at earlier phases could have improved our process (Richardson, 1986; Schaffernicht, 2010). Considering how qualitative variables might be represented as stock-and-flow structures could help identify nuances in polarity, variable accumulation, and feedback loops that do not follow traditional definitions (i.e. links representing a rate-to-level versus direct connection). For example, in our case study, we uncovered how a misfit

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between people's cultural needs and the care they receive contributes to their culturally insensitive experiences. However, a decrease in misfitting care does not directly relate to overall decreases in culturally insensitive experiences. Ultimately, this process could help identify potential dynamic hypotheses from which to develop more bounded quantitative models for simulation (Homer, 2019).

Discussion

Qualitative diagrams developed with stakeholder input are an essential component to system dynamics projects that focus on high-complexity issues. Modelers have long discussed the tension between understanding the system and modeling the problem (Größler and Milling, 2007; Sterman, 2018). Qualitative diagrams can help provide the system-level understanding necessary for developing informative and useful quantitative simulations. Furthermore, they can be critical for stakeholder communication and collaboration, representing mental models in an easily understandable format. However, both modelers and stakeholders can become quickly overwhelmed in an effort to model highly complex systems defined by interrelationships between multiple factors and levels of granularity. It is a challenge to represent the "whole" of these systems within a qualitative diagram, identify leverage points, and formulate modeling problems for simulation while coordinating multiple views and perspectives.

This paper discussed, through the lens of a case study, the practical realities of facing these challenges. We built upon our experience, on strategies that have emerged from system dynamics literature (Kopainsky and Luna-Reyes, 2008; Wagle, 2014; Ryan *et al.*, 2021; Crielaard *et al.*, 2022), and on discussions of what is still lacking (Cilenti *et al.*, 2019; Adams *et al.*, 2021) to provide a set of recommendations to address the challenges. In our case study, we found that addressing challenges through a multi-system qualitative approach provided opportunities for stronger community engagement and empowerment. We were often required to change our planned strategies for model development and analysis to account for the larger volume of stakeholders and information required for understanding the "multi-issue synergistic system," and to identify clear leverage points and actions for multi-system change. However, this approach provided unique insights and model findings. For example, devoting more time to learning about and developing a conceptual model of the broader system structure has allowed us to uncover key thematic loops common to multiple aspects of the system. One example of this is the role of external funding policy on psychosocial care provided by Indigenous community-based organizations (Deutsch *et al.*, 2023)—a finding that only became apparent when discussing the need for care across multiple subsystems that were shared between issues of interest. Furthermore, by putting more emphasis on detailing the system structure, we provided a foundation for community members to probe additional areas of interest beyond the current project (e.g. examine other potential issues of interest that exist within the overall structure).

The challenges we discuss here were not only experienced because of the complexity of the project itself. They also arose when common approaches to model

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development for qualitative diagramming and quantitative integration (in both participatory and researcher-driven contexts) were not conducive to project success. We specifically discuss the challenges between common practice and feasibility as they are not specific to high-complexity projects that include multiple systems, but can be encountered in any project with a high degree of complexity regarding stakeholders (Adams *et al.*, 2021), variable aggregation (Ryan *et al.*, 2021), and qualitative/quantitative integration (Featherston and Doolan, 2012; Sterman, 2018).

For example, ensuring that stakeholders were equitably represented in the modeling process required us to address the clear differences in the barriers that stakeholders faced for participation (considering practical constraints for participants and unequal intrapersonal and sociopolitical power dynamics between participants). Furthermore, we were tasked with making sure that all participants felt that the information they shared was heard and represented in the models (e.g. the story models). Such issues are particularly important for community-based participatory research projects (Wallerstein *et al.*, 2019) to ethically and equitably ensure that community member voices are championed and are guiding forces of the research. In turn, we had to consider how to best balance addressing such participatory challenges with productively advancing model development and policy testing, avoiding common pitfalls that are encountered during projects (e.g. modeling problems rather than systems, maintaining boundary objects). Still, given the growing interest in using high-complexity paradigms in systems science approaches (Payne-Sturges *et al.*, 2021; Bolton *et al.*, 2022), we provide these recommendations within the lens of considering the intersections between multiple systems.

Our recommendations are guided by our experience and the presented, ongoing case study. New challenges and recommendations may continue to arise as our project progresses. However, we discuss these challenges within the context of longstanding discussions within system dynamics literature regarding the challenges encountered when integrating qualitative and quantitative modeling for high-complexity issues. We also provide recommendations within the context of a growing body of literature for new strategies, approaches, and methods to develop qualitative models that are highly complex, useful, and can translate to simulation and action. The recommendations provided are not intended to be definitive best practices. We used our case study to describe major practical challenges faced by researchers and practitioners tackling highly complex issues with system dynamics tools via participatory engagement. We outlined five recommendations for the three challenges that can serve as a foundation for further conversation and research. As these recommendations are tested and solidified, we anticipate new challenges and strategies to arise. However, continued advances in computational and methodological tools (Abdelbari and Shafi, 2017; Crielaard *et al.*, 2022), alongside development of interdisciplinary research strategies (Zolfagharian *et al.*, 2018), provide new opportunities for modelers to develop increasingly more complex quantitative and qualitative models. Building upon the recommendations discussed here can contribute to the potential for such models to help further enhance the translation of system dynamics efforts into real-world actions.

DOI: 10.1002/sdr

Acknowledgements

This work was funded in part by NIH Grant R01DA050696-01 (Deutsch). The authors would like to thank Zeynep Hasgul for her assistance in creating the model figures for this manuscript.

Biographies

Arielle R. Deutsch is a Research Scientist at Avera Research Institute and an Assistant Professor at the University of South Dakota Sanford School of Medicine in Pediatrics and Psychiatry. She focuses on biopsychosocial models of health through community and multi-methodology approaches.

Leah Frerichs is currently an Associate Professor at the University of North Carolina at Chapel Hill in the Gillings School of Global Public Health and the Associate Director of the Center for Health Equity. Her research is focused on the integration of engaged and participatory research approaches with systems science methods to address health issues in marginalized and excluded communities. She has experience in community-based program planning, evaluation, and research in diverse communities and applies skills from both community-based research and systems science to diverse content areas.

Madeleine Perry earned her MPH in Health Policy from the University of North Carolina at Chapel Hill. Her research interests include social determinants of health, behavioral health services delivery, and harm reduction initiatives. She currently is a population health strategist for a health payer, where she evaluates programs aimed at improving the health of Medicaid members with chronic conditions and behavioral health needs.

Mohammad Jalali ("MJ") is an assistant professor at Harvard Medical School and a research affiliate at MIT Sloan School of Management. MJ is an expert in systems thinking and develops dynamic simulation models for complex population health problems.

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Supporting information

Additional supporting information may be found in the online version of this article at the publisher's website.

Appendix S1. Supplementary Information.

DOI: 10.1002/sdr