Opportunities for System Dynamics Research in Operations Management for Public Policy

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Operations management in the public policy context is extremely complex with many mutually interacting factors characterized by feedback loops, delays and nonlinearities as well multiple stakeholders pursuing divergent objectives. Prior researchers have called for a systems approach in these contexts, arguing that standard OM methodologies such as mathematical programming, and queuing theory often cannot fully address these problems. Researchers have employed one such systems approach, system dynamics, successfully for decades for studying OM problems in public policy because it can address such complexity and can also integrate disciplines from outside OM such as political science, epidemiology, ecology, etc.

In this paper, we create a roadmap for researchers—both those who are familiar with systems dynamics and those who are not—for the expanded use of system dynamics studying public policy-related OM problems. We review and organize relevant system dynamics literature in both traditional operations management venues *as well as public policy venues unfamiliar to OM audiences.* We then identify a set of interesting open questions and potential system dynamics building blocks for answering them by topic. Leveraging this review, we describe under what conditions system dynamics is most appropriate. We then identify several overarching methodological and domain gaps for future research.

Finally, we propose a process that extends Bessiou and van Wassenhove's (2015) process for using system dynamics with traditional operations management methodologies. It separates consensus model building into two sequential phases: consensus building models and detailed operational. It also incorporates scenario planning and feedback from implementation outcomes.

Keywords: system dynamics; operations management; public policy; literature review; computer simulation; scenario planning

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1. Introduction

Public policy is a fundamental driver of societal progress, and many policy-related challenges are evolving rapidly: climate and environmental concerns, healthcare, peacekeeping and security, infrastructure, and regulation of digitally enabled business models. Public policy programs are ultimately deployed through supply chains and operations where the "rubber meets the road." There is an obvious need to bridge public policy and operations management research and to practice it more effectively (Tang 2016). However, this has proven difficult for a number of reasons (Sodhi and Tang 2008). Foremost of these is that public policy problems are typically embedded in complex systems; this, in turn, makes it difficult to develop management strategies that achieve their intended results (Simon 1962, Weick 1989, Ackoff 1994, McDaniel and Driebe 2005, Besiou and Van Wassenhove 2015). There are multiple stakeholders and decision makers with differing perspectives and often conflicting goals (Besiou et al. 2011). There are many dynamic variables that mutually interact, creating feedback loops. Significant time delays exist between cause and effect, and there are also many nonlinearities (Forrester 1961, Sterman 1994, 2001). Uncertainty exists due to imperfect understanding of the problem, distorted or inaccurate information, and ambiguous legal and regulatory regimes. The resulting problem is twofold. On one hand, standard operations management approaches typically rely on techniques that can address only a subset of these issues (Sodhi and Tang 2008, Singhal and Singhal 2012b, 2012a). On the other, while research in public policy venues captures important policy constructs, it often insufficiently models the details of operations management due to a lack of understanding of the field (Besiou and Van Wassenhove 2015). Clearly, a high-level systems approach is needed, one that can integrate operations management issues with public policy.

For decades, the field of System Dynamics (SD) has proven to be one such systems-level approach. SD provides a powerful lens to study operations management (OM) problems in public policy contexts (Lane et al. 2000, Homer and Hirsch 2006, Besiou and Van Wassenhove 2015, Thompson et al. 2015). A long history of SD-operational management interventions exist that have performed successfully in complex systems (Sterman 2000, Größler et al. 2008, Van Wassenhove and Besiou 2013, Sterman et al. 2015a, Joglekar et al. 2016). There are several reasons for this. SD is a computer-aided approach that originally derived from the control theory and electrical engineering (Forrester 1961). The models themselves are generally nonlinear differential-equation state-space models, similar to those used in optimal control theory, albeit the models tend to be larger and require simulation. Wherever possible, variables and parameters correspond directly to real-world metrics such as "work hours per week" or "dollars per year," and many standard formulations have been developed over time (Hines 1996). Researchers developing system dynamics models often employ techniques such as scenario planning (used in most SD operations models geared towards public policy) and group model-building among stakeholders (used less frequently in research, but often in practice). The system dynamics methodology was specifically developed to analyze dynamic problems arising in complex social, managerial, economic, and ecological systems characterized by multiple stakeholders, mutual-interacting endogenous variables, interaction, information feedback, long delays between cause and effect, and circular causality. Hence, SD an ideal tool for studying public policy problems (Besiou and Van Wassenhove 2015). In fact, SD's first applications were in OM (Forrester 1958). Since then, system dynamics has had a continuous thread in the OM literature, addressing topics as diverse as project management, supply chain design, process improvement, service management, and managing complementary technologies (Sterman 1989, Sterman et al. 1997, Anderson et al. 2000, Oliva and Sterman 2001, Akkermans and van Helden 2002, Anderson and Parker 2002, Joglekar and Ford 2005). However, despite the demonstrated potential of SD, relatively few publications address OM in the public policy space. One reason for this is the number of SD papers published in the entire corpus of operations management is relatively small. (Using the methodology described in Section 3, we identified only approximately 65 papers published since 2000 in the 7 OM journals we searched.) Also, many important SD studies in this area have been targeted towards either domain-specific public policy outlets that may be unfamiliar to the OM audience or the *System Dynamics Review*.

The goal of this paper is to begin rectifying this problem by providing a roadmap for OM researchers to use of SD in public policy contexts, including both those who have done SD research in the past and those who are less familiar with the methodology. To this end, we develop a "scoping review" of SD research addressing OM problems in the policy space. Scoping reviews are literature reviews that inductively examine how research is conducted in a particular field or topic, identify key characteristics related to a concept, and identify knowledge gaps and precursors to systematic reviews. Their purpose is to exhaustively catalog a topic using a repeatable methodology (Arksey and O'Malley 2005, Munn et al. 2018). This paper is in the same vein as, and builds upon, Krishnan and Ulrich's (2001) review of new product development, Anderson and Parker's (2013) review of integrating knowledge work across supply chains, Joglekar et al.'s (2016) review of industry studies and public policy, and Parker et al.'s (2019) review of energy-related operations management. However, this paper necessarily differs from those prior surveys because, rather than providing a roadmap for *the study of a particular domain*, we seek to provide a roadmap for researchers *using a particular methodology in a domain*. To that end, we begin by describing why, how, and when SD might prove a useful tool for researching OM in public policy based on prior researchers' work in this area (Homer and Hirsch 2006, Größler et al. 2008, Besiou et al. 2011, Sterman et al. 2015b, Besiou and Van Wassenhove 2021), as well as the authors' combined 50 years of research experience in system dynamics and operations management. We then map the relevant prior literature in a structured manner by selecting a sample of approximately 150 SD papers that investigate operation managements in a public policy context. Parker et al. (2019) is especially relevant, because the authors needed to look outside the typical operations management journals. We follow them by reviewing policy-related system dynamics operations literature in both the standard operations management venues and public policy venues. We also follow Parker et al. because this review will not be exhaustive; some of the methodologies used necessarily involve judgement by the authors, such as the "KJ" clustering technique (Kawakita 1975, Shiba et al. 1993, Burchill and Fine 1997, Scupin 1997), meaning the process for selecting papers and clustering them into themes is not necessarily repeatable. However, that is not our goal for generating the sample. Rather, we seek to generate sufficient coverage and insights for future researchers to build upon, per other scoping reviews. We then use the resulting literature map to identify useful exemplars of research in each cluster, along with open or sparsely researched questions in each cluster. Finally, we distill these to identify the overarching questions of greatest opportunity. Some are domain questions that emerge as common among all clusters, while others address methodology.

The closest papers to ours treat SD and complex systems in socially responsible operations (Van Wassenhove and Besiou 2013, Besiou and Van Wassenhove 2015). We build on them by: (1) performing a detailed scoping review, (2) expanding beyond humanitarian operations and sustainability to other policy realms, (3) including references and exemplars after 2015, and (4) identifying specific open questions in the SD literature that require additional research. Homer and Hirsch (2006) and Lane et al. (2000) also have excellent reviews, although they focus exclusively on healthcare and require updating similarly. Also related are the reviews of Größler et al. (2008) and Sterman et al. (2015b) on the use of SD for operations management. However, we focus strictly on public policy, which brings specific issues into play that are not addressed by those papers, and as a result, the roadmap for research is different. One example is the need to integrate structures drawn from political science and public policy economics. We also include more recent references.

To support these specific goals, we exclude operations management literature that does not involve SD from our sample, as well as SD research that does not involve operations management. We include only those papers that both are within the intersection of these two domains and address public policy (see Figure 1). Also, we deliberately do not address how SD models are built, validated, or tested. There are a number of excellent texts on this topic, such as Sterman (2000) and Ford (1999), and exemplar papers such as Oliva and Sterman (2001), Besiou et al. (2014), and Kapmeier and Goncalves (2018).

[Insert Figure 1 about here]

Based on our work developing the roadmap above, we highlight seven gaps in the research that should be addressed to enable better use of SD for OM problems in public policy contexts. To the best of our knowledge, five of these have not been explicitly called out before, and we believe that articulating them will help other researchers.

With respect to operations management problems in public policy contexts, more research effort is needed with respect to:

1. Building consensus among stakeholders with SD models.

2. Integrate SD with traditional OM methods, such as mathematical programming or queuing theory, to create hybridized methods that combine the different strengths of both approaches. Besiou and Van Wassenhove (2015) identified this as crucial, but the literature is lacking.
3. Pay more explicit attention to identifying trajectories from the current state of affairs to a desired "ideal" state, including whether OM strategies will need to evolve over time. In particular, research must account for path dependencies that might prevent the ideal state from being achieved.
4. Feed back the results of implementation so as to adjust models and operations to improve future outcomes. Research in this area appears to be almost entirely lacking.
5. "Spillovers" among research silos in public policy (e.g., humanitarian operations often result from famine created by civil conflict. Sustainable OM, energy and transportation are also closely linked).
6. Create global supply chains that are more resilient to disruptions from pandemics, trade disputes, etc., is sparse, aside from research directly related to medical products and services.

Based on these points, we also propose that:

7. Besiou and Van Wassenhove's (2015) framework for using SD for OM in public policy contexts should be extended to include: consensus-building models, scenario planning, feedback from implementation outcomes, and multiple levels of SD models. Specifically, there should be simpler models for building initial consensus among stakeholders and detailed operations-planning models for interventions.

The remainder of the paper is organized as follows. First, we discuss the advantages of SD, when it is best used by OM researchers to supplement classic techniques, and the challenges to doing so. To illustrate our work, we leverage an in-depth example: developing a network of fast-charging stations for electric vehicles. We then describe the methodology used to select the article sample and cluster them into domain areas. Next, we present each identified domain as a separate section describing extant research. For each domain, we also identify exemplar papers, important open or under-researched questions, and SD building blocks for future research. We conclude with a discussion identifying overarching questions, detailing the proposed implementation process, and summarizing exemplars to provide building blocks for future research. In the online companion index, we also present all the papers we reference in each cluster.

2. Features of System Dynamics Modeling

Before going further, we define some terms and abbreviations to facilitate the remainder of the paper. Unless otherwise specified or obvious from context, we follow many others in referring to public policy as simply "policy" (Joglekar et al. 2016, Parker et al. 2019). This is notably distinct from the use of "policy" in operations management when describing a decision rule (e.g., "inventory management policy"). As mentioned above, we use the abbreviation SD for S*ystem Dynamics*. We also use the abbreviation OMPP to denote *operations management in public policy contexts*.

We build on Atasu and Van Wassenhove (2012), in which the authors argue that operations management problems in the public policy space are especially challenging because OM and policy decisions cannot be isolated from each other (Figure 2). Additionally, they argue, these contexts have multiple stakeholders.

[Insert Figure 2 about here]

Joglekar et al. (2016) expanded on this to explicitly argue that OM and policy influence each other bidirectionally (Figure 3). They present the example of the U.S. Clean Air Act of 1970, in which the federal government set a standard for the fuel emissions of cars sold, and once automakers met these standards, the government made the standards more stringent.

[Insert Figure 3 about here]

Once public policy is considered part of an OM problem, the result often has a number of characteristics that create a complex system (Besiou and Van Wassenhove 2015). Complex systems are characterized by multiple stakeholders with conflicting objectives, context uncertainty and problem ambiguity, multiple feedbacks that mutually interact often in nonlinear ways, and endogeneity—generally with delays, constraints, and path dependency (Ackoff 1994, Sterman 1994, Atasu and Van Wassenhove 2012, Joglekar et al. 2016, Besiou and Van Wassenhove 2021). Due to these factors, potential interventions can be difficult to validate; among other reasons, interventions often result in counterintuitive behavior that is difficult to understand without a systems approach (Weick 1989, Sterman 1994, McDaniel and Driebe 2005, Besiou and Van Wassenhove 2015). Generalizability to other policy contexts is also difficult (Joglekar et al. 2016). Another issue with complex systems was nicely articulated by McDaniel (2015) who stated, "Even if I know where I am now, and where I optimally want to be, I also need to know how to get from point A to point B. On top of that, the system might be path-dependent. Can I even get to point B?"

SD has a long history of successfully addressing problems in complex systems (Forrester 1958, 1961, Sterman 2000, Besiou and Van Wassenhove 2021). SD includes several features that are advantageous for studying the complex systems typical of OMPP problems. However, it also has limitations. In other words, SD is useful for some contexts, but not for others. Given this, how does an OM researcher recognize which contexts represent fruitful opportunities for employing SD?

To illustrate when and why system dynamics might be advantageous, we consider a policy problem for operations management of current import: how to expand the network of fast-charging stations in the U.S. for electric vehicles (EVs). Fast-charging stations are to electric vehicles what gasoline stations are to fuel-powered cars. The availability of fast-charging stations has been identified as the biggest barrier to EV adoption by many sources, including the U.S. Department of Energy and McKinsey & Co. (Jones et al. 2018, Gersdorf et al. 2020). Important questions include: How many stations should be built? Where should they be located? And in what sequence should they be built? These questions are part of a classic OM topic, that of facility location. In principle, we might assume this could be solved by a straightforward mathematical programming model. However, upon further examination, we see that aspects of the problem make it a complex system. Anderson et al. (2022) describes a number of these issues in detail. First, as more stations are built, more EVs will be bought, making it more profitable for new stations to enter the market (Struben and Sterman 2008). The resulting cross-side externalities connect the two sides in a reinforcing loop, which is the hallmark of a platform (Parker et al. 2016). That said, the cross-side externalities also show diminishing returns with respect to the number of stations, creating nonlinearities. Delays are present in both the time it takes to construct stations and the time needed for consumers to perceive the improved availability of fast-charging stations and then purchase EVs in response. Also, there are multiple stakeholders, often with conflicting objectives. State and federal governments seek to expand the number of stations as quickly as possible by setting a single standard for stations that is compatible with all firms' EVs. Yet some firms (e.g., Tesla) can and have invested in their own proprietary, incompatible charging networks to maximize profits from sales of their own vehicles while excluding benefits to their competitors. Firms without their own charging networks want to enforce interoperability. Even EV owners have their own heterogenous goals. Suburban homeowners can recharge at home at night and are less sensitive to how many stations surround them than are apartment dwellers. For this reason, suburban owners are much less likely to support new taxes to fund government subsidies for building stations. Additionally, there is the technical side of the issue: How will EV driving ranges increase over time? What investments in utilities are needed to power these stations? Finally, every one of these issues—from consumer preferences to which political party is in government, to future EV range—is characterized by uncertainty. Ambiguities also exist around the problem boundary. Should the impact of mass-transit investment and ride-sharing regulation be included (Naumov et al. 2020)? There are other issues as well, but this is enough to illustrate the complexity of what would appear at first to be a straightforward location problem.

A more detailed discussion of when an SD approach is most appropriate for addressing an OMPP problem later is presented later in this section. However, at a broad level, the EV problem illustrates these contexts. As shown by sample, SD can cope with a great deal of systems complexity because it can model a broad variety of problem contexts, decisions, and outcomes. This permits a "good" and robust solution by accounting for structures that other OM disciplines typically cannot capture. That said, it comes at a cost. SD relies on aggregating variables, and it may also miss important operational structures needed for fine-tuning solutions. Also, SD relies on computer simulation, which may result in a "good" solution that is nonetheless sub-optimal. In short, whether to use the SD methodology boils down to determining whether the system is complex enough that "good" and robust is more important than optimal and over-simplified.

Before moving on, we note that our discussion below builds on the existing body of SD work. Yet, the SD tool kit below is constantly evolving and becoming more effective (Rahmandad et al. 2015).

2.1 Modeling Complex Systems Structure

SD models, thanks to their systematic, rigorous computer simulations, can capture the interactions of the many industry-specific and policy-related “moving parts” needed to study OMPP problems (Joglekar et al. 2016). SD models are typically state-space differential-equation (or sometimes difference-equation) models based on the engineering discipline of control theory. Hence, SD models center on the modeling of systems with feedback loops and time delays (Forrester 1961). As stated earlier, we do not treat how to build SD models here because many excellent references already exist (Sterman 2000, Meadows 2008). Fundamentally, however, there are two kinds of feedback loops. One is a “reinforcing” feedback loop in which the effect of an initial perturbation is amplified over time, for example, the accumulation of interest in a bank savings account. The other type is a “balancing” feedback loop in which an initial change is resisted, resulting in goal-seeking behavior over time, such as a hot cup of coffee cooling to room temperature. In addition, Forrester recognized that many of the relationships among variables in these loops are nonlinear, and that the interaction of these loops with nonlinearities and delays can create counterintuitive behaviors. For example, SD analysis could show that subsidies for purchasing EVs may have given early movers such a big advantage in growth and market share, they could then build proprietary station networks that ultimately hindered other competitors from entering the market (Anderson et al. 2022).

SD models include several standard formulations for decision-making behavior by both organizations and individuals, such as how employee overtime is a function of demand vs. capacity, reduced productivity of newly hired employees, and how managers forecast future demand. Other standard functions model the effect of excess inventory or backlog on management decisions. Crucially, variables and parameters are grounded in real-world metrics whenever possible, which greatly constrains the plausible values of parameters and variables. Hence, validating a model with a structure fundamentally different from reality is difficult (Barlas 1989, 1996, Sterman 2000, Homer 2012). And methods for calibrating models to data are ever improving (Eberlein 2015, Hovmand and Chalise 2015, Rahmandad et al. 2015).

The powerful modeling capability of SD does come with trade-offs relative to other commonly used OM techniques (Table 1).

[Insert Table 1 about here]

It must be emphasized that the entries in each row represent “typical” models using a given technique; there are exceptions. For example, simplified optimization models of inventory or queues are often included as part of game-theoretic models in the OM space. Furthermore, the table illustrates some important trade-offs. One is that SD is useful for handling problems with ambiguous boundaries, such as the behavior of stakeholders, public perceptions, and domain-specific factors such as ecological, legislative, or technological processes, which a mathematical optimization model typically cannot handle. However, unlike mathematical optimization models, SD models operational structures in the aggregate rather than in detailed form, and it relies on numerical simulation. Hence, SD models can yield a robust operations solution that functions reasonably effectively over a broad range of scenarios (Joglekar et al. 2016). In another trade-off, it is more difficult to characterize the behavior of SD models than game theory models or even linear programming models, although advances in this area are being made (Oliva 2016, 2020). Yet another tradeoff is that SD models often need less data because they rely on a moderate number of aggregate variables. This is facilitated by modeling human beings and organizations using bounded rationality (behavioral operations management researchers may indeed consider this a plus!). However, for less complex, more straightforward systems, SD models typically deliver OM solutions that may be inferior to mathematical programming or queuing models, both of which can better leverage detailed structural data. The question then becomes how to utilize the strengths of both SD and other OM methods to get the best of both worlds. We discuss this more in Section 2.3, and it is a theme that recurs throughout the paper.

2.2 Stakeholders and Consensus Building.

Looking at Table 1 again highlights another point: SD models can be useful for consensus-building, something that is rarely described in our sample. The models that dominate our sample are commonly seen in the SD OM literature, being relatively large models used for operations design. Seen much less often are smaller models that serve as artifacts used to build consensus among stakeholders. Compared with the larger models, these smaller models are structurally simpler, need much less data, and can be built much more quickly while incorporating multiple stakeholders' inputs in a process known as "group model-building" (Andersen et al. 1997, Vennix 1999, Andersen et al. 2007). For the current purposes, stakeholders would include subject-matter experts such as ecologists and automotive engineers. This creates a powerful tool for building consensus, without which OMPP solutions often, as described earlier, fail. Once stakeholder buy-in is achieved with a simple SD model, a more detailed SD model for operations design can be pursued. However, only the latter are usually published. A good example of this is Kapmeier and Goncalves's (2018) model of island tourism sustainability. Carefully reviewing the paper, there appears to be some group model-building, but it is not stated explicitly, much less described. In our sample, descriptions of the processes by which consensus is reached is underrepresented. A related use is giving models a user interface to create "management flight simulators." This lets non-SD modelers interact easily with the model (Sterman et al. 2013). These simulators are useful for soliciting stakeholder input, helping employees and policy makers improve mental models of system behavior, and facilitating effective scenario planning.

Returning to our fast-charging station example, stakeholders include governmental agencies such as the U.S. Departments of Transportation and Energy as well as state-level equivalents. Private entities include EV firms, non-EV or traditional automotive firms, independent fast-charging station owners, battery firms, electric utilities, and technology suppliers (solar, wind, fossil, and nuclear). Finally, there are non-governmental organizations such as consumer and environmental advocacy groups. All have conflicting objectives. Perhaps more important, individual stakeholders may not fully understand what drives their counterparts, a factor that can be improved by group model-building (Andersen et al. 1997).

2.3 Triangulation with Other Methodologies

Once consensus is reached, another model may be used to add the level of detail needed to create practical OM solutions, possibly expanding the consensus-building SD model. While not often seen in this context, a mathematical optimization, queuing, or similar model more familiar to OM researchers is possible. However, that model would need to be tested against the higher-level SD model for robustness (Besiou and Van Wassenhove 2015). For example, in the EV fast-charger model, the output of a high-level SD model could be used as input for allocating investment each period to specific stations using a more traditional mathematical programming facility location model. The output of the detailed model would then feed back into the high-level model to determine how the built-out network influences high-level policy variables such as station subsidies or consumer demand. Once these policy parameters are determined, the mathematical programming model would then be run again for the next period (Homer 1999, Anderson 2019). SD models can also facilitate closed-form analytic model development by identifying which variable relationships can be safely neglected when optimizing (Ghaffarzadegan and Larson 2018).

2.4 Scenario Planning for Risk, Uncertainty, and Ambiguity

Another benefit of using SD to address public policy issues is its long history of use for scenario planning (Senge 1990, Ringland and Schwartz 1998). Scenario planning is useful in a policy context because many factors cannot be known with certainty, particularly over the long time horizons associated with policy, meaning participants must prepare for many plausible futures (Schwartz 2012). SD models can facilitate this by capturing the many interacting decision variables, actors, and uncertainties typical of policy decisions, and they can also determine the range of long-term consequences of particular policies (Schwartz 2012). Once constructed, a large parameter space can quickly be analyzed—including counterfactual scenarios—which facilitates the development of robust policies that are reasonably effective against many future eventualities (Ringland and Schwartz 1998). Accordingly, most SD models in our sample use detailed sensitivity analysis of important parameters. A smaller number of models use formal Monte Carlo analysis (Besiou et al. 2014, Thompson et al. 2015, Kapmeier and Gonçalves 2018). A third group copes with model ambiguity by testing the robustness of solutions against model structures or boundary changes. With respect to the EV fast-charging station example, this can be illustrated by asking: Would it be better for the government to influence station-location decisions by offering incentives to build infrastructure in rural areas not presently serviced by interstate highways? Or would it be better for the government to mandate these changes? Both alternatives might lead to so called “unintended consequences”, or perverse effects on social welfare under some scenarios. Another issue is whether an EV manufacturer building fast-charging stations should be required to make its stations interoperable with cars made by other brands. Arguably, allowing firms to offer incompatible stations could expedite their investment to capture rents, at least initially. However, this could also let market leaders, such as Tesla in the U.S., lock out their competitors. This might have several effects, including reducing competition by more innovative EV-makers; hindering entry by more capable incumbents (at least in manufacturing) from the gasoline-vehicle industry; and creating fragmented or inefficient standards. All these could ultimately deter EV adoption. One could imagine that enforcing compatibility standards might be optimal, but the timing would become critical. Many parameters, such as the average driving range of new EVs manufactured five years from now, are uncertain and must be accounted for. There are also structural issues such as boundary ambiguity. For example, should new highway building projects be included endogenously, or solely as an exogenous driver? Should national restrictions on lithium exports (used to make EV batteries) be included because they may become a weapon in trade wars, particularly if EV adoption is rapid? Such structures can be drawn from the various disciplines as described in the next subsection and added into an SD model for robustness testing.

2.5 Bridging Disciplines

Finally, because adding additional structure to SD models is straightforward, SD models can bridge what Tang (2016) describes as "fragmented" silos in operations management, resulting in more robust strategies (Ghaffarzadegan et al. 2011, Sterman et al. 2015a). The EV fast-charging station problem goes beyond this by involving issues from disciplines outside operations management. Bhargava et al. (2021) cites not only OM articles, but also research articles from political science, economics, and domain literature from engineering. Other policy problems may of course be examined from the perspective of different disciplines, but comparing them might prove valuable because their perspectives are common to many OMPP problems (Atasu and Van Wassenhove 2012). To this end, we follow Krishnan and Ulrich's (2001) comparison of academic perspectives involved in product development (such as marketing, engineering, and operations management) by comparing these policy disciplines (Table 2).

[Insert Table 2 about here]

Each perspective lets us see part of the complex system that is building EV fast-charging stations, much like the folk tale of the five blind men exploring an elephant. One man touches the elephant's leg and says an elephant is like a tree. Another touches the elephant's tail and likens the elephant to rope, and so on. Of particular importance here are the decisions, none of which can be taken in isolation. For example, the value chain inherent in the location of fast-charging stations cannot be decided without political decisions, such as whether all stations should be mandated to be interoperable; economic decisions, such as whether to subsidize the purchase of EVs to stimulate demand; and engineering decisions, such as whether to put a new battery technology into a vehicle, which might favor range over reliability.

This structure, at an abstract level, is relevant to many other problems with only minor changes (Rahmandad et al. 2020). Hence, many papers in our sample leverage viewpoints drawn from beyond OM. For example, Table 2 could also represent the public health problem of immunizing a population to cope with a pandemic. In this case, epidemiology and physiology experts would replace engineers as the domain experts, typical metrics such as the percent of the population immunized and infected would be used, SEIR (Susceptible, Exposed, Infected, Recovered) compartmental models would be employed as the dominant representational paradigm, and so on. This could lead to decisions around fast-tracking vaccine development, prioritizing which population segments to vaccinate first, and allocating capacity (including beds, staffing, and ventilators) to hospitals in different areas (Goncalves et al. 2022)

In short, looking at the literature sample, an SD approach is most appropriate when features of an OMPP problem must be accounted for, but cannot be captured by other OM methods. Otherwise, though the solution may appear "optimal," it will not be robust enough for the problem's complexity.

3. Sample Selection Methodology

Literature that applies SD to operations management in policy contexts is widely dispersed in many journals across many fields. What's more, every year the OM community publishes a large number of articles across a wide range of domains. To manage the scope of our literature search, we follow prior papers such as Krishnan and Ulrich (2001) and Parker et al. (2019). These had the same goal of identifying current research opportunities for OM scholars. That is, we do not attempt to create an exhaustive review, but rather a scoping review as described earlier, upon which contemporary scholars can build relevant research. Leveraging those prior surveys, we use the following methodology to select our sample:

1. We conduct a search for articles in the leading operations management journals: 1) *Production and Operations Management*, 2) *Manufacturing & Service Operations Management*, 3) *Journal of Operations Management,* 4) *Operations Research*, and 5) *Management Science*. (*Leading* is defined as the OM outlets appearing on a list compiled by the University of Texas, Dallas, of leading academic journals in major business disciplines. This list was retrieved on December 23, 2021, from https://jsom.utdallas.edu/the-utd-top-100-business-school-research-rankings/.) To identify relevant articles, we used the following search terms: "System Dynamics," "simulation," and "modeling." System Dynamics is a sufficiently unique key term, and we are confident that the vast majority of research using the SD methodology published in these journals has been identified. We limited our search to articles published since 2000 because our main goal is illustrating research questions for current and future researchers. We then eliminated those articles judged by the authors as either not related to public policy (i.e., they addressed only "inventory management policies") or not related to system dynamics. From a total of approximately 11,500 articles in these journals over the period of interest, our search resulted in approximately 50 articles.
2. We also searched the *System Dynamics Review* over the same period (post-2000) for research using the topics "operations management" and "policy." This is the journal of the System Dynamics Society, the association of SD researchers. In this sample, we did not include either "simulation" or "system dynamics," because in these outlets, these terms are redundant. Again, we eliminated those articles

judged by the authors to be unrelated to public policy. Our search resulted in a total of approximately 25 articles.

3. Because of the paucity of articles revealed in the above searches related to OM in a public-policy context, we searched the list of SD research publications maintained by the System Dynamics Society, which contains approximately 2,500 journal articles. This list can be obtained from the System Dynamics Society's bibliography webpage (https://www.systemdynamics.org/bibliography). The System Dynamics Society Bibliography revealed that SD research also appeared frequently (as defined by over 50 instances) in two operations management-related journals: (1) *Journal of the Operational Research Society* and (2) *European Journal of Operational Research*. We added these, not only for their frequency of publications, but also their explicit linkages (unlike the six journals listed above) to research societies based outside the United States. We then searched these journals for articles using the same criteria as (1) above. From the total of approximately 9,200 articles in these journals over the period of interest, our search resulted in an additional sample of approximately 15 articles.

Because the searches described above surfaced a relatively small number of articles, we then broadened our scope in three ways:

4. We searched the System Dynamic Society's bibliography again because it had earlier proved to be an invaluable resource for searching the broad swath of journals in different policy domains. The search parameters used on the database were the same as for the *System Dynamics Review* above. This yielded approximately five articles that had not been captured by the previous searches.
5. We contacted the Jay W. Forrester Award winners from the past 20 years (i.e., since 2000), asking them to provide additional guidance on relevant articles we may have overlooked. The Forrester award is given annually for the best SD research by the System Dynamics Society. We also searched for articles by Award winners written after 2010 that treated operations management in a policy context. This yielded approximately 15 articles that had not previously been captured by the above searches.
6. We searched the articles in (1)-(5) for references to expand our review to capture influential articles useful to the contemporary researcher in OMPP following the expansion by Parker et al. (2019) of their search. This resulted in approximately 40 additional articles.

Next, we clustered the sample into research areas using the "KJ" clustering method (Shiba et al. 1993, Graham et al. 2001), which was also used in prior reviews such as Anderson and Parker (2013). The resulting clusters are: (1) humanitarian operations and crisis management; (2) healthcare operations management; (3) conflict, defense, and security; (4) transportation, logistics, and infrastructure; (5) sustainable operations; (6) new business models; and (7) energy. We use these clusters to structure our review in Section 3. Some of these research areas were similar enough to Production and Operations Management Society (POMS) colleges that we used their category names where appropriate.

4. Literature Review and Open Questions by Cluster

Each subsection below addresses one of the research clusters identified in Section 3. For each cluster, we describe the nature of the cluster using review articles, and we identify those aspects of complex systems that are particularly salient. We then identify exemplar articles of rigorous and important research in the cluster as well as other articles of interest. For each cluster, a table in the electronic-companion appendix (hereafter referred to as the “e-companion”) creates a roadmap for researchers that: (1) contains both the exemplars and other relevant articles in the sample; (2) subdivides the articles into topics for ease of reference for researchers, as well as how each topic leverages contributions from SD; and (3) includes relevant open questions and additional SD “building blocks” in the extant literature relevant to the open questions.

4.1 Humanitarian Operations and Crisis Management

In the last half-century, the number of disasters—whether natural (e.g., earthquakes, hurricanes, monsoons, floods, droughts), man-made (e.g., war, displacement, forced migration, famines), or pandemics—has risen dramatically. Forecasts show that in the next half-century, these events will likely become even more frequent (Allahi et al. 2018). Humanitarian operations efforts strive to provide aid and relief in contexts typical of the complex systems described earlier. Particularly problematic are situations involving multiple stakeholders with often widely differing objectives (Starr and Van Wassenhove 2014). Additional pressures on humanitarian organizations (HOs) include inadequate funding, high staff turnover, limited time horizons in which to react, and compressed project life cycles (Besiou and Van Wassenhove 2020). The operations management literature has proposed many excellent approaches for planning and directing humanitarian aid, and these have proven to be of great help. However, studies have also shown that other organizations have faced difficulty when implementing these approaches; hence, they have posited that research into operations in this context could often benefit from an SD approach (De Vries and Van Wassenhove 2020).

Kunz et al. (2014) is an exemplar paper in this cluster. It uses extensive scenario and sensitivity analysis to explore the delivery process of ready-to-use therapeutic food items in the immediate response phase of a disaster. The paper then builds a model to analyze different preparedness scenarios for therapeutic food items to enable a fast response. The authors find that the fastest method is to preposition stocks of relief supplies in all countries prone to disasters. However, this approach, while fast, is also prohibitively expensive. An alternative approach involves investing in capabilities such as training staff and pre-negotiating customs and other arrangements in countries prone to disaster up front. In this way, centrally held stocks can be rapidly transferred to affected regions. Compared with other approaches, this is less costly, but also slower. The paper’s authors conclude that a mix of the two strategies provides the best performance, and recommend specific allocation policies for relief organizations.

Besiou et al. (2014) is another exemplar. The authors apply a similar approach to Kunz et al., but add Monte Carlo analysis to examine whether vehicle fleets for humanitarian relief should be locally purchased as needed or centrally purchased and then held in reserve. Perhaps unsurprisingly, the paper finds that a hybrid policy is generally best. However, the analysis is interesting for two reasons. First, the authors explicitly extend the dynamic programming strategies for centralized purchasing developed in Pedraza-Martinez and Van Wassenhove (2012) by adding three complexities: (1) decentralized procurement is possible; (2) relief efforts due to natural disasters may also be needed; and (3) demand for vehicles is stochastic. Second, the authors also broaden the study and span silos by studying the degradation of procurement efficiency that results when program-funding groups earmark aid to specific locations.

Other topics addressed by SD research emerged from our cluster analysis as well. One topic directly addresses the compressed "life cycle" of humanitarian operations (e.g., Ni et al. 2015). Another is humanitarian supply chains. Among these, Diaz et al. (2019) and Badakhshan et al. (2020) tie back to the original SD work of Forrester (1961) by studying the bullwhip effect in relief efforts.

One important challenge still open in the field of humanitarian operations is how to best deal with the complexity of last-mile distribution. As identified by logistics and distribution studies, the last mile accounts for most of the cost under normal day-to-day conditions, particularly in developed nations with established carrier services and good infrastructure. However, humanitarian organizations are often tasked with last-mile distribution in areas with little to no infrastructure. Related to this, extant work has used classic OM optimization approaches to plan routes, determine vehicle fleet sizes, and address coordination challenges in humanitarian relief chains (Balcik et al. 2008, 2010). Due to the complexity of the systems in which these problems are embedded, SD could prove a useful tool (De Vries and Van Wassenhove 2020). Another challenge involves developing strategies to cope with hoarding, which is commonly seen in humanitarian operations settings. Hoarding results in longer delivery times and greater perceived shortages, and it creates feedbacks that intensify scarcity and destabilize supply chains by reinforcing the perception of shortages (Sterman and Dogan 2015). If hoarding could be ameliorated with appropriate policies, then the difficulty inherent in rapidly establishing ad hoc supply chains during crises could be markedly reduced. Another open question is how to best manage the relationships among humanitarian operations, media presence and coverage of operations, and humanitarian organization funding (Burkart et al. 2016). Because of its complexity and overlap with marketing, this question is an ideal candidate for SD research. Nageswarakurukkal et al. (2020) begins to address this by examining how social media affects publicity, fundraising, and operational efficacy, and Keith et al. (2022) studies how management emphasis on fundraising can detract from operational effectiveness. Finally, humanitarian operations problems often spill over into other policy clusters, such as the possibility that drought and food shortages may result in civil unrest, which in turn can exacerbate food shortages (Besiou et al. 2011). This complex humanitarian topic is another excellent area for SD research, one that according to our sample, remains underexplored.

Table A1 in the e-companion organizes the roadmap for the cluster as described at the beginning of the section and provides additional references from our sample.

4.2 Healthcare Operations Management

Healthcare operations management (HOM) is widely recognized as an exceedingly challenging domain, one that does not lend itself to easy solutions (Koelling and Schwandt 2005, Dai and Tayur 2019). In the United States, healthcare is characterized by financial waste, amounting to approximately 5% of GDP (Leape et al. 2009), numerous safety issues—such as unnecessary hospital deaths being the country's third leading cause of death (Donaldson et al. 2000)—and poor service (Binary Fountain 2018). While not as well documented, these issues also exist in other national health systems such as Sweden (Porter and Teisberg 2006). These issues are due in no small part to stakeholders with different goals. These include: patients; doctors, nurses, and other healthcare providers; hospitals; insurance companies; pharmaceutical manufacturers and distributors; and local and national governments. Public policy makers that try to coordinate the system have limited resources, requiring trade-offs to be made. The very complexity of the healthcare system has attracted scholars from fields as varied as operations research, engineering, economics, and medicine to propose powerful and practical solutions (Dai and Tayur 2019, Keskinocak and Savva 2020). That said, many innovative approaches have challenges directly related to a fragmentation of scholarship (KC et al. 2020). To address these gaps, the Professional Society for Health Economics and Outcomes Research (ISPOR) have recently stated that HOM "exhibits a level of complexity that ought to be captured using dynamic simulation modeling methods" (Diez Roux 2011, Marshall et al. 2015). This may partly explain why this cluster has the greatest number of papers in our sample. Darabi and Hosseinichimeh (2020) document in their excellent survey of SD in health and medicine how SD has since the 1960s been successfully used to study a wide variety of topics in HOM, generally using simulation to complement empirical and observational studies. The authors often provide surprising insights into the most powerful levers to avoid policy resistance (Darabi and Hosseinichimeh 2020). Similar observations were made by an earlier survey (Homer and Hirsch 2006).

Numerous studies have explored models for public health (e.g., Dangerfield 1999, Homer and Hirsch 2006, Atkinson et al. 2015, Newell and Siri 2016, Kang et al. 2018). One outstanding example is the series of papers studying polices for polio eradication (Thompson and Tebbens 2007, Tebbens and Thompson 2018). Much of this is summarized in Thompson et al. (2015). It is the result of a multi-method approach, integrating SD with a number of other OM and research techniques, including decision analysis, game theory, linear programming, and inventory models. The series is also a model of stakeholder collaboration. Working with the Global Polio Eradication Initiative (GPEI), the researchers demonstrated that polio eradication efforts need to be continued with the utmost vigor, even as polio is brought under control. Much like a banked fire that, if disturbed, throws off embers that ignite other fires, even a small number of polio cases can flare up quickly into larger outbreaks. A quick response is paramount, even if that comes at the cost of imperfect coverage. Hence, a large stockpile of vaccine needs to be maintained at all times. The paper also develops a policy to determine the optimal timing for a switch from an oral poliovirus vaccine to an inactivated poliovirus vaccine. While the oral poliovirus vaccine is cheap and effective for snuffing out an outbreak quickly, it can (very rarely) cause dangerous side effects—or worse, mutate to create a dangerous polio epidemic of its own.

One topic area where SD has been widely adopted at a more micro level is models of disease in the human body. Estimates show that nearly half of all U.S. adults suffer from at least one chronic illness, and that these illnesses ultimately result in seven out of 10 deaths (Centers for Disease Control & Prevention [CDC] 2015). This highlights the need for new tools to determine the most effective interventions for specific illnesses. Chief among these chronic illnesses are obesity, diabetes, and heart disease. Kang et al. (2018) develop a model that incorporates goal programming to help support decision making and intervention planning at different phases of chronic kidney diseases (CKD) management. Other SD research in this area addresses mental health issues, including depression in teenagers (Hosseinichimeh et al. 2018) and Post-Traumatic Stress Disorder (PTSD) among military personnel and veterans (Ghaffarzadegan et al. 2016). The latter is an exemplar of scenario planning in an SD environment. It is also an exemplar of a commonality discussed in much SD research, namely, that investing beforehand is far more effective than providing treatment afterwards. In particular, the authors found that programs to create resiliency (in this case, the ability to rapidly recover from traumatic effects) before a combat assignment are more cost-effective than screening or treatment afterwards.

SD models have also been prominent in epidemiology, going back to traditional Susceptible, Infected (SI) models for HIV transmission (Roberts and Dangerfield 1990, Dangerfield et al. 2001). More recently, researchers have developed SEIR (Susceptible, Infected, Exposed, Recovered) models that also include behavioral responses such as social distancing and self-isolation, as well as endogenously considering increases in hospital capacity in response to the current global COVID-19 pandemic (Ghaffarzadegan and Rahmandad 2020, Struben 2020). Rigorous formulations and novel approaches have also shed light on how to best estimate parameters for global epidemics as they are unfolding, allowing for more confident and robust models, even in the face of limited and inconsistent data (Rahmandad et al. 2020). Betcheva et al. (2020) describe an intervention to build a similar model with UK National Health Service planners, and adds the mental health sector.

SD modeling has also been used successfully to study patient flows and capacity planning in healthcare institutions (Diaz et al. 2015, Wang et al. 2015). For an example of studying patient flows and capacity planning, Lane et al. (2001) explore the relationship between a reduction in hospital capacity by the UK's National Health Service (as measured in bed reductions) and emergency room waiting times. By combining sensitivity with extensive scenario testing of a calibrated SD model, the authors found that, counter to conventional wisdom, the major impact of bed shortages is most directly felt not in emergency admissions, but instead in elective admissions. Hence, the traditional practice of using emergency room waiting times to measure the effect of bed reductions can be misleading. This paper, though relatively old, remains an exemplar for three other reasons. One, it offers an extended description of SD validation tests used on the model. Two, the paper describes (if briefly) how the model was developed via group model building techniques—and ultimately accepted as valid—among stakeholders. Three, it provides an excellent discussion of the tradeoffs between modeling with SD and discrete event simulation.

As patient tracking information continues to grow, the interconnectedness of the healthcare system has become of increasing interest to scholars. Some have broadened the boundary of the systems they study to include pricing and supply chain interactions between the pharmaceuticals and insurance industries (Paich et al. 2011, Li et al. 2014, Kunc and Kazakov 2018, Darabi and Hosseinichimeh 2020). By studying the interactions among healthcare providers, payers, and patients, they also highlight how misaligned incentives among these groups may lead to rising costs and lower service levels. In addition, Azghandi et al. (2018) addresses the complication of recalls and reverse logistics. Other papers in this stream focus on product development and market entry on healthcare operations such as marketing and strategy variables (Paich et al. 2011). Kunc and Kazakov (2018) is an exemplar because it describes how they developed a model and turned it into a flight simulator to make a decision-support tool, which was used in a workshop for multiple stakeholders.

Finally, the treatment by Goncalves et al. (2021) of capacity serves as an exemplar for a number of reasons, including excellent sensitivity testing and calibration. Perhaps even more important, this paper provides one of the best descriptions of how consensus is created by stakeholders using system dynamics. Interestingly, it also offers a paradigm that differs from those provided in prior research (Andersen et al. 1997, Vennix 1999).

Our survey of the literature has identified several open questions relating to the interaction of actors, costs, and quality of service that are explored below. Dai and Tayur (2019) argue that the huge cost issues facing policy makers are not just a question of misaligned incentives, but also the result of perverse incentives among providers, physicians, pharmaceutical companies, insurance companies, and many other actors that drive unintended cost increases. Further, the dynamic complexities of these relationships inhibit process improvement and result in the characteristic "fixes that fail." For example, it is widely acknowledged that pharmaceutical companies increase prices whenever possible to offset their high R&D costs. In spite of public outcry, pharmaceutical companies continue to enjoy historically high margins, averaging close to 70% gross margins and 25% net margins (Sood et al. 2017). Pharmaceutical companies are aware of the controversies surrounding their pricing strategies, and some have taken steps to improve their public perception (Dai and Tayur 2019). Compounding the problem is the fact that healthcare pricing is generally opaque and case-specific, so that patients are not generally able to make informed decisions, instead relying on the recommendations of their networks or physicians. This is typical of many problems in healthcare. A final complication is caused by remuneration policies. Arguments have been made that paying a fee for each service increases unnecessary procedures, leading to the implementation of either a fixed-fee for a given diagnoses (“bundled payments”) or payments to institutions based purely on the population in their catchment areas (“accountable care organizations”). Clearly, SD studies could be of great help in researching these problems and guiding future policy decisions. However, the SD literature in the pharmaceutical market dynamics space is sparse. To the best of our knowledge, the only major research paper in this space is by Paich et al. (2011). Many more papers are needed.

Another important open challenge for policy makers is the need to improve quality and safety. Multiple studies have found evidence that, despite increasing costs, healthcare is not as safe as it should be. It is estimated that approximately 300,000 preventable deaths per year occur as a result of medical errors, and over $50 billion per year in costs (including lost income, lost disability, and healthcare costs) for these adverse events, 60% of which may have been preventable (Donaldson et al. 2000, Leape et al. 2009). What policies could be put in place to curb these? Part of the problem is that process improvement is difficult to implement because of the severe penalties assessed on caregivers who have made mistakes. The unintended consequence is that mistakes are underreported (Norman 2013), obscuring data that could be used to create safer processes. This behavioral feedback loop makes this topic particularly amenable to SD research.

Studies have found that the United States wastes close to half a trillion dollars annually on reducing healthcare waste (Hopp and Lovejoy 2012). Leape (2002) cites duplicated tests and procedures as the second greatest driver of healthcare waste. This is partly due to fragmented information systems, resulting in one institution being unable to see what another institution has already done with a patient. At a higher level, waste is also created by the reimbursement policies of insurers, including national health systems. For example, payments to hospitals at a per capita rate, based on the number of patients served, may lead to skimping on acute, needed healthcare. Alternately, fee-for-service can induce skimping on preventive care. This particularly affects disadvantaged groups with fewer means of payment, or insurance. Another issue is remuneration for penalties on patients being readmitted within 30 days by U.S. Medicare, which has led to mixed results. This follows from the existing pressure on hospitals to shorten patient stays during initial treatments, perhaps leading hospitals to release patients too early in some cases. All these issues call out for SD research.

Both duplicated treatments and patient safety should be improved by Electronic Healthcare Records (EHR) systems, at least in principle. That is why the United States incentivized the installation of EHRs by all healthcare institutions under the country’s Affordable Care Act. However, unintended results ensued. At the time the policy was implemented, the easiest-to-install systems were also the most difficult to integrate. This led to systems at different institutions being unable to communicate with each other, obviating some of the desired safety and cost improvements. Complicating this issue, government regulation of compatibility standards remains weak. As a result, this incompatible healthcare data ultimately confers a “winner-takes-all” advantage for those healthcare information systems vendors with the largest installed bases.

Other open questions that require urgent attention have been brought to the forefront by the COVID-19 pandemic, which laid bare the inability of many governments to deal with pandemics and other public health crises at both the operational and policy levels. For example, one shortcoming has arisen as a result of the business practice, over the last few decades, of relentlessly pursuing supply-chain efficiencies by reducing inventories and safety stock levels and instead implementing just-in-time delivery systems. This was fine when conditions were predictable, but in the face of supply shocks from the shutdown of China and later Mexico, this efficiency came at the cost of robustness. Stockouts cascaded through the supply chain, creating critical shortages of personal protective equipment (PPE), testing supplies and equipment, pharmaceuticals, and materials necessary to produce vaccines (McMahon et al. 2020). Hoarding, as discussed earlier, complicated the situation. Even more critically, both local and national governments worldwide have struggled to communicate clear policies and manage adherence fatigue. While there is some SD research on managing these issues, more is needed to provide valuable insights. For example, SEIR models have been developed to both illustrate the spread of COVID-19 and account for more behavioral responses such as public self-isolation measures when the death rate is high (Fiddaman 2020, Rahmandad et al. 2020, Struben 2020). Other studies have also included increased hospital capacity (Goncalves et al. 2021) and inventory trading between countries (Van Oorschot et al. 2022). However, few if any of these studies have linked the contagion model to the economic model to study linkages between the two. Moreover, COVID-19, as well as other recent epidemics such as Ebola, have revealed the necessity of studying project management in the specialized and heavily regulated context of accelerating vaccine and pharmaceutical development during a pandemic. While building the supply chain to bring parts and raw materials to manufacture the vaccine kits would be difficult under any circumstances, it is currently complicated by shortages due to bullwhip effects. Then there is the distribution of the vaccines. As discussed in the section on humanitarian operations later in the paper, this is also a complex problem. For example, in some areas, the last-mile problem might very well include delivery by donkeys carrying vaccines that require refrigeration or freezing (Kaplan 2020). The need for SD-based research into how this is to be done is urgent.

Clearly, as the field continues to grow, there will be ample opportunities to continue leveraging the strengths of SD modeling for HOM research. Table A2 in the e-companion organizes the roadmap for the cluster as described at the beginning of this section and provides additional references from our sample.

4.3 Conflict, Defense and Security

Conflict, whether in prosecuting “conventional” warfare, suppressing terrorism, or acquiring military assets, is by definition an expression of policy goals. Most often, governments implement these policies with OM levers. This is perhaps unsurprising given that much supply chain and operations management is derived ultimately from operations research, which finds its origins in military planning. In particular, conflicts often center on classic operations management topics such as supply chains (e.g., logistics, inventory, infrastructure), force (i.e., personnel) planning, project management, procurement, and, recently, the information management/operations interface (Van Creveld 2004, 2010). That said, a number of problems involve significant complexity due to sociological issues such as regime legitimacy. In addition, these problems often exhibit an extra layer of complexity due to the involvement of actively hostile actors whose objectives are completely at odds with those of other stakeholders. In this policy domain, there is a long history of intellectual thought that is particularly compatible with SD research. For example, scenario planning is derived in many respects from military wargaming, so much so that even private-sector firms often use the two terms interchangeably, particularly in OM. Similarly, since the 1800s, military decision-making has explicitly incorporated feedback thinking in the "command-and-control loop" (Van Creveld 1985, Lofdahl 2006). Boyd's observe–orient–define-act (OODA) loop is one well-known instantiation (Boyd 1995, Plehn 2000, Richards 2020). However, many applications of SD that address problems in this cluster are never published, making the researcher's task more difficult (Coyle et al. 1999). However, Ford and Clark (2019), in their recent survey of the literature show that this had been somewhat remedied in the areas of "conventional warfare" and weapons systems acquisition.

The oldest stream in conflict, defense, and security (CDS) research appearing in our sample includes that of conventional warfare, particularly force planning and deployment (e.g., Coyle (1981), Wolstenholme (1983)). Unsurprisingly, given the military context, research in this stream pioneered some of the earliest uses of scenario planning (e.g., Coyle (1981)), numerical optimization (Wolstenholme and Al-Alusi (1987)), and the use of flight simulators for training (Coyle et al. 1999). In a slightly different vein, SD researchers explicitly addressed the feedback between human decision-makers' ability to execute the command-and-control loop with respect to managing supply chains and force deployment using improved information and sensor technology (Bakken and Vamraak 2003, Lofdahl 2006). Lastly, Artelli et al. (2008, 2009) is an exemplar of extending operations research concepts to include psychological and political science constructs. Specifically, they extend the classic Lanchester Laws—which define the odds ratio of a larger force winning as a function of its numerical advantage in troops—to include endogenous factors such as troop fatigue and public morale.

Project management, procurement, and implementation is one of the largest areas of SD research, because SD is well suited to project rework and other feedback loops. Much of this work has treated defense project management and acquisition (Lyneis and Ford 2007). In our sample, this is reflected in the large number of papers on project management, a core OM discipline. SD can also assist project management due to its ability to handle many factors often omitted by OM work using other methods. For example, Lyneis et al. (2001) developed a model of air defense system procurement to check the bid, identify and manage risks, and assess the benefit of several process changes. They span silos into organization management to include team design. Another exemplar, Ford and Dillard (2008), examines how different OM project management strategies used (i.e., agile vs. waterfall) compare in operational effectiveness. For example, while using agile project management may expedite equipping some troops with improved weapons systems, this comes at the expense of delays in equipping other units.

Insurgency research should integrate decisions around the planning and effectiveness of prosecuting insurgent or counterinsurgent actions with organizational recruiting, demographics, propaganda, public pressure, political legitimacy, building, and finance. Due to the large number of mutually interacting factors and other system complexities, as well as feedback loops among these factors (e.g., collateral damage from missions to suppress insurgencies increasing insurgent numbers), researchers have found SD to be a particularly useful methodology (Richardson 2005, Anderson 2007, Choucri et al. 2007, Pruyt and Kwakkel 2014). One example of this work, Anderson (2011), spans all the silos just mentioned except for finance. On the methodology side, the paper uses dynamic optimization to study force allocation and the timing of force withdrawal. The paper also includes operational issues specific to the military, such as experience curves being driven by the cumulative number of actions taken by an opponent.

Generally, SD studies of operations in conflict, defense, and security are rather sparse, so all areas of inquiry could prove fruitful. However, studies on the criticality of information systems to the command-and-control loop would seem to be particularly amenable to the strengths of SD (Lofdahl 2006). Studying the relationship between insurgencies, finance, publicity, and organized crime would be extremely useful given the damage of organized crime to society, such as drug trafficking and kidnapping for ransoms (Schoenwald et al. 2009, Saeed et al. 2013, Schoenenberger et al. 2014). These papers point to some paths that should be taken in this space.

Finally, there is spillover between CDS issues and other clusters, such as humanitarian operations. For example, the decades-long conflict in the Congo has led to a widespread famine that affects over 20% of the population and has created the need for extensive humanitarian aid (Programme 2020). Famines also often lead to epidemics. Studying policy interventions that interact with humanitarian and healthcare operations would be an excellent use of SD’s strengths. Table A3 in the e-companion summarizes and organizes the research roadmap for this cluster, as described at the beginning of the section.

4.4 Transportation, Logistics, and Infrastructure

One core area of study in operations management is transportation, logistics, and other infrastructure. This may not seem to involve complex systems, and hence, it may not seem a good fit for SD approaches. However, there is important research in our sample, and it suggests that including a certain level of complexity can be helpful under some circumstances. Prominent complexity issues often involve long delays between policy decisions, customer response, and outcomes.

The model of bus maintenance by Bivona and Montemaggiore (2010) is an exemplar of how SD can create counterintuitive policies by considering human factors and “marketing” issues endogenously.

Including these factors results in a twist on the expected policy of reducing availability in the short term; instead, it favors preventive maintenance to reduce long-term cost. Surprisingly, the best strategy not only increases preventive maintenance, but also reduces the age of the bus fleet and frees up experienced mechanics to teach newly hired and inexperienced (or “rookie”) mechanics. While these actions in fact raise long-term costs, they also lead to increased service quality and customer usage, resulting in higher profitability. This paper is also an exemplar of actively describing the use of group model building with, among other things, flight simulators used by city officials to determine policy priorities. Mayo et al. (2001) is another exemplar that examines many of the same issues with respect to the London Underground, using officials to build a flight simulator and develop scenarios. While the flight simulator is discussed at length, the authors used the flight simulator as a decision-support tool. It helped officials outsource their operations by evaluating bidding firms for their ability to run the underground system.

System dynamics addresses the role of OMPP in innovation in transport (Keith et al. 2020). Naumov et al. (2020) is an exemplar in this space, because it expands the boundaries typically considered in mass-transit planning to include not only new technologies, but also (1) expansive economic models of consumer utility and resulting market share, and (2) operational issues of maintenance and service routes run. For example, in their model consumer utility includes the belief by many policy experts that automated vehicles are problematic for improving the environment; these vehicles increase the attractiveness of commuting by reducing transit times and allowing drivers to spend their “drive-time” directly on work-related activities. Hence, experts argue for policies to increase ride-sharing), which, however, reduces mass-transit ridership. The model strongly suggests that policies promoting ride-sharing will reduce mass-transit capacity by strangling the funds needed for reinvestment. This could increase, rather than decrease, both pollution and energy use. Instead, a better policy seems to be a tax levied on vehicle miles traveled; this tax is then directed in part to the mass-transit system’s upkeep. This paper also conducts an extensive, explicit analysis of trajectories that reveal path dependence and other issues via phase-plot analysis.

Another aspect of operations management addressed in an SD OMPP model is Pierson and Sterman (2013), an exemplar that examines how yield management strategies in the United States interacted with deregulation to create cyclicality in the airline industry’s capacity, airplane production, and consumer demand. They find that yield management dampened capacity cycles but increased profit volatility, leading the airlines to lower average profits and reduced viability.

A last aspect is skilled worker infrastructure. Ghaffarzadegan et al. (2017) is an exemplar for future research in this area. It examines the mismatch between work needs in the economy and education as a function of policy. It does so by creating, in their words, an “operational model” that combines a queuing model as influenced by a number of government policies, university capacity decisions, and individual behaviors. The paper then explores the model’s behavior under disruptions from the macroeconomy and other factors, using sensitivity analysis and scenario testing. One intriguing finding is that disruptions often result in shortages in filling lower-skilled jobs. This is particularly interesting given current shortages of workers in the U.S. and Europe in lower-skilled supply chain jobs such as warehouse workers, port employees, and truck drivers (Camaniti 2021). The authors also discuss how their model could be extended to examine whether job-training policies create shortages of skilled workers needed for new technologies.

Several questions regarding transport and logistics policy remain open, many of them involving interactions with other policy areas such as sustainability and new business models. For example, the COVID-19 pandemic has accelerated the move toward online business models, which in turn has intensified the last-mile problem and led to the creation of more emissions. In addition, retail outlets may be weakened in urban areas due to the pandemic-driven "flight" to the suburbs, further intensifying the last-mile problem (Bloch 2021). This may lead to a need for policies that accelerate the shift to alternative fuel vehicles and increase reliance on new business models, such as using "ride-share" companies that pool deliveries to reduce the average mileage driven per package delivered. However, these policies must also avoid weakening mass transit. How will new business modalities, such as working online, affect these decisions (Naumov et al. 2020)? Another open issue is the need to create policies to manage automated driving and flight (Naumov et al. 2020). Automated driving must be regulated for safety purposes, and new infrastructure may be needed. Automation might also lead to counterintuitive effects such as job losses from unemployed drivers. With respect to flight, regulation will be needed to cope with new modalities of delivery such as drones. How can drone parcel deliveries be done safely on a large scale, by many different business and organizations (Zelinger and Sallinger 2020)? One possibility is to require pilot licenses when commercial drones operate beyond visual range, but that may damage the cost-effectiveness of drones, particularly if these devices can lower fossil-fuel emissions. This ties in with educational policies that create national workforces inappropriate to new economic and operational needs. How can policies be designed to avoid worker shortages in supply chain and emerging high-tech jobs in operations (Van den Bossche et al. 2020, Bowman 2021)?

Table A4 in the e-companion organizes the roadmap for the cluster as described at the beginning of this section, and it also provides additional references from our sample.

4.5 Sustainable Operations

Sustainable development was defined famously by the World Commission on Environment and Development (WCED Strategic Imperatives' 1987) as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." At the heart of this issue are questions about how society consumes resources—both renewable and nonrenewable—in the presence of lengthy time delays between actions and consequences. This is complicated by the potential for self-interested and short-term behaviors that are at odds with the difficult collective actions needed to achieve true sustainability. As in other areas of policy, here governments can enact sustainability policy that align the incentives of individuals and firms with the collective good in principle. However, once again, system complexity often leads to unintended consequences and counterproductive policy-making (Moxnes 1998, 2000). Another driver of complexity, at least in some contexts, is the need to model ecological or climate factors (Moxnes 2005, Fiddaman 2007). For these issues, SD modeling can be particularly useful in developing effective sustainability policies.

Moxnes (2005) is an exemplar of an SD model that includes domain data (from ecology), economics, and operations. The larger task is to determine the impact of optimal quotas and capacity decisions on the fishing fleet for preserving the Northeast Arctic cod fishery. Moxnes found, contrary to conventional wisdom, that optimal policies and their trajectories were affected more by uncertainties in nonlinear economic relationships than those regarding the ecosystem. His method may likely apply to many other sustainability settings; that includes climate change, the management of which has proven particularly problematic. Also, this is one of the few SD papers that uses stochastic optimization, which has the added benefit of enabling an examination of the optimal trajectories as a function of uncertainties.

Another exemplar is the study by Kapmeier and Goncalves (2018) that developed a model for managing tourism to promote economic growth, using 38 years of data from the Maldives Islands. Their model also included extensive input from various expert stakeholders from the island chain with respect to their concerns, decision-making policies, and other issues. Operationally, the study included capacity and demand as well as waste management, and it performed scenario planning to develop robust policies using Monte Carlo analysis. The authors found that policies for improving waste management will not work alone; one must also limit tourist demand.

Agrawal et al. (2019) used systems thinking techniques based on those discussed by Senge (1990) to identify new opportunities for research in sustainable operations, specifically circular or “closed-loop” supply chains. These transform the linear “take-make-dispose” industrial model into a circular economy that regenerates and restores materials, products, and other resources for future use. These strategies consider three important building blocks that are particularly germane to SD: “reverse flows,” “circular design,” and “circular business models.” All three explicitly consider feedback in their decision, production, delivery, and product transformation processes. Closed-loop supply chains have been studied with some success. Modeling examples include Lehr et al. (2013), which evaluates a variety of strategies for electronics firms to meet increasing European Union regulation of waste most effectively, and Yuan (2014), which studies the design of construction-waste fees charged in China.

Interesting questions remain open. For example, despite the significant number of insightful works addressing how firms must cope with sustainability policies, studies examining how to optimize macro policies in our sample generally offer model operations as simplified national or global aggregations (Fiddaman 2002, 2007, Rooney-Varga et al. 2020). They do not examine the implications at a micro level for manufacturing and supply-chain design that may affect firm viability and other allied issues, which Joglekar et al. (2016) argue is necessary. This is unfortunate, because studies in climate change, resource and land use, and circular economies are a rapidly growing field of operations management and, arguably, the most important. Furthermore, the number of feedbacks and delays is perhaps even greater in sustainability than in any of the other policy areas discussed in this paper. We urge more development in all the areas identified above. Moxnes (2005) and exemplars from the related fields of transportation and logistics or energy clusters could be used as models to emulate (Ford 2008).

One area of inquiry not yet researched to the best of our knowledge is how to increase the durability of products, which could reduce both the future usage of materials and the creation of waste (Goworek et al. 2020). Another question is how continuous improvement programs might be actively directed to improve sustainability alongside regulatory changes. "Lean" continuous process improvement could be a powerful tool here, because its prime tenet is to "minimize waste." However, continuous improvement takes time. Would abrupt regulatory changes (e.g., the sudden introduction of a carbon price) encourage the incremental minimization of waste, or would they result in risky "big bang" process-improvement projects? Similarly, firms might use process improvement to reduce their carbon footprints (Aguado et al. 2013), but what sorts of regulation, carbon taxes, cap and trade, etc., would be needed to drive firms to effectively minimize their carbon footprints using continuous improvement?

Table A5 in the e-companion organizes the roadmap for the cluster as described at the beginning of this section and provides additional references from our sample.

4.6 New Business Models

Since 2000, there has been a flurry in the development of new business models. While many have been driven by improved information technology such as the internet, they also rely on operational innovations such as online ordering and home delivery. This has attracted the interest of OM researchers (Sorescu 2017, Kumar et al. 2018). This area, ripe for policy and regulation, is clearly a complex system. The seminal work Parker et al. (2016) explicitly uses the language of SD, defining platforms as the center of reinforcing loops that connect different markets. While these markets are not owned by the platform firm, they create value for each other. Uber is a classic example of a firm that exploits the cross-side externalities between passengers and drivers, in which more passengers attract more drivers, which attract more passengers. To enable this often requires an operational innovation. Uber replaced employees with freelance "gig workers" who essentially act as spot-market suppliers. However, the book also discusses the negative effects of platforms on the community. For example, Uber's drivers do not receive health insurance, monopoly effects might harm service and affect antitrust policy. Despite this rich discussion using SD terminology and concepts, however, there is no associated simulation model. Very few other extant SD research articles use models that analyze policy for platforms. This is unfortunate, because most of the extant literature on platforms, on which much policy is being decided, employ single-period game theory models. That said, there are a few SD papers treating OMPP issues in platforms. These include the study by (Keith and Rahmandad 2019) of winner-takes-all outcomes in the gig economy. Another is the study by Anderson and

Parker (2013) of an energy power storage startup's new product-development choices in technology; it explicitly considers cross-side externalities as well as funding mechanisms for startups. However, both papers could easily have done more to study potential public-policy interventions.

Startups are their own business models, differing from mature firms in important ways, such as their lack of cash combined with the need to balance R&D, marketing, capacity, and production during rapid growth. These lead to OM problems that lend themselves to SD research (Paich and Sterman 1993, Milling and Stumpfe 2000, Bianchi and Bivona 2002). Another issue is that the overwhelming majority of startups fail (Marmer et al. 2011). SD models are particularly useful here because it can study unsuccessful firms and avoid the survivor bias when studying only those firms that "make it." Policymakers often see startups as desirable, and the U.S. and other countries have policies to encourage startups (Hsieh and Chou 2018). However, that raises two questions. Which policies actually help startups while also avoiding unintended consequences? And which policies, such as tax laws, inadvertently hurt startups and small enterprises? While SD studies are strongly indicated, published studies are currently rare (Zali et al. 2014).

Questions around new business-model policy are plentiful. For example, should gig employees be treated as independent contractors? But these issues remain understudied by SD scholars. There are many other issues that, to the best of our knowledge, remain completely unstudied. For example, the shift to more online ordering has led to interest by OM scholars in the last-mile problem created by increased deliveries as well as increased problems in reverse-logistics. This has a variety of knock-on effects that may need regulation. For example, increased vehicle emissions may potentially increase government interest in accelerating requirements for alternative fuel vehicles, which has been discussed previously. Waste-management problems also increase as a function of extra shipping materials and returned goods (Slabinac 2015). Further, while warehouse workers represent a larger section of the economy, they are perceived to be underpaid or otherwise exploited by firms such as Amazon. As it has with gig workers, this situation has led to calls for employment regulation (Long 2018), which may have unintended effects such as the acceleration of automation. SD models could be helpful in studying all these issues.

With respect to new business models that rely on externalities, several questions need to be studied, especially those relating to operations and policy, such as antitrust issues. For example, Amazon's reverse engineering of popular products from small and medium enterprises is now being investigated as a potentially unfair trade practice (Kalra and Stecklow 2021). However, are regulatory remedies truly necessary, given that other platforms such as Shopify and BigCommerce are creating systems to enable small and medium enterprises to compete with Amazon (Lu 2020)? Also, to the best of our knowledge, SD studies of the interaction of open or crowdsourced innovation with policy is completely absent. How should startups be promoted more broadly through policy? For example, could some worker regulations that make sense for large enterprises be problematic for small enterprises? Ultimately, policies are needed to encourage this development in nations that have a chronic shortage of the skilled labor needed to maintain automation, such as the United States (Moreno and Bauer 2017). Similarly, to the best of our knowledge, additive manufacturing—better known as rapid prototyping or 3D printing—has also not been studied. This area is ripe for regulation given the possibilities for intellectual property (IP) infringement and the production of dangerous or other undesirable products, such as handguns. At the same time, additive manufacturing is desirable for encouraging R&D and leveraging open innovation. It also could have been used during the COVID-19 pandemic to produce critical subcomponents for equipment with otherwise disrupted supply chains. Another area of new business models includes those based on disruptive technologies in operations such as artificial intelligence, machine learning, and automation. Much of this is covered in the transportation, logistics, and supply chain section of this paper, and includes Naumov et al. (2020). Much is also captured by prior SD models, such as Forrester's, if parameters are used to reflect improved forecasting accuracy and promote coordination. However, some applications of artificial intelligence (AI) need new models. For example, the rise of automation requires a new type of labor force, one with fewer unskilled workers and more who are skilled. However, the U.S. is chronically short of skilled workers, so how can this be remedied?

In short, the literature in all these topics is sparse, the suitability of SD is high, and the importance of policy questions is of the utmost importance. Table A6 in the e-companion organizes the roadmap for the cluster as described at the beginning of this section and provides additional references from our sample.

4.7 Energy

Parker et al. (2019) provide a scoping review of articles published on current operational and policy issues related to the electric power industry. The authors highlight the need for new models, to both help the industry better utilize resources in complex systems involving environments of increasing uncertainty and aid government policy makers better understand the potential impact of regulatory decisions. Specifically, they argue that there are opportunities for research recognizing the mutually interacting and dual-causality dynamics between operations and public policy. For these reasons, there is a long history of using SD models as a decision support method in the energy sector (Ford 1997, Ahmad et al. 2016, Leopold 2016). Work has spanned areas including fossil fuels, renewables (Fontes and Freires 2018, Zapata et al. 2019), power generation and distribution (Ford 2008), and the evaluation of alternatives for both utilities and governments (Johnson et al. 2006, Tan et al. 2010). Particular complexities handled in these models include uncertainty in technology development. Another issue is—at least in the U.S.—considerable fragmentation of the power-generation industry.

The literature in this space is burgeoning. Several review papers are helpful in classifying recent work. Teufel et al. (2013) proposed a categorization into regulated and liberalized electricity markets, and the authors further subdivide these two markets into a number of sub-categories. Leopold (2016) provides a detailed review of other works using SD to model energy related systems. Qudrat-Ullah (2015) conducts a review of different modelling and simulation studies in service energy policy, including system dynamics, linear programming, econometric methods, optimization, scenario analysis, and agent based models.

An exemplar article in this cluster is the study by Ford (2008) of technology choice, capacity planning, carbon-capture technology, incentives for switching to renewables, and pricing cap-and-trade allowances to reduce carbon emissions in the U.S. Western Energy Grid. Using extensive scenario testing in a model deeply grounded in technological detail, Ford found a number of results concerning different legislative and regulatory proposals, particularly that carbon pricing should be implemented even absent development of advanced technologies such as carbon capture and sequestration. A more recent exemplar paper by Castaneda et al. (2017) builds a model including electricity demand and capacity markets to study the impact of roof-top solar systems on electric utilities' business models. It also includes the Bass marketing model for demand for rooftop solar capacity. They analyzed several scenarios based on input from stakeholders including managers, engineers, energy specialists, and policy makers to cope with the numerous uncertainties involved. The paper ultimately finds that some environmental policies promoting rooftop solar may actually increase the likelihood of a death spiral for utilities.

Other areas that have been studied by SD researchers include electricity market design, renewable integration, effects of climate policy on electric power infrastructure, the rise of electric powered vehicles, energy storage, and the growing interdependence between natural gas and electric power sectors (Kilanc and Or 2008, Arango and Larsen 2011). These often overlap with other areas of OM, such as sustainability, and further highlight the importance of the interdisciplinary study of complex topics. While there is a fair amount of SD literature with respect to OMPP problems in energy, the number of open questions remains extensive. Perhaps the most interesting are those that overlap with other clusters already identified in this paper. In particular, there is an obvious overlap between sustainability and energy. Hence, many of the questions related to combining energy models with climate models are critical (Fiddaman 2002, 2007). However, these questions must also include the impact at the micro-level operations issues faced by energy generation and distribution firms. A related question is: how can electricity systems be designed to cope with the extra capacity and uncertainty created by electric vehicles? For example, Bhargava et al. (2020) estimates that the load of a single electric truck is similar to that of a small city. There is also clear overlap between energy distribution, electricity markets, and new business models. For example, electricity grids are multisided markets and have cross-sided externalities with respect to technology adoption, particularly around power generation and storage (Parker et al. 2019) How does one account for these new business models when drafting regulations? Capacity decisions by utilities depend upon whether power markets are based on guaranteed capacity (as in the U.S. Eastern and Western Grids for electricity distribution) versus based purely on delivered kilowatt-hours (as in the Texas Grid). Which design is better, and under which conditions? Are there other designs that can combine the best parts of both? Or is some other design even better?

Table A7 in the e-companion organizes the roadmap for the cluster as described at the beginning of this section and provides additional references from our sample.

5. Discussion and Conclusion

In this review, we have sought to create a roadmap for researchers interested in using system dynamics to study operations management in public-policy-related contexts. Our intended audience includes both those experienced in using SD and those new to the field. To this end, we collected a sample of approximately 150 SD articles at the interface of operations management and public policy. The research areas surveyed are vast: including humanitarian operations; healthcare operations; conflict, defense, and security; transportation, logistics, and infrastructure; sustainable operations; new business models; and energy. Necessarily, we have imposed boundaries to keep the task manageable. For example, we avoided studies that represented operations at a macro level, typical of labor economics or macroeconomics research. While such research is valuable, it does not effectively inform operations management research. We also do not attempt to be exhaustive in our sample; instead, we focus on a scoping review, establishing a useful knowledge base for contemporary researchers interested in this area.

We leverage our sample in several ways. First, we describe why, when, and how SD models might be valuable for studying operations management problems in a public-policy context. Second, we identify the tradeoffs in data gathering, aggregation, optimality, boundaries, and other issues involved in using system dynamics models versus "classic" operations management modeling methodologies such as game theory, mathematical optimization, and queuing. Henceforth, we find this is often not an either-or question—nor should it be. Instead, multiple methodologies can and often should complement each other.

Next, we clustered the articles by topic. For each topic cluster, we then identified a list of extant literature, the extant contributions of system dynamics research, open questions, and potential SD building blocks for scholars investigating these questions. We gathered these into tables for each cluster to organize that knowledge for future researchers. We also identified and described exemplars in each cluster that could serve as models for future academic work.

Several overarching challenges, all common to multiple clusters, emerge for researchers in public policy-related operations. On the methodology side, the biggest area for potential improvement is researching the use of SD models for consensus-building among stakeholders. In our sample, we cite exemplars that document group-model building as well as the use of flight simulators (see Table 3). However, overall, detailed literature remains sparse in the context of operations management for public policy. This is unfortunate, because stakeholder resistance is often a major hindrance to implementation (Besiou and Van Wassenhove 2015). One simple step to improve research in this area would be providing more description on how stakeholder consensus is reached, even in papers primarily centered on the nature of the ultimate solutions. An exemplar for this approach is Goncalves et al. (2021), particularly because it describes a consensus-building approach different from those traditionally described in SD research (Andersen et al. 1997, Vennix 1999).

[Insert Table 3 about here]

Another challenge is the dearth of research on integrating system dynamics with other OM modeling techniques, whether mathematical programming, queuing, or otherwise. Table 3 identifies exemplars that have addressed this issue. Other than those exemplars, however, few papers have investigated this area. As a result, this represents an important area for future research. Ghaffarzadegan and Larson (2018) and Anderson (2019) have outlined several potential paths of inquiry. One possibility is to build on the SD model of Homer (1999) for managing service capacity, which solves an optimal assignment problem for each time period. Additional building blocks for this area include articles by various authors in the book edited by Rahmandad et al. (2015). Among other things, the chapters by various authors address the use of Markov chains, decision analysis, optimization, and game theory. A related issue that shows up repeatedly in our survey is the last-mile problem. Formulations from operations management exist that can approximate the mileage at an aggregate delivery level for a fleet of vehicles traveling within a geographic location (Figliozzi 2009).

The topic of trajectories between the current and desired states is also a natural opportunity for system dynamics research (Moxnes and Davidsen 2016). A particularly fruitful area to concentrate on is not only optimal trajectories between current and desired states, but also whether path-dependence precludes such a trajectory to that desired state. If that is the case, the question arises: What would be a useful path of inquiry, particularly when system dynamics models integrated with traditional operations management methods are employed? While this is implicitly discussed in some articles in our sample, explicit discussion is very sparse. One exemplar is Naumov et al.(2020).

Based on these findings, we propose building on the Besiou and Van Wassenhove (2015) framework for addressing operations management problems in public policy, as shown in Figure 4.

[Insert Figure 4 about here]

The major addition to their framework is a feedback loop on the left side of the model at the “systems level” to build consensus: convening stakeholders, gathering extant data at hand, and building small system dynamics models using a group modeling process. The goal is to facilitate stakeholder consensus on a systems-level approximation of what an operational solution might look like. We propose that in practice this feedback loop be pursued for several cycles before moving on to the detailed “operational level” on the right-hand side. Within the operational loop, more detailed operations planning models can be developed using traditional OM techniques such as mathematical programming or, alternately, by expanding the SD model appropriately to obtain an operational solution (or set of solutions). The potential solutions are then tested for robustness against the systems-level model, and additional data is gathered as needed. Every few cycles of the loop at the operational level, the proposed implementation should be fed back to the stakeholders at the systems level to gather input and maintain consensus. Flight simulators can be employed where appropriate. After a few more iterations between the two levels, the solution is implemented, and appropriate effectiveness metrics are gathered. These metrics should then be incorporated at the operational level to adjust the solutions to improve effectiveness and, from time to time, at the systems level to receive input and maintain consensus.

On the domain side, studying spillovers among public policy research clusters is a rich area for future research. The electric vehicle fast-charging stations problem, used as a motivating example earlier in the article, spans multiple areas: transportation and logistics, energy, and new business models. In another area—conflict, defense, and security—insurgency suppression involves questions that go beyond the purely military in nature, because insurgencies destroy infrastructure and food supplies, which in turn contribute to weakening a population with respect to disease. On the opposite side, military conflicts often hinder humanitarian operations in the area and endanger nearby personnel.

Finally, several opportunities for research emerge from recent global disruptions, including international trade disputes and the COVID-19 pandemic, that have laid bare the fragility of global supply chains. Research into bolstering these supply chains with policy initiatives (e.g., U.S. President Biden's "Infrastructure Investment and Jobs Act" initiative to increase infrastructure resiliency) is a fruitful and necessary area for exploration by researchers leveraging system dynamics. However, there is currently little, if any, SD research addressing these areas outside of supply chains directly related to medical devices and supplies. Some starting points do exist, and they could be built on. Coping with smaller-scale supply chain fragility occurs in articles in three clusters of our sample: humanitarian operations; healthcare operations management; and conflict, defense, and security. Some policy efforts emphasize near-sourcing. For example, the U.S. CHIPS Act of 2022 subsidizes firms building semiconductor capacity in the United States with the aim of reducing reliance on manufacturers located in Asia. Twenty years ago, some SD modeling research touched on the consequences of offshoring manufacturing, which included a hollowing out of nations' strategic manufacturing competencies (e.g., Anderson et al. 2000). In addition, Akkermans et al. (1999) developed an extensive set of causal loop diagrams around international outsourcing that included the impact of customs and regulations policies. Another potential building block comes from Joglekar and Phadnis (2020) and Phadnis and Joglekar (2021) which propose to expand scenario planning to cope with policy disruptions by including suppliers in the planning process, which is a natural fit for SD.

To conclude, we believe this survey describes how system dynamics can provide a powerful lens for studying policy issues in supply chain and operations management. Further, this article is intended as a roadmap for all researchers who might profit from using SD to address public policy problems, whether they have used SD before or are interested in trying it for the first time.

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Figure 1: Questions Addressable by System Dynamics

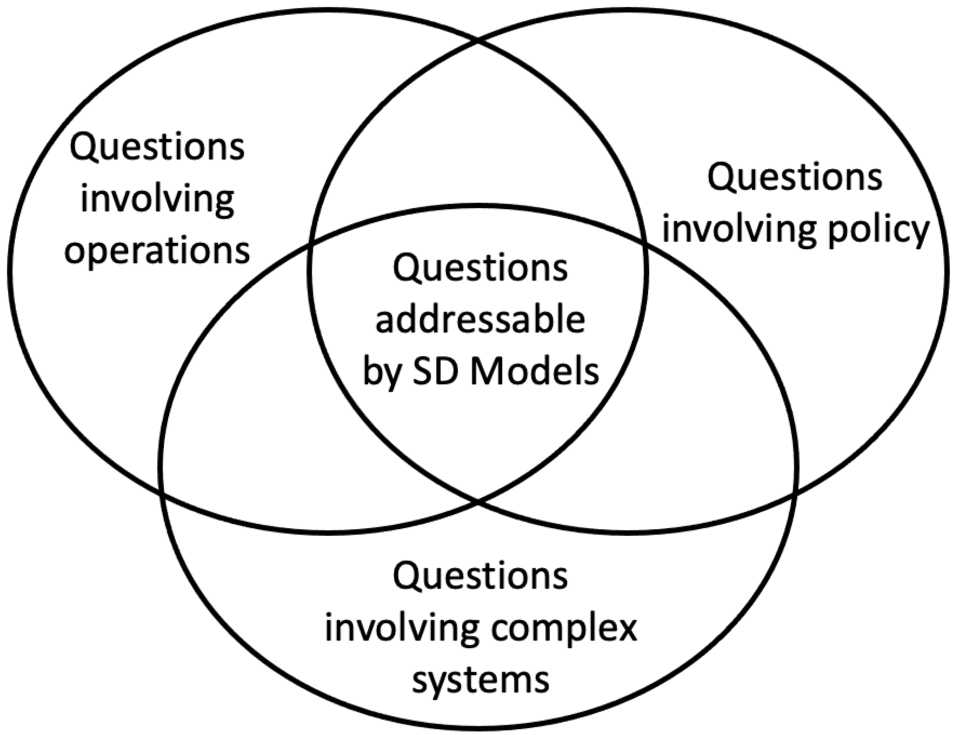

Figure 2: Atasu and Van Wassenhove's "Gray Zone"

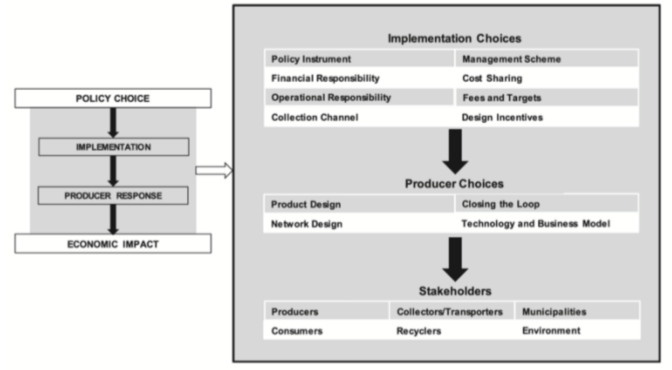

Figure 3: Joglekar et al.'s Diagram of Bidirectional Causality Between Operations and Public Policy

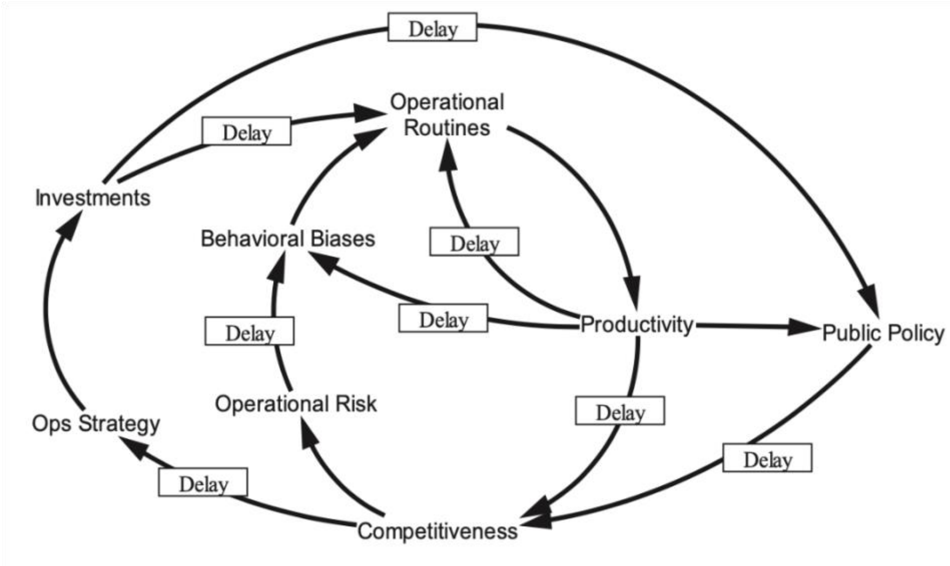

Figure 4: System Dynamics Modeling Process for Operations in Public Policy Contexts

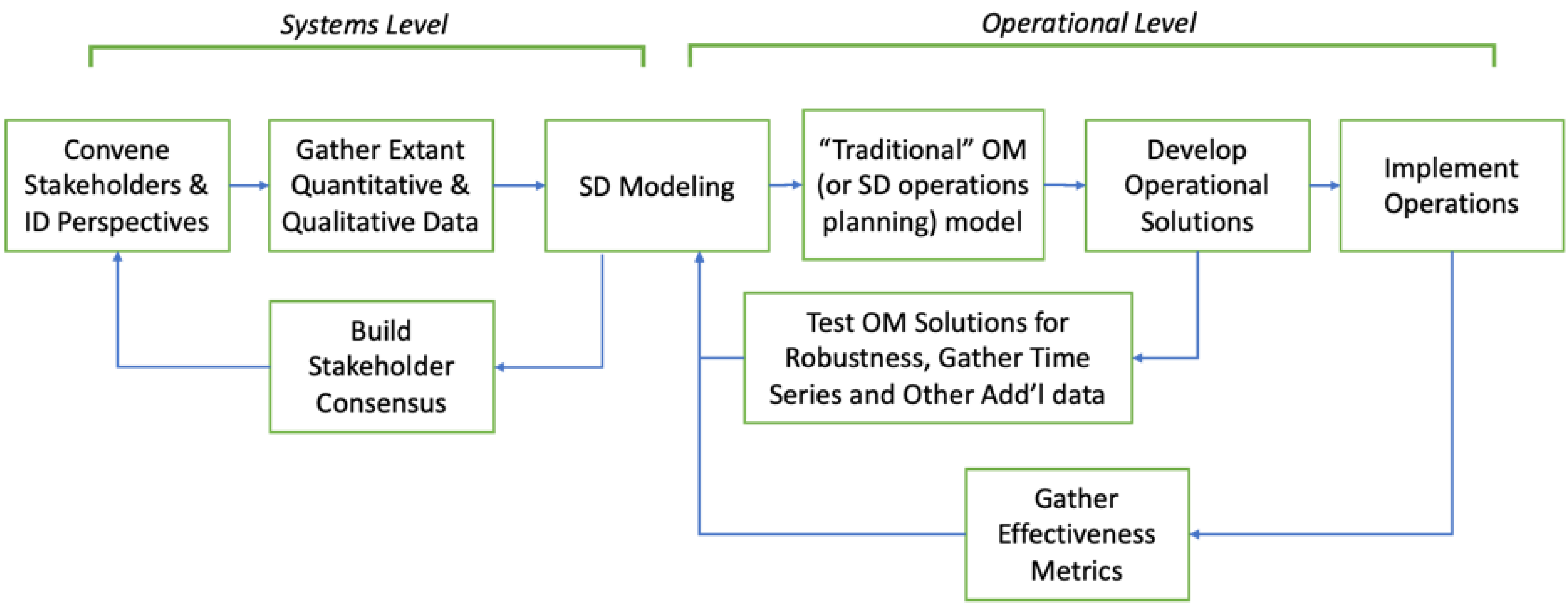

Table 1: Characteristics of Different Modeling Techniques

	Typical Application in OM Context	Data required for typical model	Number of Variables for typical model	Dynamic feedback in typical model	Other complexity in typical model	Modeling of uncertainty in typical model	Typical modeling of human behavior	Understanding of behavior modes within model boundaries for a typical model
Game Theory	High -Level Insights (Competition/ Cooperation)	Very Low (qualitative data, if any)	Low	Yes, but rarely more than 1-3 periods	Different objective functions	Probabilistic outcomes	Rational optimizers	Very high via closed-form analytic results
Econometrics	Detailed insights (Correlation/ Causality)	High - Very High from archival and/or surveys (varies from aggregate to detailed data)	High - Very High	None (cross-sectional) Moderate (time-series)	Low	Identification strategy, clustering, residuals	Occasionally probabilistic distributions for stochastic processes.	Low - moderate due to limited ability to model counterfactuals
Optimization Models (e.g., linear programming)	Detailed operations design (particularly for capacity, Inventory, and scheduling	Moderate - Very High (Detailed structural data)	High - Very High	Depends on application. If so, linear (LPs) or multiplicative (Mixed IPs)	Low	Very Low, if any, with the exception of Inventory models, which include demand uncertainty.	None. All "physics."	High because of algorithmic optimal policies plus detailed model structure permit counterfactuals
Dynamic & stochastic programming	Detailed operations design	Moderate (detailed structural data)	Low - Moderate	Yes. Typically, but not always, linear other than constraints	Generally low	Probability modeling for stochastic programming	Utility functions, if any	Moderate – Very High (depending on whether closed-form solutions or approximations obtain – usually related to number of variables)
Queuing Theory	Design of operations, esp. capacity planning, process, and queuing discipline design	Moderate (wait, demand & capacity, constraints)	Moderate - High	Yes. Linear Markov chains with constraints such as maximum queue size	Low	Probabilistic distributions for demand, capacity, and waiting	Only with respect to waiting (e.g., reneging, balking)	Moderate - High (depending on whether optimal closed-form solution can be found, or else, tightness of bounds)
System Dynamics	Consensus Building, High- or mid-level operations design	Low-Moderate from case, expert opinion, or trade journals (consensus) Moderate-High (Ops Planning) including both econometric and some structural data	Low -Moderate (Consensus), Moderate - High (Ops. Planning)	Yes. Nonlinear state-space/ compartment models	Multiple stakeholders, problem ambiguity	Generally, through sensitivity analysis for scenario planning and/or Monte Carlo analysis.	Boundedly rational (typically derived from behavioral economics of behavioral operations)	Moderate - High depending on number of variables (via numerical simulation/optimization and assuming detailed sensitivity analysis)

Agent-based modeling	Consensus Building, Mid or low-level operations design	Moderate from case, expert opinion, or trade journals (consensus) High (Ops Planning) including micro-level behavioral data of agents and structural data	Moderate-High (Consensus), High - Very High (Ops. Planning)	Yes. Nonlinear interactions of low-level agents.	Multiple stakeholders, problem ambiguity	Probabilistic distributions of individual agents' behaviors captured by Monte Carlo analysis. Sensitivity tests to probabilistic distributions and other parameters.	Boundedly rational, usually based on individual-level economic or psychological underpinnings	Moderately low – Moderately High depending on number of agents and complexity of their interactions (via Monte Carlo simulation and assuming detailed sensitivity analysis)
Discrete Event Simulation	Same as queuing theory	Moderate-Very High (Data needed is similar to queuing theory, but possibly also routing, demand etc. as well as entity-level characteristics)	Moderate – High (generally modeled at entity level, but generally small number of types of entities)	Yes, feedback between queues, routing, and potentially, capacity, demand and entity characteristics	Low	Probabilistic distributions for demand, capacity, waiting, routing and potentially other entity behaviors	Only with respect to waiting (e.g., reneging, balking, routing choice)	Moderate – Moderately High depending on how much more complex model is than analytic queuing models (via Monte Carlo analysis of numerical simulations assuming good ranking and selection criteria)

Traditional OM techniques drawn from Winston, W.L. 2004. *Operations research: applications and algorithms* (4th edn). Boston: Cenage.
Simulation techniques from Heath, S.K., Brailsford, S.C., Buss, A. and Macal, C.M., 2011, December. Cross-paradigm simulation modeling: challenges and successes.
In *Proceedings of the 2011 winter simulation conference (WSC)* (pp. 2783-2797). IEEE and Anderson, E.G., Lewis, K. and Ozer, G.T., 2018. Combining stock-and-flow, agent-based, and social network methods to model team performance. *System Dynamics Review*, *34*(4), pp.527-574.

Table 2: Comparison of Perspectives by Academic Communities Researching Public Policy: The Electric Vehicle Fast Charging Question as an Example				
	Political Science (Sociology)	**Subject Matter Experts**	**Economists**	**OM**
Perspective on Problem	A bundle of societal functions and polities' wants	Bundle of interacting "physical" phenomena needing attention	Network of macroeconomic factors including national accounts, factors of production, and monetary supplies	Set of supply chains, operational processes, and projects that create value
Typical Metrics	Public approval polls, policy compliance, citizen unrest, national security	Problem dependent (e.g., EV fleet adoption, disease mortality, etc.)	GDP gain or loss, unemployment, inflation, national accounts	Utilization, service levels, customer satisfaction measures, wait/lead times, cost
Dominant Representational Paradigm	Public welfare as a function of societal and political factors.	"Physical" models of phenomena (e.g., Climate models, Epidemiological compartment models, etc.)	Mathematical and econometric models	Value chain maps, process diagrams, project structures (e.g., critical path models, work-breakdown structures)
Example Decision Variables	Communication policies, mandates vs. incentives, centralization vs. decentralization of administration	Mandates (e.g., Lockdowns, masks, vaccine mandates; company EV mix requirements; charging compatibility standards)	Interest rates, monetary & fiscal stimuli, cost tradeoff calculations	Distribution logistics, capacity planning, facility location, sequencing of tasks
Critical Success Factors	Political legitimacy, Compliance with government mandates	Understanding of phenomena, cost/benefit ratio of interventions, quality of data	Quality of economic data, effectiveness of stimuli	Supply chain design, process design, project management processes

Table 3: Summary of Noteworthy Use of Methods in Exemplars

Note: An "x" indicates an especially noteworthy use of a method. For example, all papers in the sample do rigorous sensitivity analysis. However, Ford's (2008) is particularly detailed and extensive, even relative to the other exemplars, and is an excellent model for future researchers.

Exemplar	Topic	Sensitivity Analysis	Scenario Analysis	Calibration Against Time Series Data	Monte Carlo Simulation	Trajectory Analysis	Dynamic Numerical Optimization of Decision Variables	Integration with Traditional OM/OR Methods/Models	Group Model Building	Flight Simulators	Spans Discipline Silos	Notes
Anderson (2011)	Counterinsurgency force planning			x			x				x	Integrates sociology and political science concepts. Nontraditional experience curve based on enemy activity
Artelli et al. (2008, 2009)	Psych. & political factors' effect on Lanchester Laws							x				Expansion of OR Lanchester Laws with Psychological and Political Science Constructs
Besiou et al. (2014)	Central vs. local purchasing of relief vehicles				x			x			x	Tests against dynamic programming models. Address concept of "earmarking" by funding organizations
Casteneda et al. (2017)	Roof-top solar power incentives' effect on electric utilities								x	x	x	Uses Bass Marketing Model
A. Ford (2008)	Carbon reduction and technology choice by electric utilities	x	x									Extensive grounding in technical engineering literature
D. Ford and Dillard (2009)	Agile deveopment of weapons systems							x				Compares agile and waterfall project management methodologies.
Ghaffarzadegan et al. (2016)	Post-traumatic stress disorder management		x								x	Incorporates human psychological factors
Ghaffarzadegan et al. (2017)	Workforce Education	x	x					x				Incorporates queuing model
Goncalves et al. (Forthcoming)	Healthcare capacity planning during pandemics			x					x			Uses nontraditional group model building techniques
Kapmeier and Goncalves (2018)	Sustainable Island Tourism		x	x	x							Links behavioral econonomics model of a service industry with environmental impact. Extensive Monte-Carlo simulation to evaluate OMPP policies. Excellent description of consensus building
Kang et al. (2018)	Public policies chronic disease management											Integrates multi-object goal planning model, scenario planning, and Markov model of disease progression
Kunz et al. (2014)	Preparedness strategies for disaster relief	x	x									Extensive scenario and sensitivity analysis
Kunc and Kazakov (2018)	Pharmaceutical competition for heart disease									x		Transforms a developed model into a flight simulator for building consensus in a workshop for multiple stakeholders.
Lane et al. (2001)	Reducing hospital emergency dept. waiting time			x					x	x		Uses time and motion studies to directly calibrate parameters rather than via optimization algorithm
Mayo et al. (2001)	Subway vendor selection		x							x		Flight simulator used to teach vendors successful business models
Moxnes (2005)	Quotas & capacity effects on fishery sustainability					x					x	Stochastic optimization. Integrated ecological modeling.
Naumov et al. (2020)	Autonomous Vehicles, Ride-Sharing, and Mass Transit					x					x	Economic utility functions extensively used.
Pierson and Sterman (2013)	Deregulation and aircraft purchase cyclicaltiy							x				Integrates yield management
Thompson et al. (2015)	Polio eradication	x	x	x	x			x	x			This is a summary of a series of articles. Incorporates game theory, linear programming, decision analysis, and inventory models

E-Companion

This electronic companion to **Opportunities for System Dynamics Research in Operations Management for Public Policy** provides additional information in the form of summary tables that create a roadmap for future research in each cluster discussed in the paper. Each table includes a summary of the research cluster in our sample, which we have further subdivided and organized the work by common topics and provide a list of selected references. We comment on some relevant system dynamic features that have proven useful in these works to highlight benefits from adopting the methodology. We collect and posit important ongoing and novel questions in the policy and operational domains and propose relevant established and new system dynamic structures that can be used to explore future work in these areas.

Table A1: Humanitarian Operations and Crisis Management Literature and Open Questions*					
Research Topics	**Selected References**	**Useful SD Features**	**Policy Questions**	**Operational Questions**	**Relevant SD Structures for Future Research****
Literature Review	Tomasini et al. (2009), Starr and Van Wassenhove (2014), Van Wassenhove and Besiou (2013), Besiou and Van Wassenhove (2015), Allahi et al. (2018), Besiou and Van Wassenhove (2020, 2021)	Ability to include both short term and long term time horizons (Van Wassenhove and Besiou 2013) Complex problems with multiple stakeholders and conflicting goals (Van Wassenhove and Besiou 2013)	How to can we holistically understand the relationship of humanitarian operations with other policy challenges?	How can we apply our knowledge from traditional OM problems to maximize recipient outcomes in humanitarian relief operations?	Use and build on existing small models per Ghaffarzadegan et al. (2011) to aggregate for larger, more complex problems
Disaster Life Cycle Models and Emergency Preparedness	Cooke (2003), Deegan (2006), Ni et al. (2015), Diaz et al. (2019)	Accounts for models of managerial behavior (BD-13.1 & BD-15) Uses established models of project management (BD-2.3)	How can we find the optimal level of preparedness given economic constraints and cyclical and stochastic nature of disasters? What are the contexts of disaster relief recipients that might complicate relief delivery?	How to manage compressed relief effort/project lifecycle? How to manage complications in demand due to hoarding in a disaster area?	Behavioral Model of Hoarding (Sterman and Dogan 2015) Extend existing models to endogenize production rates
Balancing Competing Demands in Disaster Management	Gonçalves et al. (2011), Kunz et al. (2014)	Capability Trap model of the tradeoffs between providing relief and building capacity (Gonçalves 2011), where immediate needs are not aligned with long term goals	How to can different stakeholders coordinate to get crisis relief to affected areas quickly and efficiently?	How to manage last mile distribution in underdeveloped areas? Where do on-the-ground problems differ from those in for-profit settings?	Capability traps in non-profit fundraising (Keith et al. 2022)
Vehicles and Fleet Maintenance	Besiou et al. (2011), Pedraza-Martinez and Van Wassenhove (2012), Besiou et al. (2014), Cruz-Cantillo (2014)	Maintenance models vs customer satisfaction (BD-2.4)	How do we set up and maintain capacity to be quickly deployed in a disaster zone?	What are the effects of earmarks and other constraints from donors?	Maintenance Traps (Bivona and Montemaggiore 2010) Media/public relations effects (Keith et al. Forthcoming)
Humanitarian Supply Chains and Logistics	Peng et al. (2014), Remida (2015), Cortés et al. (2019), Badakshan et al. (2020)	Bullwhip and oscillation models (BD-17.1) Stock management (BD-17.3)	How can we set up an efficient system to deal with the unpredictability of demand, suddenness of the disasters, and urgency of action?	How is the success of a relief operation affected by the political characteristics of the region affected? What is the effect of experience and burnout on relief worker capabilities?	"Rookie-Pro" aging chains that account for heterogeneous productivity of experienced vs inexperienced employees (BD-19.1, 19.2) Dynamics of worker burnout (Homer 1985)

*Source of question is from authors as opposed to from research agendas in sample papers **Unless otherwise indicated, SD structures can be found in Sterman (2000), which summarizes seminal research in system dynamics, and presents many of the commonly used structures and formulations for a wide variety of modeling applications. For ease of reference, we will note the Chapter and Section where a relevant structure is presented as "BD-xxx yyy" where xxx is the chapter and yyy is the section.

Table A2: Healthcare Operations Management Literature and Open Questions*					
Research Topics	**Selected References**	**Useful SD Features**	**Policy Questions**	**Operational Questions**	**Relevant SD Key Structures for Future Research****
Literature Review	Luke and Stamatakis (2012), Darabi and Hosseinichimeh (2020)	Complex problems with multiple stakeholders and conflicting goals (Darabi and Hosseinichimeh 2020)	What can we learn from modeling in relation to diseases and disease-spread, organizational and healthcare delivery structures, and how can it be adapted to different regions?	How can we improve quality and consistency in healthcare delivery, while reducing costs and increasing coverage?	Use and build on existing small models per Ghaffarzadegan et al. (2011) to aggregate for larger, more complex problems
Models for Public Health	Taylor and Dangerfield (2005), Homer and Hirsch (2006), Mustafee et al. (2010), Homer and Curry (2011), Katsaliaki and Mustafee (2011), Atkinson et al. (2015), Marshall et al. (2015), Newell and Siri (2016), Betcheva et al. (2020), Van Oorschot, (2021), Goncalves (2021)	Accounts for models of managerial behavior (BD-13.1 & BD-15) Uses established models of project management (BD-2.3)	How should the interactions between healthcare stakeholders be designed to reduce costs? How do we reduce inequity in patient outcomes for the disadvantaged?	How can information systems be better designed to support processes and healthcare supply chains? How can process improvement in safety be addressed in a system that blames individuals rather than processes?	Dynamics of worker burnout (Homer 1985), corner cutting and overtime (Oliva and Sterman 2001). Also summarized in BD-14.
Epidemiology	Roberts and Dangerfield (1990), Dangerfield (1999), Dangerfield et al. (2001), Ghaffarzadegan and Rahmandad (2020), Fiddaman (2020), Rahmandad et al. (2020), Struben (2020)	Endogenous response to risk perceptions	What policies improve treatment quality, consistency and safety overall?	How can we be better prepared for outbreaks? How do we make supply chains more robust during pandemics?	SEIR models, extended to include quarantines, vaccinations, distancing mandates, adherence fatigue, and behavioral risk perceptions.
Effectiveness of Interventions	Tengs et al. (2001), Ahmad and Billimek (2005), Kang et al. (2018), Jalali et al. (2019)	Dynamics of communication, motivation and erosion, impact adoption and implementation (BD-1.1)	How can waste be removed from current processes?	How can we improve project management for crashed programs? How can supply chains be erected quickly?	Temporal trade-offs or “Capability Traps” (Repenning and Sterman 2002)
Patient Flows and Capacity Planning	Van Ackere and Smith (1999), Lane et al. (2000, 2001), Smith and Van Ackere (2002), Diaz et al. (2012), Wang et al. (2015), Lane and Husemann (2018)	Modeling queues, and the interaction of delays and bottlenecks (BD-11.2)	How can specific drivers, such as payment structures, be redesigned to reduce excessive or duplicated services? What are the effects of improving transparency of costs?	How can patient flows be designed in a way that maximizes efficiency and improves patient outcomes? How can novel inventory replenishment models ensure availability of supplies and minimize costs?	Dynamics of worker burnout (Homer 1985) “Rookie-Pro” aging chains that account for heterogeneous productivity of experienced vs inexperienced employees (BD-19.1 and 19.2)
Human Body and Disease Prevention	Abdel-Hammid (2003), Jones et al. (2006), Karanfil and Barlas (2008), Abdel-Hammid et al.	Stock and flow structures inside the human body	What are the government policies or behavioral interventions that can most	How to manage healthcare operations during humanitarian operations in areas with poor infrastructure?	Treatment starves prevention structures (Jones et al. 2006)

	(2014), Fallah-Fini et al. (2014), Ghaffarzadegan et al. (2016), Hosseinichimeh et al. (2018), Rogers et al. (2018)	(BD-6)	cost effectively help contain the spread viral diseases?	How to manage the complications in regions affected by war, corruption, or related issues?	
Addictions and Pharmaceutical Use	Paich et al. (2011), Wakeland et al. (2011), Wakeland et al. (2015), Azghandi et al. (2018), Kunc and Kazakov (2018)	Aging chains (BD-12)	What are the government policies or behavioral interventions that can most cost effectively help drug epidemics?	How can critical drug distribution be improved in emergencies?	Treatment starves prevention structures (Jones et al. 2006)

*Source of question is from authors as opposed to from research agendas in sample papers **Unless otherwise indicated, SD structures can be found in Sterman (2000), which summarizes seminal research in system dynamics, and presents many of the commonly used structures and formulations for a wide variety of modeling applications. For ease of reference, we will note the Chapter and Section where a relevant structure is presented as “BD-xxx yyy” where xxx is the chapter and yyy is the section.

Table A3: Conflict, Defense, and Security Literature and Open Questions*					
Research Topics	**Selected References**	**Useful SD Features**	**Policy Questions**	**Operational Questions**	**Relevant SD Key Structures for Future Research****
Literature Review	Cunico et. al (Forthcoming)	Causal representation in SD models provides insights Due to the lack of physical attacks to draw data from, simulation and scenario analysis are key.	How can threats be mitigated in an increasingly interconnected, and more technologically dependent world? How do we train personnel to cope with conflicts (e.g., wargaming)	What are the effects of militarily hostile "stakeholders" objective functions on operations?	Flight simulators (Coyle et al. 1999) (Sterman et al. 2013) Adversarial decision making (Martinez-Moyano et al. 2015) Artelli et al. (2008, 2009) Scenario analysis for conflicts (Anderson 2011), Coyle (1981)
Conventional Warfare	Coyle (1981, 1989, 1992, 1996), Wolstenholme (1983, 1988), Wolstenholme and Al-Alusi (1987) , Artelli and Deckro (2008), Artelli et al. (2009), Backus et al. (2010)	Relaxes the assumptions of the traditional force-loss ratio models (Lanchester Equation), to allow for conflicts that don't end in total annihilation or predetermined force numbers	How do we create and maintain effective military forces? How can the command-and-control loop be improved?	How to manage the complications in regions affected by war, corruption, or related issues? How can technology improve the speed of the command-and-control loop? How can processes be developed to prevent control loop disruption, particularly of information systems?	Ageing chains for recruitment including vacancy creation and hiring delays. BD (19.1) Maintenance structures for infrastructure, vehicles, etc. (BD 2.4) Decision support systems for military operations (Lofdahl 2006, 2014)
Defense Acquisition and Capacity Planning	Lyneis et al. (2001), Bakken and Gilljam (2003), Bakken and Vamraak (2003), Lyneis and Ford (2007), Ford and Dillard (2008), Ford (2009), Ford and Clark (2019)	Highlights the tradeoffs and benefits of preventive policies versus reactive responses. Allows for exploration of different policies	How can defense acquisition costs be reduced while improving effectiveness?	Can agile or other project management methodologies improve acquisitions? How can organizational structures be designed to facilitate acquisition?	Project management models with rework, modularity, etc. (Lyneis and Ford 2007) Organizational structures for acquisition (Ford and Clark 2019)
Insurgency and Counterinsurgency	Coyle (1985), Richardson et al. (2005), Anderson (2007b), Choucri et al. (2007), Sardell et al. (2009), Schoenwald et al. (2009), Anderson (2011), Saeed et al. (2013), Pruyt and Kwakkel (2014), Martinez-Moyano et al. (2015)	Explores the effects of timing on the effectiveness of engagement and withdrawal efforts	How can the interconnectedness of insurgencies with other policy challenges be managed? What policies can manage the "business" aspects of insurgencies including links with organized crime?	How are increasingly global and interconnected SCs making governments more vulnerable to threats? How can supply chains for weapons etc. to support insurgencies be disrupted? How can funding for insurgencies and terrorism be cut without increasing organized crime?	Insurgency-crime dynamics (Saeed et al. 2013) Blockading weapons imports and cutting finance to insurgents (Anderson 2007a)
Infrastructure and Information Security	Martinez-Moyano et al. (2011), Schoenberger et al. (2014), Nazareth and Choi (2015), North et al. (2015), Armenia et al. (2019)	Bass diffusion and SEIR epidemiological models to cyber virus attacks.	How can we protect critical infrastructure from terrorism in a cost-effective manner?	Is it better to use redundancy or some other method to increase resiliency? Are there new technologies to help predict attacks? How can we change managerial behavior to adopt a "security mindset?"	Using AI to predict attacks on infrastructure (North et al. 2015) Behavioral models of information security (Martinez-Moyano et al. 2011, Armenia et al. 2019)

*Source of question is from authors as opposed to from research agendas in sample papers **Unless otherwise indicated, SD structures can be found in Sterman (2000), which summarizes seminal research in system dynamics, and presents many of the commonly used structures and formulations for a wide variety of modeling applications. For ease of reference, we will note the Chapter and Section where a relevant structure is presented as “BD-xxx yyy” where xxx is the chapter and yyy is the section.

Table A4: Transportation, Logistics, and Infrastructure Literature and Open Questions*					
Research Topics	**Selected References**	**Useful SD Features**	**Policy Questions**	**Operational Questions**	**Relevant SD Key Structures for Future Research****
Literature Review	Abbas and Bell (1994), Shepherd (2014)	Clarify the relations between multiple stakeholders with different goals	What policies will encourage transport and logistics efficiency and sustainability improvements?	What sorts of new business models should be encouraged to improve operational efficiency?	Group model building to elicit decision maker's mental models.
Mass Transit	Coyle and Gardiner (1991), Homer et al. (1999), Mayo (2001), Bivona and Montemaggiore (2010)	Shows the effects of "induced demand" and why road building is a "policy resistant" alternative to reducing traffic	What policies can be enacted that can ensure the attractiveness, and improve the economics of mass transit?	How do we coordinate price setting and long-term maintenance and purchasing?	The mass transit "death spiral" (Naumov et al. 2020)
Highway Maintenance	Chasey et al. (2002), Friedman (2006), Fallah-Fini et al. (2010)	Combination of SD and optimization to improve priority setting schemes	How do we improve infrastructure functionality while reducing long term infrastructure costs?	What maintenance schedules should be followed? When should we build new infrastructure?	Maintenance structures (BD-2.4)
Airlines, Airport and Other Infrastructure	Liehr et al. (2001), Rudolph and Repenning (2002), Miller (2007), Pierson and Sterman (2013)	Models of supply line acquisitions that incorporate operational decisions such as revenue management	What is the impact of COVID-19 on transportation and logistics policies?	To what extent will telecommuting reduce traffic congestion and flying?	Aging chains that allow for heterogenous attributes of different stock vintages. (BD-12.1)
Innovation in the Automobile Market and Alternative Fuel Vehicles	Struben and Sterman (2008), Stepp et al. (2009), Kieckhäfer et al. (2014), Keith et al. (2019), Bhargava (2020), Keith et al. (Forthcoming), Naumov et al. (2020)	"Chicken-egg" dynamics in two sided markets	How should automation be regulated?	What are the unanticipated effects of policies to encourage automation that may lead to increased congestions? How can alternative fuel vehicles be incentivized or made attractive for last-mile deliveries?	Platform competitions under technology changes (Anderson 1996). Also summarized in BD-10.4 Congestion modeling (Naumov et al. 2020)
Skilled Worker Infrastructure	Ghaffarzadegan et al. (2017)	Feedback between current workforce structure and managerial decision making	How to create a workforce that can maximize competitiveness?	How do we incent universities to encourage students to study the skills most useful to long-term national needs? How do we incent firms to offer ongoing training?	“Rookie-Pro” ageing chains that account for heterogeneous productivity of experienced vs inexperienced employees (BD-19.1, 19.2) Homer assignment model for resources (1999)

*Source of question is from authors as opposed to from research agendas in sample papers **Unless otherwise indicated, SD structures can be found in Sterman (2000), which summarizes seminal research in system dynamics, and presents many of the commonly used structures and formulations for a wide variety of modeling applications. For ease of reference, we will note the Chapter and Section where a relevant structure is presented as “BD-xxx yyy” where xxx is the chapter and yyy is the section.

Table A5: Sustainable Operations Literature and Open Questions*					
Research Topics	**Selected References**	**Useful SD Features**	**Policy Questions**	**Operational Questions**	**Relevant SD Key Structure for Future Research****
Literature Review	Abdelkafi and Täuscher (2016), Rebs et al. (2019)	Clarify the fundamental tension between the desire for unlimited growth with limited resources	How can we rethink the concept of "sustainable growth"?	What are the appropriate time horizons for evaluating sustainable operations models?	Compared to analytical models and mathematical programming, simulation models are underrepresented in sustainability SD models of expectation formation, uncertainty and risk (BD-16)
Models for Climate Change and the Environment	Fiddaman (2002, 2007), Kunsch and Springael (2008), Sterman et al. (2012), Currie et al. (2018)	Interactive flight simulators for understanding and communication Understanding overshooting systems	What is the right communications strategy to educate decision makers on climate policy? What is the impact of technological change for sustainability on operations?	How should we design flight simulators to improve stakeholders' intuition?	Flight simulator design (Sterman et al. 2013) Feedback loop between technology and sustainability (Fiddaman 2007)
Planning, Development and Construction	Saysel et al. (2002), Shen et al. (2005), Kapmeier and Gonçalves (2018)	Model the tradeoff between growth and environmental impacts	What is the rate at which regulation target levels be raised? Should they be continuously increasing or "lumpy?"	How do regulations impact capacity planning?	(Kapmeier and Gonçalves 2018)
Resource Management, Circular Economy and Closed Loop Supply Chains	Moxnes (1998, 2004, 2005), Mendoza and Prabhu (2006), Georgiadis and Besiou (2008, 2010), Purnomo and Mendoza (2011), Bhattacharjee and Cruz (2015), Do Val (2019)	Broad model boundaries allow for analysis that incorporate both the environmental and economic aspects of sustainability	What is the role of legislation in achieving compliance?	How do different regulation or incentive structures affect individual industries, and how do they affect operations at firm level? What is the impact of production techniques on sustainability?	Models that include social aspects of Sustainable Development (Kapmeier and Gonçalves, 2018) Scrap reduction from Lean Manufacturing. (Gupta et al. 2018)
Fuel Economy, Emissions and Waste Reductions	BenDor (2012), Lehr et al. (2013), Saysel and Hekimoglu (2013), Yuan (2014)	Induced demand Rebound effects	What is the optimal recycling percentage that should be pursued?	How should lifetime recycling policies be designed to best encourage compliance? What incentives would drive more durable products?	Aging chain structures for age of product vs. likelihood of disposal (BD-12)

*Source of question is from authors as opposed to from research agendas in sample papers **Unless otherwise indicated, SD structures can be found in Sterman (2000), which summarizes seminal research in system dynamics, and presents many of the commonly used structures and formulations for a wide variety of modeling applications. For ease of reference, we will note the Chapter and Section where a relevant structure is presented as "BD-xxx yyy" where xxx is the chapter and yyy is the section.

Table A6: New Business Models Literature and Open Questions*

Research Topics	Selected References	Useful SD Features	Policy Questions	Operational Questions	Relevant SD Key Structures for Future Research**
Entrepreneurship and Start-ups	Paich and Sterman (1993), Bianchi and Bivona (2002), Oliva et al. (2003), Sterman et al. (2007), Zali et al. (2014)	Boom and Bust Dynamics Limits to Growth	What are policies needed to encourage new business model innovation to best enhance operational efficiency and social welfare?	What supply chain models result from new business models? How can regulators design antitrust regulation that enhances operational effectiveness in a supply chain ecosystem? What policies will encourage a firm's new product development?	Startups and integration of complementary products (Anderson 1996) "Market Growth Model" for scaling new businesses. (BD-15) "Design win" model for new product development pipeline
Automation	Nieuwenhuijsen et al. (2018), Naumov et al. (2020), Yu and Chen (2021)	Models of innovation diffusion Broader modeling boundaries for analysis of so-called "unintended consequences" of interventions	What policies should be in place to promote startups and small and medium enterprises' innovations?	How can the innovativeness of small and medium firms be measured? How will regulation and taxation policies affect startup and small & medium enterprises' operations differentially from large, mature firms? How can large platforms be prevented from suppressing IP infringement?	Innovation diffusion models coupled with product "hype cycle" dynamics. (BD-9.3)
Platforms	Anderson and Parker (2013), Parker et al. (2016), Keith and Rahmandad (2019)	Models that combine SD and game theory	How should new business models such as platforms be regulated?	What are the operational effects of converting "gig workers" to employees? How can waste production by online firms' deliveries be reduced?	Platform models of demand, technology, and supply (Anderson 1996) Search on complex landscapes (Rahmandad 2019)
R&D and Product and Process Interdependencies	Anderson (1996), Milling and Stumpfe (2000), Akkermans and van Oorschot (2016), Hsieh and Chou (2018)	Models for project management, and concurrency for "strange projects" that face many unknown risks (Pitch et al. 2002, as quoted in Akkermans and van Oorschot 2016)	What policies are needed to manage new technologies and their potentially deleterious effects?	What is the effect of automation on reduction of a firm's unskilled workforce and increase in skilled employees? How should 3D printing be regulated to increase safety and reduce IP theft without stifling innovation and improving supply chain resilience?	"Design wins" model of new product development pipeline Project models including concurrency, rework, etc. (Lyneis and Ford 2007)

*Source of question is from authors as opposed to from research agendas in sample papers **Unless otherwise indicated, SD structures can be found in Sterman (2000), which summarizes seminal research in system dynamics, and presents many of the commonly used structures and formulations for a wide variety of modeling applications. For ease of reference, we will note the Chapter and Section where a relevant structure is presented as “BD-xxx yyy” where xxx is the chapter and yyy is the section.

Table A7: Energy Literature and Open Questions*					
Research Topics	**Selected References**	**Useful SD Features**	**Policy Questions**	**Operational Questions**	**Relevant SD Key Structures for Future Research****
Literature Review	Ford (1997, 2020), Teufel et al. (2013), Qudrat-Ullah (2015), Ahmad et al. (2016), Leopold (2016), Parker et al. (2019), Selvakkumaran and Ahlgren (2020)	Models that allow for understanding of the dynamics of energy transitions Delays in the demand control loops and capacity acquisition generate cycles	How can we most effectively use regulation and incentives most effectively supply energy in terms of cost, reliability, and sustainability?	How can we accurately forecast demand and match generation capacity in an increasingly decentralized market? How do we design markets to ensure reliable energy and utility viability?	Platform structures (Anderson 1996) also summarized in (BD 10.4) Capacity acquisition behavior by managers Forecast structures and perceptions of other actors forecast structures (BD 16)
Power Generation and Electricity Markets	Fan et al. (2007), Sánchez et al. (2008), Kilanc and Or (2008), Arango and Larsen (2011), Moumouni et al. (2014)	Models for project management (BD-2) Models that combine simulation with credit risk theory and game theory (Sánchez et al. 2008)	How can a platform market for the electric power industry be developed to improve the integration of distributed energy resources into electricity distribution systems? (Parker et al. 2019) Are there sufficient incentives to build adequate generation capacity in liberalized energy markets? How should utility business models be revised to avoid the utility death spiral?	What's the impact of dynamic electricity pricing on capacity investments, demand response adoption, emission levels and technology mix of electricity generation portfolios? (Parker et al. 2019) How do different rate structures affect renewable energy capacity investments?	Prices and desired capacity (BD 20) Perception delays (BD 11.3) Yield management structures and capacity planning (Pierson and Sterman 2013)
Clean Energy, Sustainable and Renewables	Movilla et al. (2013), Aslani et al. (2014), Franco et al. (2015), Osorio and Van Ackere (2016), Castaneda et al. (2017), Fontes et al. (2018), Zapata et al. (2019), Liu et al. (2019)	Modeling competing scenarios	How does regulation & deregulation impact efficiency of integration of renewables into the grid? What market policies or regulations can help improve the large-scale integration of renewables?	How can renewables be used to secure supply, provide competitive prices and provide environmental protection? What is the impact of large-scale renewable integration on optimal schedule and dispatch of power generation resources?	Design of energy storage technology in presence of grid platform effects (Anderson and Parker 2013)
Evaluating Alternatives and Risk Management	Johnson et al. (2006), Tan et al. (2010), Jeon and Shin (2014), Shafiei et al. (2015), Fazeli and Davidsdottir (2017).	Modeling competing scenarios	Can clean energy policies be improved by bringing in an OM perspective?	How can operations and supply chain management be revised to reduce emissions?	See approximations for mileage in a vehicle routing problem (Figliozzi 2009)

*Source of question is from authors as opposed to from research agendas in sample papers **Unless otherwise indicated, SD structures can be found in Sterman (2000), which summarizes seminal research in system dynamics, and presents many of the commonly used structures and formulations for a wide variety of modeling applications. For ease of reference, we will note the Chapter and Section where a relevant structure is presented as “BD-xxx yyy” where xxx is the chapter and yyy is the section.

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