Opportunities for System Dynamics Research in Operations Management for Public Policy

Edward G. Anderson Jr.

University of Texas at Austin, Austin TX

David R. Keith

Jose Lopez

Massachusetts Institute of Technology

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Abstract

Policy-related research is a rapidly growing area of operations management. However, the policy context is often an exceedingly complex system with many mutually interacting factors and multiple stakeholders with diverging objectives, which can result in unintended and deleterious consequences for operational strategies. For decades, researchers have used the system dynamics approach for analyzing such systems to study public policy problems because of its ability to model the interaction of multiple non-linear relationships with delays, its suitability for testing policies with scenario planning, its ability to bridge between different disciplines, and its highly-developed methodology for reaching stakeholder consensus. 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 when researching public policy-related operations management. We conduct a scoping review of the relevant literature, both in traditional operations management venues as well as in domain-specific policy venues that are less known to the operations management community. From this literature, we describe why, when, and how system dynamics might be useful. We then cluster the extant literature for ease of reference for scholars, identifying a set of interesting open questions and potential building blocks for answering them for each cluster. We conclude by identifying several overarching questions for future research and propose a refined process for using system dynamics with traditional operations management methodologies in public policy contexts. Methodological questions include: (1) the integration of common operations management techniques, such as mathematical programming, directly into system dynamics models; (2) expansion of group modeling methodologies to reach consensus; (3) identifying feasible trajectories from current to desired states; (4) feeding back implementation results into the modeling and implementation process. Domain questions include: (1) spillover between research silos that affect potential operations strategies; and (2) buttressing supply chains to cope with global disruptions such as pandemics.

Keywords*: System Dynamics, Operations Management, Public Policy, Simulation; Scenario Planning*

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 practice more effectively (Tang 2016). However, this has proven difficult for a number of reasons (Sodhi and Tang 2008). Foremost of these is public policy problems are typically embedded in complex systems, which make 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). They have 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 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 problem is two-fold. 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 hand, research in public policy venues captures important policy constructs but often insufficiently models the details of operations management because of a lack of understanding of the field (Besiou and Van Wassenhove 2015). Clearly, a high-level systems approach that can integrate operations management issues with public policy is needed.

For decades, the field of system dynamics (SD) has proven to be one such systems-level approach that 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 OM interventions exist that have functioned successfully in complex systems (Sterman 2000, Größler et al. 2008, Van Wassenhove and Besiou 2013, Sterman et al. 2015, Joglekar et al. 2016). There are a number of reasons for this. System dynamics is a computer-aided approach that originally derived from control theory and electrical engineering by Jay Forrester. The models themselves are generally nonlinear differential-equation state-space models similar to what is used in optimal control theory, albeit the models tend to be larger and require simulation. Variables and parameters correspond directly to real-world metrics such as 'work hours per week' or 'dollars per year' wherever possible, and many standard formulations have been developed over time (Hines 1996). Researchers developing SD models often employ techniques such as scenario planning (used in the majority of SD operations models geared towards public policy) and group-model building among stakeholders (used less frequently in research, but often in practice). The SD methodology was specifically developed to analyze dynamic problems arising in complex social, managerial, economic, or ecological systems characterized by multiple stakeholders, mutual-interacting endogenous variables, interaction, information feedback, long delays between cause and effect, and circular causality, which makes it an ideal tool for studying public policy problems (Besiou and Van Wassenhove 2015). That said, its first applications were in operations management (Forrester 1958). Since then, SD has 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 its demonstrated potential, there are relatively few publications addressing OM in the public policy space. Reasons for this include that the number of System Dynamics papers published in the entire corpus of operations management is relatively small. (Using the methodology described in Section 3, we only identified approximately 65 papers published since 2000 in the seven OM journals searched). Also, many important system dynamics 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 to rectify this problem by providing a roadmap for OM researchers for the use of system dynamics in public policy contexts, including those that have done SD research in the past as well as those that 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*, the purpose of which 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 the supply chain, Joglekar et al.'s (2016) review of industry studies and public policy, and Parker et al.'s (2019) review of energy-related operations management (Parker et al. 2019). However, this paper necessarily differs from these 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 system dynamics might prove a useful tool for researching OM in public policy based on prior researchers' work in this area, particularly (Homer and Hirsch 2006, Größler et al. 2008, Besiou et al. 2011, Sterman et al. 2015, Besiou and Van Wassenhove 2021), as well as the authors' [omitted to maintain author anonymity] years of research experience in system dynamics and operations management. We then map out 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 they needed to look outside the typical operations management journals in their survey. We follow them by reviewing policy-related system dynamics operations literature both in the standard operations management venues and in public policy venues. We also follow Parker et al. (2019) in that this scoping review will not be exhaustive because 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 that 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 overarching questions of greatest opportunity. Some of these are domain questions that emerge as common among all clusters, while others address methodology.

The closest papers to ours treat system dynamics 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) updating all realms to include references and exemplars after 2013 (or 2015), and (4) identifying a number of specific open questions in the system dynamics 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. Größler et al.'s (2008) and Sterman et al.'s (2015) reviews of the use of SD for operations management are also related. However, we focus strictly on public policy, which brings specific issues into play that are not addressed by those papers, and hence the roadmap for research is different. An example is the need to integrate structures drawn from political science and public policy economics. We also include more recent references.

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

[Insert Figure 1 about here]

Based on our work developing the roadmap above, we highlight six gaps in research that should be addressed to enable better use of SD for OM problems in public policy contexts. To the best of our knowledge, these have not been explicitly called out before as challenges, but we believe that articulating them would be helpful for researchers.

With respect to operations management problems in public policy contexts:

1. More research is needed with respect to building consensus among stakeholders with system dynamics models.
2. More research is necessary on integrating system dynamics with traditional OM methods, such as mathematical programming or queuing theory, to create hybridized methods that combine the different strengths of both approaches. Besiou-Van Wassenhove (2015) identified this as crucial, but the literature is lacking.
3. Research must pay more explicit attention to the fact that system dynamics studies can identify trajectories from current state of affairs to a desired "ideal" state, including whether OM strategies will need to evolve over time. In particular, this research must account for path dependencies that might prevent the ideal state being achieved.
4. Research with respect to feeding back the results of implementation into adjusting models and operations to improve future outcomes appears almost entirely lacking.
5. More research is needed into the "spillovers" between research silos in public policy (e.g., humanitarian operations often result from famine created by civil conflict; sustainable operations, energy and transportation questions can be closely linked).
6. Research on creating global supply chains more resilient to disruptions from pandemics, trade disputes, etc. is sparse, aside from that directly related to medical products and services.

Based on these points, we also propose that 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 system dynamic 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. We first discuss the advantages of SD and when it is best used by OM researchers to supplement classic techniques and the challenges to doing so. To motivate our work, we leverage an in depth example: developing a network of fast-charging stations for electric vehicles. We then describe the methodology behind selecting the article sample and clustering 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.

2. Features of System Dynamics Modeling

Before going any 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) and 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’). We use the abbreviation SD for system dynamics. We also use the abbreviation OMPP to denote “operations management in public policy contexts.”

We build upon Agrawal et al.’s (2019) proposal that argued that operations management problems in the public policy space are problematic because OM and policy decisions cannot be isolated from each other (Figure 2). Additionally, they argue that these contexts have multiple stakeholders.

[Insert Figure2 about here]

Joglekar et al. (2016) expanded upon this to explicitly argue that OM and policy influence each other bidirectionally (Figure 3). Their example was the US Clean Air Act of 1970. The government set a standard for the emissions of cars sold, and once automakers met these standards, the government then increased their stringency.

[Insert Figure 3 about here]

Once public policy is considered part of an operations management problem, however, the result has a number of characteristics that often make it a complex system (Besiou and Van Wassenhove 2015). Complex systems are characterized by—among other things—multiple stakeholders with conflicting objectives, context uncertainty and perhaps problem ambiguity, multiple feedbacks that mutually interact often in nonlinear ways, 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). Because of these factors, potential interventions are difficult to validate, because, among other reasons, interventions result in often 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 (2005) in a conversation with one of the authors. He said “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?”

System Dynamics has a long history of successfully addressing problems in complex systems (Forrester 1958, 1961, Sterman 2000, Besiou and Van Wassenhove 2021). The reason is that SD has 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 and not others. How does an OM researcher recognize which contexts are 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 US to recharge electric vehicles (EVs). Fast charging stations are to electric vehicles what gasoline stations are to gasoline-powered cars. Their availability has been identified by many sources as the biggest barrier to electric vehicle adoption, including the US Department of Energy and McKinsey & Co. (Jones et al. 2018, Gersdorf et al. 2020). How many stations should be built? Where should they be located? And what sequence they should be built in are part of a classic OM question, that of facility location. In principle then, we might assume this could be solved by a straightforward mathematical programming model. However, upon further examination, there are aspects of the problem that make it a complex system. Bhargava et al. (2020) describes a number of these issues in detail. First of all, as more stations are built, more EVs will be bought, which makes it more profitable for 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). The cross-side externalities show diminishing returns with respect to the number of stations, creating nonlinearities. Delays are present in the time it takes to construct stations and the time for consumers to perceive the improved availability of fast-charging stations and then purchase EVs in response. There are also multiple stakeholders with conflicting objectives. State and Federal governments seek to expand the number of stations as fast as possible by setting a single standard for stations that is compatible with all firms' EVs. On the other hand, some firms (e.g., Tesla) can and have invested in their own proprietary, incompatible networks to maximize profit from sales of their own vehicles while excluding benefits to their competitors. Firms without their own networks want to enforce interoperability. 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 compared with renters and apartment dwellers. Hence, suburban owners are much less likely to support the taxes to fund government subsidies for building stations. Additionally, there is the technical side of the issue: how will EV driving ranges increase with time? What are the investments in utilities 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.

We note that we are building off of the existing corpus of SD work in our discussion below. That said, the SD tool-kit below is constantly evolving and becoming more effective over time (Rahmandad et al. 2015).

2.1 Modeling Complex Systems Structure

System dynamics models with 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 upon the engineering discipline of control theory. Hence, SD models center upon the modeling of systems with feedback loops and time delays (Forrester 1961). As stated earlier, we do not treat how to build SD models in this paper because there are many excellent references on how to do this (Sterman 2000, Meadows 2008). Fundamentally, however, there are two kinds of feedback loops. One type is a 'reinforcing' feedback loop where the effect of an initial perturbation is amplified over time, such as the accumulation of interest in a bank savings account. The other type is a 'balancing' feedback where the effect is to resist an initial change, resulting in goal-seeking behavior over time, such as a hot cup of coffee cooling to room temperature. In addition to this, Forrester recognized that many of the relationships between variables in these loops are non-linear, and that the interaction of these loops with nonlinearities and delays can create counterintuitive behavior. For example, SD analysis could show that subsidies for purchasing EVs may have given early movers a sufficient advantage in growth and market share that they could benefit from building proprietary station networks that ultimately hinder other competitors entering the market (Bhargava et al. 2020).

SD models include a number of standard formulations for decision-making behavior by both organizations and individuals, such as how much overtime should be worked as 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 differing 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 tradeoffs relative to other techniques commonly used in OM. Please refer to Table 1 below.

[Insert Table 1 about here]

It must be emphasized that the entries in each row are for "typical" models using a given technique, and various exceptions exist. For example, simplified optimization models of inventory or queues are often included as part of game-theoretic models in the OM space. That said, the table illustrates some important trade-offs. One is that SD is useful for handling problems whose—often ambiguous—boundaries include the behavior of stakeholders, public perceptions, and domain-specific factors such as ecological, legislative, or technological processes, which a mathematical optimization model typically cannot do. However, unlike mathematical optimization models, it models operations structure in aggregate rather than detailed form and relies on numerical simulation. Hence, system dynamics models can yield a robust operations solution that functions reasonably effectively over a broad range of scenarios (Joglekar et al. 2016). Related to this is that it is more difficult to characterize the behavior of system dynamics models than game theory models or even linear programming models, although advances are being made in this arena (Oliva 2016, 2020). Another tradeoff is that SD models often need less data gathering 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 that can better leverage detailed structural data. The question then becomes how to utilize the strengths of both system dynamics and other OM methods to get the best of both worlds. We discuss this in more detail 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 concerning SD models, which is that SD models can be useful for consensus building – something that is rarely described in our sample. The models that dominate our sample are of the type commonly seen in the system dynamics OM literature, which are relatively large models used for operations design. Seen much less often are smaller models in which the model serves as an artifact used to build consensus among stakeholders. These models are significantly simpler structurally, need much less data, and can be built very quickly while incorporating multiple stakeholders' inputs in a process of "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 or automotive engineers. This creates a powerful tool for building consensus, without which many OMPP solutions will fail as described earlier. Once the buy-in of stakeholders is achieved with a simple SD model, a detailed SD model for operations design can be pursued. However, it is only the latter that is published. A good example of this is Kapmeier and Goncalves's (2018) model of island tourism sustainability. Reading between the lines, there appears to be some group model building going on, but it is not stated explicitly, much less described. Hence, descriptions of the processes by which consensus building is reached is underrepresented in our sample. One other related use is that models are often given a user interface to create “management flight simulators” allowing non-SD modelers to easily interact with the model (Sterman et al. 2013). These simulators can be useful for soliciting stakeholder input, helping employees and policy makers develop improved mental models of system behavior, and facilitate effective scenario planning.

Returning to our fast-charging station example, stakeholders include governmental agencies such as the Department of Transportation and the Department of Energy as well as their state-level equivalents. Private entities include EV firms, non-EV, or transitioning automotive firms, independent fast-charging station owners, battery firms, and electric utilities and their technology suppliers (solar, wind, fossil, nuclear). Finally, there are non-governmental organizations (NGOs) such as consumer and environmental advocacy groups. All of these have conflicting objectives. Perhaps, even more importantly, they do not fully understand the drivers behind other stakeholders’ viewpoints, which group model building has been shown to successfully improve (Andersen et al. 1997).

2.3 Triangulation with Other Methodologies

Once consensus is reached, another model may be used to add the detail needed to create practical OM solutions, which could be an expansion of the consensus-building SD model. In principle, while it is not often seen, 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 as per Besiou and Van Wassenhove (2015). In the EV fast-charger model, for example, the output of a high-level SD model could be used as input for allocating a period’s investment in specific stations using a more traditional facility layout model based on mathematical programming. 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 be then 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 system dynamics for 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 are not known with certainty, particularly over the long time horizons associated with policy, meaning that many plausible futures must be prepared for (Schwartz 2012). SD models can facilitate this by capturing the many interacting decision variables, actors, and uncertainties typical of policy decisions, and 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). Most SD models in our sample use detailed sensitivity analysis of important parameters as one way of coping with these issues. A smaller number use formal Monte Carlo analysis (Besiou et al. 2014, Thompson et al. 2015, Kapmeier and Gonçalves 2018). A third group cope with model ambiguity problems by testing the robustness of solutions against model structure or boundary changes.

With respect to the EV fast-charging station example: Would it be better if the government influences station location decisions by offering incentives to build infrastructure in rural areas not serviced by interstate highways, or alternatively to mandate them? Either way might lead to perverse effects on social welfare under some scenarios. Another issue is whether or not an EV manufacturer building fast-charging stations should be required to make their stations interoperable with other brands? Arguably, allowing firms to make their stations incompatible with other brands could expedite their investment in stations to capture rents, at least initially. However, it could allow market leaders, such as Tesla in the US, to lock out their competitors. This might have a number of effects: reducing competition by more innovative EV-makers; hindering entry by more capable incumbents (at least in manufacturing) from the gasoline vehicle industry; and fragmented or inefficient standards. All these would ultimately deter EV adoption. One could imagine then that transitioning at some point from permitting incompatibility to enforcing compatible standards might be optimal, but 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 to make 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

Lastly, because adding additional structure to system dynamics 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. 2015). The fast-charging station problem actually goes beyond this by involving issues that are looked at from other disciplines outside operations management. In addition to operations management articles, Bhargava et al. (2021), cites research articles from political science, economics, and domain literature from engineering as well as operations management. Other policy problems may of course be looked at from other disciplines, but comparing them might prove of value 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 in Table 2 below.

[Insert Table 2 about here]

Each perspective lets us see part of the complex system that is building out EV fast-charging stations, much like the folk tale of 5 blindfolded people, each exploring part of an elephant by touch. One touching the elephant's leg says an elephant is like a tree. Another touches the elephant's tail and likens the elephant to a rope, and so on. Of particular import to our discussion 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 the political decisions of whether all stations are mandated to be interoperable, the economic decision of whether to subsidize the purchase of EVs to stimulate demand, or the engineering decision regarding whether to put a new battery technology into a vehicle (which might favor range over reliability).

We note that this structure is, at an abstract level, relevant to many other problems with only minor changes (Rahmandad et al. 2020). Hence, many of the 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 if epidemiology and physiology replaced the engineering discipline as domain experts, typical metrics such as the percent of the population immunized and infected were used, SEIR compartment models were employed as the dominant representational paradigm and so on. This would result in decisions such as how to fast track vaccine development and how to prioritize which population segments are vaccinated first. Or when and how much capacity (including beds, staffing, and ventilators) should be added to different area hospitals (Goncalves et al. 2021).

Looking at the SD literature sample in this paper, we find a wide range of commonly shared structures that can model a broad variety of problem contexts, decisions and outcomes. Hence, much systems complexity can be captured, permitting a "good" solution that is robust by accounting for structures that typically cannot be captured by other OM disciplines. However, this does come at some cost. In particular, aggregation of variables may miss important operational structure needed for fine-tuning solutions, and reliance on computer simulation, which makes it more difficult to optimize, may cause this "good" solution to be sub-optimal. Hence, 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.

3. Sample Selection Methodology

Literature that applies System Dynamics to operations management in policy contexts is widely dispersed in many journals across many fields. At the same time, the operations management community publishes a high volume of articles across a wide range of domains every year. To manage the scope of our literature search, we follow prior papers such as Krishnan and Ulrich (2001) and Parker et al. (2019) that have had the same goal of identifying current research opportunities for OM scholars. That is, we will 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 conducted 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*, 5) *Management Science*. (Leading is defined as being the operations management outlets appearing on the University of Texas Dallas's list of leading academic journals in major business disciplines. This 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 that 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 the year 2000, because our main thrust is to illustrate research questions of interest for current and future researchers. We then eliminated those articles because they were judged by the authors as not public policy-related (e.g., they addressed only "inventory management policies") or were not system dynamics related. This 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 system dynamics researchers. In this sample we did not include "simulation" or "system dynamics," because these terms are redundant in these outlets. Again, we eliminated those articles because they were judged by the authors as not public policy-related. This 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 system dynamics research publications maintained by the System Dynamics Society, which contains approximately 2500 journal articles. It can be obtained from the System Dynamics Society's bibliography webpage (https://www.systemdynamics.org/bibliography). The System Dynamics Society Bibliography revealed that system dynamics research also appeared frequently (as defined by over 50 instances) in the following two operations management-related

journals: (1) *Journal of the Operational Research Society* and (2) *European Journal of Operational Research*. We added these because of not only their frequency of publications, but also their explicit linkages (unlike the six journals listed above) to research societies based outside of the United States. We then searched on these journals for articles using the same criteria as in (1) above. This resulted in a further sample of approximately 15 articles.

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

4. We then searched the System Dynamic Society's bibliography again, because this proved 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 5 articles that were not captured by the above searches
5. We contacted the Jay W. Forrester Award winners from the past twenty years (i.e. since 2000) to provide us with additional guidance on relevant articles that we may have overlooked. The Forrester award is given annually for the best System dynamics research by the System dynamics Society. We also searched on the Award winners articles since 2010 that treated operations management in policy contexts. This yielded approximately 15 articles that were not 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 Parker et al.'s (2019) expansion of their search. This obtained the balance of the sample, approximately 40 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 that we use to structure our review in Section 3 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. Some of these research areas were similar enough to 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 identify what aspects of complex systems are particularly salient. We then identify exemplar articles of rigorous and important research in the cluster and occasionally some other articles of interest. A table contains the relevant articles in the sample and further subdivides them into topics for ease of reference. The tables also contain how each topic leveraged contributions from SD. They also include relevant open questions and additional SD "building blocks" in the extant literature relevant to the open questions. The tables and exemplars are intended to be the primary product for use by researchers.

4.1 Humanitarian Operations and Crisis Management

In the last half a century, the number of disasters, natural (e.g., earthquakes, hurricanes, monsoons, floods, droughts), man-made (e.g., war, displacement, forced migration, famines), and most recently pandemics, has risen dramatically. Forecasts show that in the next half century, these events are expected to increase in frequency even more (Allahi et al. 2018). Humanitarian operations efforts strive to provide aid and relief in context typical of complex systems as described earlier. Particularly problematic are multiple stakeholders with often widely differing objectives (Starr and Van Wassenhove 2014). Additional pressures on humanitarian organizations (HOs) include inadequate funding, high staff turnover, very limited time horizons to react to catastrophes, compressing project lifecycles (Besiou and Van Wassenhove 2020). The operations management literature has proposed many excellent approaches for planning and directing humanitarian aid that have proven of great help. However, studies have shown that others have faced difficulty in implementation and hence 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 and builds a model to analyze different preparedness scenarios for therapeutic food items to enable fast response. He finds that the fastest method is to preposition stocks of relief supplies to all countries that are prone to disasters. However, while that is fast, it is also prohibitively expensive. Alternately, investing in capabilities such as training staff and pre-negotiating customs and other arrangements in countries prone to disaster up front so that centrally held stocks can be rapidly transferred to affected regions is less costly, but also slower. The paper finds that a mix between the two strategies provides the best performance and goes on to recommend specific allocation policies to relief organizations to achieve the best mix.

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

There are other topics addressed by SD research that emerged from our cluster analysis as well. One directly addresses the compressed "life-cycle" of humanitarian operations (e.g., Ni et al. 2015). The other is humanitarian supply chains. Among the latter, Diaz et al. (2019) and Badakshan et al. (2020) tie back to the original SD work of Forrester (1961) by studying the bullwhip in relief efforts. Table 3 summarizes the existing research in Humanitarian Operations and Crisis Management that uses SD.

One important open challenge in the field in humanitarian operations is how best to deal with the complexity of last mile distribution. Logistics and distribution studies have identified that the last mile accounts for most of the cost under normal day-to-day conditions in developed nations with established carrier services and good infrastructure. In contrast, humanitarian organizations are often tasked with last mile distribution in areas where there is little to no infrastructure to get aid to those that most need it. Related to this, extant work has used classic OM optimization approaches to plan routes and determine vehicle fleet sizes and to address coordination challenges in humanitarian relief chains (Balcik et al. 2008, 2010). However, because of the complex systems in which these problems are embedded, SD could prove a useful tool (De Vries and Van Wassenhove 2020). Another challenge is to develop strategies to cope with hoarding, which is commonly seen in humanitarian operations settings, resulting in longer delivery times and greater perceived shortages, creating positive feedbacks that intensify scarcity and destabilize supply chains by reinforcing the perception of shortages (Sterman and Dogan 2015). If hoarding could be ameliorated by appropriate policies, then the difficulty inherent in rapidly establishing ad hoc supply chains during crises could be markedly reduced. Another open question is the relationship between humanitarian operations, media presence and coverage of operations, and humanitarian organization funding (Burkart et al. 2016). Because of its complexity and overlap with marketing, it is an ideal candidate for SD research. Nageswarakurukkal et al. (2020) begins to address this by examining how social media publicity, its effects on fundraising, and ultimately operational efficacy mutually interact. 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 can in turn exacerbate food shortages (Besiou et al. 2011). This makes humanitarian options even more complex and is another excellent area for SD research, though, looking at our sample, it remains underexplored at present. Table 3 summarizes the research map for this cluster.

[Insert Table 3 about here]

4.2 Healthcare Operations Management

Healthcare operations management (HOM) is also widely recognized to be an exceedingly challenging domain 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, accounting for approximately 5% of GDP (Leape et al. 2009), numerous safety issues—such as unnecessary hospital deaths being the 3rd leading cause of death in the U.S. (Donaldson et al. 2000)—and poor service (Binary Fountain 2018). While not as well documented, there is evidence that 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 the "usual suspects" in OMPP contexts: numerous interacting stakeholders that constitute healthcare such as patients; doctors, nurses, and other health care providers; hospitals; insurance companies, pharmaceutical manufacturers and distributors; as well as local and national governments, all of which have different goals. Public policy makers that try to coordinate the system have limited resources that require 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, who have proposed 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 explain in part 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, dating back to the 1960's, SD has successfully been used to study a wide variety of topics in HOM, generally using simulation to complement empirical and observational studies. often providing surprising insights into the most powerful levers to avoid policy resistance (Darabi and Hosseinichimeh 2020). An earlier survey by Homer and Hirsch (2006) make similar observations.

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). An outstanding example of the potential of SD research in this area is the series of papers by Thompson 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 System dynamics with a number of other operations management/research techniques including decision analysis, game theory, linear programming, and inventory models. It 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 rather than slacking off as polio is brought under control. The reason being that, much like a banked fire that if disturbed can give off embers that can ignite other fires, even a small number of polio cases can flare up quickly into larger outbreaks. To deal with them, responding quickly is paramount, even if that speed comes at the cost of perfect coverage. Hence, a large stockpile of vaccine needs to be maintained at all times. The paper also develops a policy to determine when to switch from administering an oral poliovirus vaccine to an inactivated poliovirus vaccine. The oral poliovirus is cheap and more effective for snuffing out an outbreak quickly; however, it can (very rarely) cause dangerous side effects or worse, mutate sufficiently to create a dangerous polio epidemic of its own. Hence, at some point it should be abandoned in favor of the inactivated vaccine.

At a more micro level, models of disease in the human body is another topic area where SD has been widely adopted. Estimates show that nearly half of all adults in the United States suffer from at least one chronic illness and those illnesses ultimately result in seven out of ten 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 chronic illnesses are obesity, diabetes and heart disease. Kang et al. (2018) develop a model incorporating 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 in much SD research—such as discussed in humanitarian operations earlier—of investment beforehand being more effective than treatment afterwards. In particular, the authors found that programs to create resiliency (or the ability to rapidly recover from traumatic effects) before a combat assignment are more cost-effective than screening or treatment afterwards.

SD models have been prominent in epidemiology, going back to traditional SI (Susceptible, Infected) 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 best to 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, but adds in a mental health sector.

SD modeling has also been successfully used to study patient flows and capacity planning in healthcare institutions (Diaz et al. 2015, Wang et al. 2015). As an exemplar, in 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 through bed reductions) and emergency room waiting times. Through sensitivity and extensive scenario testing of a calibrated SD model, the authors, counter to the conventional wisdom, found that the major impact of bed shortages is not directly felt in emergency admissions, but rather first felt in elective admissions. Hence, the traditional practice of using emergency room waiting times to measure the effect of bed reductions is misleading. This paper, while relatively old, has three other reasons to stand as an exemplar. It has an extended description of SD validation tests used on the model. Despite touching on it only briefly, the paper also describes that the model was developed via group model building techniques—and ultimately accepted as valid—among stakeholders. Finally, it has an excellent discussion of the tradeoffs between modeling with SD or discrete event simulation.

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

Finally, Goncalves et al.'s (2021) treatment of capacity is an exemplar for a number of reasons including exemplary sensitivity testing and calibration. Perhaps even more importantly, it has one of the best descriptions of creating consensus among stakeholders using system dynamics, and interestingly it offers a different paradigm from 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 a result of perverse incentives between providers, physicians, pharmaceutical companies, insurance companies, and many other actors driving unintended cost increases. Furthermore, 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 have sought to 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 margin 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 remuneration policies. Arguments have been made that paying a fee for each service increases unnecessary procedures, leading to implementation of 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, System dynamics studies could be of great help in researching these problems and guiding future policy decisions. However, the SD literature in this 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 to consider is how to improve quality and safety. Multiple studies have found evidence that, despite increasing costs, healthcare is not as safe as it should be. Estimates have put this number at approximately 300,000 preventable deaths occurring as a result of medical errors, and over $50 billion 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), which obscures 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 US wastes close to half a trillion dollars annually on healthcare expenditures that do not improve care (Hopp and Lovejoy 2012). Leape (2002) cites duplicated tests and procedures as the second greatest drive of this waste. Partly this is due to information systems fragmentation resulting in one institution not being able to see what another institution has already done with a patient. At a higher level, reimbursement policies by insurers, including national health systems, also create waste. For example, payment to hospitals at a per capita rate based on the number of patients they serve may lead to skimping on acute healthcare when it is needed. Alternately, fee-for-service can induce skimping on preventive care, which disadvantaged groups have fewer resources such as insurance, to pay for themselves. Another issue is that remuneration for penalties on patients being readmitted within 30 days by U.S. Medicare has led to mixed results, which is unsurprising as there is pressure on hospitals to shorten the time patients are in hospitals during the initial treatment, perhaps leading patients to be released too early in some cases. All of these issues call out for SD research.

Both duplicated treatments as well as patient safety should be improved by Electronic Healthcare Records (EHR) systems in principle in principle. Hence, the U.S. incentivized the installation of EHR's by all healthcare institutions under the Affordable Care Act. However, unintended results ensued. The easiest-to-install systems were also the least intercompatible at the time the incentivization policy was implemented. This led to systems at different institutions that cannot communicate with each other, obviating some of the safety and cost improvements that were supposed to occur. To complicate this issue, government regulation of combability standards remains weak. Thus, healthcare data intercompatibility actually results in an advantage in "winner-take-all" games for healthcare information systems vendors with the high installed base.

Other open questions that require urgent attention have been brought to the forefront by the COVID-19 pandemic, which laid bare many governments' inabilities to deal with pandemics and other public health crises at both operational and policy levels. For example, over the last few decades, business has relentlessly pursued supply chain efficiency by reducing inventories and safety stock levels in an effort to reap the benefits of just-in-time delivery systems. This was fine when conditions were predictable. In the face of supply shocks from the shutdown of China and later Mexico, however, efficiency has come 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). As discussed earlier in humanitarian operations, hoarding complicated the situation. Even more critically, local and national governments around the world have been dealing with the same problems of communicating clear policies and managing adherence fatigue. While there is some SD research on managing these issues, more is needed to provide insights that can be built upon. For example, SEIR models have been developed to illustrate the spread of COVID-19 and to account for more behavioral responses such as self-isolation measures taken by the public when deaths are 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. 2021). Few, if any, of these studies, however, have been able to link the contagion model to the economic model to study the linkages between the two. Moreover, COVID-19, as well as recent epidemics such as Ebola, have also revealed the necessity to study project management in the specialized and heavily regulated context of accelerating vaccine and pharmaceutical development during pandemics. Building the supply chain to bring parts and raw materials to manufacture the vaccine kits would be difficult under any circumstances, but 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). SD-based research into how this is to be done is urgent and complex.

Clearly, as the field continues to grow there are ample opportunities to continue to leverage the strengths of SD modeling for HOM research. Table 4 below organizes the roadmap for the cluster and provides additional references.

[Insert Table 4 about here]

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, and governments implement policy most often by using operations management levers. This is perhaps not surprising as much of 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., supply chains, logistics, inventory, infrastructure), force (personnel) planning, project management, procurement, and recently the information management/operations interface (Van Creveld 2004, 2010). That said, a number of problems have significant complexity because of sociological issues such as regime legitimacy, and they often have an extra layer of complexity because of the involvement of actively hostile actors with objective functions completely at odds with other stakeholders. There is a long history of intellectual thought in this policy domain that is particularly compatible with SD research. 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 operations management. Second, since the 1800s, military decision making explicitly incorporates 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 of this (Boyd 1995, Plehn 2000, Richards 2020). Interestingly, many of the applications of SD addressing problems in this cluster are never published, which makes the researcher's task more difficult (Coyle et al. 1999). Ford and Clark (2019), however, include a recent survey of the literature shows that this had been somewhat remedied in the areas of "conventional warfare" and weapons systems acquisition.

The oldest stream in CDS research appearing in our sample include that of conventional warfare, particularly force planning and deployment (e.g., Coyle (1981), Wolstenholme (1983)). Unsurprisingly, perhaps, 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 use of flight simulators for training (Coyle et al. 1999). In a slightly different vein, SD researchers explicitly addressed 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 suited to the multiple feedback loops including project rework. Much of this work has treated defense project management and acquisition (Lyneis and Ford 2007). This is reflected in the large number of papers on project management, a core OM discipline, in our sample. SD can also assist in project management because it can handle many factors often not included in OM work using other methods. 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. Interestingly, they span silos into organization management to include team design. Also noteworthy, Ford and Dillard (2008) is an exemplar that examines how different project management strategies used in OM (agile vs. waterfall) trade off against operational effectiveness. For example, using agile project management may expedite equipping some troops with improved weapons systems, but this is at the expense of delays in equipping other units.

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

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 SD's strengths (Lofdahl 2006). Studying the relationship between insurgencies, finance, and 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) illustrate some paths forward in this space.

Finally, there is a spillover between CDS issues, with other clusters, such as humanitarian operations. For example, the decades-long conflict in the Congo has led to widespread famine affecting over 20% of the population, creating the need for extensive humanitarian aid (Programme 2020). Famines often lead to epidemics as well. Studying policy interventions that must interact with operations in humanitarian and healthcare operations would be an excellent use of SD's strengths. Table 5 summarizes and organizes the roadmap for this cluster.

[Insert Table 5 about here]

4.4 Transportation, Logistics, and Infrastructure

One of the core areas of study in operations management is transportation, logistics, and other infrastructure. One would initially think that this would not generally involve complex systems and hence not SD. However, there is some important research in our sample that 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.

Bivona and Montemaggiore's (2010) model of bus maintenance 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 in favor of preventive maintenance to reduce long-term cost. The twist is that the best strategy not only increases preventive maintenance, but also reduces the age of the bus fleet and diverts experienced mechanics' time to teaching rookie mechanics. These actions actually end up raising long-term costs, but also lead to increased service quality and customer usage, resulting in increased profitability. This paper is also an exemplar of actively describing the use of group model building with, among other things, flight simulators that were used by city officials to determine policy priorities. Mayo et al. (2001) is an exemplar that examines many of the same issues with respect to the London Underground, using officials to help build a flight simulator and develop scenarios. The flight simulator itself is discussed at length. Interestingly, however, the authors used the flight simulator as a decision support tool for officials to assist in outsourcing their operations by evaluating bidding firms to determine whether they were in fact capable of running the underground system.

System dynamics addresses the role of OMPP in innovation in transport as well (Keith et al. Forthcoming). 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, consumer utility in their model includes the belief by many policy experts that automated vehicles are problematic for improving the environment because they 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 (car-pooling), which, however, contributes to reducing usage of mass transit. With less usage, the model strongly suggests that pro-ride sharing policies ultimately will reduce mass transit capacity through strangling the funds needed for reinvestment to the point that pollution and energy usage will increase, rather than decrease. Instead, one policy that seems to work well is a tax levied on vehicle miles traveled, which is directed in part at the upkeep of the mass transit system. One other item to note in this paper is the 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), which is an exemplar that examines how yield management strategies interacted with deregulation in the U.S. to create cyclicality in airline's capacity, airplane production, and consumer demand. They find that yield management dampens capacity cycles but increases profit volatility, leading to reduced average profits and lessened viability for airlines.

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 by creating an "operational model" [authors' description] that combines a queuing model as influenced by a number of government policies, university capacity decisions, and individual behaviors. It then explores the behavior of the model under disruptions from the macroeconomy and other factors using sensitivity analysis and scenario testing. An intriguing finding is that disruptions often result ultimately in shortages in filling lower-skilled jobs. This is particularly interesting given current job shortages in the US and Europe in lower-skilled supply chain jobs such as warehouses, ports, and trucking (Camaniti 2021). While the authors do not model it, they also discuss how their model can be extended to look at job training polies that create shortages of skilled workers needed for new technologies.

There are a number of open questions with respect to transport and logistics policy, many involving interactions with other policy areas such as sustainability and new business models. For example, COVID-19 has accelerated a move towards online business models, which in turn intensify the last mile problem, creating more emissions. In addition, retail outlets may be weakened in urban areas because of pandemic-driven "flight" to the suburbs, further intensifying the last-mile problem (Bloch 2021). This leads to a need for policies to accelerate the shift to alternative fuel vehicles and perhaps 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 online work, 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). Automation of driving must be regulated for safety purposes, and new infrastructure may be needed to facilitate it. 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 requiring pilot licenses to operate commercial drones beyond visual range, but that may damage their cost-effectiveness, particularly if they can reduce fossil fuel emissions. This ties in with educational issues that create national workforces inappropriate to economic, and especially to 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 6 summarizes the articles, open questions, and other information for this cluster.

[Insert Table 6 about here]

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 these issues are questions about how we consume resources as a society—renewable and non-renewable—in the presence of lengthy time delays between actions and consequences in combination with the potential for self-interested and short-term behaviors that are at odds with the difficult collective actions needed to achieve true sustainability. Like other areas of policy, governments can enact sustainability policy to align the incentives of individuals and firms with the collective good in principle, but system complexity often leads to unintended consequences and counterproductive policy-making (Moxnes 1998, 2000). Another driver of complexity in some contexts is the necessity for modeling ecological or climate factors (Moxnes 2005, Fiddaman 2007). It is for these reasons that System dynamics modeling can be particularly useful in the development of effective sustainability policies.

Moxnes (2005) is an examplar of an SD model including domain data (from ecology), economics, and operations to determine the uncertainties that impact optimal quotas and capacity decisions for the fishing fleet for preserving the Northeast Arctic cod fishery. He found that—contrary to conventional wisdom in most research—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, including climate change, the management of which is proving particularly problematic. Also, this is one of the few SD papers that uses stochastic optimization, which has the added benefit enabling examination the optimal trajectories as a function of uncertainties and other papers.

Another exemplar is Kapmeier and Goncalves's (2018) study that developed a model for managing tourism to promote economic growth calibrated to 38 years of data from the Maldives Islands. The 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 performed scenario planning to develop robust policies using Monte Carlo analysis and found that policies for better waste management alone will not work without limiting demand from tourism.

Recently, 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 that 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," which explicitly consider feedback into 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), who studies the design of construction waste charge fees in China.

There remain interesting open questions. 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 often 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 are perhaps even greater in sustainability than in any of the other policy areas discussed in this paper. We would 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 interesting area of inquiry not researched, to the best of our knowledge, is increasing the durability of products, which would automatically reduce future usage of materials and the creation of waste that needs to be disposed of (Goworek et al. 2020). Another is how continuous improvement programs might be actively directed to improving sustainability alongside regulatory changes. “Lean” continuous process improvement could be a powerful tool because its prime tenet is to “minimize waste.” However, continuous improvement takes time. In this case, would abrupt regulatory changes (e.g., the sudden introduction of a carbon price) encourage the incremental minimization of waste, or result in risky “big bang” process improvement projects? Similarly, process improvement might be used to reduce the firm’s carbon footprint (Aguado et al. 2013). What sort of regulation, carbon taxes, cap and trade, etc. would drive firm’s operations to minimize their carbon footprint using continuous improvement most effectively?

The articles, open questions, and system dynamics structures for future research for sustainability are listed in Table 7.

[Insert Table 7 about here]

4.6 New Business Models

Since 2000, there has been a flurry of development of new business models. Many of these are driven by improved information technology such as the internet, but they rely on operational innovations as well, such as online ordering and home delivery, which has attracted the interest of OM researchers (Sorescu 2017, Kumar et al. 2018). This area is ripe for policy and regulation, but is clearly a complex system. *The Platform Revolution*, (Parker et al. 2016) uses the language of SD explicitly by defining platforms as a firm at the center of two reinforcing loops between two different markets that are not owned by the platform firm, but which 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 innovation in operations, in Uber's case, substituting free-lance "gig workers," which act essentially as spot-market suppliers rather than employees. However, it also discusses the negative effects of platforms on the community, such as Uber's drivers not having health insurance or Airbnb's renters increasing noise and disruption for neighbors in residential areas as well as many others, all of which have invited policy interventions in various locales. The potential for monopoly effects on operations as well as consumers and the antitrust policy are also discussed. Despite this rich discussion using SD terminology and concepts, however, there is no associated simulation model. There are few other extant research SD articles with models that analyze policy for platforms either. This is unfortunate, because most of the extant literature on platforms, upon which much policy is being decided, are single-period game theory models. That said, there are a few SD papers treating OMPP issues in platforms such as (Keith and Rahmandad 2019) study of "winner-take-all" outcomes in the gig economy and Anderson and Parker's (2013) study of an energy power storage startup's new product development choices in technology that explicitly considers cross-side externalities as well as funding mechanisms for startups. Both papers could, however, easily have done more in terms of studying potential public policy interventions.

Startups themselves are their own business models, differing from mature firms in a number of ways, such as their lack of cash combined with the need to balance R&D, marketing, capacity, and production during rapid growth, which lead can lead to a number of pathologies lending themselves to SD research (Paich and Sterman 1993, Milling and Stumpfe 2000, Bianchi and Bivona 2002). Another important advantage of modeling entrepreneurship or startups with SD, is that SD models do not exclude unsuccessful firms, and thus is less subject to the biases (selection/survivorship) inherent in studying only those firms that "make it." These are especially important in startup studies because the overwhelming majority startups fail (Marmer et al. 2011). Policymakers often see startups as desirable, and the U.S. has a number of policies to help startups as do others (Hsieh and Chou 2018). However, what policies actually help startups and avoid unintended consequences? What policies such as tax laws inadvertently hurt startups and small enterprises? Such SD studies are strongly indicated, but published studies are currently rare (Zali et al. 2014).

New business model policy questions are plentiful, such as gig employees being treated as independent contractors, but they remain understudied by SD scholars. There many others that are--to the best of our knowledge—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 number 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). Warehouse workers are also becoming a larger section of the economy, yet are perceived to be underpaid or otherwise exploited by firms such as Amazon. As with gig workers, this 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 of these issues.

With respect to new business models that rely on externalities, any number of questions need to be studied with respect to operations and policy, such as antitrust issues. For example, Amazon's backwards engineering of popular products from small and medium enterprises is now being investigated as part of unfair trades practices. However, are remedies necessary given that other platforms such as Shopify and BigCommerce platforms 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 through policy more broadly? For example, are some regulations on workers that make sense for large enterprises problematic for small enterprises? However, policies are needed to encourage this development in nations such as the U.S. that have a chronic shortage of the skilled labor needed to maintain automation (Moreno and Bauer 2017). Additive manufacturing (better known as rapid prototyping or 3D printing) has also not been studied to the best of our knowledge. It is ripe for regulation given the possibilities for IP infringement and production of dangerous or other undesirable products, such as handguns. However, additive manufacturing is desirable for encouraging R&D leveraging open innovation. It also would have been helpful during COVID-19 to produce critical subcomponents for equipment whose supply chains were disrupted. 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 such as by Naumov et al. (2020). Much of it also is captured by prior SD models, such as Forrester's, if they are parameterized to reflect improving forecasting accuracy and promoting coordination. However, some applications of AI need new models. For example, automation is forcing a change in the labor force towards fewer unskilled workers and more skilled tradespeople. However, the U.S. is chronically short of skilled workers. 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 are of the utmost importance. Table 8 lists the cluster's articles and outlines potential areas for further study in this burgeoning field of using SD for innovation and new business model study.

[Insert Table 8 about here]

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 help the industry better utilize resources in a complex system involving environment of increasing uncertainty and to aid government policy makers in their understanding of 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 (Parker et al. 2019). For these reasons, there is a long history of using system dynamics 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 US—considerable fragmentation of the power generation industry.

The literature in this space is burgeoning, and several review papers are helpful in classifying recent work. In particular Teufel et al. (2013) proposed a categorization into regulated and liberalized Electricity Markets, and further subdivide both of these a number of sub-categories. Leopold (2016) provides a detailed review of other works using System dynamics 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 Ford's (2008) study 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 US's Western Energy Grid. Using extensive scenario testing in a model deeply grounded in technological detail, he 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 Casteneda et al. (2017a) builds a model including electricity demand, 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 roof-top solar capacity. They analyzed a number of 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, 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 interdisciplinary study of complex topics. While there is a fair amount of SD literature with respect to OMPP problems in energy number, 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 the 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, they must also include the impact at the micro-level operations issues faced by energy generation and distribution firms as well. Related to this 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 an electric vehicle 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 with respect to 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 US 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 better?

Table 9 contains a list of the articles in this cluster as well as associated open questions.

[Insert Table 9 about here]

5. Discussion and Conclusion

In this review, we have sought to create a map for future researchers interested in using system dynamics to study operations management in public policy-related contexts. Our intended audience includes both those experienced in using system dynamics and those new to the field. To this end, we collected a sample of approximately 150 system dynamics 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, some boundaries have been imposed to keep the task manageable. For example, we avoided studies that represented operations at a macro level, typical of labor economics or macroeconomics research. Such research is useful, but does not effectively inform operations management research. We also do not attempt to be exhaustive in our sample, instead focusing on a scoping review establishing a base of knowledge useful for contemporary researchers interested in this area.

We leverage our sample in a number of ways. First, we describe why, when, and how system dynamics models might be valuable for studying operations management problems in a public policy context. Second, we identify the trade-offs 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. After doing this, we find that this is often not, nor should it be, an either-or question. Rather, multiple methodologies can and often should complement each other.

We then clustered the articles into different topics. For each cluster, we identified a list of extant literature, the extant contributions of system dynamics research, open questions, and potential system dynamics building blocks for scholars investigating these questions. These are gathered into tables for each cluster to organize that knowledge for future researchers. We also identified and described exemplars in each cluster that might serve as models for future researchers.

Several overarching challenges 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 system dynamics models for consensus building among stakeholders. In our sample, there are some exemplars cited that document group-model building to some extent and also the use of flight simulators (see Table 10). 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 towards improving 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 traditional in system dynamics research (Andersen et al. 1997, Vennix 1999)

[Insert Table 10 about here]

Another challenge is the dearth of research on the integration of system dynamics with other OM modeling techniques, whether mathematical programming, queuing or otherwise. Table 10 identifies exemplars that have addressed this issue. Other than those exemplars, however, there have been few papers investigating this area, which 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 Homer's (1999) system dynamics model for managing service capacity that solves an optimal assignment problem each time period. Additional building blocks for this area are the articles by various authors in the edited book 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. There do exist formulations from operations management that can approximate the mileage at an aggregate level of a fleet of delivery or other 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. In that case, what can be done to cope with these issues 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 that can be built off of 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 are developed using traditional OM techniques such as mathematical programming or alternately by expanding the system dynamics model appropriately in order 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 on the operational level, the proposed implementation should be fed back to the stakeholders on the systems level to gather input and maintain consensus. Flight simulators can be employed the latter where appropriate. After a few more iterations between the two levels, the solution is implemented and appropriate effectiveness metrics 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 between 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 & logistics, energy, and new business models. In 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, humanitarian operations are often hindered and personnel literally endangered by conflict in the area where they are operating.

Finally, there are a number of emergent opportunities for research resulting from recent global disruptions including international trade disputes and the COVID-19 pandemic that have laid bare the fragility of the complex systems that are global supply chains. Research into bolstering them through policy initiatives (e.g., the US Biden Administration's "Build Back Better" initiative to increase the resiliency of infrastructure) is a fruitful and necessary area for exploration by future researchers leveraging system dynamics. However, there is currently little if any system dynamics research addressing these areas outside of supply chains directly related to medical devices and supplies. Some starting points do exist that can 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 proposed US CHIPS for America Act in 2021 would subsidize firms building semiconductor capacity in the United States with the aim of reducing reliance on manufacturers located in Asia. Twenty years ago there was some system dynamics modeling research touching on the consequences of offshoring manufacturing leading to a "hollowing out" of nations' strategic manufacturing competencies (e.g., Anderson et al. 2000). 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 is Phadnis and Joglekar (Forthcoming) and Joglekar and Phadnis (Forthcoming) that proposes to expand scenario planning to cope with policy disruptions by including suppliers in the planning process, which is a natural fit for system dynamics.

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

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Figure 1: Questions Addressable by System Dynamics

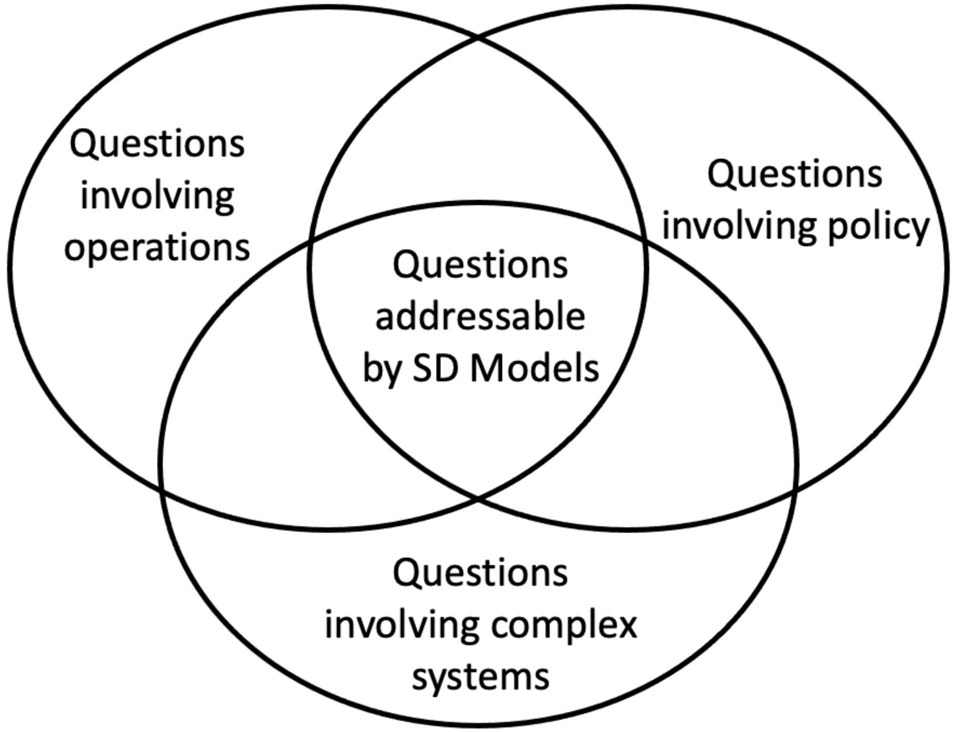

Figure 2: Atasu and Van Wassenhove's "Gray Zone"

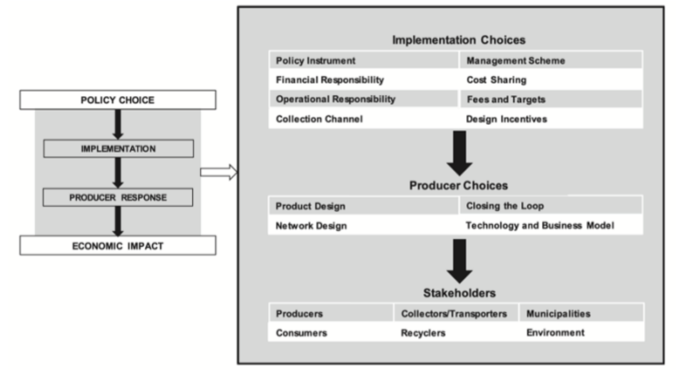

Figure 3: Joglekar et al.'s Diagram of Bidirectional Causality Between Operations and Public Policy

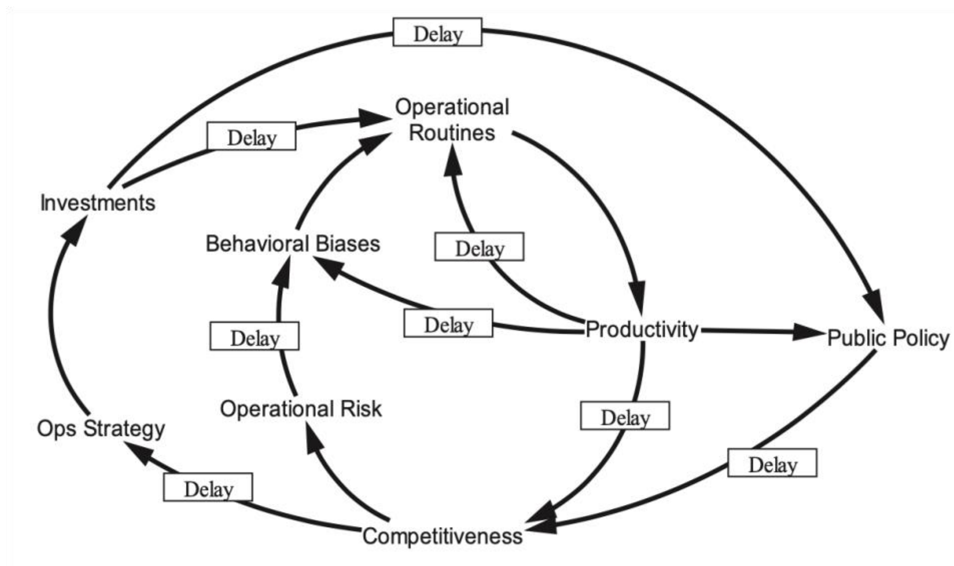

Figure 4: System Dynamics Modeling Process for Operations in Public Policy Contexts

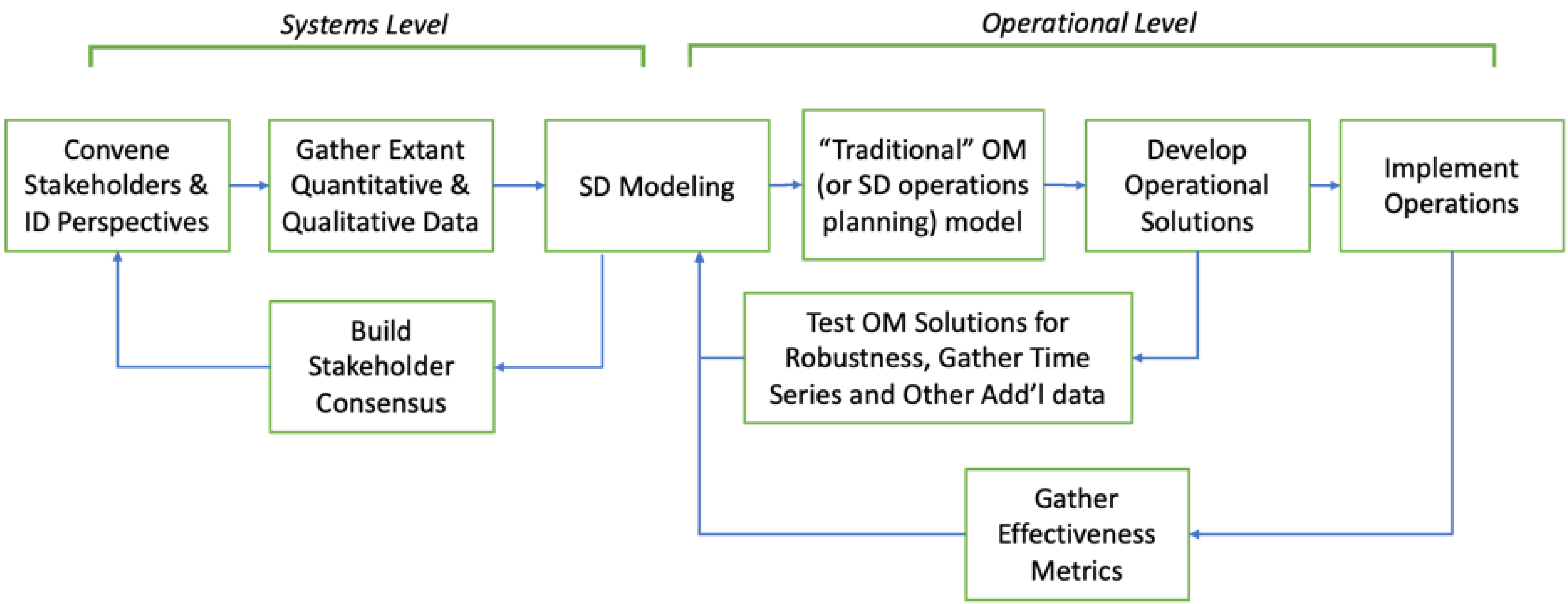

Table 1: Characteristics of Different Modeling Techniques								
	Typical Application in OM Context	**Data required for typical model**	**Number of Variables for typical model**	**Dynamic feedback in typical model**	**Other complexity in typical model**	**Modeling of uncertainty in typical model**	**Typical 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 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 - Moderately High depending on number of variables (via numerical simulation/optimizatio n and assuming detailed sensitivity analysis)

Table 2: Comparison of Perspectives by Academic Communities Researching Public Policy: The Electric Vehicle Fast Charging Question as an Example				
	Political Science (Sociology)	**SME's**	**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: Humanitarian Operations and Crisis Management Literature and Open Questions					
Research Topics	**Selected References**	**SD Contribution***	**Policy Questions**	**Operational Questions**	**Relevant SD Key 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)	Models of managerial behavior Models of project management	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?	Non-profit fundraising (Keith et al. Forthcoming)
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	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 doners?	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	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?	Productivity of experienced vs inexperienced employees Employee "burnout"

*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)

Table 4: Healthcare Operations Management Literature and Open Questions					
Research Topics	**Selected References**	**SD Contribution***	**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)	Models of managerial behavior Models of project management	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)
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	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	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 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” structure to capture experience Employee burnout structure
Human Body and Disease Prevention	Abdel-Hammid (2003), Jones et al. (2006), Karanfil and Barlas (2008), Abdel-Hammid et al. (2014), Fallah-Fini et al. (2014), Ghaffarzadegan et al. (2016), Hosseinichimeh et al. (2018), Rogers et al. (2018)	Stock and flow structures inside the human body	What are the government policies or behavioral interventions that can most cost effectively help contain the spread viral diseases?	How to manage healthcare operations during humanitarian operations in areas with poor infrastructure? How to manage the complications in regions affected by war, corruption, or related issues?	Treatment starves prevention structures (Jones et al. 2006)
Addictions and Pharmaceutical Use	Paich et al. (2011), Wakeland et al. (2011), Wakeland et al. (2015), Azghandi et al. (2018), Kunc and Kazakov (2018)	Ageing chains	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)

Table 5: Conflict, Defense, and Security Literature and Open Questions					
Research Topics	**Selected References**	**SD Contribution***	**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 Maintenance structures for infrastructure, vehicles, etc. 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 that 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)

Table 6: Transportation, Logistics, and Infrastructure Literature and Open Questions					
Research Topics	**Selected References**	**SD Contribution***	**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"
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 game structures Capacity acquisition
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 Capacity acquisition
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) 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?	Aging chains combined with “Rookie-pro” structures for productivity to model workforce effectiveness 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)

Table 7: Sustainable Operations Literature and Open Questions					
Research Topics	**Selected References**	**SD Contribution***	**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 uncertainty and risk
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), Agrawal et al. (2019), 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 Mfg. (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. Likeliness of disposal

*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)

Table 8: New Business Models Literature and Open Questions					
Research Topics	**Selected References**	**SD Contribution***	**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 "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 Analysis of "unintended consequences"	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
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
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)

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Table 9: Energy Literature and Open Questions					
Research Topics	**Selected References**	**SD Contribution***	**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 Capacity acquisition behavior by managers Forecast structures and perceptions of other actors forecast structures
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 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 Perception delays 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. (2017b), 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)

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Table 10: 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 a 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. (2021)	Healthcare capacity planning during pandemics			x					x			Uses nontraditional group model building techniques
Kapmeier and Goncalves (2018)	Sustainable Island Tourism		x	x	x							
Kunz et al. (2014)	Preparedness strategies for disaster relief	x	x									
Kunc and Kazakov (2018)	Pharmaceutical competition for heart disease									x		
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