An Integrated Platform for Smart City Design:

Structured Market-Based Incentive Architecture Design for Sustainable 'System of Systems' Supply Chain Orchestration

Scott Mongeau - s.mongeau@edp1.nyenrode.nl
Nyenrode Business University - Executive Doctorate Program

KEYWORDS: *operations management, sustainability, multi-agent analysis, simulation, model-based systems engineering, SysML, management control systems, complexity science, market-based mechanisms, knowledge-based view of the firm, smart cities*

ABSTRACT

The research proposes and evaluates a structured approach to the development of complex multi-organizational incentive architectures for complex sustainable supply chains. It is proposed that Model-Based Systems Engineering (MBSE), a process for software and systems development, combined with SysML, a structured systems modeling standard, can be combined to design and test complex multi-organizational supply chain incentive architectures. Such an approach is a suitable for architecting complex 'system-of-systems' architectures such as 'Smart Cities'. A review of trends in associated literature is conducted to ground research design and scope:

1) Perspectives concerning sustainable, multi-stakeholder resource supply chain management;
2) Formal systems engineering and modeling practices (as relevant to multi-organizational and multi-stakeholder economic systems); and
3) Multi-stakeholder incentive architectures for sustainable resource value chain orchestration.

A *yet-to-be-determined* central reference case involving sustainable multi-stakeholder resource management will be followed throughout to demonstrate the methodology (i.e. Dutch water management or Smart Grids). Structured multi-agent simulation is applied to analyze incentive alignment and systemic competition according to *as-is* and hypothetical *to-be* cases. General market-based models for satisficing sustainable value are extrapolated and examined for industry and regulatory consideration. The proposed methodology is thus an *in vitro* approach to exploring novel incentive and regulatory models, whereas field testing via live critical infrastructure is largely impractical.

1. INTRODUCTION AND BACKGROUND

With 70% of the earth's population expected to be living in urban settings by 2050, architecting sustainable cities via efficient resource supply chains is a major human imperative. Whereas the technical infrastructures for advanced 'smart city' initiatives have been rapidly developing, an understanding of the associated political and economic dynamics raised by these emerging tools is less well understood. However, the methods and tools for complex systems engineering have developed in terms of their ability to incorporate human systems dynamics into formal engineering models. Meanwhile, understandings of organizational and economic behavior have developed an appreciation of uncertainty, economic game playing, multi-agent dynamics, and bounded-rationality in complex systems decision making.

This research proposes applying Model-Based Systems Engineering (MBSE), a methodology typically used for software and engineered systems development, and SysML, a systems modeling standard, to design and test advanced regulatory and incentive models for public-private collaborations. A practical reference case is used to analyze *as-is* and proposed *to-be* incentive structures intended to optimize aggregate sustainability goals. The benefit of the proposed approach is that SysML models can be formally tested for aggregate systemic efficiency via computer-based simulation and optimization. Thus hypothetical regulatory and market models can be tested *in vitro* to derive insight and revise assumptions.

Uniting formal methods for design and testing with research models of organizational and behavioral economic dynamics, it becomes possible to consider the composition of an incentive design 'toolkit' for multi-stakeholder satisficing. In particular, the Knowledge-Based View theory of the firm allows for a structured analysis of management control system incentives, information exchanges, and assessment schemes (Grant, 1997). Being able to design and test combinations of such models in complex environments via simulation allows regulators and stakeholders to engage in the mutual design of complex resource supply chains with the goal of satisficing multi-stakeholder sustainability.

The research scope focuses on multi-stakeholder economic incentive architectures in sustainable supply chains. Sustainability and structured modeling as *state-of-the-art* topics in Operations Management research are central foundations (Sodhi & Tang, 2010). The research of Paul Kleindorfer focusing on sustainability in extended supply chains is a central reference (Kleindorfer, Singhal, & Wassenhove, 2005). The *Natural Capitalism* perspective that multi-stakeholder sustainability is an inherent value driver in business is embraced (Lovins, Lovins, & Hawken, 2007). Extended supply chains, viewed as economic systems with multiple, conflicting stakeholders, are modeled as complex 'systems of systems'. Complexity science thus serves as an overarching methodological foundation for the structural-functional analysis of modeled multi-organizational systems. See *Appendix 1* for a 'Research Context Diagram'.

The goal of this research is the proposal and assessment of a practical methodology for the development of complex, sustainable multi-stakeholder incentive architectures. While the aim is to develop a practice-oriented methodology, the research has a *theoretical orientation*, inductively building a series of proposals which culminate in a practice-based approach (Verschuren, 2010). Interdisciplinary by nature, the inductive stance of the research relies upon triangulation from existing research. However, a rough hierarchal 'disciplinary chain' is implicit, as per Figure 1 below (major domains in **bold**):

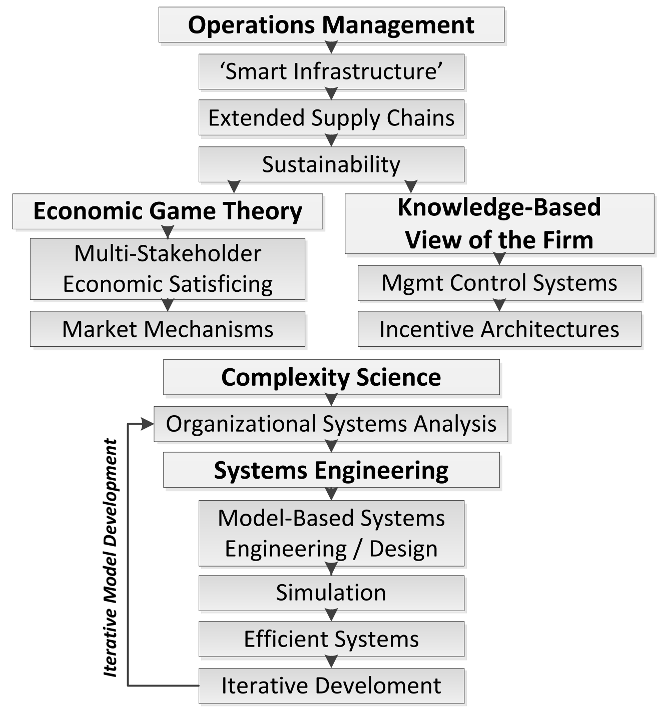


Figure 1: Inductive hierarchical theoretical foundation

Operations Management as a discipline embraces a broad, interdisciplinary swath of methods and perspectives, ranging from the intensively quantitative (Operations Research) to the epistemologically introspective (Behavioral Operations Research). A major assertion of this research is that 'sustainability' is first and foremost a challenge of political and socio-economic semantics, and thus inherently involves multi-stakeholder *satisficing*. While Operations Research is quite efficacious in optimizing quantifiable factors in supply chains, the behavioral aspects which gird and, indeed, provide a *raison d'être* for supply chains, are the emerging state-of-the-art for Operations Management research. The field, having been successful in technical and engineering terms over the last two decades, arguable is now extending its efficacious purview into the realm of social science.

Taking a cue from the recent work 'A Long View of Research and Practice in Operations Research and Management Science', two emerging trends in the field are objects of this inquiry: sustainability and structured systems modeling of behavioral dynamics (Sodhi & Tang, 2010). This research asserts a connection between these two emerging challenges: viewing sustainability foremost as a problem susceptible to structured-analytical social systems analysis via formal *economic game satisficing models*. The proposed design methodology, via the recent advent of the SysML specification, has the advanced capability of being able to model both structural and behavioral systems dynamics. In particular, adding the capacity of capturing bounded decision-making behavior in formal models provides the ability to explore multi-stakeholder and economic-incentive-driven behaviors in complex multi-organizational systems. Thus, it becomes feasible to formally model and test theoretical social constructs such as Management Control System (MCS) (Merchant & Stede, 2003) incentive schemes as resting on purely conceptual schemes such as the Knowledge-Based View (KBV) of the firm (Grant, 1997).

From the perspective that sustainability has different contexts for different stakeholders, the ability to formally model, and thus to simulate, boundedly-rational behavior in multi-agent systems provides an *in vitro* experimental capacity to the exploration of multi-organizational macro-systems. In essence, the research scope thus has as its ultimate objective the provision of a methodology for the design and testing of macro-scale human-computer interfaces, to the degree that complex, modern supply-chains are macro-scale technical decision infrastructures, and public-private resource supply chains (as collaborations between regulators, consumers, and commercial entities) are complex socio-behavioral systems, also susceptible to modeling and simulation.

2. CORE CONCEPT ONE: SUSTAINABILITY AND MULTI-STAKEHOLDER SUPPLY CHAINS

Core Concept: *Multi-agent value satisficing is a central factor in driving sustainable supply chains*

Master Hypothesis: *Supply chains which efficiently satisfice multi-agent value drivers are more sustainable*

Beneath this assertion and hypothesis is a set of five underlying theoretical propositions which will be explained in detail below. A diagrammatic perspective can be seen in Figure 2, following.

2.1. Theory One: Extended Supply Chains are Result of Technical Advancement

Theory: *Technical and procedural advancements have led to the ability to manage extended supply chain complexity*

Hypothesis: *Extended supply chain complexity is an emergent phenomenon which is evidencing unanticipated social and economic effects*

2.1.1. Essentials

Advancing information and automation technologies have led to the emergence of increasingly adept supply chain solutions (Kleindorfer et al., 2005). Improved accounting, tracking, and forecasting methods have allowed for advanced supply chain cost and value analysis (Kaplan & Anderson, 2004; Kaplan & Porter, 2011). Combined, emerging technologies and advanced accounting methods have led to the ability to manage the increasingly extended breadth of modern supply chains. The technical ability to manage efficiency along such extended supply chains has led to an understanding of the deep potential value resident in these systems. Along with appreciating an increasingly wide breadth in supply chain management reach, corporations have begun to embrace broader stakeholder interests as potential value drivers, sustainability in particular.

The efficacy of operations research has been made tangible and potent via emergent hybridization with advancing computing and automation technologies, leading to Schumpeterian “creative destruction”. As company case examples, Wal-Mart, Amazon, Dell, Zara, and Netflix all have created powerful supply-chain management solutions as effective weapons to largely revolutionize their respective industries. Using ‘smart infrastructure’, a hybridization of efficiency identification algorithms, automation technology, and computing decision management solutions, such firms have dispatched substantial competitors by investing heavily in an emerging vision of the firm as an electronically mediated information orchestrator.

The means with which to more effectively track and quantify the broad terms and goals of sustainability are advancing via the co-evolution of technologies and processes to deliver rich cost accounting process solutions. Information technology-based tracking and analysis has steadily improved cost accounting practices in order to quantify the economic benefit of sustainable business practices. As an example, luminaries Robert Kaplan and Michael Porter recently proposed a new approach to health care cost accounting in a *Harvard Business Review* piece, ‘How to Solve the Cost Crisis in Health Care’. The research proposes optimizing a measure of ‘patient welfare’ (which can be arguably seen as a fiat currency) to satisfice stakeholder profitability while maximizing care (Kaplan & Porter, 2011). Such a cost accounting process could easily be adapted to other industries to satisfice customers or consumers. For instance, a broad measure of ‘aggregate citizen happiness’ could be adopted as a basic satisficing condition for advanced water management.

2.1.2. Position in the Domain

Rapid technical evolution is leading to increasingly sophisticated machine agents capable of autonomous decision making, or of making expert level recommendations to human agents. Thus human agents, autonomous machine agents, and hybrid ‘cyborg’ agents are increasingly part of the rich ecosystems within and across the firms and organizations which orchestrate critical infrastructure (as complex systems of systems). Currently there is a rather poor understanding of how machine and cyborg agents are and will increasingly impose structural changes within and across firms as complex systems. The complex systems phenomena of emergence and phase transition are evident when energy states in large systems shift (Braha, Minai, & Bar-Yam, 2006; Miller & Page, 2007; Sargut & McGrath, 2011; Steger, Amann, & Maznevski, 2007). For instance, it is possible that certain thresholds will be crossed whereby autonomous machine-agent "decision density" in organizations leads to phase transitions in the inherent aggregate behavior of complex infrastructure. As an example, it has been asserted that the proliferation of automated algorithmic stock trading has led to equity market instabilities (Lauricella, 2010; Mehta & Kisling, 2010).

So called smart systems and intelligent infrastructure are the rapidly evolving fruits of hybridized advancements in computing power, artificial intelligence, automation, sensors, and algorithmic decision analysis. Adept expert systems are increasingly capable of autonomous decision making, establishing computational agents as autonomous actors within and across firms. It is thus possible to

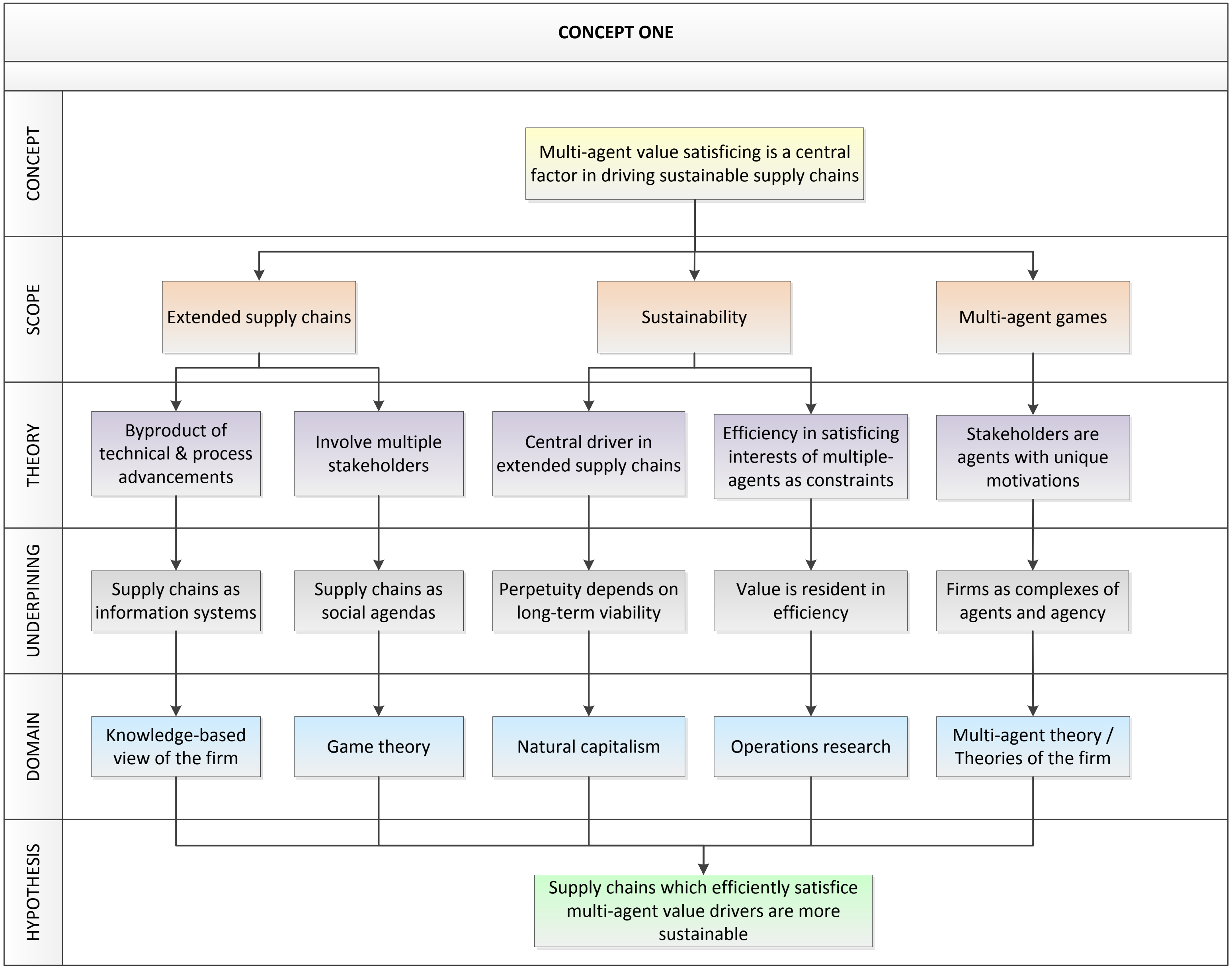


Figure 2: Concept One - Multi-agent value satisficing is a central factor in driving sustainable supply chains

liken expert decision systems to agents alongside human agents in viewing a firm or industry (as a complex of firms and organizations) as a multi-agent hybrid of human actors, machine agents, and 'cyborg' agents (machine enhanced human actors).

In principle, extended resource supply chains can be framed as 'smart systems' to the degree they involve complex systems of systems composed of components which negotiate rough cooperation via networks of sensors, communication channels / protocols , and control / feedback mechanisms. The central notion is that such complex systems are composed of multiple semi-autonomous agents who, via dynamic coordination, evidence emergent and unpredictable behavior at the macro level. Unique challenges are presented in managing, or better said, orchestrating such systems as they are inherently non-linear. Multi-agent analysis is promising in the ability to analyze the effect of machine agents alongside human and organizational agents to assess systemic behavior and stability. When assessing incentive architectures, the role of machine-agents as enablers, assistants, and, potentially, as independent goal-seeking actors must therefore be considered.

2.1.3. Orientation of Theory

In order to pursue effective modeling and analysis, there must be a firm theoretical grounding for the application of multi-agent simulation to the study of sustainable supply chain incentive systems. As per Figure 3 below, theory triangulation will be used to cross-associate theoretical perspectives in order to provide a comprehensive foundation for multi-agent modeling: management science, operations research, control systems engineering, game theory, network theory, computational organizational theory, sustainability, theories of the firm, behavioral research, incentive design / management control systems, and complexity science. Operations management research is proposed as the multidisciplinary 'anchor' field to bring these theoretical outlooks together in order to pursue multi-agent modeling. A survey of the operations management field suggests that such multi-disciplinary inquiry would not be out-of-place as long as a logical foundation is set via a compelling narrative stream.

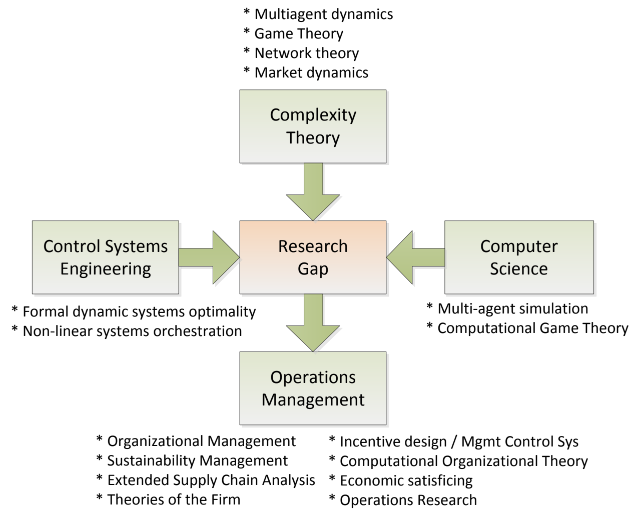


Figure 3: Conceptual multi-disciplinary research gap

The basis for the assertion of the research gap is the effect technological development is having on the practical scope of managed enterprise systems, supply chains in this case. Hybrid technologies involving computer analytics, decision systems, automation, and sensors have resulted in systems that can be managed over broad geographies, in future timeframes (planning orientation), as well as in multi-organizational contexts (i.e. contract manufacturing, outsourced supply chains, offshore labor, etc.). The assertion is that the technical facility to manage extended supply chains has overshot the ability to manage the accompanying broader breadth of stakeholder interests involved.

2.1.4. Theoretical Strength

'Proof' concerning the basic proposition that technological and knowledge development is leading to increasingly complex social and economic effects in supply chain management is easily available via case study analysis of the efficacy of advanced operations management technologies and practices. For instance, it can be asserted that the following firms dispatched powerful competitors via the strategic force of technologically orchestrated supply chain practices: Wal-Mart -> Kmart, Amazon -> Borders, Dell -> Gateway / Compaq / HP, Zara -> multiple clothing retailers, Netflix -> Blockbuster.

This research intends to bridge a gap in operations management research between operations research, engineering, and organizational understandings of sustainability in operational management. A related challenge regarding establishing rigor in architectural principles relates to disciplinary scope. As extended supply chains are a fusion of software, engineering, systems design and encoded algorithms, underlying disciplines combine computer science, operations research, control systems engineering, complexity science, economics, behavioral research, and organizational and management research. Research from each field offers rich levels of detail which could justly exhaust the capacity of single individuals to master. Thus, a recognized danger is to avoid 'interdisciplinary overload' whereby an agglomeration of, on the surface, compatible multidisciplinary research streams builds into a baroque tower of babel. Thus, the KISS (Keep-It-Simple-Silly) principle and *the need for a strong and clear carefully architected theoretical logic to gird the pursuit of building a structured modeling methodology*.

2.2. Theory Two: Extended supply chains inherently invoke multiple stakeholders

Theory: *Extended supply chains involve multiple stakeholders with diverse goals*

Hypothesis: *Value in extended supply chains is subject to multi-stakeholder economic satisficing*

2.2.1. Essentials

Motivations driving sustainability as a goal of the firm include corporate image and profitability, synergies between lean and green, regulatory compliance, liability and negligence, employee health and safety, and improved tools and management systems for better product and process design (Kleindorfer et al., 2005). Sustainability as a goal for commercial infrastructure management is largely efficiency-based, seeking to optimize profit-driven operational output and to minimize adverse collateral impact on bordering systems as a constraint.

However, the systemic scope for sustainability solutions is much broader than the typical commercial supply chain. Whereas a commercial supply chain must optimize efficiency within cost constraints to realize shareholder profit, managing resource infrastructure involves a much broader set of stakeholders and overlapping systems. Social, political, legal, and cultural factors come into play, with goals and constraints which may be unclear, shifting, or competing. As such, the identification of broad stakeholder constraints and optimization goals, many of which may be conflicting, is a super-process which must overarch and guide the management of resource utility infrastructure.

2.2.2. Position in the Domain

Kleindorfer in particular extols the notion of extended supply chains as being multi-stakeholder value constructs (Kleindorfer et al., 2005). It is the discussion of value in multi-stakeholder perspectives on supply chain management that sustainability becomes central to the discussion of value in Operations Management (Lin & Wang, 2010).

2.2.3. Orientation of Theory

When enlarged to include an enlarged chain of dependencies, supply chain management becomes multi-stakeholder aware, and thus moves beyond discussions of mechanical movements of resources and towards a discussion of 'value' as a social construct which depends on multi-stakeholder perspectives.

2.2.4. Theoretical Strength

Viewing extended supply chains as multi-stakeholder challenges admits to the fact that extension of the economic scope of the supply chain embraces a broader set of stakeholders, and thus a broader purview for the definition of 'value'. Viewing the supply chain as acting in the sole in interests of shareholder wealth risks supply chains which are ultimately self-destructive, to the degree they potentially will drain resources and destroy the fundament of their perpetual value.

2.3. Theory Three:

Theory: *Sustainability is a central value driver in extended supply chains*

Hypothesis: *Optimally sustainable supply chains evidence higher long-term economic value*

2.3.1. Essentials

Technologically advanced operations management is emerging as both a vehicle and driver for sustainable solutions via an extension of the effective scope of supply chains. Figure 4 below displays the systemic interconnection of sustainable goals with multiple stakeholders via a value model of the extended supply chain.

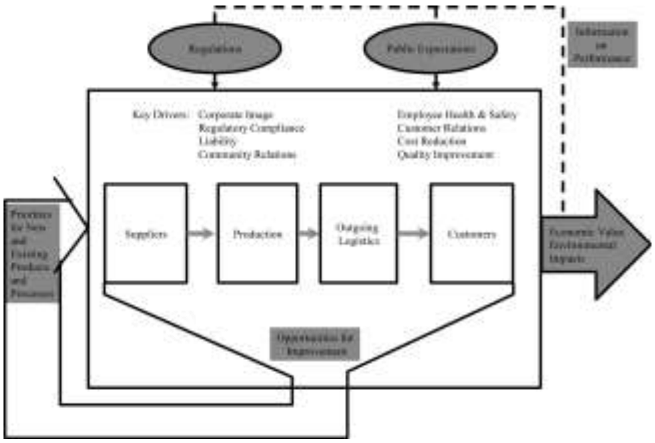


Figure 4: Sustainability and the extended supply chain (Kleindorfer et al., 2005)

2.3.2. Position in the Domain

Current research positions sustainability as a value driver in the domains of operations management (Kleindorfer et al., 2005; Lin & Wang, 2010), extended supply chain analysis (Lin et al., 1994), and multi-agent resource management (Berger, Birner, Mccarthy, DíAz, & Wittmer, 2007; Bousquet et al., 2002).

2.3.3. Orientation of Theory

Research has been emerging which proposes sustainability as a unique locus in-of-itself. Sustainability research focuses in particular on the relationship between long-term value creation and efficiency as defined in a multi-stakeholder context. An example is the concept of 'natural capitalism', which situates sustainability as a central value driver (Lovins et al., 2007). Whereas these perspectives will be used to provide ancillary context, the core reference to sustainability will be via the lens of Operations Management. The reasons are conceptual economy and to maintain focus on the goal of modeling and systematizing sustainability as phenomenon. This research views sustainability principally as phenomenon of multi-stakeholder economic value satisficing game playing.

2.3.4. Theoretical Strength

A central weakness in broader sustainability research concerns not addressing semantics and context directly. What is meant by the key terms 'value' and 'efficiency' vis á vis sustainability? By viewing sustainability centrally as being a multi-stakeholder 'argument' over value, it can then be modeled as a satisficing game, as a negotiation to arrive at an acceptable aggregate definition of value for all participating stakeholders. By forcing a philosophical 'ground', that of sustainability as a negotiated notion of aggregate social value, it can then be modeled in term of the behavioral perspectives of the associated stakeholders.

2.4. Theory Four: Sustainability invokes multi-stakeholder definitions of value which need to be satisficed

Theory: *Sustainability in extended supply chains involves efficient satisfaction of multiple-stakeholder interests*

Hypothesis: *Sustainability is a phenomenon which can be modeled in terms of an argument concerning different perspectives on value within a particular domain*

2.4.1. Essentials

Contemporary to this writing a groundswell of popular advocacy swirls around the term sustainability, driven by globalization, population growth, resource pressures, growing environmental awareness, and associated socio-political factors. The increasing interest in sustainability resulting from global interconnectivity and associated resource pressures has also led to a desire to embrace broader understandings of multi-stakeholder resource management. Extended supply chain analysis is an emerging approach to sustainability analysis, by nature embracing a broader network of stakeholders in terms of defining value (Kleindorfer et al., 2005).

As an example, flood management must satisfy budget constraints minimize environmental impact, maximize water quality, and control for acceptable risk thresholds. Each set of constraints and goals involves many stakeholders or 'agents'. With conflicting directives, optimally efficient solutions are unlikely; multi-agent satisficing is a more realistic goal in the orchestration of sustainable solutions. Sustainability thus embraces a multi-stakeholder (multi-agent) viewpoint whereby major domains overlap in order to optimize, or satisfice, an ideal, aggregate definition of 'value' via shifting coalitions of interests and goals. The notion of smart infrastructure to realize smart sustainability adds a technical substrate or vehicle as an efficiency-seeking platform to assist in the satisficing of such coalitions of interests. These principles are illustrated below: Figure 5 displays the broad stakeholder goals associated with sustainability (*see Appendix 2 for expanded view*), while Figure 4 previously, displays the potential for feedback processes to technically satisfice multi-stakeholder interests in extended supply chains.

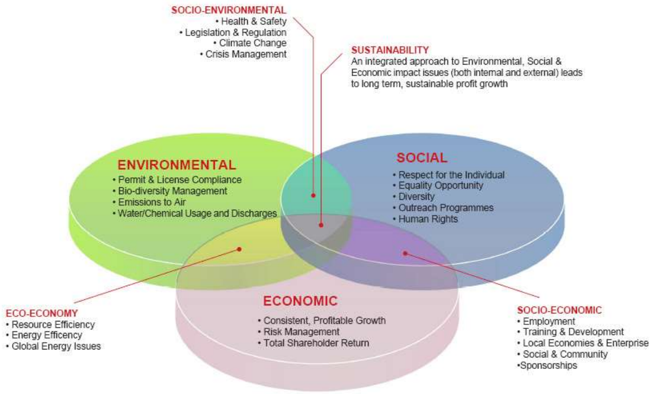


Figure 5: The sustainability solution matrix (Staff, 2008)

2.4.2. Position in the Domain

Resource supply chains raise the complication of quickly introducing competing stakeholders and interests. Sustainability further expands the range of stakeholder interests involved. For instance, sustainable flood management touches on environmental quality, drinking water quality, budget constraints, and economic and moral risk (i.e. the risk of property destruction and lives lost in flooding) (Brugge, Rotmans, & Loorbach, 2005). Within a socio-political context, it is quite assured there will not be an optimal solution where all stakeholders are satisfied (Adams, 2006). Instead, the system itself must focus on a continual process of satisficing sets of interests amongst the distributed stakeholders.

2.4.3. Orientation of Theory

Academic inquiry has mirrored the interest in sustainability, producing research focused on sustainability in disciplines as diverse as marketing, software engineering, public policy, and environmental science, reflecting the broad context surrounding this domain. The bulk of inquiry has been discipline specific, pursuing focused targets in particular spheres of expertise. It is proposed that a gap in sustainability-associated research has been the lack of multidisciplinary, inter-systemic perspectives, particularly those involving commercial interests.

There is a need to bridge technical and engineering perspectives with political, economic, and organizational management perspectives to architect stable, value-evidencing, and sustainable macro-systems. Sustainability faces a "forest for the trees" challenge whereby a lack of integrative, inter-systemic understanding leads to unstable super-systemic architectures, unrealistic incentive schemes being a particular shortcoming.

Sustainability without market context faces quandaries:

- Sustainability is goal being driven by a complex of socio-political, economic, cultural, & resource factors, and is being propelled by globalization & technical development
- In order to be feasible in the capitalist context (proposed as the dominant current global framework for trade and international business), there must be strong incentive structures and evidenced value for sustainability goals to be pursued with realistic expectations for tangible results
- Sustainable solutions require systemic architectures which recognize an economic basis, value satisficing, aligned incentives, and a market-based context (often involving regulatory and incentive distortions when government involved)

2.4.4. Theoretical Strength

It is proposed that the 'hype' surrounding the drive toward sustainability has resulted in a poverty of semantics: what, precisely, is 'sustainability'? The proposition here is that sustainability depends on a rough balance of definitions amongst those interested in achieving sustainability for a particular domain. Thus, it is asserted that sustainability is in fact a structured negotiation concerning value specific to a particular target domain. Gaining agreement on such a definition for sustainability relies on a philosophical grounding for the semantics of the term.

2.5. Theory Five: Stakeholders in markets compete to optimize their own incentives

Theory: *Stakeholders are agents with unique sets of incentives which they seek to optimize in multi-agent markets*

Hypothesis: *Stakeholder games can be modeled as multi-agent incentive optimization games*

2.5.1. Essentials

As shareholder capitalism has come under increasing critique in the wake of the Global Financial Crisis, multi-stakeholder perspectives in corporate value creation has come to the fore. A complication posed by multi-stakeholder supply chain value analysis is the complexity of identifying optimal states. Sustainability in supply chains involves the convergence and overlapping of multi-systemic agendas. The often conflicting goals of disparate stakeholders (or agents) must be satisficed, for example the overlapping interests of: firms (capital), workers (labor), society (welfare), customers (utility), natural resources (environment), politics (government), markets (economic), and machines (automation).

2.5.2. Position in the Domain

Multi-agent simulation and analysis is an emerging computer-based analytical methodology which allows for the analysis of complex non-linear systems. A working definition for agent-based modeling is “a computational method that enables a researcher to create, analyze, and experiment with models composed of agents that interact within an environment” (Gilbert, 2008). Such methods hold promise for analyzing complex systems of systems, particularly multi-stakeholder systems and complex infrastructure combining organizational actors, machine agents, and hybrid machine-human agents.

Multi-agent analysis is applied frequently in social science research and allows for the deep analysis of complex game theory scenarios to determine stead-state conditions and satisficing criteria. Extended managed supply chains, as complex, non-linear composites of complicated sub-systems, are also feasible targets for such analysis. Multi-agent simulation has hope as a systems design and analysis tool, as a root cause analysis method, and, potentially, as an advanced scenario monitoring and control system (i.e. basis for software design) when integrated properly into information and decision architectures.

Computational organizational theory offers the perspective that organizations can be studied by viewing interacting individuals and groups as computational agents (Prietula, Carley, & Gasser, 1998). Machine and human agents in and across organizations can be viewed similarly as goal-seeking, multi-agent actors, all interacting within a complex systems context.

2.5.3. Orientation of Theory

Computational organizational theory provides a basis with which to analyze existing resource management architectures via computational simulation, particularly where combinations of machine and human decision agents cooperate and compete. The management of advanced electricity ‘smart grids’ is such an example: smart systems, regulators, consumers, and market agents (human and ‘cyborg’) all interact to elicit unpredictable behavior.

2.5.4. Theoretical Strength

Rapid advances in expert systems solutions (automation technology, hardware, software, and processes) have led to revolutionary supply chain efficiencies as machine-agents are capable of increasingly sophisticated autonomous decision analysis. Even as technical advances are shifting the boundaries of the traditional firm and transforming industries, human organizational actors are increasingly understood according to advancing knowledge concerning inbuilt human decision making processes and behavior. Organizational management research, economic behavioral research, and experimental psychology have advanced in an understanding of human behavioral decision making and organizational dynamics. Behavioral research has begun revealing subtle intricacies in human decision making, revealing that decisions are guided by sets of evolved cognitive systems which operate on innate heuristic rules and inbuilt biases (Kahneman, 2011). Advancements in experimental understandings of human decision making has provided a basis for studying organizations as bundles of semi-autonomous agents acting according to bounded rational behavioral frameworks. The Knowledge-Based View (KBV) of the firm has provided a strong theoretical foundation for understanding agents within an organizational context (Grant, 1997).

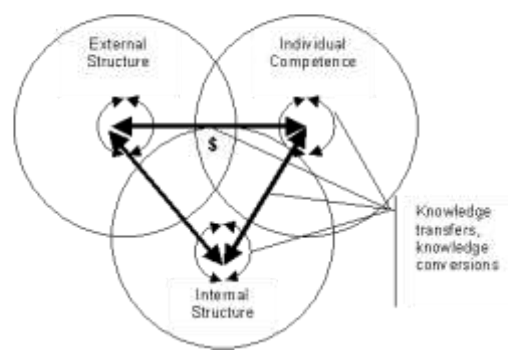


Figure 6: Knowledge-Based View of the Firm (Sveiby, 2001)

3. CORE CONCEPT TWO: SUSTAINABILITY AND MULTI-STAKEHOLDER SUPPLY CHAINS

Core Concept: *Structured systems modeling and simulation can be used to assess systems efficiency*

Master Hypothesis: *Performance in structured extended supply chain models can be evaluated via computer-based simulation of structured multi-agent models*

Five additional underlying theoretical propositions will be explained in detail below. A diagrammatic perspective of the overarching concept in terms of the derived theories can be viewed in Figure 7, following.

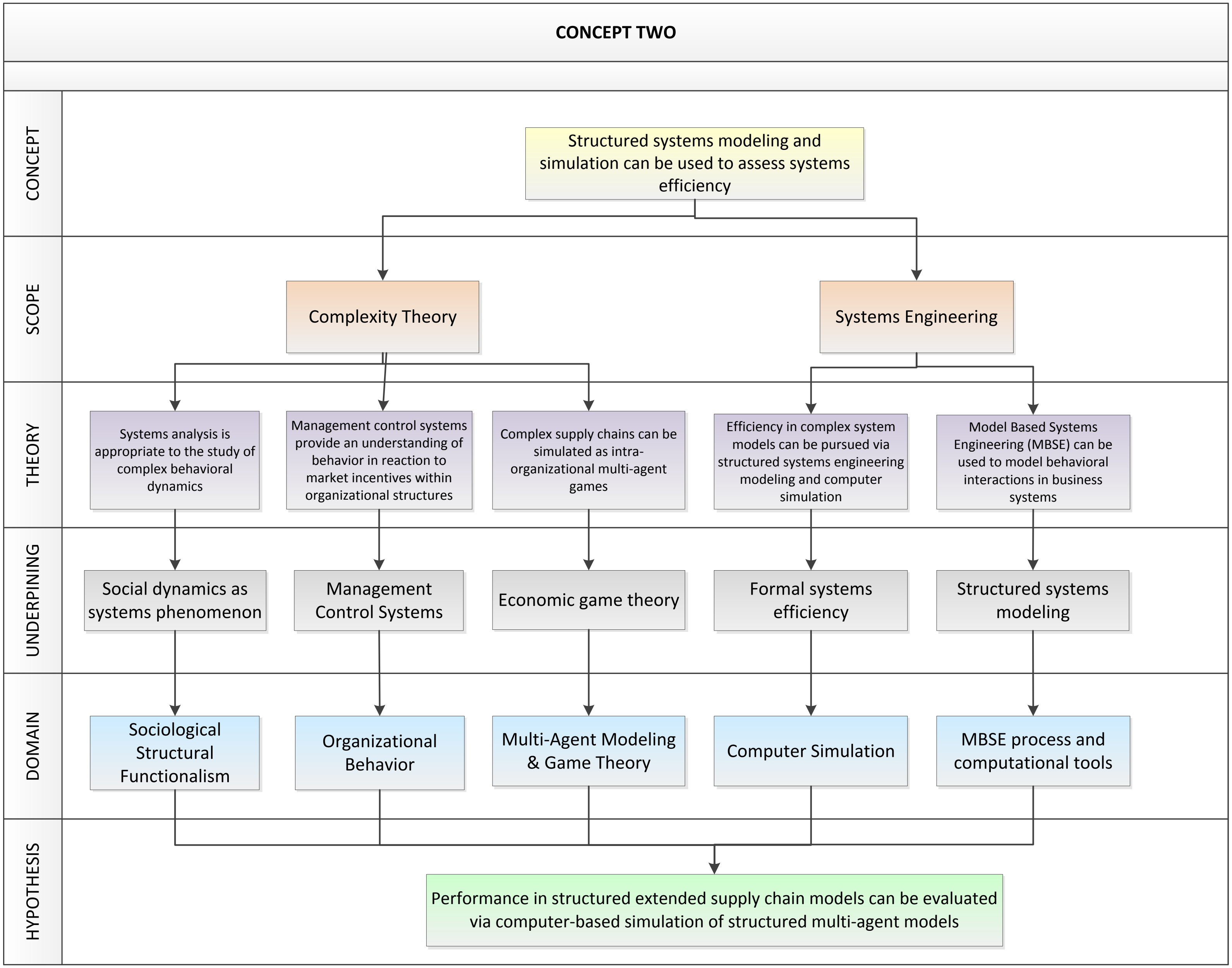


Figure 7: Concept Two - Structured systems modeling and simulation can be used to assess systems efficiency

3.1. Theory Six: Social Phenomenon is Systemic by Nature

Theory: *Systems analysis is appropriate to the study of complex behavioral dynamics*

Hypothesis: *Organizational phenomenon can be meaningfully modeled in terms of systems dynamics*

3.1.1. Essentials

By viewing human and machine actors as common players across complex multi-agent systems, dynamics in sustainable supply chain management can be simulated to elicit understandings of how incentive and goal architectures affect sustainable value.

3.1.1. Position in the Domain

Theories of the firm have advanced understandings of how and why firms operate. By hybridizing theories of the firm, computational organizational theory, and behavioral perspectives, satisficing phenomenon across complex systems can be examined with the goal of orchestrating sustainable solutions.

3.1.2. Orientation of Theory

The Knowledge-Based View (KBV) (Sveiby, 2001) otherwise serves as a central theoretical foundation which validates the notion of firms as being composed of agents acting to optimize incentives according to boundedly rational understandings of context. KBV refers to Management Control Systems as being the central logic girding and guiding organizational actors (Merchant & Stede, 2003).

3.1.3. Theoretical Strength

Behavioral research allows for a view of humans as ‘boundedly-rational’, thus allowing for modeling of ‘limited information’ scenarios and cross-purpose incentives in keeping with real markets (Wellman, 1996). In this context, as per the principle of “the tragedy of the commons” (Hardin, 1968), Malthusian scenarios in which actors destroy a shared resource are permissible. Indeed many sustainability advocates charge that the majority of current commercial supply chains are unsustainable in the long-term, thus dramatizing the importance of identifying methods to curtail such situations.

There is a strong tradition of applying systems theory to the study of social phenomenon. With the emergence of powerful computational methods, there has been a surge of interest in using computational simulation and complexity theory to assess social systems dynamics (Castellani & Hafferty, 2010). Talcott Parson’s structural-functional sociological outlook from the 1950’s has been experiencing resurgence. Complexity science embraces a systems view of social phenomenon and utilizes a broad set of methodological tools to study complex social systems phenomenon.

3.2. Theory Seven: Management Control Systems Provide a Context for Understanding Behavior in Organizations

Theory: *Management control systems provide an understanding of behavior in reaction to market incentives within organizational structures*

Hypothesis: *Management Control Systems can be used to model behavior according to incentives in organizational contexts*

3.2.1. Essentials

Management Control Systems (MCSs) are organizational systems for evaluating and rewarding the performance of organizational agents according to the decision rights and information access provided to those agents (Merchant & Stede). The MCS perspective validates the notion that firms are composed of semi-autonomous agents that react to incentives within assessment schemes. As well, the firm is viewed as a composite of information resources, or agents with knowledge, that are granted decision rights.

3.2.2. Position in the Domain

Agents may pursue pre-programmed goals according to narrow goals which replicate the ways in which human agents may pursue rather narrow rewards. “Partial observability and stochasticity are ubiquitous in the real world, and so, therefore, is decision making under uncertainty. Technically speaking, a rational utility-based agent chooses the action that maximizes the expected utility of the action outcomes – that is, the utility the agent expects to derive, on average, given the probabilities and utilities of each outcome” (Russell & Norvig, 2010). As with the example of the Global Credit Crisis, misaligned micro-utility maximization can lead to macro-systemic value destruction (Lin & Wang, 2010).

3.2.3. Orientation of Theory

The study of MCSs can be said to mesh closely with the Knowledge-Based View (KBV) of the firm (Grant, 1997). It is proposed that MCSs, in conjunction with a

KBV view of the firm, allows for a structured understanding of organizational agent behavior within firms. In the context of a extended supply chain in which common interests and constraints (such as regulations) bind inter-organizational agents together, it is proposed that inter-organizational MCS structures similarly can reveal much about composite systemic behavior.

3.2.4. Theoretical Strength

A strong benefit of multi-agent analysis in analyzing organizational and market architectures is the ability to simulate bounded rationality. That is, software agents can be programmed to seek to fulfill goals based on bounded understandings of their immediate environment. This becomes especially interesting and useful in attempts to study potential flaws in large and complex architectures, for instance via computer-based agent simulations. Whereas it has been remarked that agent-based simulations often lack coherent guiding models (Dolk, 2010), this research seeks to address the gap directly via a structured systems modeling language (SysML) and model-based management approach (MBSE). The two can be combined methodologically to architect and analyze complex systems-of-systems (Huynh & Osmundson, 2006; Rivaldo et al., 2007).

3.3. Theory Eight: Complex Supply Chains as Multi-Agent Games

Theory: *Complex supply chains can be simulated as intra-organizational multi-agent games*

Hypothesis: *Multi-agent simulation is a suitable method for gaining insight into complex supply chains*

3.3.1. Essentials

Multi-agent simulation is a trending methodology in the analysis of complex organizational and supply chain research (Dolk, 2010). Use of this methodology draws from organizational research which espouses the view of firms being bundles of boundedly-rational agents, including computational organizational theory, the Knowledge-Based View of the firm, and behavioral research. Game theory also supports the premise of organizations being agent-based (Fink, 1998; Shoham & Leyton-Brown, 2009; Zagare, 1984). Supply chains, particularly when involving multiple stakeholders in extended analysis, thus are susceptible to deeper understanding via multi-agent analysis.

3.3.2. Position in the Domain

Multi-agent analysis is a compelling interdisciplinary tool for examining complex social systems, incentive schemes in particular. Interdisciplinary methodologies connected to the field of complexity science provide input and guidance (Castellani & Hafferty, 2010; Steger et al., 2007):

- Complexity theory
- Game theory
- Computational organizational theory (in this case as a basis for modeling human and machine agents interacting across multi-system, multi-context resource supply chains)
- Network theory
- Management control systems and incentive scheme design
- Technical and engineering methods: control systems engineering, formal mathematical approaches to satisficing, and non-linear systems orchestration

3.3.3. Orientation of Theory

To give a practical example of exploring bounded rationality models in multi-agent games, it is anticipated that distributed stakeholders involved in extended resource supply chains will each behave according to a belief that they are participating in quite different games. This will lead to complex game architectures. As a high-level example of a generic semi-regulated, managed resource supply chain such as electricity supply:

- Regulators will assume they are establishing ultimatums which are at risk of non-compliance by industry (thus requiring monitoring),
- Legislators will assume they need to stimulate regulations to satisfice both shifting electorates and political patrons,
- Resource managers will assume they need to satisfice public welfare within financial and operating resource constraints,
- Consumers will moderate consumption based on price according to supply and demand equilibrium,
- Citizens will agitate legislators and attack via legal routes if resource quality, safety, and/or cost constraint thresholds are broken,
- Judicial and legal player will harass public and private interests when provoked by irate citizens,
- Environmentalists will pursue legal recourse when perceived environmental damage occurs, and
- Free-market brokers will seek to optimize arbitrage profit conditions by attempting to manipulate supply-and-demand information and may attempt to influence legislators via patronage.

3.3.4. Theoretical Strength

Using multi-agent simulation to study sustainable supply chains requires a solid interdisciplinary research foundation. Research should provide a strong thoeretical justification and basis for applying multi-agent analysis to the study of resource supply chain dynamics, particularly as related to social satisficing in complex multi-stakeholder venues with competing goals and incentives. Theories One through Five herein otherwise provide a strong theoretical foundation for such research.

3.4. Theory Nine: Supply Chain Incentive Architectures Lead to Differing Social Welfare Value End-States

Theory: *Efficiency in complex system models can be pursued via structured systems engineering modeling and computer simulation*

Hypothesis: *Different sustainable supply chain incentive architectures will result in more or less efficient social welfare value outcomes*

3.4.1. Essentials

Control systems engineering is a rich discipline which continues to advance the technical ability to control complex systems such as aircraft, robotics, and vision systems. The forefront of control systems engineering thus suggests formal approaches to the engineering of organizational systems, to the degree such systems can be comprehensively described in terms of their structure and behavior. However, being social and contextual, such systems require flexible and adaptive approaches by nature as social systems are inherently given to evolving context. It is asserted that such flexibility can be formalized into systems modeling via methods which address variable and uncertain states such as fuzzy logic, game theory, meaning negotiations, and stochastic processes. In short, a variety of market-associated mechanisms can be used to formally describe the flexible meaning negotiations which occur within and across organizations (Fink, 1998; Grote, 2009; Penserini, Perini, Susi, & Mylopoulos, 2006; Raghu, Jayaraman, & Rao, 2004; Wolpert, 2006).

3.4.2. Position in the Domain

Economic value efficiency given system constraints is a strong objective of applied Operations Research. It is proposed that similar methods can be used to identify more or less efficient organizational systems (to the degree organizations manage supply productivity to achieve particular ends). However, while control systems can identify 'ideally efficient states', multi-organizational systems, being complex social systems, can only 'satisfice', or achieve a rough balance of interests. In other words, social systems are dynamic and involve shifting meanings which do not have final or authoritative 'ideal' states beyond the contextual social definition of stakeholder value. As well, as social interests shift, the systemic architecture must be flexible enough to rebalance the consensual definition of 'value'. 'Brittleness' in organizational architectural design will lead to broken systems when internal and external conditions inevitably shift. It is in this context that market-mechanisms and methodologies associated with probabilistic and fuzzy meanings are invoked.

3.4.3. Orientation of Theory

Control systems engineering research has resulted in complex control solutions for non-linear, complex systems ranging from airplane autopilot to software-based visual recognition (Catterson, Davidson, & McArthur, 2011; Liu, Yang, Wen, Zhang, & Mao, 2011; Nise, 2011; Ramos & Liu, 2011). The criticism of the control systems engineering solutions applied to organizational dynamics is that it is essentially a 'black box' approach: a self-contained, computationally complex 'learning' system which accepts inputs from a dynamic system and seeks to reach optimal orchestration conditions. Proposing such an approach for orchestrating organizational phenomenon is thus an 'implementation' and does not result in novel observations of the system under observation (Monch, Lendermann, McGinnis, & Schirrmann, 2011). Thus, the application of pure control systems solution approaches methodologically is not as powerful as assembling architectural combinations of market-based, game theoretic, and fuzzy logic associated approaches to systems orchestration. As the goal here is to achieve better understandings of organizational dynamics, explicitly modeled structure and relations thus are necessary to the design process, as addressed by the combined MBSE and SysML approach (Jayatilleke, Padgham, & Winikoff, 2005; Rivaldo et al., 2007).

3.4.4. Theoretical Strength

A systems engineering approach to designing multi-agent frameworks for organizational models must evidence several central modeling principles to establish validity:

1. *Theoretical grounding:* modeling must rest on a firm theoretical foundation,

2. *Precedent in literature:* utilizing established models, processes and techniques established in prior research,
3. *Simplicity:* conscious attempts must be invested in making models clear and comprehensive and to avoid the 'black box' critique, and
4. *Transparency:* clear documentation of assumptions in modeling, model composition and conditions under which simulation was pursued.

Concerning validity related to formal mathematical proof, it is anticipated that 'satisficing' conditions will be established in many of the posed organizational architectures (likely using the formal logic of game theory to describe the conditions for interaction). It is important to note that the extended group of stakeholders involved in 'sustainable resource supply chains' will likely be operating from conditions of conflicting bounded rationality.

3.5. Theory Ten: Model-Based Systems Engineering Combined with SysML for Modeling Multi-Agent Organizational Dynamics

Theory: *Model-Based Systems Engineering (MBSE) combined with SysML can be used to model multi-agent behavioral interactions in business systems*

Hypothesis: *Different sustainable supply chain incentive architectures will result in more or less 'social welfare enhancing' outcomes*

3.5.1. Essentials

Models designed and simulated via multi-agent analysis must have a firm theoretical foundation in order to establish 'valid' modeling frameworks and analysis targets (Sterling & Taveter, 2009). The Model-Based Systems Engineering (MBSE) methodology addresses the need for a structured development approach. As well, the SysML specification provides a structured descriptive design language for describing complex systems (Huang & Ramamurthy, 2007).

3.5.2. Position in the Domain

This research uses a broad definition for an autonomous agent as "a system situated within and a part of an environment that senses that environment and acts on it, over time, in pursuit of its own agenda and so as to effect what it senses in the future" (Franklin & Graesser, 1996). The broader research context of multi-agent analysis is recognized to be interdisciplinary, embracing aspects of economics, particularly game theory; computer science, particularly artificial intelligence research; operations management, particularly operations research; engineering, particularly control systems; and formal mathematics, particularly as related to fuzzy set theory, combinatorial analysis, non-linear systems analysis, and information theory (see *Appendix 1* for a high-level Research Context Diagram).

Concerning the specifics of particular multi-agent models to be employed in this research, actual detailed designs are beyond the scope for the research proposal at this point. However, there is a strong and growing multi-agent research tradition providing guidance on modeling and analysis approaches that will serve to inform the modeling process:

- *Comprehensive multi-agent design & analysis methods:* integrated modeling and analysis approaches (Allen, 2011; Epstein, 2006; Gilbert, 2008; Gilbert & Troitzsch, 2005; Railsback & Grimm, 2012; M. Wooldridge, 2009; Michael Wooldridge, Jennings, & Kinny, 2000),
- *Organizational design:* human organizations provide context for structuring multi-agent model frameworks (Aart, 2004; Horling & Lesser, 2005; Prietula, Carley, & Gasser, 1998),
- *Computational organizational theory:* offers a perspective on modeling human organizational actors as computational agents (Brewerton, 2001),
- *Behavioral dynamics in organizations:* modeling the 'boundedly-rational' behavior of individuals and groups within and across organizations (Ferber, Gutknecht, Jonker, Mueller, & Treur, 2001; Sun, 2006),
- *Management control systems and incentive design:* offers a context for incentives as a motivator for goal-seeking behavior (Merchant & Stede, 2003),
- *Knowledge based view of the firm:* theory of the firm which views the firm as a composite of informational nodes and decision points (Grant, 1997),
- *Game theory:* provides a basis for modeling competition and coalition building in complex social systems (Fink, 1998; Ramos & Liu, 2011; Shoham & Leyton-Brown, 2009; Wolpert, 2006; Zagare, 1984),
- *Network theory:* offers a perspective in modeling organizations and industries (Carrington, Scott, & Wasserman, 2005),
- *Complexity theory:* provides context for analysis of simulation results – covers the phenomenon of

emergence, unintended consequences, unpredictability, phase changes, diagnostic and optimization challenges, network effects, Black Swan risks, etc. (Castellani & Hafferty, 2010; Erdi, 2008; Lewin, 1993; Morrison, 1991; Nicolis & Nicolis, 2007; Stacey, 2010; Steger et al., 2007),

- *Engineered complex systems and control theory:* offers perspectives on non-linear optimization algorithms and formal mathematical 'black box' approaches to determining optimality for complex systems (Braha et al., 2006; Erdi, 2008; Nise, 2011).

3.5.3. Orientation of Theory

In order to bolster validity in research design, multi-agent modeling should follow a structured, iterative process of model design and analysis:

- Identification of systemic scope,
- Identification of stakeholders,
- Establishment of notion of systemic value,
- Definition of boundary conditions and constraints,
- Network mapping,
- Risk sharing matrix,
- Interaction conditions,
- Testing and analysis,
- Model revision.

Grimm and Railsback recommend a basic iterative approach to multi-agent modeling, cyclically formulating, testing, and refining the base model:

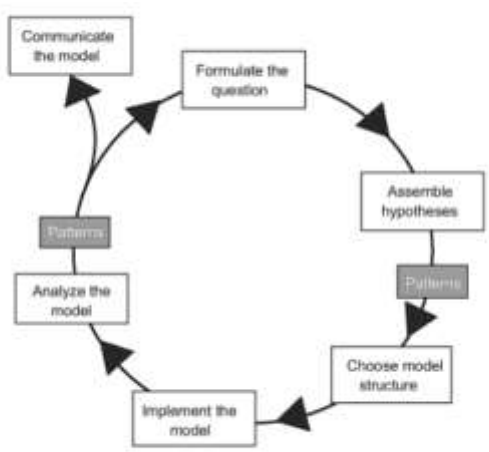


Figure 8: Multi-agent modeling cycle (Grimm & Railsback, 2005)

The work 'Case Study Research' by Robert Yin will provide particular guidance on the application of a reference case to be followed (Yin, 2009). As the principle research target is understanding of the effects of incentive design on macro-systems, the context of operational management and organizational research will be adopted (which in turn provides a solid foundation for subsequent multi-agent modeling) (Brewerton, 2001).

3.5.4. Theoretical Strength

Multi-agent simulation is a powerful and extensive tool. However, its use is constrained to the degree there must be a carefully crafted theoretical foundation underlying any models pursued – the 'garbage-in-garbage-out' maxim applies. The use of multi-agent methods thus must be framed carefully, with reference to prior research and transparency in the setup of the model. As Law and Kelton comment: "a fundamental problem in simulating complex systems is verifying that the simulation model adequately describes the system being simulated (Law & Kelton, 2000). This research supplies a well-grounded theoretical foundation: an economic, organizational, and behavioral context for modeling stakeholders and their pursuance of incentives within and across organizational and market contexts as relevant to sustainable resource management supply chains (see *Appendix 1*).

The Operations Management field recognizes the need for more universal models and design approaches in multi-agent simulation (Dolk, 2010). This concern is addressed by the structured application of MBSE and SysML.

Within this research, simulation should be considered as a tool to stimulate discussion and theory formation, but it is not anticipated that an attempt will be made to use the technique as the foundation for 'formal mathematical proof' or as a conclusive method to ground an assertion (formal mathematical proof is considered out-of-scope). Rather, the method is part of the research goal: to evidence value in the research process itself by utilizing the method to stimulate introspection in an area that involves irreducible factors of social meaning.

While such research could quickly become quite engineering focused and/or mathematically intensive, much work has already been done on formal methods for optimizing non-linear games and systems. Mathematical and formal-logic intensive research oriented towards formal proofs has been conducted to analyze non-linear, game-theoretic, and multi-agent systems from the standpoint of disciplines such as of control systems engineering, computer science, and economics. The intention for this research is to remain firmly anchored in the 'organizational management' discipline via a tie to organizational theory, grounding in core case study research, and a disciplinary anchor in operations management.

Otherwise, the central guiding principle in multi-agent modeling and analysis will be the KISS principle ("Keep It Simple, Stupid"). The intention is not to create complex and impressive mathematical models as much as it is to show how relatively simple simulation models, created based on careful organizational research and observation, can produce interesting and informative results of use to organizations and regulators.

4. CORE CONCEPT THREE: SUSTAINABILITY AND MULTI-STAKEHOLDER SUPPLY CHAINS

Core Concept: *Market-based mechanisms serve to align multi-stakeholder interests to sustainability goals*

Master Hypothesis: *Market incentives and constraints can be carefully architected to promote systemic collaboration to optimize social value targets*

Five final theoretical propositions are explained following. A diagrammatic perspective of the overarching concept in terms of the derived theories can be viewed in Figure 9, following.

4.1. Theory Eleven: Optimal Sustainability is a Negotiated Social Value Construct

Theory: *Purely technical attempts to optimize sustainability in extended supply chains will lead to inefficiencies and instability due to agency and behavioral bias factors*

Hypothesis: *Sustainability optimality involves foremost the negotiation of a multi-stakeholder definition of 'value'*

4.1.1. Essentials

Underlying this investigation is the proposal that evolving technology is extending the complexity and abilities of automated supply chain macro-systems while organizations, also evolving due to technology, are becoming increasingly complex. However, it is proposed that there is a gap in that there is a clearer understanding of formal complex, non-linear systems optimization problems than there are of the effects of social and political behavior upon such systems, incentive schemes in particular. Between automated and semi-automated engineered systems and complex organizations is an interface 'edge' whereby organizational systems and engineered systems need to integrate to satisfice broad human goals.

The unraveling of the U.S. housing bubble beginning in 2006 - 7 stands as a dramatic and graphic example of the failure of regulators and firms to co-architect stable and sustainable incentive architectures. Through a complex chain of misaligned incentives, banks and mortgage firms provided highly risky mortgages to a large population of individuals lacking long-term prospects for servicing the resulting debt (Kroft & Jacoby, 2011). Additionally, credit rating agencies, investment banks, and credit derivative trading firms advanced the crisis by repackaging and reselling the risky loans across the global financial system, providing fuel for more bad loans. The ensuing collapse has been termed the Global Credit Crisis, and is yet unraveling throughout the interconnected global financial system. A major lesson from the still resident Global Credit Crisis is that large-scale extended resource management architectures can hide systemic instabilities when aggregate, long-term sustainability is not explicitly considered by firms and regulators. In particular, hidden flaws can destabilize macro-systems when misaligned stakeholder incentives lead to self-destructive macro-outcomes.

The gravid example of the U.S. Housing Bubble which preceded the Global Financial Crisis is central: the technical system for loan servicing was both technologically and technically advanced, utilizing electronic infrastructure, computer-based analysis, and sophisticated financial instruments to provide housing financing resources to those in need. However, a lack of socio-political, economic, and behavioral context resulted in a system which was fatally flawed, and, ultimately, dramatically destructive to the global financial infrastructure. The lesson in the failure to effectively design sustainability into such a system needs to be heeded as a call to closely architect incentive systems alongside technical systems. As similarly advanced, complex 'technological resource management systems' are being developed to administer key social resources such as water, power, and telecommunications, the risk is that a lack of consideration of the potentially destabilizing effects of poorly considered incentive schemes may lead to similar tragedies.

This research proposes an interdisciplinary triangulation approach to examine the organizational challenges and opportunities posed by rapidly evolving technical approaches to the operational management of complex resource infrastructure. Without such grounding, operations management, via the efficacy of operations research, risks a bias towards engineering-

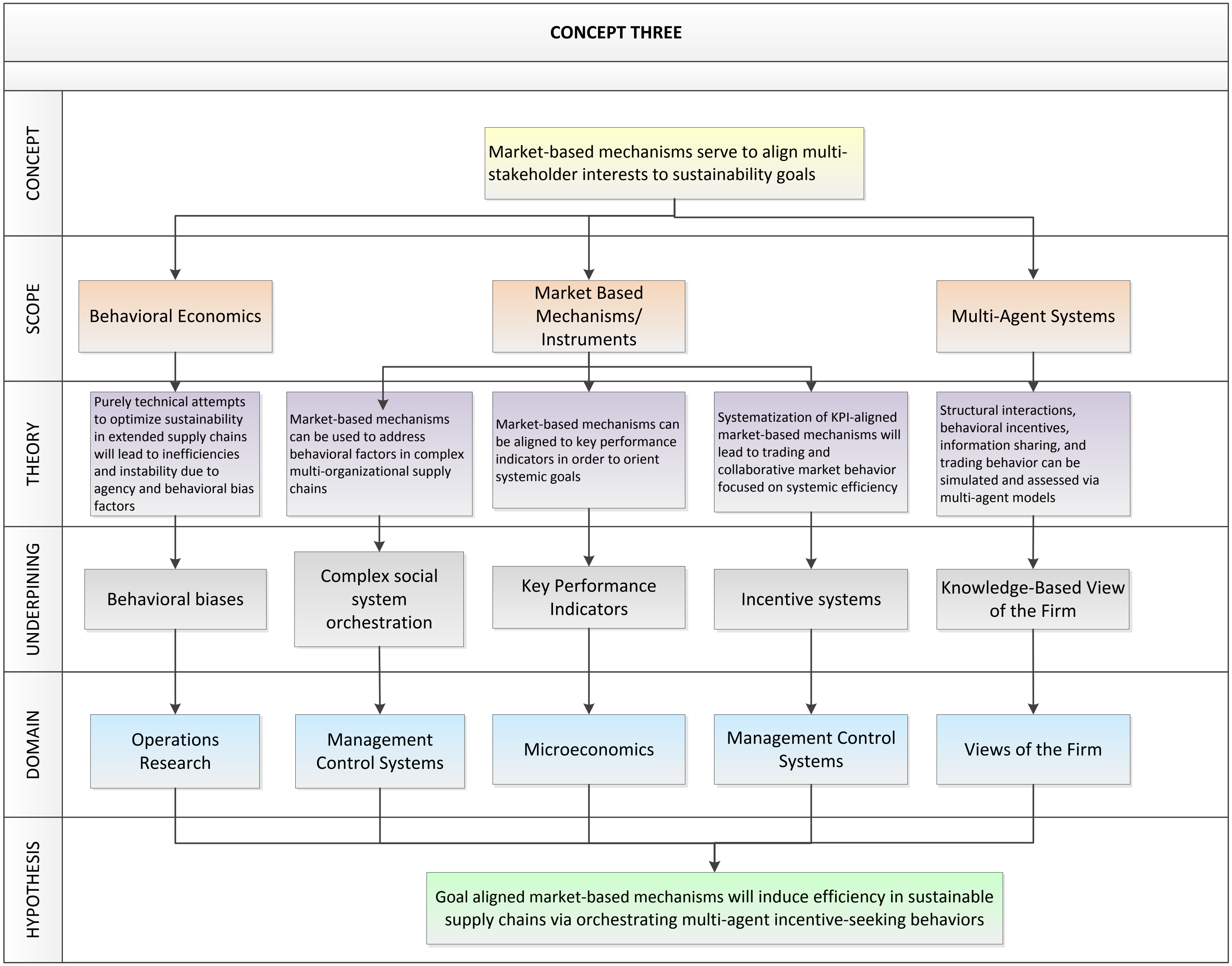


Figure 9: Concept Three – Market-based mechanisms serve to align multi-stakeholder interests to sustainability goals

based, computational, and formal algorithmic solutions to supply chain efficiency problems while ignoring the larger associated contextual organizational and general management challenges, which focus on human dynamics and behavioral understandings of organizations (Edmonds, 2011; Miller & Page, 2007). Simply stated, macro-technical infrastructure solutions without human organizational context risk embedded super-systemic instabilities. Thus, architecting sustainability infrastructure operational management solutions, which inherently are complex multi-stakeholder systems, must embed organizational context and understanding in order to achieve satisficing conditions.

4.1.2. Position in the Domain

Operations Management optimization of supply chains, via Operations Research, touches upon a substantial body of research involving engineered systems optimality in the domain of control systems. While references will be made to formal systems optimization and associated complex mathematical approaches, the main goal is to assert that systems optimality cannot be pursued without a stable social, political, regulatory, and economic super-structure in place to identify satisficing conditions for engineered systems to address (Edmonds, 2011). Thus, the review of research will attempt to clarify that formal systems optimality for complex extended supply chains is first and foremost a social agenda identification problem and demands methods appropriate to analyzing complex social systems, incentives in particular.

Within the sphere of business and management research, it is proposed that technical and engineering approaches to sustainability have not been pursued with an explicit view towards super-systemic models for multi-lateral stakeholder incentives. Notions of interfacing with and adapting to human behavioral perspectives, bounded rationality in particular, have generally not been explicitly designed into technical solutions for optimizing critical infrastructures, such as those associated with utility supply management (i.e. water and power). Much research literature and technical advancement concerning sustainability is now being pursued according to rather narrow efficiency goals. For instance, power systems are being architected for power efficiency and management, but little thought is being given to engineering systemic architectures for optimizing social welfare in electricity provision according to the best mix of public, private, and mixed agent incentives. As such, the risk is that technical advancement provides a stage for faulty incentive systems to cause social waste and even destruction, as was the case with Enron energy market trading manipulation.

Operations research, as a discipline focused on efficiencies in supply chains, has proceeded in advance of stakeholder management context and understanding. It is asserted that there is a research gap concerning sustainable supply chain design challenges, principally the need to interface engineering optimality with constantly shifting multi-stakeholder regulatory, organizational, and human welfare satisficing contexts. Multi-stakeholder incentive schemes, as the central rationale for agent participation, in particular are not often explicitly examined alongside proposals for supply chain technical re-engineering. This is not to critique focused research in operational technical efficiency: indeed, the efficacy of evolving methods has led to a revolution in supply-chain efficiencies. Rather, it is to exclaim that remarkable operational management technical advances have proceeded in advance of management understandings, leading to poorly understood shifts in the very nature of the firm and the increasingly unmanageable complexity of extended supply chains. As with the Global Credit Crisis, there is a great danger in simply applying commercial supply chain technologies and solutions to critical resource supply chains. The broader stakeholders and interests involved demand deeper consideration. In particular, it is essential that regulators and designers consider carefully the long-term effects of incentive schemes across such supply chains.

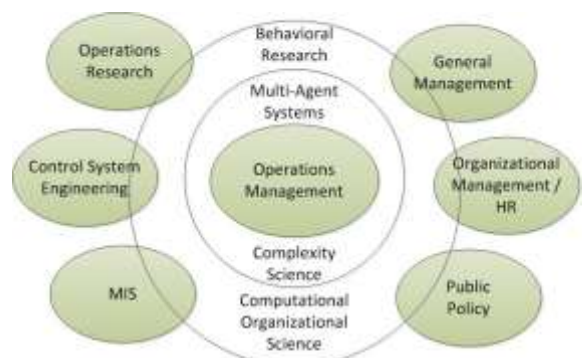


Figure 10: Proposed operations management research gap

4.1.3. Orientation of Theory

This research seeks to propose methods to bridge the gap between engineering- and solutions-based research with organizational management, economic, and behavior perspectives. It is proposed that multi-agent analysis addresses a methodological gap in operations management research by providing the ability to explore satisficing inter-systems value architectures for broad social welfare resource management.

4.1.4. Theoretical Strength

Technical supply chain advancements are outpacing understandings of related organizational factors:

- Rapid advancement of supply chain automation technology as a hybrid of computer and sensor technology, automation, and software analytics / decision management are occurring,
- Advancement is expanding the geographic, temporal, and stakeholder systemic boundaries of traditional supply chain 'frames',
- Technical operational management capabilities are growing faster than socio-political management understanding / capabilities,
- There is a gap requiring methods and tools for resolving extended supply chain operational management to broad organizational management principles,
- This gap is reflected in an academic research gap,
- However, there is a growing stream of research in assessing sustainable solutions within the discipline of operations management and accompanying research on multi-agent extended supply chain analysis, thus providing a disciplinary 'on-ramp' or foundation

4.2. Theory Twelve: Market-Mechanisms as Complexity Orchestrators

Theory: *Market-based mechanisms can be used to address behavioral factors in complex multi-organizational supply chains*

Hypothesis: *Market incentive and constraint instruments and processes can be used to optimize multi-stakeholder value in complex supply chains*

4.2.1. Essentials

The multi-agent model must: provide for a political process, have a context for quantifying and balancing 'value' (in terms of the various stakeholders), and offer incentives in the form of a variety of currencies and concessions to satisfice the relative values. Thus, an extended sustainable supply chain is one which both allows for political negotiation and is flexible enough to accommodate regime shifts, changes in the satisfaction of certain stakeholder goals, and fluctuating value contexts as power and coalitions shift. From this perspective, an integrated sustainable resource supply chain is perhaps best thought of as a 'shared micro-market' whereby the integrated system satisfices a virtual, shared fiat currency which fluctuates in value and is used to satisfice the various stakeholders. virtual currencies have great promise in satisficing the complex, overlapping systems and stakeholders which compose, for instance, modern urban environments.

4.2.2. Position in the Domain

Advances are occurring in multiple disciplines in the ability to satisfice complex real-world systems involving non-linearity, fuzzy logic, behavioral factors (i.e. bounded rationality), and shifting coalitions (Shoham & Leyton-Brown, 2009). As an example, information theory has been applied to connect game theory and statistical physics to allow for the satisficing of multi-agent scenarios involving agents operating under bounded rationality conditions (Wolpert, 2006). When triangulated between core research, case study research, and applied multi-agent simulation, such techniques hold great promise for the study of the systemic effects of incentive systems. The intent of such extrapolation is to produce useful guidance and best practices for practitioners, planners, and regulators.

4.2.3. Orientation of Theory

There is a great body of research concerning the application of particular market games and structures. Auctions, regulatory structures, and collaborative games have all been studied in terms of their ability to evidence economic optimality. More research will be conducted concerning which particular market-mechanisms would be suitable for modeling and simulation.

4.2.4. Theoretical Strength

Existing research provides formal mathematical proof of the 'efficient' value inducing effects of particular market-related mechanisms, such as auctions and multi-player value games (Fink, 1998). An attempt will be made to connect prior research to tools used in modeling and simulation.

4.3. Theory Thirteen: Aligning Market-Mechanisms with Stakeholder Value

Theory: *Market-based mechanisms can be aligned to key performance indicators in order to orient systemic goals*

Hypothesis: *Market-mechanisms can be aligned to multi-stakeholder value targets via metrics*

4.3.1. Essentials

This research proposes that the identification of satisficing solutions must in the end be achieved via a common measure. Drawing upon a firm foundation in emerging research, it is proposed that economic measures be the lingua franca of satisficing solutions. While this proposition may initially be philosophically adverse to environmental and social stakeholders, there have been a number of recent research pieces which have proposed models for capturing environmental and social goals in net economic terms via improved process cost accounting (Lovins et al., 2007). As well, industries are converging on standard indices to score products on sustainability measures, allowing consumers to satisfice their purchasing decisions (Chouinard, Ellison, & Ridgeway, 2011).

4.3.2. Position in the Domain

Extending research into market mechanisms, the role and nature of performance metrics will be further researched. Kaplan and Porter have produced research related to processes and systems for value chain management via metrics and cost accounting (Kaplan & Anderson, 2004; Kaplan & Porter, 2011).

4.3.3. Orientation of Theory

It is proposed that virtual currency, as an informational locus for realizing systemic utility, could be used as a formal mechanism to optimize informational exchanges between machine and human stakeholders to optimize the functioning whole. In the case of the Smart City, current research is quite engineering focused, and largely ignores the challenge posed by political stakeholders attached to overlapping resource supply chains. Thus, virtual money also holds some promise in allowing for a localized market-based metric for satisficing broad systemic goals outside the bounded interests of localized stakeholders and resource chains. Thus, broad social welfare measures such as citizen health and happiness can be targeted by creating and trading upon virtual currencies pegged to a quantifiable metric for such measures (i.e. a combination of metrics for citizen safety, availability of shelter, clean drinking water, long-term environmental resource stability, etc.).

4.3.4. Theoretical Strength

There is a solid body of research concerning metrics. Triangulation will be used to tie incentive design to metric target design.

4.4. Theory Fourteen: Aligned Metrics with Market Incentives

Theory: *Systematization of KPI-aligned market-based mechanisms will lead to trading and collaborative market behavior focused on systemic efficiency*

Hypothesis: *Simulation can be used to test the feasibility of market incentives as aligned to shared stakeholder metrics*

4.4.1. Essentials

This proposition closes the loop by suggesting that properly aligned incentives, as tied to shared metrics, within a market context will promote systemic efficiency. Sustainability can thus be ‘architected’ into multi-organizational systems provided metrics and incentives are aligned properly.

4.4.2. Position in the Domain

Research involves an understanding of Management Control Systems in terms of their ability to impel agent behavior according to incentives, assessment schemes, and decision rights combined with knowledge.

4.4.3. Orientation of Theory

Related theory can be studied as systemic phenomenon in the context of the Knowledge-Based View of the firm.

4.4.4. Theoretical Strength

Further research will be conducted to establish theoretical strength. Research on Management Control Systems (Merchant & Stede, 2003) and the Knowledge-Based View (Grant, 1997) will serve as a foundation.

4.5. Theory Fifteen: Multi-Agent Simulation as a Multi-Organizational Management Control Systems Assessment Methodology

Theory: *Structural interactions, behavioral incentives, information sharing, and trading behavior can be simulated and assessed via multi-agent models*

Hypothesis: *Multi-agent simulation is suitable for the assessment of multi-organizational Management Control System fitness*

4.5.1. Essentials

Multi-agent simulation is proposed to pursue analysis of the effect of inter-organizational incentive architectures on sustainable value satisficing for resource supply chain management. Incentive architectures derived from case research will be modeled and analyzed to assess satisficing efficiency and aggregate 'sustainable value' (as established in the case analysis). The application of multi-agent modeling will be guided by theoretical underpinning established in the core research, including perspectives on complexity theory and organizational complexity (Erdi, 2008; Lewin, 1993; Morrison, 1991; Nicolis & Nicolis, 2007; Stacey, 2010), network theory (Carrington et al., 2005), game theory (Fink, 1998; Ramos & Liu, 2011; Wolpert, 2006; Zagare, 1984), engineered complex systems (Braha et al., 2006), control systems (Nise, 2011), incentives (Merchant & Stede, 2003), and computational organizational theory (Brewerton, 2001) - see Appendix 1 for a Research Context Diagram.

4.5.2. Position in the Domain

Multi-agent analysis is a technique which shows great promise in straddling computational (formal mathematics and logic) approaches to problem analysis with the fuzzy, non-linear, and stochastic dynamics common to social dynamics. For a computer science and engineering perspective example, as related to mathematical and formal reasoning techniques, an analysis of submissions to the recent 2011 IEEE Intelligent Systems special issue on 'AI in Power Systems and Energy Markets' (see *Appendix 3*) reveals the breadth of formal techniques applied to multi-agent associated optimization problems (Ramos & Liu, 2011). Multi-agent analysis, in the broad sense, potentially subsumes all such techniques from the perspective that agents can be computationally enabled to reason using any combination of formal techniques. Indeed, it is the ability to model populations of agents who pursue quite different reasoning methods, or ways of 'sense-making' in their contextual environment, that makes this technique so compelling.

4.5.3. Orientation of Theory

Technological development is steadily and inexorably chipping away at the traditional boundaries of the firm, leading to companies which are both tighter and broader, melting into electronic partnerships with suppliers and customers. The firm, defined according to varying "theories of the firm", can be viewed as a set of transaction efficiencies - Transaction Cost Economics (Holcomb & Hitt, 2007; McIvor, 2009; Williamson, 1973, 1975); a bundle of unique competitive resources - Resource Based View (Barney, 1991, 1999), or an optimal set of information and decision making rights - Knowledge-based View (Grant, 1997). Each theory of the firm explicitly validates the notion that technological efficiencies impose shifts in the equilibrium boundaries that gird the size and nature of the firm.

The proposed research is interdisciplinary, attempting to resolve a set of macro- principles via a combination of deductive triangulation and inductive extrapolation from real cases. The intent of the research is to inform management practice, and to provide a guide to an emerging area of endeavor with both commercial and broad social impact. As has been covered in the previous sections, there is a need for a firm theoretical foundation for multi-agent analysis to be an effective methodology. A comprehensive literature review will be used to set this foundation. The work of Chris Hart, 'Doing a Literature Review', will be applied in particular (Hart, 2000). As well, meta-theoretical aspects of research design and theory formation will be considered (Sutton, 1995; Verschuren, 2010; Whetten, 1989).

4.5.4. Theoretical Strength

Sustainable resource management via multi-agent analysis has recent research precedence in case analysis (Berger et al., 2007; Bousquet et al., 2002). A concern for this research is that the complexity of multi-agent models quickly outstrips the scope for simple game theory modeling. Multi-agent research does evidence more complex game formats and notions of dynamic agents, for example the application of Bayesian algorithms in competitive negotiation (Hindriks & Tykhonov, 2008) and learning agents (Shoham & Leyton-Brown, 2009). As this researcher is not a mathematician, there is a limitation regarding the extent to which this research can expect to pursue novel proofs or mathematical methods to achieve satisficing conditions. It is likely that the literature review will cite models and that modeling will attempt to apply as applicable. However, establishing formal rigorous proof conditions and lengthily novel mathematical modeling is considered out-of-scope.

5. CONCLUDING COMMENTARY

The guiding intention of this research is to address the Operations Management gap between operational efficiency in managed technical infrastructure and poor related understandings of organizational architecture factors and effects. Beyond providing companies with guidance in defining and addressing sustainability specifically, the general intent is to provide a methodology for architecting better and more efficient systems from the standpoint that organizational architectures ground and guide technical architectures.

The assertion is that human guidance and context is a contextual 'wrapper' around operational efficiency, such that powerful operational infrastructure without a socio-economic context and design is essentially wasteful and/or flawed. Thus the addressed gap intends to arrive at a better understanding of human-computer interfaces between complex technical infrastructure and complex multi-organizational systems (from both a structural and relational standpoint). It is hoped that by charting best practices related to complex resource infrastructure orchestration this research can provide a map to areas where software and technology interfaces (i.e. 'smart agent' driven technology and systems) can collaborate to ensure human resources are orchestrated at peek sustainability and efficiency levels.

At a more general level, the hope is that this research will raise awareness of an emerging trend: rapidly advancing supply chain automation technology leading to increased organizational complexity, and thus uncertainty and potential risk. By mapping organizational 'boundaries' in terms of their interface with complex supply chains, this research can serve to orient managers to where organizations need to evolve to adapt to growing complexity. Given the growing state of 'information overload' facing most managers, this research should also serve to orient the attention of management to key concerns related to complex technical systems architectures, with special relevance to the 'organizational orchestration' capacity of multi-agent aware Management Control Systems.

REFERENCES

Aart, C. v. (2004). *Organizational Principles for Multi-Agent Architectures*. Berlin: Birkhauser.

Adams, W. M. (2006). The Future of Sustainability: Re-thinking Environment and Development in the Twenty-first Century *Report of the IUCN Renowned Thinkers Meeting*: International Union for Conservation of Nature.

Allen, T. T. (2011). *Introduction to Discrete Event Simulation and Agent-based Modeling*. London: Springer.

Barney, J. (1991). Firm resources and sustained competitive advantage. *Journal of Management, 17*(1), 21.

Barney, J. (1999). How a Firm's Capabilities Affect Boundary Decisions. *Sloan Management Review, 40*(3), 9.

Berger, T., Birner, R., Mccarthy, N., DíAz, J., & Wittmer, H. (2007). Capturing the complexity of water uses and water users within a multi-agent framework *Water Resources Management, 21*(1), 19.

Bousquet, F., Barreteau, O., d'Aquino, P., Etienne, M., Boissau, S., Aubert, S., . . . Castella, J. C. (2002). *Multi-agent systems and role games: collective learning processes for ecosystem management*. Retrieved from http://www.dpi.inpe.br/gilberto/cursos/cst-305/papers/bousquet_2002_mas_review.pdf

Braha, D., Minai, A. A., & Bar-Yam, Y. (2006). *Complex Engineered Systems*. New York: Springer.

Brewerton, P. M., Millward, L. J. (2001). *Organizational Research Methods: A Guide for Students and Researchers*. London: SAGE Publications Ltd.

Carrington, P. J., Scott, J., & Wasserman, S. (Eds.). (2005). *Models and Methods in Social Network Analysis*. New York: Cambridge University Press.

Castellani, B., & Hafferty, F. (2010). *Sociology and Complexity Science: A New Field of Inquiry*. Heidelberg: Springer.

Catterson, V. M., Davidson, E. M., & McArthur, S. D. J. (2011). Embedded Intelligence for Electrical Network Operation and Control *Intelligent Systems, IEEE 26*(2), 8.

Chouinard, Y., Ellison, J., & Ridgeway, R. (2011). The Sustainable Economy. *Harvarb Business Review, 89*(10), 11.

Dolk, D. (2010). Structured Modeling and Model Management. In M. S. Sodhi & C. S. Tang (Eds.), *A Long View of Research and Practice in Operations Research and Management* (Vol. 148, pp. 25). New York: Springer.

Edmonds, B. (2011). Context in social simulation: why it can't be wished away. *Computational & Mathematical Organization Theory 17*(4).

Epstein, J. M. (2006). *Generative Social Science: Studies in Agent-Based Computational Modeling*. Princeton: Princeton University Press.

Erdi, P. (2008). *Complexity Explained*. Heidelberg: Springer.

Ferber, J., Gutknecht, O., Jonker, C. M., Mueller, J. P., & Treur, J. (2001). *Organization Models and Behavioural Requirements Specification for Multi-Agent Systems.* Paper presented at the 10th European Workshop on Modelling Autonomous Agents in a Multi-Agent World, MAAMAW'01.

Fink, E. C. (1998). *Game Theory Topics: Incomplete Information, Repeated Games and N-Player Games*. London: SAGE Publications, Inc.

Franklin, S., & Graesser, A. (1996). *Is it an Agent, or just a Program?: A Taxonomy for Autonomous Agent.* Paper presented at the Proceedings of the Third International Workshop on Agent Theories, Architectures, and Languages.

Gilbert, N. (2008). *Agent-Based Models*. Thousand Oaks: SAGE Publications, Inc.

Gilbert, N., & Troitzsch, K. G. (2005). *Simulation for the Social Scientist*: Open University Press.

Grant, R. M. (1997). The Knowledge-based View of the Firm: Implications for Management Practice. *Long Range Planning, 30*(3), 4.

Grimm, V., & Railsback, S. (2005). *Individual-based modeling and ecology*. Princeton, New Jersey: Princeton University Press.

Grote, G. (2009). *Management of Uncertainty: Theory and Applications in the Design of Systems and Organizations*. London: Springer.

Hardin, G. (1968). The Tragedy of the Commons. *Science, 162*, 5.

Hart, C. (2000). *Doing a Literature Review*. London: Sage.

Hindriks, K., & Tykhonov, D. (2008, May, 12-16, 2008). *Opponent Modelling in Automated Multi-Issue Negotiation Using Bayesian Learning.* Paper presented at the 7th International Conference on Autonomous Agents and Multiagent Systems, Estoril, Portugal.

Holcomb, T., & Hitt, M. (2007). Toward a model of strategic outsourcing. *Journal of Operations Management, 28*(2), 17.

Horling, B., & Lesser, V. (2005). A Survey of Multi-Agent Organizational Paradigms. *The Knowledge Engineering Review, 19*, 35.

Huang, E., & Ramamurthy, R. (2007). *System and simulation modeling using SysML.* Paper presented at the Winter Simulation Conference.

Huynh, T. V., & Osmundson, J. S. (2006). *A Systems Engineering Methodology for Analyzing Systems of Systems*. Department of Systems Engineering, Departments of Information Sciences and Systems Engineering. Naval Postgraduate School. Retrieved from http://www.sosece.org/pdfs/2ndConference/Presentations/SoSECE%20Breakout%20Day%201/HUYNH_Paper.pdf

Jayatilleke, G., Padgham, L., & Winikoff, M. (2005). A model driven component based development framework for agents. *International Journal of Computer Systems Science and Engineering, 20*(4), 9.

Kaplan, R. S., & Anderson, S. R. (2004). Time-Driven Activity-Based Costing. *Harvard Business Review, 9*(11).

Kaplan, R. S., & Porter, M. E. (2011). How to Solve the Cost Crisis in Health Care. *Harvard Business Review, 89*(9), 18.

Kleindorfer, P. R., Singhal, K., & Wassenhove, L. N. V. (2005). Sustainable Operations Management. *Production and Operations Management, 14*(4), 10. History of Operations Management with focus on sustainability as emerging trend

Kroft, S., & Jacoby, J. (2011). Prosecuting Wall Street. *60 Minutes*. Retrieved from Prosecuting Wall Street website: http://www.cbsnews.com/8301-18560_162-57336042/prosecuting-wall-street/?pageNum=2&tag=contentMain;contentBody Eileen Foster, Countrywide Executive Vice President - Fraud Investigations

Foster: The loan officers received bonuses, commissions. They were compensated regardless of the quality of the loan. There's no incentive for quality. The incentive was to fund the loan. And that's-- that's gonna drive that type of behavior.

Lauricella, T. (2010, October 2, 2010). How a trading algorithm went awry, *The Wall Street Journal*. Retrieved from http://online.wsj.com/article/SB10001424052748704029304575526390131916792.html

Law, A. M., & Kelton, W. D. (2000). *Simulation modeling and analysis*. Boston: McGraw-Hill.

Lewin, R. (1993). *Complexity: Life at the Edge of Chaos*. Chicago: Phoenix.

Lin, G., Ettl, M., Buckley, S., Bagchi, S., Yao, D. D., Naccarato, B. L., . . . Koenig, L. (1994). Extended-Enterprise Supply-Chain Management at IBM

Personal Systems Group and Other Divisions. *Interfaces, 30*(1), 18.
Lin, G., & Wang, K.-Y. (2010). Sustainable Globally Integrated Enterprise (GIE). In M. S. Sodhi & C. S. Tang (Eds.), *A Long View of Research and Practice in Operations Research and Management* (Vol. 148, pp. 22). New York: Springer.

Liu, Z., Yang, D.-s., Wen, D., Zhang, W.-m., & Mao, W. (2011). Cyber-Physical-Social Systems for Command and Control. *Intelligent Systems, IEEE 26*(4), 5.
Lovins, A. B., Lovins, L. H., & Hawken, P. (2007). A Road Map for Natural Capitalism. *Harvard Business Review*.
McIvor, R. (2009). How the transaction cost and resource-based theories of the firm inform outsourcing evaluation. *Journal of Operations Management, 27*(1), 18.
Mehta, N., & Kisling, W. (2010). Futures sale spurred May 6 Panic as Traders lost faith in data Retrieved December 5, 2010, 2011, from http://www.bloomberg.com/news/2010-10-01/automatic-trade-of-futures-drove-may-6-stock-crash-report-says.html

Merchant, K. A., & Stede, W. A. V. d. (2003). *Management Control Systems: Performance Measurement, Evaluation and Incentives*. London: Prentice Hall.

Miller, J. H., & Page, S. E. (2007). *Complex Adaptivce Systems: An Introduction to Computational Models of Social Life*. Princeton, New Jersey: Princeton University Press.

Monch, L., Lendermann, P., McGinnis, L. F., & Schirrmann, A. (2011). A survey of challenges in modelling and decision-making for discrete event logistics systems. *Computers In Industry, 62*(6), 557-567. doi: 10.1016/j.compind.2011.05.001

Morrison, F. (1991). *The Art of Modeling Dynamic Systems: Forecasting for Chaos, Randomness and Determinism*. New York: Dover Publications, Inc.

Nicolis, G., & Nicolis, C. (2007). *Foundations of Complex Systems: Nonlinear Dynamics, Statistical Physcis, Information and Prediction*. Singapore: World Scientific.

Nise, N. S. (2011). *Control Systems Engineering* (Sixth ed.). Asia: John Wiley & Sons.

Penserini, L., Perini, A., Susi, A., & Mylopoulos, J. (2006). From Stakeholder Intentions to Software Agent Implementations. In B. Steinholtz, A. Solvberg & (Eds.), *Advanced Information Systems Engineering* (pp. 14): Springer.

Prietula, M. J., Carley, K. M., & Gasser, L. (1998). *Simulating Organizations*. Cambridge, Massachusetts: MIT Press.

Raghu, T. S., Jayaraman, B., & Rao, H. R. (2004). Toward an Integration of Agent- and Activity-Centric Approaches in Organizational Process Modeling: Incorporating Incentivce Mechanisms. *Information Systems Research, 15*(4), 19.
Railsback, S. F., & Grimm, V. (2012). *Agent-Based and Individual-Based Modeling*. Princeton, New Jersey: Princeton University Press.

Ramos, C., & Liu, C.-C. (2011). AI in Power Systems and Energy Markets *Intelligent Systems, IEEE 23*(2), 4.

Rivaldo, R., Germoglio, G., Santos, F., Chen, Y., Milojicic, D. S., & Adams, R. (2007). *SML Model-based Management*. Paper presented at the 10th IFIP/IEEE International Symposium on Integrated Network Management, Munich.
Russell, S., & Norvig, P. (2010). *Artificial Intelligence: A Modern Approach* (Third ed.). New Jersey: Prentice Hall.

Sargut, G., & McGrath, R. G. (2011). Learning to live with complexity. *Harvard Business Review*, 9.
Shoham, Y., & Leyton-Brown, K. (2009). *Multiagent Systems: Algorithmic, Game-Theoretic, and Logical Foundations*. New York: Cambridge University Press.

Sodhi, M. S., & Tang, C. S. (Eds.). (2010). *A Long View of Research and Practice in Operations Research and Management Science: The Past and the Future* (Vol. 148). New York: Springer.

Stacey, R. D. (2010). *Complexity and Organizational Reality: Uncertainty and the Need to Rethink Management After the Collapse of Investment Capitalism*. London: Routledge.

Staff, V. T. L. (2008). Sustainability - The Solution Matrix Retrieved December 3, 2011, 2011, from http://www.verifysustainability.com/Pie%20Diagram/PieDiagram_Open_Page.aspx

Steger, U., Amann, W., & Maznevski, M. (2007). *Managing Complexity in Global Organizations*. Cornwall, UK: John Wiley & Sons, Ltd.

Sterling, L. S., & Taveter, K. (2009). *The Art of Agent-Oriented Modeling*. Boston: MIT Press.

Sun, R. (2006). *Cognition and Multi-Agent Interaction: From Cognitive Modeling to Social Simulation*. New York: Cambridge University Press.

Sutton, R. I., & Staw, B. M. (1995). What Theory Is Not. *Administrative Science Quarterly, 40*(3), 13.

Sveiby, K.-E. (2001). A knowledge-based theory of the firm to guide strategy formation. *Journal of Intellectual Capital 2*(4).

Verschuren, P., & Doorewaard, H.. (2010). *Designing a Research Project* (2nd ed.). The Hague: Eleven International Publishing.

Wellman, M. (1996). The Economic Approach to Artificial Intelligence. *ACM Computing Surveys, 28*(4).

Whetten, D. (1989). What constitutes a theoretical contribution? *Academy of Management Review, 14*(4), 5.

Williamson, O. E. (1973). Markets and Hierarchies: Analysis and Antitrust Implications. *American Economic Review, 63*(2), 10.

Williamson, O. E. (1975). *Markets and Hierarchies*. New York: Free Press.

Wolpert, D. H. (2006). Information Theory - The Bridge Connecting Bounded Rational Game Theory and Statistical Physics. In D. Braha, A. A. Minai & Y. Bar-Yam (Eds.), *Complex Enigeered Systems* (pp. 29). Cambridge, Massachusetts: Springer.

Wooldridge, M. (2009). *An Introduction to MultiAgent Systems* (2nd ed.). Chichester: Wiley & Sons Ltd.

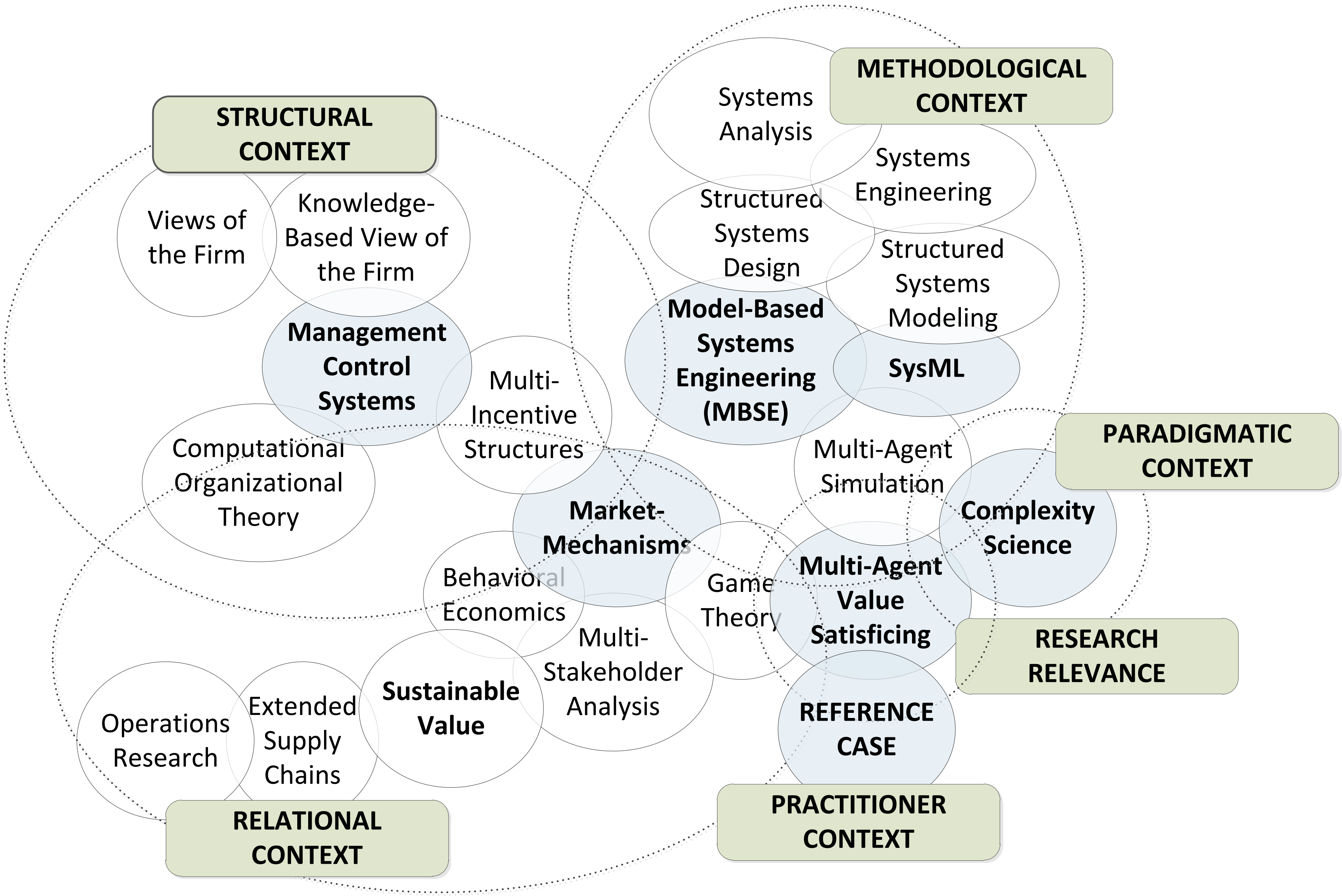
Wooldridge, M., Jennings, N. R., & Kinny, D. (2000). The Gaia Methodology for Agent-Oriented Analysis and Design. *Autonomous Agents and Multi-Agent Systems, 3*, 27.

Yin, R. (2009). *Case Study Research: Design and Methods* (Fourth ed.). London: SAGE Publications, Inc.

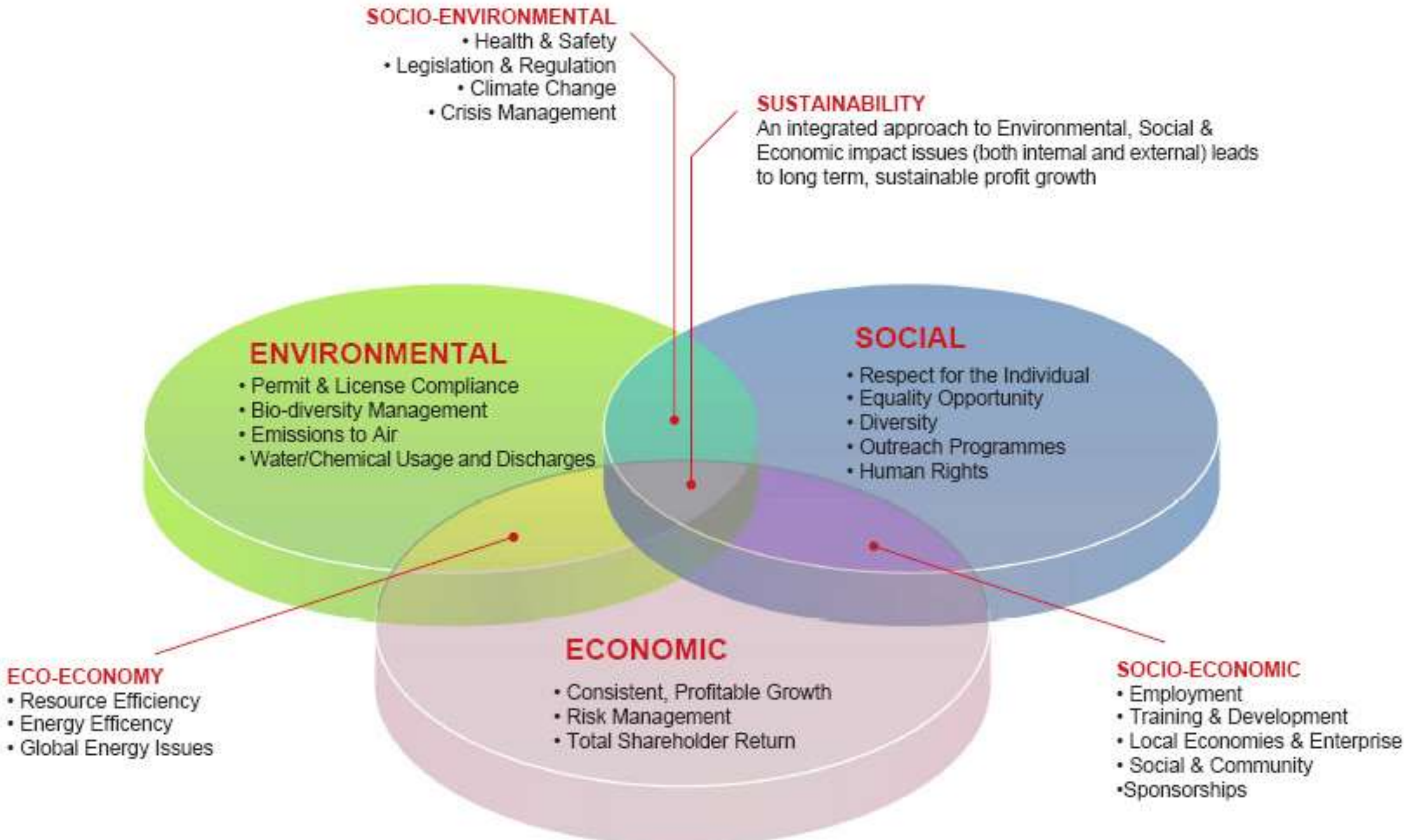
Zagare, F. C. (1984). *Game Theory: Concepts and Applications*. London: SAGE Publications, Inc.

APPENDIX

Appendix 1: Research Context Diagram



Appendix 2: The Sustainability Solution Matrix



The Sustainability Solution Matrix (Staff, 2008)[1]

[1] In the context of Figure 2, satisficing in overlapping regions are described as (Adams, 2006): Economic + Environmental = **Viable**; Social + Economic = **Equitable**; Environmental + Social = **Bearable**; Economic + Environmental + Social = **Sustainable**

Appendix 3: Example of Multi-Agent Value Optimization Methodologies

AI generic areas	Number of submissions	Intelligent systems techniques*	Type of problem*	Power and energy applications
Knowledge-based systems	3	Expert systems (2), intelligent tutoring systems	Design, monitoring, training	Cogeneration power plants, transformer quality control, incident analysis in power systems control centers
Probabilistic reasoning	1	Probabilistic reasoning	Monitoring	Viscosity control in fossil fuel power plants
Incomplete information	1	Incomplete information	Forecasting	Electricity market pricing
Fuzzy systems	4	Fuzzy systems (3), Neuro-fuzzy	Diagnosis, control (2), optimization	Oscillations in interconnected systems, incident analysis in power systems control centers, minimization of voltage sag and swell metering systems, power system stability
Constraints	1	Constraint satisfaction	Control	Smart grid
Basic search	2	Local search, tabu search	Planning	Switch allocation in distribution networks, distributed network expansion planning
Evolutionary algorithms	9	Genetic algorithms (9)	Optimization (6), test, assignment, planning	General power systems, distribution systems, assigning computer resources to real-time digital simulators, market power, short-term scheduling of distributed energy resources, benefits of distributed generation owners, minimization of voltage sag and swell metering systems, distributed generation planning, vulnerability analysis in power systems
Swarm intelligence	8	Particle swarm optimization (8)	Optimization (4), planning (2), reconfiguration, dispatching, selection, classification, estimation, forecasting	Composite load model parameters, short-term load forecasting, demand response, short-term scheduling of distributed energy resources, dispatching wind farms reactive power sources, distributed network expansion planning, feeder reconfiguration in distribution systems, feature selection in nontechnical losses detection
Game theory	2	Game theory (2)	Classification (2)	Learning behavior of electricity markets players, generation reliability in power markets
Pattern matching	1	Pattern recognition	Monitoring	Reduction of power consumption
Machine learning, data mining	15	Neural networks (6), reinforcement learning (4), k-means (2), decision trees, support vector machines, neuro-fuzzy	Classification (4), forecast (3), monitoring (2), estimation (2), clustering, control, optimization, modeling	Stability assessment, transmission expansion planning, hydrocarbon development, viscosity control in fossil fuel power plants, generation reliability in power markets, short-term load forecasting, control of wind generators, analysis of overvoltages in power system restoration, nonintrusive load monitoring, power system stability, learning behavior of electricity markets players, electricity market pricing, bids in electricity markets, profits in electricity markets, incident analysis in power system control centers
Agent-based systems	4	Multiagent systems (2), agent-based simulation (2)	Modeling, forecasting, optimization, control, negotiation	Electricity markets, electricity market bids, electricity markets profits, smart grid

*The numbers in parentheses represent the number of articles using that IS technique or covering that type of problem.

2011 IEEE Intelligent Systems special issue on 'AI in Power Systems and Energy Markets' (Ramos & Liu, 2011)