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ABSTRACT

Cyber Physical Social Systems (CPSS) represent a dynamic landscape where contemporary challenges often take the form of enigmatic "Wicked Problems." These problems are marked by their complexity, with incomplete information and multiple stakeholders, each with different views and goals. This necessitates the incorporation of human judgements and abilities compounded through computational capabilities to carry interpretive and evidentiary analysis to frame wicked problems. One prominent area where these problems arise is in the realm of public policy. Public policies require a nuanced approach that recognizes their inherently complex nature and employs appropriate methods to navigate these intricacies. Viewed through the systems thinking lens, social issues, particularly wicked problems, resemble evolving CPSS. Understanding the evolving nature of CPSS is fundamental for designers, as it lays the foundation for comprehending their intricate dynamics, characteristics, and requirements, serving as a prerequisite for navigating these complex domains.

In this context, the hypothesis is that public policy is an evolving CPSS. To design effective public policies, one must grasp the interaction between social integration strategies, problem structure, and the social environment. This holistic understanding not only frames wicked problems and integrates the foundational knowledge required for evolving CPSS but also illuminates the concept of public policy as a dynamic and evolving entity. This enlightenment empowers a comprehensive approach to design public policy and synthesizing design options that address multifaceted societal challenges within a systems framework.

The primary objective through this thesis is to define a Ph.D. proposal that will be submitted to the National Science Foundation (NSF) and will anchor in research gaps which I will address in my dissertation. The key takeaways from this thesis include a deeper understanding of effectively framing wicked problems, establishing foundational knowledge for designing evolving cyber-physical-social systems, and exploring the foundational approach for holistic design of public policy. This is anchored

in establishing the characteristics of evolving CPSS and identifying the requirements list to aid designers to design evolving CPSS. Said that, the further stage lies in developing a cognitive map for evolving CPSS from the perspective of design based decision support to design public policies and assist policy makers to make better informed decisions. This is furthered by establishing an approach and a conceptual map to design public policies that is defined technically in the proposal as the outcome of this thesis.

CHAPTER 1

DESIGNING PUBLIC POLICIES: FOUNDATIONAL PERSPECTIVE FOR SOCIAL PROBLEMS AS COMPLEX SYSTEMS

The principal goal through this thesis is to establish fundamental and foundational models required for **designing public policy** as an **Evolving Cyber-Physical-Social System**. This is backed by establishing a fundamental model to design Evolving Cyber Physical Social Systems that forms one of the parallel goals in this thesis.

The principal motivation to write this thesis is to establish a groundwork for a Ph.D. dissertation by defining the Ph.D. proposal that utilizes the foundational models established through this thesis.

In this Chapter a foundation is laid to initialize the journey through this thesis to design public policy as an Evolving Cyber-Physical-Social System. This thesis is written to adopt a transdisciplinary approach, seamlessly integrating three main domains: comprehending social problems that are wicked in nature, establishing fundamental knowledge in the paradigm of evolving cyber-physical social systems, and strategically designing public policies, that build on the first two domains. Due to the intricate transdisciplinary nature of the research undertaken in this thesis, coupled with the diverse characteristics of each domain, through Chapter 2 an introduction to the foundational literature on wicked problems is provided, followed by dedicated chapters delving into the specific literature of each domain. Chapter 2 is aimed to serve as the cornerstone for elucidating the motivation behind tackling wicked problems, and subsequent chapters build upon this foundation to address specific issues identified as research gaps. Through each chapter the objectives are outlined that are aimed to address through this thesis, contributing to a comprehensive exploration of the identified challenges. By transcending disciplinary boundaries, through this research it is aimed to weave together diverse knowledge sets, fostering a more holistic understanding of wicked problems and the development of fundamental and integrated models to design public policies.

The broader picture through this thesis is to establish a foundational reservoir of knowledge, serving as a catalyst for policymakers to make better informed decisions in designing policies that significantly contribute to the broader welfare of society.

1.1 BACKGROUND

Designing public policies has been a longstanding and extensively discussed topic in the literature and state of the art. While the discourse on policy design approaches and methods is ceaseless, a persistent void exists in the knowledge and fundamental research in this field, attributed to the ever-evolving and complex nature of problems that continually take on new forms. This underscores the pressing need for more effective policy design, as the challenges at hand not only evolve but also grow in complexity each day, demanding solutions that surpass those of yesterday.

Designing effective public policy is not just about wielding the tools; it's about being intertwined with the complexities of the social issues that to be addressed. Unlike a neatly defined puzzle, these problems are often "wicked problems" – characterised by incomplete information, multifaceted challenges that lack a single, universally accepted solution. Their true nature is constantly evolving as societal values, demographics, and technology shift. *Imagine trying to paint a moving picture – that's the dynamic dance policymakers engage in when tackling social woes.*

This inherent complexity is precisely why a deep understanding of the problem's nature is paramount. *It's like deciphering a cryptic message – without grasping the underlying causes and interconnected factors, designing a well-targeted policy becomes an exercise in frustration.* By unraveling the intricate web of a social problem, policymakers gain the critical insights needed to design solutions that are not just effective but also adaptable to the ever-changing landscape.

To comprehend the issue targeted by a designed policy, it becomes crucial to recognize the "instruments" as outlined in policy literature, encompassing tools, strategies, and frameworks. This forms a link between the problem's nature, its understanding, and the application of well-considered approaches that facilitate policy design based on diverse considerations.

Through this thesis the essential groundwork to tackle the challenges, as outlined in the previous paragraphs is provided. The strategic approach to addressing fundamental issues involves the creation of foundational models for public policy design. This process is integral to how research gaps are identified, and objectives are formulated within the thesis. The results derived from addressing these research gaps align with the novel knowledge generated through proposed transdisciplinary research.

1.2 SOCIAL PROBLEMS AS COMPLEX SYSTEMS

Jay W. Forrester, more commonly regarded as the ***Father of System Dynamics,*** in his article *"Counterintuitive Behavior of Social Systems"*[1] argues "*It is my basic theme that the human mind is not adapted to interpreting how social systems behave*." ~~ "*Evolutionary processes have not given us the mental skill needed to properly interpret the dynamic behavior of the systems of which we have now become a part.*" These two sentences guide almost 80% of the challenges that are faced by the systems designers today who aspire to design social systems in some or another way. Surprisingly after this article was published back in 1971, there are still same issues that persist; the behaviour of social problems (*when viewed a system*) and addressing evolution remains research gap. Understanding social systems is more challenging than comprehending technological systems, particularly when the focus shifts from seeking **'solutions'** for technological systems to **'addressing'** social systems.

Characteristics of Social Problems as described by Jay W. Forrester in [1] are,

1. ***Social systems are inherently insensitive to most policy changes that people select in an effort to alter the behavior of the system.***

   One of the probable reasons for this characteristic are undirected approaches to consider the social space in system design through the **collective behavior** of systems. It includes not just thinking about designing policies but going at a deeper level to understand to effect of flow of information in people and resulting change in objectives, interests, and goals of various stakeholders in the problem. This anchors in designing effective public policies and comprehensive policies characterised by collective behavior. This anchors in Chapter 5 of thesis, the foundation for which lies in Chapter 4.

2. ***All the social systems seem to have a few sensitive influence points through which the behavior of the system can be changed.*** *"These influence points are not in the locations where most people expect"*

   This characteristic anchor in problem understanding and problem framing in order to understand what makes the problem complex, or wicked as commonly regarded for social problems and explained in Chapter 2 and Chapter 3 of this thesis.

3. ***There is usually a fundamental conflict between the short-term and long-term consequences of a policy change.***

   Policies should not only focus on short-term benefits but also consider their long-term effects. While predicting the future may be challenging and even expert opinions may become ineffective over time, model-based policy design appears to be a promising tool. This concept is further explored in Chapter 4, Chapter 5, and Chapter 6, where the Ph.D. Proposal is elaborated upon.

1.3 MOTIVATION: DESIGNING PUBLIC POLICIES

The primary motivation to write this thesis is to propose foundational models required to design public policy with an objective to assist policymakers to make better informed decisions by designing effective public policies. One of the parallel motivations is to advance 'design' and 'systems engineering' for greater social good. Below is the detailed description of motivations that guided me to pursue this research.

1.3.1 Framing Wicked Problems

Effective policy designs are based on accurate understanding of the problems that underscores the importance of framing wicked problems. The efficacy of the policy design depends on how well the problem is formulated. To design public policies, it is critical to understand the nature of problem and recognize why the policies are designed. This has broader impacts in terms of correctly identifying the problem and going to the core of the wickedness of the problems in order to address them. Thus, to establish models to design policies it is of utmost importance to allow designers to frame policies and enable them to identify the underlying causes of wickedness of any problem. Hence, the drive stems in designing public policies and gaining a thorough understanding of the existing challenges.

1.3.2 Evolving Cyber Physical Social Systems

Public policy is an Evolving Cyber-Physical-Social System (E-CPSS). Over the past decade there have been decent developments in the paradigm of CPSS, however, E-CPSS still remains untapped. To view public policy as an E-CPSS it is necessary to fill the gap and establish foundational knowledge by defining E-CPSS, understanding the characteristics of E-CPSS and establishing a requirements list for designers to design E-CPSS. The motivation behind this lies in proposing a cognitive map which can thus be utilised to design public policy as an E-CPSS.

1.3.3 Designing Public Policies

In the rapidly changing landscape of today's society, designing impactful public policies necessitates a fundamental change in viewpoint. Conventional methods frequently prove inadequate, dealing with the nuanced intricacies of modern challenges. The design of public policies requires an all-encompassing perspective that accounts for not just the immediate issue but also the diverse viewpoints, evolving preferences, and dynamic essence of the problem. This intricate nature emphasizes the requirement for a framework capable of embracing this multifaceted terrain and guiding the creation of flexible and responsive policies.

1.3.4 Defining Ph.D. Proposal

A key motivation in this thesis is to define a Ph.D. proposal, through which the practicality of the proposed models for designing public policy will be demonstrated, leveraging the fundamental and foundational perspectives elucidated in this thesis. Through this thesis a groundwork is laid that will be used in the Ph.D. research to design public policies and assist decision makers/policy makers in making better informed decisions for the greater well being of the society.

1.4 GOALS AND FOCUS IN THE MASTERS THESIS

In this Section the goals through this thesis are discussed that anchors in research gaps, objectives and deliverable through this Thesis. The principal goal through this thesis is to establish fundamental and foundational models required for **designing public policy** as an **Evolving Cyber-Physical-Social System.** Aligning with this broader goal, the focus through this thesis is presented by enlisting the fundamental research gaps and the objectives that will be addressed in this thesis. In Section 1.4.2 the research gaps that will be addressed through this thesis are presented while the main research gap for the Ph.D. proposal is presented in Section 1.6.

1.4.1 Problem to be addressed: Establishing Fundamental Models to Design Public Policy as an Evolving Cyber Physical Social System

The primary objective through this thesis is to establish a holistic approach to design public policy as an evolving Cyber Physical Social system. This also includes addressing the research gaps to create new knowledge required in terms of creation of foundational model in the domains of E-CPSS and public policy.

The approach advocated in this thesis for designing public policies, drawing upon existing knowledge of problem nature, insights from policy literature, and integrating design through meticulous considerations, facilitates the development of a solid foundational footing in the field of policy design. This provides a fundamental basis for the seamless integration of design, policy, and the relevant technological infrastructure.

1.4.2 Research Gaps and Objectives

The primary research gap that is addressed through this Thesis includes:

Primary Research Gap: What foundational knowledge is essential for designing an evolving cyber-physical-social system to address significant societal challenges by expanding the scope of design engineering to previously uncharted social domains (like wicked problems) through a systems lens, with a focus on designing public policy?

The primary research gap is addressed systematically by breaking into four research gaps that are described in the following section.

Following are the research gaps addressed in this thesis.

The research gaps presented in Chapter 1 that are discussed in this thesis are as follows:

RG.1 How can wicked problems be effectively framed through the combination of interpretative and evidentiary analysis, incorporating human-computer synergies?

RG.2 What is the fundamental knowledge required in terms of key characteristics, requirements, and principles underlying the design of Evolving CPSS, and how does it impact decision support in complex situations?

RG.3 How can the collective adaptation construct be applied to facilitate policy design within Evolving CPSS?

RG.4 What are common themes, theories, and frameworks that emerge across the domains of public policy, and how can they be integrated to provide a comprehensive approach to design public policies?

The research questions along with the objectives and new knowledge that will be delivered are as follows.

Research Gap 1: How can wicked problems be effectively framed through the combination of interpretative and evidentiary analysis, incorporating human-computer synergies?

Objective: *To frame wicked problems with the integration of human cognition, experience, and judgments through human-in-the-loop, and to comprehend system behavior by simulating the system and analyzing the interaction between variables.* ***(O1)***

New Knowledge:

i. *An approach and a framework to frame wicked problems through* ***evidentiary*** *and* ***interpretive*** *analysis.* ***(K1)***

In addressing Research Gap 1, the central inquiry revolves around the effective framing of wicked problems, achieved through the integration of interpretative and evidentiary analyses, while incorporating human-computer synergies. The primary objective is to define the framing of wicked problems by integrating human cognition, experience, and judgments through the application of human-in-the-loop methodologies. Additionally, it is aimed to gain a comprehensive understanding of system behavior by employing simulations that analyze the intricate interactions among variables. The outcome is the development of an innovative approach and a robust iterative framework, establishing a systematic method for framing wicked problems through the integration of evidentiary and interpretive analyses. This exploration will be meticulously unfolded and detailed in Chapter 3 of the thesis.

Research Gap 2: What is the fundamental knowledge required in terms of key characteristics, requirements, and principles underlying design of Evolving CPSS, and how do they impact decision support in complex situations?

Objectives:

i. *Explore and establish the relationship between fundamental and application sides of the E-CPSS paradigm by exploring the design characteristics and requirements.* ***(O2)***

ii. *Establish a list of requirements of E-CPSS characteristics to guide designers.****(O3)***

iii. *Put-forth a cognitive map for E-CPSS.* ***(O4)***

New Knowledge:

i. *Establishing the definition of E-CPSS and providing a fundamental model to address decision-making through E-CPSS.* ***(K2)***

ii. *Establishing the characteristics and outlining requirements that designers should consider to design an E-CPSS.* ***(K3)***

iii. *A fundamental and foundational cognitive map to design E-CPSS.* ***(K4)***

In addressing the Research Gap 2, the focus lies on discerning the essential knowledge required for the design of Evolving Cyber-Physical Social Systems (E-CPSS), encompassing key characteristics, requirements, and principles that underlie this evolving paradigm. Objectives through including exploring and establishing the intricate relationship between the foundational and application aspects of the E-CPSS paradigm by delving into its design characteristics and requirements. Another objective is to compile a comprehensive list of requirements detailing the characteristics of E-CPSS, serving as a guiding framework for designers in this dynamic domain. Furthermore, a cognitive map for E-CPSS is proposed, aiming to offer a foundational understanding and visualization of the intricate relationships within this evolving system. The new knowledge anticipated from these objectives involves a clear definition of E-CPSS and the introduction of a fundamental model for decision-making within this paradigm, as well as the establishment of characteristics, requirements, and a cognitive map crucial for designers navigating the complexities of E-CPSS. These facets will be thoroughly explored and elucidated in the relevant section of the thesis.

***Research Gap 3* -** What common themes, theories, and frameworks emerge across the domains of public policy, and how can they be integrated to provide a comprehensive approach to design public policies?

***Research Gap 4* -** How can the collective adaptation construct be applied to facilitate policy design within Evolving CPSS?

Objective: Propose an approach to design public policies by tapping into synergy between Collective Adaptive Systems (CAS) as a cognitive map and Evolving Cyber-Physical Social Systems (CPSS) as the technological infrastructure. ***(O5)***

New Knowledge: An approach for designing public policies by establishing the utility of interaction between E-CPSS and CAS. ***(K5)***

The Research Gap 3 is associated into the exploration of common themes, theories, and frameworks that transcend the diverse domains of public policy, with the overarching aim of integrating these elements to design a comprehensive approach to policy design. This involves identifying and understanding the intersections and synergies that exist across these domains to inform a holistic policy design methodology.

In addressing Research Gap 4, the focus is to investigate the application of the collective adaptation construct in facilitating policy design within Evolving Cyber-Physical Social Systems (E-CPSS). The objective is to propose an innovative approach to policy design by leveraging the symbiotic relationship between Collective Adaptive Systems (CAS) as a cognitive map and E-CPSS as the underlying technological infrastructure. The anticipated new knowledge involves the development of a distinct approach for designing public policies, emphasizing the utility and interaction between E-CPSS and CAS, which will be comprehensively expounded upon in Chapter 5.

1.5 CONTRIBUTIONS THROUGH THIS THESIS

The contributions through this work are highlighted in Section 1.4.2 as the new knowledge. Through this thesis it is aimed to contribute to the integration of insights from wicked social problems, evolving cyber-physical social systems, and strategic public policy design, adopting a transdisciplinary approach. This effort seeks to contribute to addressing complex societal challenges with a more comprehensive perspective. The contributions are explained in detail in the following Section.

New Knowledge 1 ***(K1)*****:** *An approach and a framework to frame wicked problems through* ***evidentiary*** *and* ***interpretive*** *analysis.*

The initial contribution through this thesis centers on constructing a framework that aids designers in framing wicked problems, ultimately enhancing the comprehension of such intricate issues. This framework facilitates the integration of both human abilities and computational capabilities to address wicked problems. The contributions of this new knowledge revolve around the practical functionality and effectiveness of the proposed framework, encapsulated in the following points.

Through the proposed framework, a designer can:

i. Convert heuristics into insights to frame a wicked problem through the integration of evidentiary and interpretative analysis.
ii. Understand the interaction among variables through behavior of the simulated system by the virtue of System Dynamics.
iii. Identify the correct size of the problem by eliminating the variables which do not impact the outcome/model, are not relevant to the wicked problem, or are not under a designer's control.

The utility of the proposed framework for framing a wicked problem are:

i. Enhancing the synergy between human-computer interaction by allowing human-in-the-loop to enhance framing of the wicked problem through computational capabilities and human abilities.
ii. Enables a designer to convert the heuristics into insights through a structured process.
iii. Perfect integration of interpretative and evidentiary analysis to frame the wicked problems which forms the fundamental step of modelling a public policy.

New Knowledge 2 *(K2)*: *Establishing the definition of E-CPSS and providing a fundamental model to address decision-making through E-CPSS.*

New Knowledge 3 ***(K3)*****:** *Establishing the characteristics and outlining requirements that designers should consider to design an E-CPSS.*

New Knowledge 4 ***(K4)*****:** *A fundamental and foundational cognitive map to design E-CPSS.*

Within the current state of the art, a notable gap exists, specifically centered around the absence of fundamental knowledge within the context of Evolving Cyber-Physical Social Systems (E-CPSS). The contribution through this thesis, specific to New Knowledge 2, 3, and 4 underscores the realization of the evolving nature of Cyber-Physical Social Systems (CPSS) and the pivotal role played by social entities in decision support. The contribution further aligns in examining the essential features and attributes of Evolving CPSS (E-CPSS), illustrating their practical significance in the decision-making process within complex environments. Building upon this, a cognitive map is introduced delineating the identified characteristics and its significance in the overall decision-making process. This map serves to provide designers with a comprehensive overview of the system's evolutionary mechanism as it navigates uncertainties and complexities, ultimately reaching a steady state. This contribution is further enhanced by pinpointing potential areas for exploration and identifying research gaps within the field.

New Knowledge (K5): An approach for designing public policies by establishing the utility of interaction between E-CPSS and CAS.

Through this contribution a method is proposed to fill the identified gap by conceptualizing public policy as an Evolving Cyber-Physical-Social System (CPSS). This approach utilizes Collective Adaptive System as the cognitive map and CPSS as its technological infrastructure. Employing this model allows us to grasp the dynamic interactions among social agents, social environments, and the structural facets of a given problem. Embracing a comprehensive outlook grounded in CPSS principles, this approach enables the formulation of all-encompassing and adaptable public policies that respond adeptly to the continually evolving societal needs. The broader implication of this contributions lies in enhancing the decision-making abilities of policymakers, guiding them towards the development of adaptive and responsive public policies.

1.6 WAY FORWARD AND RESEARCH QUESTION FOR Ph.D.

As explained in this chapter, the primary motivation to write this thesis is to lay the groundwork for a Ph.D. proposal, wherein the research will extend and build upon the fundamental and foundational models established within this thesis. This section will outline the primary research questions for Ph.D. and provide pertinent background information. Nevertheless, for a comprehensive presentation of the entire proposal is included in Chapter 6 of this thesis.

The existence of social problems within society necessitates the formulation, regulation, and implementation of public policies. This involves simultaneous yet discrete research challenges. The initial challenge focuses on **addressing the technical objectives and constraints** inherent in the problem structure, while the **concomitant challenge revolves around accommodating decision-making processes in public entities.** This encompasses the diverse objectives, interests, opinions, and preferences of various stakeholders. This consideration will assist decision makers/policy makers to make better-informed decisions. The proposed exploratory approach aims to tackle these dual challenges and unveil the hidden dynamics of their interaction.

The decision to concurrently address both research challenges is inspired by the inclusion of the 'social entity.' This not only renders the approach vividly interdisciplinary but also entails a high-risk aspect, exploring the interplay between human behavioral and cognitive aspects and the problem structure in designing public policies. The social entity is grounded in decision-making and stakeholder interactions within public entities, where stakeholders have distinct and potentially conflicting objectives, opinions, and preferences. The hypothesis posits that ***public policy is an evolving cyber-physical-social system*** (CPSS), encompassing three major trajectories: social integration strategies, social environment, and problem structure, collectively addressed as collectives.

Recognizing the limitations of traditional operations research approaches in dealing with the complexities of evolving cyber-physical-social systems, there is a need to explore and develop a design approach. This approach should employ collaborative methods and frameworks capable of addressing the aforementioned dual research challenges, effectively tackling the intricacies associated with public policy problems.

Based on the explanation given in the preceding and delving deeper into the dynamics of stakeholders, it is observed that Government, Industry, and the Community play pivotal roles as major stakeholders addressing grand challenges such as climate change, healthcare, etc. Recognizing the imperative to generate a set of policy options for stakeholders to consider within a specified time period, our hypothesis posits that these intricate problems can be effectively computationally modeled as Evolving Cyber-Physical-Social (CPS) systems. Acknowledging the inherent abstraction and differing fidelity levels of computational models, through the proposal it is suggested that researchers within the engineering design community have developed theories and tools to address challenges associated with grand challenges, primarily from a cyber-physical perspective. Through this proposal it is aimed to delve into the following question:

What are the fundamental theories and principles needed in the model-based design and systems engineering to facilitate decision-making in public and private entities to consider concurrently competing and conflicting objectives, opinions, and preferences of the stakeholders and understand their effects in generating, adapting, and evolving policy decision options for the problem structure of the social problems to be addressed?

The research in Ph.D. is directed towards exploring the following untested construct.

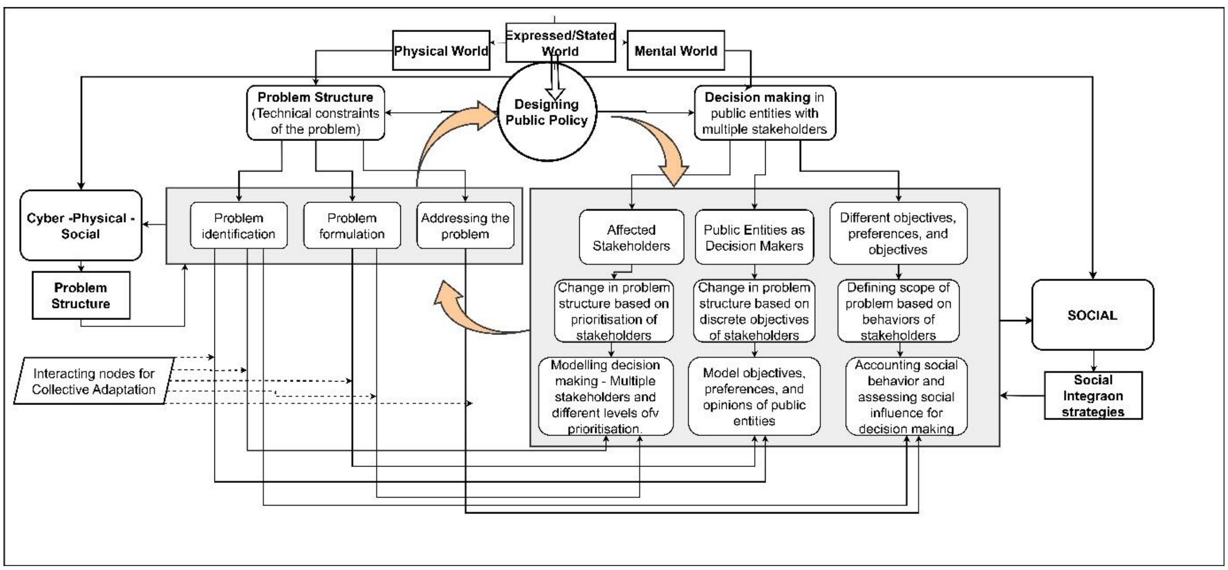

Figure 1.1: Untested Construct to Design Public Policies

The construct proposed in Figure 1.1 is logical but untested. Embodied in Figure 1 is the contention that designing public policy requires providing effective policy options and scenarios to the stakeholders that can be analyzed from individual stakeholder and collective stakeholder perspectives. In Figure 1.1, the emphasis is to show different aspects of holistic policy design which anchor in the structure of problem and the social interaction among different stakeholders that guides decision making. This is encompassed and guided through cyber, physical, and social layers of CPSS. Being able to propose scenarios together with the capability to demonstrate impact adds transparency to the public policy-making process. Thus, as shown in Figure 1.1, two different branches that relate to the problem structure and decision making are critical in designing public policies. To instantiate the preceding, following four-part approach that anchors in Figure 1.1 is proposed:

1) *Understand how public policy decisions are formed.* We hypothesize that his happens through the interaction among three aspects of collective adaptation. This will provide us an opportunity to advance design engineering for the social sciences by exploring and creating new methods.
2) *Formulate procedures for identifying and modeling problem structure.* In this effort, we will rely heavily on information models.
3) *Explore methods for integrating social (cognitive and behavioral) and engineering (cyber-physical) strategies to make decisions to design public policy.*
4) *Test Problems.* This involves designing two test problems associated with urban pollution that can be used to test and verify the computational framework.

The detailed proposal and additional information can be found in Chapter 6 of the thesis.

1.7 VERIFICATION AND VALIDATION

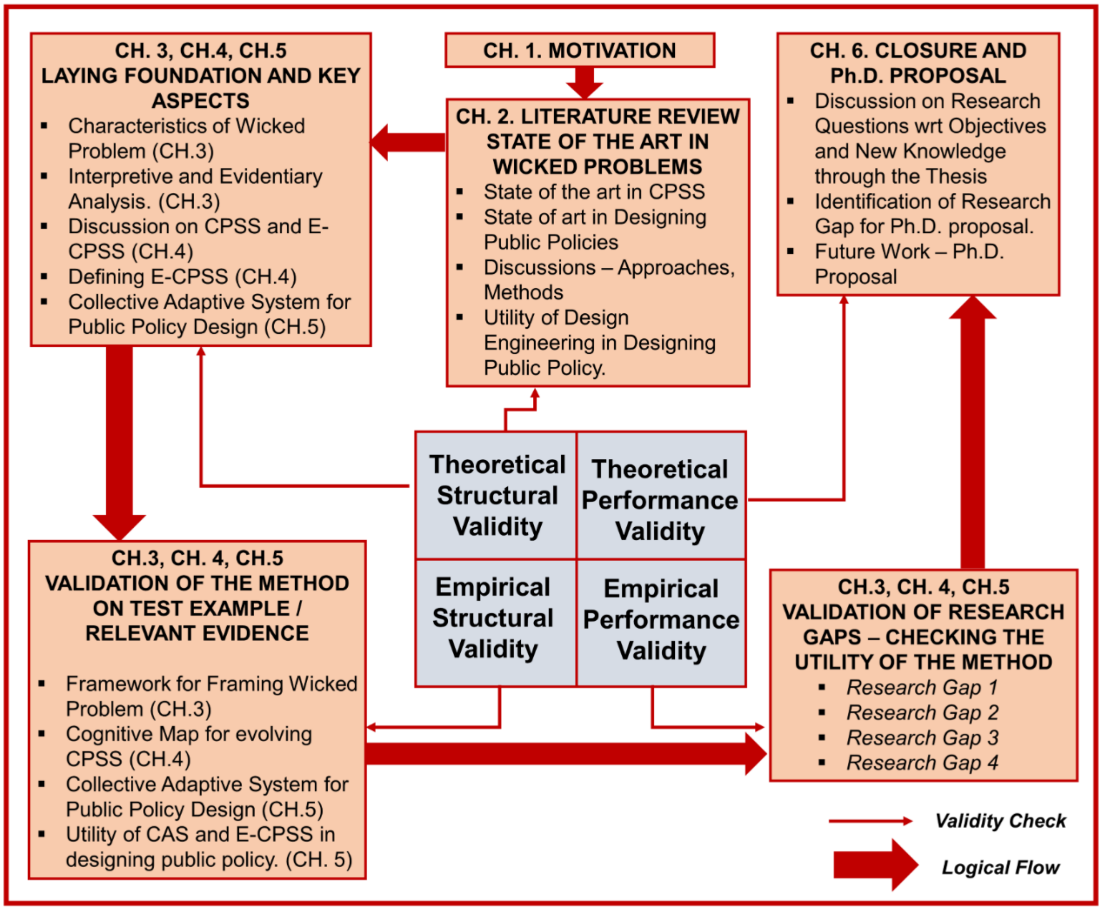

Figure 1.2: Validation Square for Thesis

The majority of the Verification and Validation as explained in the following section is in the context of logical soundness of the proposed models and approaches, the process followed, and the story line embodied in this thesis.

1.7.1 Theoretical Structural Validation

The theoretical structural validation of the research method employed in this thesis is crucial for ensuring the internal consistency and logical soundness of its constructs, both individually and when integrated.

- ✓ **Critical Literature Review and Research Opportunities (Chapter 2, Sections 3.1, 4.1, 4.2, 4.3, 5.2, 5.2, 5.3)**
  - A comprehensive review of relevant literature pertaining to social problems.
  - Identification of research opportunities within the context of addressing social problems as complex systems.
- ✓ **Logical Formulation of Research Gaps (Chapter 2 majorly)**
  - Justification of the logical formulation of the four hypotheses that appropriately cover the identified research opportunities.
- ✓ **Merits, Limitations, and Application Domains**
  - Identification of the merits and limitations of the developed research framework.
  - Exploration of potential application domains for the framework, including the requirements list through FBS and Cognitive Map for evolving CPSS.

Through this section I focus on establishing the theoretical structural validity of the research method, including its logical soundness, construct integration, and the development of hypotheses within the context of addressing complex social problems.

1.7.2 Empirical Structural Validation

Empirical structural validation in this research assesses the capability of the research method to generate practical results for comprehensive issues.

- ✓ **Challenging aspects for testing Research Gap 1 and Objective 1 (Chapter 3)**

- Deliberation on challenging aspects of framing wicked problems and argue that aspects are appropriate for Hypothesis 1.
- Argumentation for the appropriateness of these aspects in testing Research Gap 1.

✓ **Challenging Aspects for testing Research Gap 2 and Objective 2,3,4 (Chapter 4)**

- Deliberation on the challenging aspects of addressing evolving systems and argue the aspects are appropriate for Research Gap 2.
- Argumentation for the appropriateness of these aspects in testing Research Gap 2.

✓ **Challenging Aspects for testing Research Gap 3 and Research Gap 4 (Chapter 5)**

- Examination of challenging elements concerning collective adaptation for public policy as an evolving CPSS and argue the aspects are appropriate for Hypothesis 3.
- Justification of the suitability of these aspects for validating Research Gap 3.

✓ **Challenging Aspects for Research Gap 4 (Chapter 4, 5, 6)**

- In-depth analysis of the challenging facets within the context of designing public policy, with a specific emphasis on Hypotheses 4.
- Presentation of arguments supporting their relevance for validating Research Gap 4.

Empirical structural validation ensures that the research method not only aligns with theoretical foundations but also demonstrates its utility in addressing practical issues within the evolving cyber-physical-social systems and public policy design domain.

1.7.3 Empirical Performance Validity

Empirical performance validity assesses the research method's capability to produce valuable and practical results that contribute to comprehending complex problems.

✓ **Validation of Research Gap 1 and Objective 1 in Framing Wicked Problems (Chapter 3) (RQ1)**

- Discussion on results obtained from the demonstration of framing wicked problems (Section 3.5)

✓ **Validation of Hypotheses in Evolving CPSS (Chapter 4) (RQ2)**

- Analysis of the empirical outcomes within the evolving cyber-physical-social systems (CPSS) domain to validate the hypotheses established in this chapter.
- Confirmation of the alignment between the empirical findings and the formulated hypotheses related to evolving CPSS.

✓ **Validation of Hypotheses in Public Policy Design (Chapter 5) (RQ3, RQ4)**

- Evaluation of the critical literature review and related data in the context of designing public policy to confirm the validity of the hypotheses established in this chapter.
- Verifying the applicability of the formulated hypotheses in practical policy design scenarios.

Empirical performance validity ensures that the research method is not only theoretically grounded but also capable of generating results that contribute to a comprehensive *understanding of complex problems within the context of framing wicked problems, evolving CPSS, and designing public policy.*

1.7.4 Theoretical Performance Validity

Building leap of faith which is eased by the process (1-3) of building confidence in the general usefulness of design method.

- ✓ Evaluate the logical coherence and internal consistency of the developed theoretical framework for addressing multifaceted issues (Chapter 1).
- ✓ Examine the alignment of research questions with the overarching objectives of the study and the theoretical underpinning (Chapter 2).
- ✓ Explore how the theoretical constructs are employed to frame wicked problems and understand evolving cyber-physical-social systems (Chapters 3 and 4).
- ✓ Discuss the limitations and constraints of the theoretical framework and acknowledge its applicability in the context of designing public policy and addressing complex societal challenges (Chapters 3, 4, and 5).
- ✓ Identify research gaps and suggest potential avenues for expanding the theoretical foundations through Ph.D. proposal to address the aspects of designing public policy as an evolving CPSS as foundational to this Thesis. (Chapter 6).

✓ **Construction of Research Framework (Chapter 3 and Chapter 4)**

- Detailed discussion of the construction of the research framework for framing wicked problems and evolving CPSS.

- Evaluation of the intellectual and method related aspects to ensure that the hypotheses are well instantiated within the framework.

1.8 GENERAL ASSUMPTIONS FOLLOWED THROUGH OUT THIS THESIS

1. The decision makers will primarily be government.
2. Policy designers should account for irrationality of decisions by stakeholders involved, however, provide government with transparent analysis.
3. Government agencies have limited resources and capacity, requiring prioritization and efficiency in policy implementation.
4. The political landscape and power dynamics can influence the decision-making process and the ultimate shape of policies.

1.9 Mental Model for Unfolding the Thesis

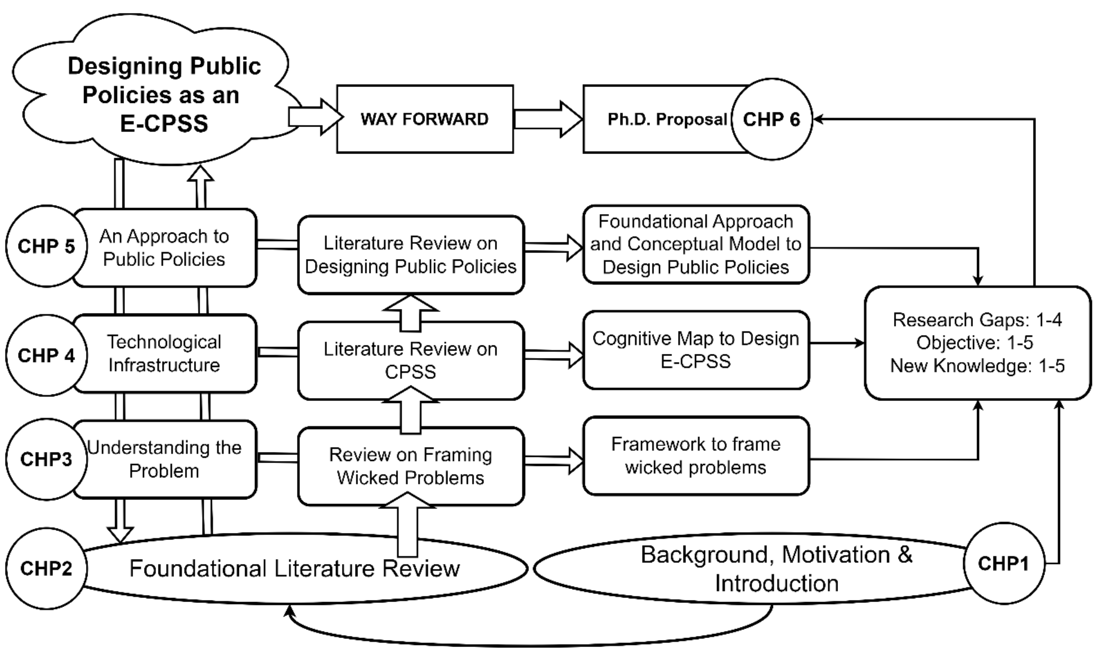

Figure 1.3: Mental Model followed for the writing of this thesis

The mental model that will help readers to unfold this thesis and understand its organisation is as shown in Figure 1.3. In Chapter 1 the Background, Motivation and Introduction is presented. Further, in Chapter 1 the plan for Verification and Validation is presented as well. The focus in Chapter 2 is to provide a foundational literature review that will set the stage to delve into the objectives that are accomplished through this thesis. Owing to the transdisciplinary nature of the research embodied in this thesis, the specific sections of literature are presented in respective chapter so that it is easy for the readers to connect to the literature and the Research Gap, Objectives and New Knowledge presented in respective chapter. Thus, the starting sections of each chapter are denoted towards briefing about literature in respective areas. Then the further sections in each chapter are written to accomplish the objectives embodied through this thesis. The focus is Chapter 3 is on framing wicked problems that relates to understanding the problems in public policy. The emphasis on Chapter 4 is to discuss the relevant literature and a suitable technological infrastructure that is establish through a foundational model of Evolving Cyber Physical Social Systems to design a public policy. In Chapter 5 the focus is to integrate the knowledge established in previous chapters to establish a foundational approach and a conceptual model for designing public policy as an evolving cyber physical social system. In chapter 6 this knowledge is used to present a Ph.D. proposal that provides the detailed technical definition of models established in this thesis that is furthered by a plan of action for research in subsequent stages. In chapter 6 a parallel objective is to summarize the contributions made through this thesis.

1.10 SYNOPSIS OF CHAPTER 1

In this Chapter the background for the thesis is laid by providing a foundational basis to design public policy as an evolving cyber physical social system. The thesis proposes a comprehensive framework for designing public policies within the context of Evolving Cyber-Physical-Social Systems (E-CPSS), integrating insights from wicked problem framing, CPSS, and policy design. It aims to fill critical gaps in foundational knowledge and establish fundamental models to address the complexities of contemporary societal challenges.

The motivation stems from the need to address wicked problems effectively, understanding their evolving nature and multifaceted dimensions. Framing wicked problems accurately is highlighted as crucial for effective policy design. Additionally, recognizing public policy as an E-CPSS presents an opportunity to leverage evolving technological and social dynamics.

The goals through the thesis revolve around establishing foundational models for designing public policy within E-CPSS, addressing research gaps, and contributing new knowledge in framing wicked problems and understanding E-CPSS characteristics. Through a transdisciplinary approach, the thesis aims to provide policymakers with better-informed decision-making tools.

Key contributions include:

1. A framework for framing wicked problems, integrating evidentiary and interpretive analysis.
2. Definition and modeling of E-CPSS, outlining its characteristics and requirements for policy design.

3. Introduction of a cognitive map for designing E-CPSS, facilitating decision-making in complex environments.
4. Proposing an approach for designing public policies by integrating E-CPSS and Collective Adaptive Systems (CAS), enhancing adaptability and responsiveness.

A guideline for validation is presented in Section 1.7, and Figure 1.2. Through this chapter it is set to lay the groundwork for a Ph.D. proposal, aiming to extend and build upon the established models in further chapters. Research questions for the Ph.D. focus on developing theories and principles for model-based design and systems engineering to facilitate decision-making considering competing stakeholder objectives, opinions, and preferences. This is briefed in Section 1.1. Through PhD research it is intended to provide a generalizable method address grand challenges such as climate change and healthcare through computational modeling of E-CPSS.

Chapter 1 concludes here and stage is set to transition to Chapter 2 where the literature review is presented. The brief of the thesis is presented in Figure1.3.

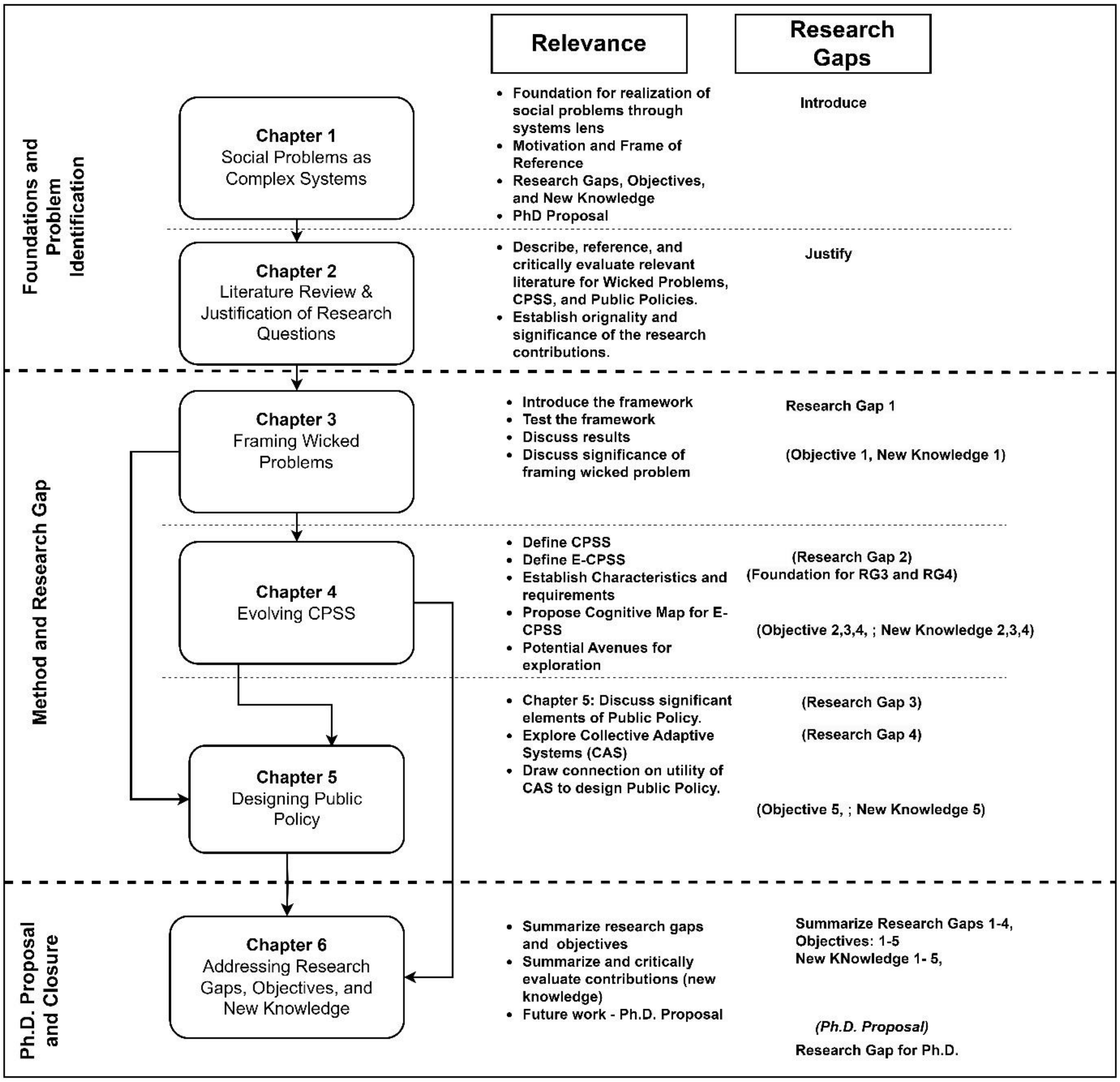

Figure 1.3: Layout of Thesis

CHAPTER 2

FOUNDATIONAL LITERATURE REVIEW

The realm of public policy is a constant battleground where policymakers must deal with the formidable challenge of "wicked problems." Unlike traditional problems with readily available solutions, these complex issues defy simplistic approaches. Their dynamic nature, intertwined with evolving contexts and divergent stakeholder perspectives, creates a tangled web that resists conventional problem-solving techniques.

Framing wicked problems presents a fundamental hurdle. What one stakeholder defines as the core issue might be disregarded or even contested by another. This lack of a shared understanding, compounded by limited knowledge and understanding, can lead to a stalemate in addressing wicked problems. Furthermore, a dearth of robust technological infrastructure designed to handle such complexities significantly hinders effective policy design. In the absence of tools that can integrate diverse perspectives and facilitate collaborative solutions, disagreements among stakeholders are amplified, stymieing progress.

This lack of consensus among stakeholders stems from a fundamental reality: values, priorities, and interests deeply influence how individuals perceive a problem and its potential solutions. These inherent differences in viewpoints create a fragmented landscape where policymakers must navigate competing expectations and demands. Without a framework to reconcile these divergent perspectives, finding common ground on which to build effective and sustainable policies becomes pivotal.

Through Chapter 2 we will embark on a journey to discuss on these complexities. It delves into the challenges of framing wicked problems, exploring the limitations of traditional approaches and highlighting the need for innovative methods that can incorporate multifaceted perspectives. This chapter lays the foundation for exploring technological solutions that can support collaboration, knowledge-sharing, and adaptive policymaking in this challenging arena.

Rittel and Webber's [2] seminal paper form the origin of the idea that problems in social policy are fundamentally different than problems in natural sciences. Wicked problems stand in contrast to issues categorized within the natural sciences, characterized as well-defined problems amenable to problem-solving approaches. The literature on wicked problems extensively explores the conceptualization of these challenges, revealing varied perspectives and interpretations among different scholars and individuals. Nonetheless, a predominantly adopted framework, outlined by Rittel and Weber, delineates 10 characteristics that define wicked problems, as follows:

1. ***There is no definitive formulation of wicked problem. They are difficult to frame.***
2. ***Wicked problems have no stopping rule.***
3. ***Solutions to wicked problems are not true or false, but good or bad.***
4. ***There is no immediate and no ultimate test of a good solution to a wicked problem.***
5. ***Every solution to a wicked problem is a "one-shot operation"; because there is no opportunity to learn by trial-and-error, every attempt counts significantly.***
6. ***Wicked problems do not have an enumerable (or an exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan.***

7. ***Every wicked problem is essentially unique.***

8. ***Every wicked problem can be a symptom of another problem.***

9. ***There are numerous explanations for a wicked problem.***

10. ***The planner has no right to be wrong.***

In this chapter discussion on the literature of wicked problems is presented with an objective of getting an understanding of the different viewpoints and opinions on wicked problems. The discussion will center primarily on the context of different perspectives of wicked problems, aligning with the direction in which the thesis is structured in the subsequent chapters that finally merges in the broad picture of designing public policies.

The chapter is organized as follows:

In this chapter the emphasis is laid on the intricate world of "wicked problems" in public policy, exploring the challenges they pose and offering potential pathways for their effective management. The chapter is initiated begin by establishing the crucial role of understanding diverse viewpoints (Section 2.1) in tackling these complex issues. Next, we explore the inherent complexities associated with wicked problems (Section 2.2), highlighting their dynamic nature and the limitations of traditional approaches. Building upon this foundation, in Section 2.3 the focus is on framing wicked problems by incorporating diverse perspectives and innovative methodologies. In Section 2.4 the focus is on specific strategies for both framing and addressing these challenges, while in Section 2.5 the emphasis is to broaden the conversation, connecting the insights gained to the broader context of public policy and potentially paving the way for further research and action.

2.1 UNDERSTANDING DIFFERENT VIEWPOINTS

There has been a vast discussion on the understanding and conceptualisation of wicked problems in the literature. The concept of wicked problems is frequently characterized as a 'generic concept' that has been applied indiscriminately [3]. In recent decades, there has been robust advocacy for embracing scientific approaches in policymaking, program evaluation, and performance-based public management [4]. The urge of having evidence based policy making has further triggered the utility of technology in addressing problems in social space. However, conversely, there has been resistance, predominantly centered around the question of whether scientific approaches are not only suitable and comprehensive but also whether they tend to oversimplify the intricate nature of social problems. Multiple criticisms are based on the evidence based approaches contributing to the intentions of policy making to address these problems. For example, as mentioned in [4] the political economy critique for evidence based approaches being that though evidence demonstrates the prevalence of poverty, public policy decisions may not always align perfectly with the needs of the most disadvantaged, despite the existence of democratic mechanisms like elections. Critics of positivist social science argue that reaching shared understanding is difficult in a society with diverse values, due to differences in how we think and our cultural backgrounds [5], [6]. This is a significant aspect in the incorporation of design of public policy that is further expanded in Chapter 5 of this thesis. In social problems it is critical to incorporate multiple opinions, perspectives, and viewpoints of various stakeholders. Rittel and Webber argued that standard planning methods, based on logic and analysis, are inadequate for addressing complex and controversial social issues [1]. While sometimes the focus has been on solving the problems, I argue in the support of other side of this perspective that we do not essentially solve social problems but we address them. Since "wicked problems" are complex and persist over time, the goal for decision-makers is to effectively manage them, not necessarily find permanent solutions. the core challenge of addressing "wicked problems" lies not in finding a single, definitive solution, but rather in facilitating a shared understanding and meaning of the problem and its potential solutions among stakeholders. Through this collaborative negotiation process the aim is to achieve coherent action, not a finalized answer [7]. This necessitates a design-centric approach to public policy, where solutions are iteratively developed and refined through extensive engagement with diverse stakeholders [8], [9]. Such approaches focus on iterative development, stakeholder engagement, and systems thinking to understand problem intricacies [10]. This allows for co-creation of multifaceted policy options responsive to diverse perspectives [11], [12], rather than seeking quick, one-size-fits-all solutions. According to Hoppe [13], effectively responding to policy problems necessitates a comprehensive analysis that incorporates several interrelated dimensions. These dimensions encompass power, knowledge, values, and processes. Analyzing these interconnected aspects can provide a deeper understanding of the complexities involved in tackling policy problems and formulating effective responses. Echoing the inherent challenges associated with addressing persistent social issues, Wildavsky [14] acknowledges the limitations of seeking definitive solutions. He argues that such problems are rarely "solved" in a complete or permanent sense, but rather "alleviated, superseded, transformed, and otherwise dropped from view". This notion aligns with the perspectives of other scholars who highlight the evolving and dynamic nature of wicked problems. For instance, Rittel and Webber [2] emphasize their "indefinable nature", while Rosenhead [15] describes them as "continuous rather than discrete". These combined perspectives underscore the need for ongoing engagement, adaptation, and re-evaluation when confronting complex and long-standing social challenges.

Public policy is continuously evolving with respect to time and the variables often change with states. This relates to the notion that ‘Past solutions create future problems faster than present troubles can be left behind’ [14]. This creates another major setback for understanding the impacts of policies for wicked problems, for example as Selman correctly says:

“In practice, despite enormous amounts of dedication and inspiration, environmental planning only ever achieves partial success. This is due to the ‘wickedness’ of environmental issues, deriving not only from their technical complexity, but also from the multiple arenas where they are contested and debated. As capacities are built to overcome one barrier, another one arises; as progress is made towards sustainability, so the finishing line recedes”[15].

The variables influencing these problems, such as demographics, technological advancements, and environmental conditions, often undergo significant changes over time and across different regions [17]. This dynamic interplay between evolving policy landscapes and the evolving nature of wicked problems necessitates a flexible and adaptable approach to policymaking.

According to Rittel and Webber [2], evaluating the success of different approaches to tackling "wicked problems" is inherently challenging due to the absence of reliable criteria. Additionally, learning from past experiences in these contexts proves difficult due to the unique and complex nature of each problem. While acknowledging the inherent complexities of wicked problems, a more practical approach is adopted in this research. Similar to [3], [18], [19], [20] I believe that continuous evaluation and adaptation, rather than seeking perfect solutions, are crucial for effectively addressing these ongoing challenges. This highlights the value of iterative adjustments in policymaking for complex issues. Lindblom and Weick [21], [22] emphasizes the importance of incremental steps and ongoing engagement with stakeholders. Instead of being discouraged by the complexity of wicked problems, I advocate for a proactive approach. By focusing on achievable, "small wins" and utilizing design and technology, we can make continuous progress in addressing these challenges.

To tackle complex, persistent social issues (wicked problems), the importance of crafting well-designed public policies is emphasized through this thesis. Inspired by the insights of [8], [9], [10], [11], who advocate for design-centric approaches to addressing complex societal issues, we believe well-designed public policies can act as a crucial tool. These policies, built on iterative development, stakeholder engagement, and systems thinking, offer the potential to navigate the complexities of wicked problems and contribute to progress, even if definitive solutions might not always be achievable.

Designing public policies necessitates understanding the wicked problems. This is critical to identify the variables causing the problem to be wicked. This is broadly categorised as framing wicked problems. The focus in Chapter 3 of this thesis is to propose a method to frame wicked problems. In the Section 2 of this chapter we will review some important literature to accompany our objective in Chapter 3.

2.2 COMPLEXITIES IN ADDRESSING WICKED PROBLEMS

Summarising Section 2.1, addressing complex societal challenges often requires confronting wicked problems. These persistent and multifaceted issues, unlike traditional problems with readily available solutions, present unique hurdles for policymakers and stakeholders. As Rittel and Webber [2] famously argued, wicked problems lack definitive solutions due to their dynamic nature, often becoming entangled with evolving contexts and diverse stakeholder perspectives. Head [4] further emphasizes the interconnectedness of these problems, highlighting the need for collaboration amidst conflicting values and the challenge of accurately measuring progress.

This section delves into the inherent complexities associated with tackling wicked problems, laying the groundwork for exploring how to navigate these complexities and navigate them effectively. The policy landscape is not objective, but rather a dynamic interplay shaped by historical context, institutional legacies, and the diverse perspectives of stakeholders. As acknowledged by Kingdon [23] and Sabatier [24], what constitutes a "problem" and its potential "solution" are products of ongoing discourse and negotiation.

The objective in this section is to delve into the inherent challenges associated with addressing wicked problems, categorized into four key areas:

- **Limited knowledge and understanding:** Insufficient information and diverse perspectives regarding the problem and its solutions can hinder effective action.
- **Conflicting interests, values, and priorities:** Different stakeholders hold varying values and priorities, leading to potential disagreements and roadblocks.

- **Power dynamics:** Unequal power distribution among stakeholders can create challenges in achieving consensus and implementing solutions.
- **Lack of resources and capacities:** Addressing wicked problems often requires significant resources, expertise, and ongoing efforts, which might not always be readily available.

2.2.1 Limited Knowledge and Understanding

Building on the work of social policy and professional education experts, it becomes clear that a purely data-driven approach falls short in addressing the complex challenges of our time. These experts highlight the significant role of diverse values in shaping these issues, demanding a more holistic understanding and innovative solutions [25]. While real-time data analysis and decision-making methods have undoubtedly enhanced our ability to tackle complex issues, relying solely on the knowledge gleaned from such data proves insufficient. The inherent complexities and value-laden nature of wicked problems require broader understanding beyond just data points. Real-time data may not capture the full spectrum of viewpoints crucial for tackling multifaceted problems as these problems are often deeply rooted in diverse values and require considering the ethical implications of decisions. From a cognitive and sociocultural perspective, knowledge relevant to policy decisions regarding social issues cannot be singular, but rather is always multifaceted and reflects diverse viewpoints [4]. This necessitates acknowledging and engaging with these divergent perspectives as they are expressed, mobilized, and potentially reconciled [5], [6], [26].

Understanding wicked problems requires recognizing that knowledge itself becomes multifaceted and contested. Different stakeholders, driven by their unique objectives, preferences, and interests, will hold varying perspectives on the issue and the "knowledge" associated with it. What one stakeholder considers crucial information might be disregarded or even actively avoided by another [27], [28]. This results in conflicting data. Different stakeholders may present data that supports their preferred solution or interpretation of the problem, leading to confusion and difficulties in establishing a shared understanding. (See: [29]). Another crucial factor to consider is bounded rationality. Wicked problems, by their very nature, involve vast amounts of information from diverse sources. However, human cognitive limitations make it impractical, if not impossible, to process and account for every single piece of information, hindering our ability to fully grasp the complexities of the issue. Individuals and groups have limited cognitive capacity to process and analyze vast amounts of information. This can lead to simplified understandings of complex issues and hinder the ability to consider diverse perspectives (See:[30]). Thus, limited knowledge and understand remains a continuous challenge to address wicked problems.

2.2.2 Conflicting Interests, Values, and Priorities

Social problems are characterised by the presence by multiple stakeholders who have different viewpoints, preferences, objectives and goals. The inherent complexities of wicked problems, including stakeholder conflicts and limited knowledge, necessitate the development of effective policy processes. These processes must address the messy, ambiguous, controversial, and unstructured nature of these issues (See: [13], [31]). Stakeholders in wicked problems often hold divergent interests and values, leading to conflicts regarding the nature of the problem and potential solutions.

Each stakeholder contributes unique perspectives and potentially brings to the table expectations of the decision-maker, information, resources, or permission. Sharing and integrating these diverse contributions is critical for jointly defining the problem and identifying appropriate responses [27]. The presence of conflicting interests among stakeholders in wicked problems can create situations where parties leverage their unique knowledge for strategic advantage, potentially engaging in “gaming behavior” [2]. This strategic maneuvering, where stakeholders use their knowledge to influence decision-making in their favor, can further complicate the already intricate nature of wicked problems and hinder collaborative efforts towards solutions. Thus, the conflicting values coming from various stakeholders calls for more nuanced approaches to integrate multiple preferences.

2.2.3 Power Dynamics

Social problems, along with abilities to address them also lies in the intentions to address them. The priorities of problems or the decision making is shaped in the direction of interests of elite section of the society. The selection and framing of policy issues often reflect the influence of powerful entities, such as businesses, their lobbyists, and their political representatives [32], [33]. According to Hoppe [13], effectively addressing policy problems necessitates a multifaceted approach that considers four key dimensions: power dynamics, knowledge availability, underlying values, and the processes used to address the issue. However, power dynamics can shape and manipulate the other three aspects. While tackling complex issues may involve reconciling or accommodating diverse perspectives on knowledge and values, there are instances where these differences are simply suppressed by authorities who leverage their power to silence dissenting views. Notably, politicians' claims of simple solutions through bold actions for challenging issues, like enhanced border protection for illegal immigration, often serve as rhetorical tools to garner public support rather than reflecting genuinely attainable solutions [4].

2.2.4 Lack of Resources and Capacities

In contemporary democratic systems, public policy discussions often prioritize managing political risk, building competence, deploying resources wisely, and maintaining support for leadership. The focus on these aspects can overshadow the crucial element of the knowledge base, which encompasses both policy-relevant evidence and experiential knowledge [4]. This, in turn, places a significant burden on the capacities and resilience of state institutions when it comes to designing and delivering successful interventions for the complex challenges known as "wicked problems." Beyond analyzing performance and future options, policy capacity, as described by Howlett [34], involves:

- **Strategic foresight:** Encompassing long-term planning and goal setting.
- **Adaptive agility:** Adjusting strategies to navigate changing circumstances.
- **Collaborative engagement:** Fostering collaboration and diverse perspectives.

This multifaceted approach empowers institutions to tackle complex challenges in an ever-evolving landscape. The concept of "wicked problems" finds new resonance in the realm of disasters and crises. These complex events brutally expose the (in)capacities of governmental systems. Designers are often hindered by resource limitations and competing priorities, becomes a daunting task. Effective response demands seamless inter-organizational collaboration, often hampered by siloed structures and conflicting interests. The rapid mobilization of resources, crucial for mitigating damage, faces hurdles in the form of complex procurement processes and logistical challenges. Addressing these vulnerabilities requires [3], [35], [36]:

- **Proactive investment:** Strengthening early warning systems, conducting risk assessments, and developing contingency plans.
- **Enhanced inter-agency cooperation:** Building trust and establishing clear communication channels between diverse stakeholders. However, achieving intra-agency cooperation forms the foundation for this.
- **Streamlined resource mobilization:** Optimizing procurement, reducing bureaucratic red tape, and investing in robust logistics systems.

By addressing these critical areas, governments can strengthen their capacities to tackle the ever-present challenges of disasters and crises. This deeper understanding of the multifaceted limitations faced by governmental systems paves the way for further research. Exploring innovative solutions in areas like proactive preparedness, inter-organizational collaboration, and streamlined resource mobilization holds immense potential for enhancing the effectiveness of responses to wicked problems across various contexts. Through continued research and collaborative efforts, we can build more resilient and responsive systems capable of navigating the complexities of an ever-changing world.

2.3 FRAMING WICKED PROBLEMS

Unlike traditional problems, "wicked problems" require deeper understanding rather than simple solutions. The focus to address wicked problems should be on confronting these challenges, not solely achieving a definitive resolution. We believe that the efficacy of design to address wicked problems is based on how well they are framed. The diverse interpretations of wicked problems, shaped by stakeholders' individual interests, necessitate a nuanced approach to frame wicked problems. In this Section we will focus on literature on framing wicked problems.

2.3.1 Understanding the Importance of Framing Wicked Problems

Recognizing that social problems are specific to different times, locations, and contexts implies that their definitions are socially constructed realities. These widely shared and accepted definitions become part of our common knowledge base ("collective stock of knowledge") as described by Berger & Luckmann [37]. However, despite their social origin, this knowledge, often presented as expert opinion, appears objective and significantly influences both how we view social problems and the solutions we consider. In essence, our understanding of social problems and their potential solutions is partly shaped by the underlying assumptions of our culture, which can both restrict the options we explore and determine who or what is perceived as problematic [38].

Social scientists are not immune to the reflexive loop linking preconceptions, problem definitions, and proposed solutions [6]. Embedded within their own social and cultural contexts [39], they are susceptible to the influences of established societal leaders and narratives. This, however, presents a paradox: while the public often perceives social scientists as objective experts [29], their proposed solutions might inadvertently reinforce the initial, culturally-defined problem definition [40]. Thus, there is a need to have detailed insights on problems understanding. This highlights the crucial need for critical self-reflection within the social science community dealing with complex social problems. As Rappaport [41] emphasizes, they must actively challenge conventional wisdom and question the inherited problem definitions that may be shaped by underlying cultural assumptions. By engaging in reflexive critique [42], social scientists can strive to break free from this embeddedness and contribute to a more nuanced understanding of social problems.

The understanding and interpretation of social problems are not static but rather dynamic and influenced by the prevailing sociopolitical climate. Levine and Levine (1970) observe a cyclical pattern: during conservative periods, the blame for mental health issues often falls on the individual. Conversely, in liberal eras, the focus shifts towards the social environment as a contributing factor. This illustrates how problem definitions can be shaped by the dominant political ideology. Rappaport [43] and Rothman [44] highlight the fluctuating emphasis within human services between addressing the "needs" or the "rights" of vulnerable individuals. This fluctuation, they argue, can be attributed to the prevailing "political-social zeitgeist", suggesting that the way we frame and approach social problems reflects the broader cultural and political context. These observations emphasize the crucial need for critical reflection when addressing social problems. By recognizing the potential influence of sociopolitical factors on our understanding of these issues, we can avoid reproducing biased perspectives and strive for a more nuanced and comprehensive knowledge base. This allows us to move beyond solely fixing individuals and consider the broader societal structures that may contribute to the problem, ultimately leading to a more holistic and effective approach to achieving sustainable solutions.

2.3.2 Key Challenges in Framing Wicked Problems for Social Good

Defining and debating "problems" is central to policymaking in contemporary democracies. Leaders and stakeholders frame the public agenda by highlighting issues deemed worthy of attention and discussion [27]. Policy studies often explore how different people involved in policymaking (like politicians or experts) define problems. This approach, called "problematizing," helps us understand why issues are seen differently and how these different perspectives might affect the solutions proposed [45], [46].

Public discussions and debates on how to "frame" a policy issue significantly influence how we understand and approach it [27]. The perception of what the problem is starts on the how well it is framed. According to Schön and Rein [47], framing isn't just about presenting information; it's a dynamic process involving selection, organization, interpretation, and sense-making (p. 146). This process transforms complex realities into manageable concepts, providing guiding principles for various purposes. These purposes include:

- **Knowing:** Framing helps us understand the problem and its context by highlighting specific aspects and filtering out others.
- **Analyzing:** Framing allows us to identify key elements and relationships within the problem, facilitating deeper exploration and analysis.
- **Persuading:** Different framings can be used to convince others of the importance of the problem and the need for action.
- **Acting:** Effective framing provides clear direction for decision-making and taking action to address the problem.

By shaping how we interpret and interact with complex issues, framing plays a crucial role in shaping the nature and course of policy discussions and solutions. The way we frame and define social issues is critical, as it significantly influences the solutions we propose. Bacchi [48] and Peters [46] emphasize this connection: different problem definitions lead to different solution sets. For instance, framing an issue as an individual's responsibility might result in solutions focused on personal behavior change, while framing it as a systemic issue might lead to interventions aimed at changing underlying structures and policies. This highlights the power of framing in shaping our understanding of problems and ultimately, our capacity to address them effectively. Head [3] offers an interesting example on framing wicked problems in the context of poverty. He states *"If poverty is largely seen as an individual-centred problem, generated by deficits in personal skill and motivation, the solutions proposed will be oriented toward encouraging individuals to develop their skills and work orientation. By contrast, if poverty is largely seen as an enduring structural feature of society, generated by economic systems and market forces, the solutions proposed are likely to be oriented toward social security systems, employment programs and income safety nets"*[49], [50], [51], [52].

The way policymakers frame problems isn't a one-size-fits-all approach. Instead, it's heavily influenced by the specific institutional context and the local political landscape. These factors significantly impact how policymakers define the scope, design, and implementation of effective policies. Ultimately, understanding these influences allows for the creation of more robust and tailored solutions to address complex challenges.

Summarizing the literature covered in Sections 2.1 to 2.3, it becomes evident that framing wicked problems critically involves incorporating human judgment, perspectives, and various viewpoints. Simultaneously, it necessitates support with evidence to guide the system under consideration. In this context, two terminologies are introduced: interpretive analysis and evidentiary analysis. They are defined as follows:

Interpretative Analysis: *An approach for analyzing qualitative data that involves exploring and interpreting the meaning of data from the perspectives of individuals/actors involved.*

Evidentiary Analysis: *Analysis that involves the systematic process of collecting, examining, and evaluating data and analyzing it with rigorous research methods, in order to provide decision support through that evidence.*

This is described in detail in Chapter 3 of this thesis.

The research gap that is identified from Section 2.2 – 2.3 anchors in the correct understanding of the wicked problems. Thus, the first research gap in this thesis that is identified is:

RG.1 How can wicked problems be effectively framed through the combination of interpretative and evidentiary analysis, incorporating human-computer synergies?

2.4 STRATEGIES FOR FRAMING AND ADDRESSING WICKED PROBLEMS

Forcing a complex problem into a simple solution framework is like trying to fit a square peg into a round hole. As Paul Seybold [53] aptly states, "It is painful to try to solve a complex problem using tools and approaches that are designed for simple problems" (p. 2). In the following section, the discussion on some specific tools and strategies that are used in literature to address wicked problems will be focussed upon.

Design thinking has become arguably the most widely recognized and implemented problem-solving methodology within the design field [9], [54], [55], [56]. Notably, its application extends beyond simple problems, encompassing the complexities of "wicked problems" as well [56]. These "wicked problems," unlike their simpler counterparts, often lack clear definitions, definitive solutions, and readily identifiable root causes, making them challenging to address with traditional approaches. This inherent adaptability allows design thinking to be tailored to various problem types, offering a valuable framework for navigating both straightforward and intricate scenarios. The method's emphasis on human-centeredness, iterative processes, and collaborative exploration makes it particularly well-suited for tackling the multifaceted nature of wicked problems. Researchers [57] have proposed using Double Diamond that allows researchers to discover, define, develop and deliver to address wicked problems.

In contrast to traditional "command-and-control" approaches that view problems in isolation and favor linear solutions, systems thinking offers a holistic and interactive perspective [58], [59], [60]. This framework acknowledges the interconnectedness and dynamic nature of social systems, emphasizing the complex web of causes, processes, and impacts that influence outcomes. Systems Thinking is valuable in addressing wicked problems for various reasons including:

- **Beyond Linearity:** It moves away from simplistic cause-and-effect reasoning, recognizing that systems often exhibit circular causality where actions can have unintended consequences and feedback loops can amplify or dampen effects.

- **Holistic View:** It encourages consideration of the entire system, not just its individual parts. This includes understanding how different elements interact and influence each other, preventing the optimization of one component at the expense of the overall system's performance.

- **Provisional Knowledge:** It acknowledges that our understanding of social systems is constantly evolving and context-dependent. This encourages flexibility, continuous learning, and adaptation based on new information and feedback.

Mess MapTM and Resolution MapTM are two complementary tools developed by MacroVU(r), Inc. and Strategy Kinetics, LLC [61]. Designed to be used in sequence, these methods offer a unique approach to address wicked problems (WPs). Mess MapTM acts as the first step, drawing inspiration from scenario planning [61]. This improved method helps identify and explore the multifaceted complexities of WPs, laying the groundwork for the subsequent stage[62]. Similar to the collaborative exploration encouraged in design thinking methods, Dialogue Mapping[53] and its close counterpart, Issue Mapping [63], foster collective understanding and solution development. These tools enable participants to not only analyze past successes and failures, but also identify potential constraints and promising opportunities.

This collaborative approach, often utilizing an interactive display [53], allows participants to visualize the evolution of ideas throughout the discussion, fostering a more dynamic and engaging problem-solving experience. This emphasis on shared exploration and visualization can be valuable in various contexts beyond design thinking, such as brainstorming sessions, strategic planning meetings, or even educational settings where collaborative learning is desired. By providing a shared visual space to capture and build upon diverse perspectives, these methods can support effective problem-solving and decision-making in various scenarios. Morphological analysis emerges as a valuable tool for tackling the intricate nature of wicked problems (WPs) [66]. This systematic approach allows for the structured exploration and analysis of complex relationships within WPs, fostering deeper understanding and creative solutions. The versatility of morphological analysis makes it applicable to various aspects of addressing WPs. It can be utilized for scenario development, alternate strategy development, risk analysis, and mapping complex relationships. While these methods are widely used due to their broad applicability there are multiple other strategies that primarily focus on linkage and variables in the wicked problem that allows designers to frame the problems. According to Schon and Rein [47], some social policy issues are inherently complex and resist simple solutions. They argue that traditional approaches, like authoritative decision-making, are not effective in addressing these "endemic problems." These problems require a different approach, one that emphasizes framing and reflection on how we define and approach the issue.

Policymakers often face intricate issues with interwoven components, unpredictable outcomes, and constantly evolving dynamics. These "complexities" have recently drawn interest from scholars who turn to complexity theory, a framework originally developed in the physical and computational sciences[65], [66], [67], [68]. Complexity theory encourages a shift in perspective by highlighting key aspects of these challenging situations:

Interdependence: Unlike linear thinking, this approach recognizes the interconnectedness of elements within a system. This means that a change in one part can ripple through the entire system, often leading to unforeseen consequences.

Feedback Loops: Systems don't operate in isolation; actions can trigger feedback loops where the outcome of an intervention influences future conditions, potentially requiring adjustments to the initial approach.

Emergent Features: As different elements interact within a system, unforeseen patterns and characteristics can arise, known as "emergent features." These can't be predicted by simply analyzing individual components.

Surprises: The unpredictable nature of complex systems means unexpected outcomes, both positive and negative, are always a possibility. This necessitates a flexible and dynamic approach to tackling these challenges.

While not offering a magic formula for crafting flawless solutions, complexity theory has proven valuable in environmental policy for understanding ecological processes and the ripple effects of human interventions [69]. This knowledge has informed the development of adaptive management strategies, emphasizing the need for continuous learning and adjustment in response to evolving contexts and unforeseen circumstances [68], [70], [71]. Therefore, complexity theory serves as a valuable tool for analyzing complex trends and challenges in policy settings. This understanding lays the groundwork for the exploration of complementary approaches such as collaboration and coordination, effective leadership, and fostering enabling processes in public governance, which will be discussed in later sections.

Termer and Dewulf [72] have proposed a small wins framework in order to prevent stakeholders from getting overwhelmed from the idea of wicked problems. This framework hinges on the principle of accumulating small wins to achieve progress, replacing linear approaches with non-linear complex systems thinking. This perspective draws inspiration from several key theoretical concepts:

- **Incrementalism** [21]: This policy science concept acknowledges the limitations of comprehensive planning in complex environments. It advocates for breaking down large goals into smaller, manageable steps, allowing for adjustments and learning as progress is made.

- **Continuous change** [73]: This notion emphasizes the dynamic and evolving nature of social systems. It recognizes that achieving change is an ongoing process, requiring continuous adaptation and learning from experience.

- **Sensemaking** [74]: This theory focuses on how individuals and groups collectively create meaning and understanding in ambiguous situations. By engaging in "social interaction" - talking, acting, and observing - people actively construct their understanding of complex situations and can develop strategies for navigating them. As Termer [72] states **“Sensemaking is also retrospective, meaning that actions are not known until they have been completed and have become lived experiences.”**

Sensemaking plays a particularly crucial role in addressing wicked problems. As Weick [74] points out, traditional routines and understandings may not be adequate in confronting these ambiguous issues. Instead, sensemaking encourages:

Isolating Elements: Focusing on specific aspects of the problem for closer inspection.

Probing Activities: Experimenting with different approaches and observing their effects.

Gauging Responses: Analyzing stakeholder reactions and adjusting strategies accordingly.

Deepening Insights: Continuously learning from experiences to refine understanding.

By embracing this iterative process of sensemaking and pursuing smaller, achievable wins, the small wins evaluation framework empowers policymakers to navigate complex challenges effectively. It encourages continuous learning, adaptation, and collaborative action, ultimately contributing to more sustainable and impactful solutions.

As observed in Sections 2.2, 2.3, and 2.4, it is crucial to integrate human judgments, experiences, and diverse perspectives when addressing with wicked problems. This approach is further emphasized in the context of framing wicked problems, enabling designers to include a variety of interpretations, perspectives, and experiences, which is currently lacking in the state of the art. To support these interpretations with logical relevance, it is essential to collect evidence based on the social problem in question. It is observed that when viewing the issue as a system and simulating its behavior is vital for designers to comprehend its dynamics. Moreover, the two aspects mentioned should not be considered in isolation; there must be a linkage between interpretations supported by human involvement and further evidence obtained by observing the system's behavior. This identifies the research gap addressed through Research Gap 1. The subsequent research gaps in this area are outlined in the section that follows.

The major objective through this chapter is to set the stage for addressing wicked problems in public policy and present the foundational literature review. Due to the transdisciplinary nature of the research involved, the thesis is designed in a way that provides context and necessary literature in every chapter to ensure connectivity and enhance comprehension of the knowledge provided throughout this thesis. In Section 2.5 the necessary context for Research Gaps 2,3, and 4 is provided.

2.5 CONTEXT FOR RESEARCH GAPS 2, 3, AND 4 (RG2, RG3, RG4 - CHAPTER 1)

In the context of complexities arising from the nature of wicked problems described in Sections 2.3 and 2.4, and recognizing the presence of wicked problems for which public policies are designed, there is a need for a systems-based approach that not only considers the challenges described in Section 2.4 but also further enables designers to have additional capabilities in addressing evolution and interdependencies due to the transdisciplinary nature of the problems. To address this, the paradigm of Cyber-Physical-Social Systems (CPSS) is explored, and the knowledge gap in addressing Evolving CPSS is highlighted in Chapter 4. The second research gap (RG2) described in Chapter 1 stems from this aspect. The gap is as follows:

RG2. What is the fundamental knowledge required in terms of key characteristics, requirements, and principles underlying design of Evolving CPSS, and how do they impact decision support in complex situations?

The relevant literature for this research gap is provided in Chapter 4 of this thesis.

The utility of E-CPSS in designing public policies is explored in Chapter 5. The relevant literature that guides this gap is provided in Chapter 5 in order to maintain the connectivity in the flow of logic and to pivot smoothly to another transdisciplinary element of this thesis. The research gaps are as follows:

RG.3 How can the collective adaptation construct be applied to facilitate policy design within Evolving CPSS?

RG.4 What are the common themes, theories, and frameworks that emerge across the domains of public policy, and how can they be integrated to provide a comprehensive approach to design public policies?

2.6 ESTABLISHING CONNECTION WITH BROADER PICTURE

Sections 2.1~2.3 of this chapter revolves around understanding Wicked problems, important aspects of framing and addressing wicked problems, and some strategies and tools to address wicked problem. Sections 2.1~2.3 are designed in a way to help readers understand different viewpoints and perspectives of literature on wicked problems that will merge into a broader understanding to design public policies. In this section the emphasis is placed on order to providing a meaningful connection and conclusion to this chapter that will open up directed avenues that are developed in Chapter 3, Chapter 4, and Chapter 5, of this Thesis.

In Section 2.1 various perspectives of wicked problems and the way various scholars interpret it was emphasized. We saw that addressing one issue of wicked problem does not guarantee that the problem will stop, but more generally it is observed that there will be a continuing problem to address. This is critical to become familiar about various viewpoints in the field of Wicked Problem. In Section 2.2 the discussion revolves around complexities in addressing wicked problem. We deal with four major challenges in terms of limited knowledge and understanding, conflicting interests, values, and priorities, power dynamics, and lack of resources and capacities. These four major categories umbrella a large number of mini challenges. In Section 2.3 the major focus is on framing wicked problems and its importance. Effective framing of wicked problems provides efficient design to address then. This anchors in wider picture of designing public policies. Section 2.4 is developed to provide strategies and essential requirements to address wicked problems. Figure 2.1 gives a quick brief of all the essential points that were discussed and I call it as "Mind Catcher" that signifies some quick relation of each cloud to one or more Sections.

Figure 2.1: Mind Catcher

Public policy often deals with complex issues called wicked problems, as described in this Chapter. Effectively framing these problems involves incorporating multiple viewpoints and perspectives, integrating human judgment, experience, and insights into the analysis. The first research gap addressed through this thesis explores the process of framing wicked problems in this manner and delves into mathematical modeling to comprehend the behavioral intricacies of such systems. Chapter 2 of this thesis is dedicated to addressing this research gap.

Examining public policies entailing wicked problems prompts consideration of the technological infrastructure required to address challenges discussed in this chapter. Through this thesis Cyber-Physical-Social System (CPSS) are identified as a valuable tool in addressing wicked problems in general and designing public policies specifically. Public policy is viewed as an Evolving Cyber-Physical-Social System, a domain largely unexplored in CPSS literature. Chapter 4 explores the need for a foundational cognitive model for Evolving CPSS (E-CPSS). The utility of E-CPSS and the associated research gap are further explored in Chapter 5. The goal in this chapter it to provide a detailed overview of designing public policies through the integration of a cognitive map and technological infrastructure, proposing a pathway to address the challenges outlined in the preceding chapters.

CHAPTER 3

FRAMING WICKED PROBLEMS

Wicked problems are characterized by incomplete and conflicting information. To frame a wicked problem, it is necessary to analyze the interaction among variables and then identify a reduced set of variables to identify wickedness of the problem.

In this chapter, a combination of interpretative and evidentiary analysis through the application of Dilemma Triangle Method and System Dynamics, respectively is proposed. A computational framework that allows a designer to convert heuristics into insights by using System Dynamics modelling, thus allowing a designer to analyze the interaction between variables is discussed. Further, the framework is based on the notion of involving human-in-the-loop, wherein wicked problems are framed through synergistic actions between a human and a computer. The benefits of using this framework are:

- *Converting heuristics into insights,*
- *Understanding the interaction among variables by analyzing the behavior of the system,*
- *Identifying the correct size of the problem to enhance better understanding of the problem*

To demonstrate the efficacy of the framework, data pertaining to Kantashol village in Jharkhand, India is used. The data was provided by SunMoksha Power Pvt. Ltd. The focus in this chapter is on describing the framework rather than the results on the ground in India.

Keywords: Wicked Problems, Evidentiary Analysis, Interpretative Analysis, Heuristics, Human-in-the-loop, System Dynamics, Dilemma Triangle Method

GLOSSARY

Wicked Problem: A class of problems which are ill formulated, where the information is confusing and conflicting, where there are many clients and decision makers with conflicting values, and where the ramifications in the whole system are thoroughly confusing [1].

Decision Maker: An individual who can affect, through his/her decisions, the achievement of objectives for an organization.

Stakeholder: An individual who can affect or is affected by the achievement of the objectives for an organization.

Framing: Identifying the problem correctly before solving a problem to ensure that the problem is correctly addressed.

Interpretative Analysis: An approach for analyzing qualitative data that involves exploring and interpreting the meaning of data from the perspectives of individuals/actors involved [2].

Evidentiary Analysis: Analysis that involves the systematic process of collecting, examining, and evaluating data and analyzing it with rigorous research methods, in order to provide decision support through that evidence [3].

Heuristics: Heuristics are the assumptions, experiences, domain expertise, that are applied in a way to hasten the process of approaching a solution.

Thematic Area: An area or category in which issues related to the same subject are considered.

Human-in-the-loop: Humans act as an embedded component in the system where their intent, emotions, cognition, etc. are intrinsic part of the computational system [4,5].

3.1 FRAME OF REFERENCE

3.1.1 Wicked Problems – Definition, Characteristics and Broader Impacts

Horst Rittel defines wicked problems as 'a class of social system problems which are ill formulated, where the information is confusing, where there are many clients and decision makers with conflicting values, and where the ramifications in the whole system are thoroughly confusing', which is considered as one of the earliest definitions of wicked problem; see editorial by Churchman, [75]. Rittel and Weber in their seminal paper emphasize the notion of focusing on the nexus of goal formulation, problem definition and equity issues. Social processes are seen as links connecting the open systems into large, interconnected networks which follow continuity of input-output relations. Rittel and Weber enunciate the importance of correctly identifying and framing the wicked problem by stating *"In that structural framework it has become less apparent where problem centres lie, and less apparent where and how we should intervene even if we do happen to know what aims we seek"* [80]. Further, they state that describing and locating the problem is one of the most challenging and intractable difficulties to address. The ten characteristics of a wicked problem recognized by Rittel and Weber are:

i. ***There is no definitive formulation of wicked problems. They are difficult to frame.***[1]

For ordinary problems, you can create a detailed statement that includes all the necessary information for solving it, assuming you have the required expertise. However, this approach doesn't work for wicked problems. The information you need to understand a wicked problem depends on your perspectives, preferences, and

[1] We have italicized the characteristics that we have considered in the proposed framework.

opinions incorporated through ideas for solving it. In other words, to describe a wicked problem thoroughly, you have to come up with a complete list of all possible solutions in advance. This is because any question asking for additional information relies on the current understanding and resolution of the problem. Understanding and solving wicked problems go hand in hand. To anticipate all the questions and information needed for a solution in advance, you must have knowledge of all conceivable solutions. The process of formulating the problem is the problem itself. Formulating the problem and coming up with a solution are the same, as every specification of the problem also specifies the direction of a potential solution.

ii. ***Wicked problems have no stopping rule.***

Rittel and Weber delineate this characteristic with exact words as quoted – "In solving a chess problem or a mathematical equation, the problem-solver knows when he has done his job. There are criteria that tell when the or a solution has been found." This is not the case with planning problems owing to the lack of criterion for adequate understanding and the limitless causal claims connecting interacting open systems, those attempting to plan can continually strive for improvement.

iii. ***Solutions to wicked problems are not true or false, but good or bad.***

There are established criteria in conventional problem-solving, allowing for an objective evaluation of the accuracy of a proposed solution to an equation or the structural formula of a chemical compound. These criteria can be independently verified by qualified individuals familiar with the established standards, and the response is typically clear-cut. In contrast, when dealing with wicked planning problems, there are no definitive right or wrong answers. Numerous parties may possess the capability, interest, and/or authority to assess solutions, yet none is able to hold the authority to establish formal decision rules for determining correctness. Their evaluations are likely to vary significantly based on their group or personal interests, unique value systems, and ideological preferences. Assessments of proposed solutions are often framed in terms of "good" or "bad," or more commonly, in terms of "better or worse," "satisfying," or "good enough."

iv. ***There is no immediate and no ultimate test of a good solution to a wicked problem.***

For tame problems, it's possible to quickly assess the effectiveness of a solution attempt. The evaluation is entirely within the control of the few people engaged and interested in the problem. In contrast, with wicked problems, any implemented solution sets off a cascade of consequences that can extend over an extended, virtually limitless period. Additionally, the repercussions of the solution the next day may lead to entirely undesirable outcomes, outweighing the intended benefits or those achieved so far. In such instances, it might have been better if the plan had never been executed. The complete consequences cannot be accurately gauged until all the repercussions have played out, and there's no way to predict or trace all the effects on affected lives in advance or within a limited time frame.

v. ***Every solution to a wicked problem is a "one-shot operation"; because there is no opportunity to learn by trial-and-error, every attempt counts significantly.***

In scientific and mathematical realms, as well as in areas like mechanical engineering design, designers can often experiment freely without significant consequences. The outcomes of individual trials have minimal impact on the subject system or societal affairs at large. Every solution implemented in wicked planning problems carries consequences that are irreversible and leave lasting "traces." Large public works projects, once executed, have enduring impacts, influencing people's lives irreversibly, requiring substantial expenditures, and setting off consequences with long half-lives. The same holds true for most large-scale public works and nearly all public-service programs. When actions are effectively irreversible, and the consequences have long-lasting effects, each attempt matters. Trying to reverse a decision or correct undesired consequences introduces a new set of wicked problems, subject to the same challenges.

vi. Wicked problems do not have an enumerable (or an exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan.

There are no criteria to prove that all possible solutions to a wicked problem have been identified and considered. The absence of a solution might result from logical inconsistencies in defining the problem, such as requiring both A and not-A to happen simultaneously. Alternatively, a lack of a solution may be due to a failure to develop an idea, though another person might find success. Typically, when dealing with wicked planning problems, numerous potential solutions emerge, and some are never even thought of. It becomes a matter of judgment whether to expand the set of solutions and which ones to pursue and implement.

vii. Every wicked problem is essentially unique.

Certainly, every pair of problems can be distinguished by at least one property, making each one trivially unique. However, when we refer to a problem as "essentially unique," we mean that, despite extensive lists of similarities between a current problem and a previous one, there might always be an additional distinguishing property that holds paramount importance. Dealing with wicked problems involves the art of not prematurely determining which type of solution to apply.

Wicked problems do not fall into classes where universal principles of solution can be developed to suit all members of a class. In mathematics, there are rules for classifying problems based on specific characteristics. Tame problems share explicit characteristics that define similarities, allowing a set of techniques to be effective across the board. Despite apparent similarities among wicked problems, it's impossible to be certain that the unique details of a problem do not override its commonalities with others already encountered.

While conditions for constructing a subway in one city may appear similar to those in San Francisco, planners should be cautious about directly transferring solutions. Differences in commuter habits or residential patterns may outweigh similarities in infrastructure layout. In the more intricate realm of social policy planning, each situation is likely to be unique. If this is accurate, directly applying the thought processes of physical sciences and engineering to social policy might be counterproductive, potentially leading to applying "solutions" that are incompatible with seemingly familiar problems.

viii. Every wicked problem can be a symptom of another problem.

Problems are essentially disparities between the current state of affairs and the ideal state. The process of addressing a problem begins with seeking the cause of this disparity. Eliminating that cause gives rise to another problem, of which the initial problem is a mere "symptom." In turn, this new problem can be viewed as a symptom of an even higher-level issue. The level at which a problem is resolved is subjective and relies on the analyst's confidence rather than logical grounds. Wicked problems lack a natural level. While higher-level formulations broaden the problem and make it more general, they also make it more challenging to address. Despite the difficulty, it is essential to aim for higher-level resolutions to avoid merely treating symptoms. Incrementalism, a policy advocating small steps for systematic improvement, faces challenges. If a problem is tackled at too low a level, success at that level may inadvertently worsen things by making it harder to address higher-level problems. Marginal improvements don't guarantee overall progress. For instance, computerizing an administrative process may lower costs and increase operational ease, but it can simultaneously hinder structural changes within the organization. Technical advancements can reinforce existing organizational patterns and elevate the cost of change. Consequently, members of an organization often perceive problems at a level below their own.

ix. There are numerous explanations for a wicked problem.

In scientific discourse, if conditions C and hypothesis H suggest that effect E must occur, but under C, E does not happen, then H is refuted. In wicked problems, additional modes of reasoning are admissible. For example, one can deny that E has not occurred or explain the nonoccurrence of E through intervening processes without abandoning H.

In the realm of wicked problems, the modes of reasoning used in arguments are more diverse than those allowed in scientific discourse due to the unique nature of the problems and the absence of opportunities for rigorous experimentation. Consequently, it's not possible to subject hypotheses to a crucial test. The choice of explanation is arbitrary in a logical sense, guided by attitudinal criteria. Individuals select explanations that seem most plausible to them, often aligning with their intentions and available courses of action. The designers "world view" strongly influences how a discrepancy is explained and, therefore, how a wicked problem is addressed.

x. ***The planner has no right to be wrong.***

In "The Logic of Scientific Discovery," Karl Popper asserts that in science, solutions to problems are essentially hypotheses presented for potential refutation. This approach stems from the understanding that there are no proofs for hypotheses; instead, they are subject to possible refutation. The scientific community does not criticize its members for putting forth hypotheses that are later refuted, as long as they adhere to the rules of the scientific process. However, in the realm of planning and wicked problems, no such immunity is granted. The primary objective here is not the pursuit of truth but rather the improvement of certain aspects of the world people inhabit. Planners are held accountable for the consequences of their actions, which can have significant implications for those affected by them. Consequently, the problems planners face are considered wicked and incorrigible, resisting efforts to define their boundaries, identify their causes, and reveal their inherently problematic nature. Planners working with open systems grapple with the ambiguity of their causal webs, and their proposed solutions are further complicated by the growing pluralism of contemporary public opinions. These publics evaluate proposals using diverse and conflicting scales, presenting the planner with additional dilemmas.

Rittel and Weber contend that a systems approach is appropriate to frame wicked problems. They argue that for wicked problems one cannot understand the problem without knowing about its context and that the systems approach of the ‘first generation’ is futile to deal with wicked problems. Accordingly, a designer might be overwhelmed and feel paralyzed about addressing wicked problems. We believe that wicked problems can be addressed by identifying the correct size of the problem, instead of getting overwhelmed by its notion. Paralysis occurs when one acts too reflexively and considers wicked problems so overwhelming that it discourages them from doing anything about them [81]. Termeer and coauthors emphasize the significance of small wins to tackle wicked problems and the value in bringing in transformative change [82]. We agree with the notion that it is important for a designer to take small steps to address the “wickedness” embodied wicked problems. This is reflected in our proposed approach for framing a wicked problem.

The United Nations General Assembly adopted the 2030 Agenda for Sustainable Development [83] where the major focus is on “transform[ing] the world to better meet human needs” and “leave no one behind and create a world of dignity”. “We need to tackle root causes and do more to integrate the economic, social and environmental dimensions of sustainable development.” In a subsequent editorial published in Nature in 2020, the writers contend that the world is almost set to miss all the goals except two, namely, “eliminating preventable deaths among newborns and under-fives,” and “getting children into primary schools”, which are the closest to being achieved [84]. Eden and coauthors argue that irrespective of Covid 19 pandemic, the agenda to achieve the goals was inevitable due to the fact that the United Nations are addressing issues which are wicked problems [85]. Instead of trying to solve wicked problems, designers/ policymakers should focus on managing or coping with the wicked problems [86]. In order to manage or cope with wicked problems it is important to correctly frame the problem at the start of a design process. This has broader impacts in terms of correctly identifying the problem and going to the core of the wickedness of the problems in order to solve them. In this chapter an example of wicked problem in a village in India, namely, Kantashol is considered. The three thematic areas that are consider in framing the Kantashol wicked problem are water, forestry, and agriculture. These thematic areas are anchored in demographics, culture and socioeconomics associated with this village. We require a comprehensive understanding when we deal with wicked problems with the goal of sustainable development. It is observed that water, forestry, and agriculture are interdependent areas with challenges that are intertwined, however, they are approached separately in silos [87]. Wickedness of the problem lies in modeling the synergy between the different thematic areas of consideration that makes it essential to initially frame the wicked problem and correctly identify the variables of consequence and its size. With the goal to provide a framework to frame wicked problems as well as anchor with sustainable development goals we select three `Drivers`[2] for our problem namely, People, Planet and Prosperity[3] [88].

3.1.2 Interpretative Analysis and Evidentiary Analysis

Various authors have commented on the role of interpretative and evidentiary analysis in approaching wicked problems. Evidence-based analysis for public policy analysis is mired in debates in terms of its utility. Several authors stress the need for an orderly approach and explore the evidentiary analysis to aid policy making [89]. Daviter, argues that the main aim

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[2] Key words associated with the Dilemma Triangle Method are shown in Courier font.

[3] *Progress* used in our earlier publications has been replaced by *prosperity* to conform to the definition adopted for sustainable development at COP 26 in Glasgow.

of evidence-based analysis, that is evidentiary analysis, is to provide design options for conflicting interpretations by enabling analytical tasks to be more objectifiable [90]. Various authors in the past argue that the problems that are ill structured (wicked problems) are not open to analytical methods. Strong evidence seldom contributes in the analysis of problems when the boundaries are not well defined [91]. Authors who contest evidentiary analysis assert that the evidence is often value-laden which suggests that the evidence is more likely based on biased conclusions [92]. Authors argue that, with this notion, evidence-based analysis for wicked problems like public policy are arrived through an order of ranking of technological method rather than consensus between various stakeholders and actors involved in the process [93]. However, the notion of evidentiary analysis for wicked problems is widely bolstered by academicians, administrators, and politicians [94]. Daviter [86] argues that when we deal with wicked problems, the knowledge base we have is often 'fragmented' and 'contested' due to the notion of available evidence being 'incomplete', 'inconclusive' and 'incommensurable'.

This chapter we accounts for the issues cited in the preceding paragraph by proposing a framework to frame a wicked problem that embodies the integration of interpretative and evidentiary analysis through Dilemma Triangle Method and System Dynamics, respectively. Framing of any wicked problem and identifying the core of it allows a designer to understand the problem and proceed in a structured way to address the wickedness of any wicked problem. Through the inclusion of interpretative and evidentiary analysis we enable humans in the loop to account for human cognition, mental capabilities, and socio-cultural elements [95]. By including a human-in-the-loop we facilitate the efficient framing of wicked problems by maximizing the synergy between human abilities and computational capabilities.

A. *Dilemma Triangle Method (DTM)*

The Dilemma Triangle Method is used to identify the dilemmas embodied in wicked problems. A Dilemma is defined as follows:

Dilemma: *"A dilemma is a difficult choice between two options, each of which is unacceptable or unfavorable"* [96].

A schematic of the Dilemma Triangle Method is shown in Figure 3.1. Following key words are used in the Dilemma Triangle Method:

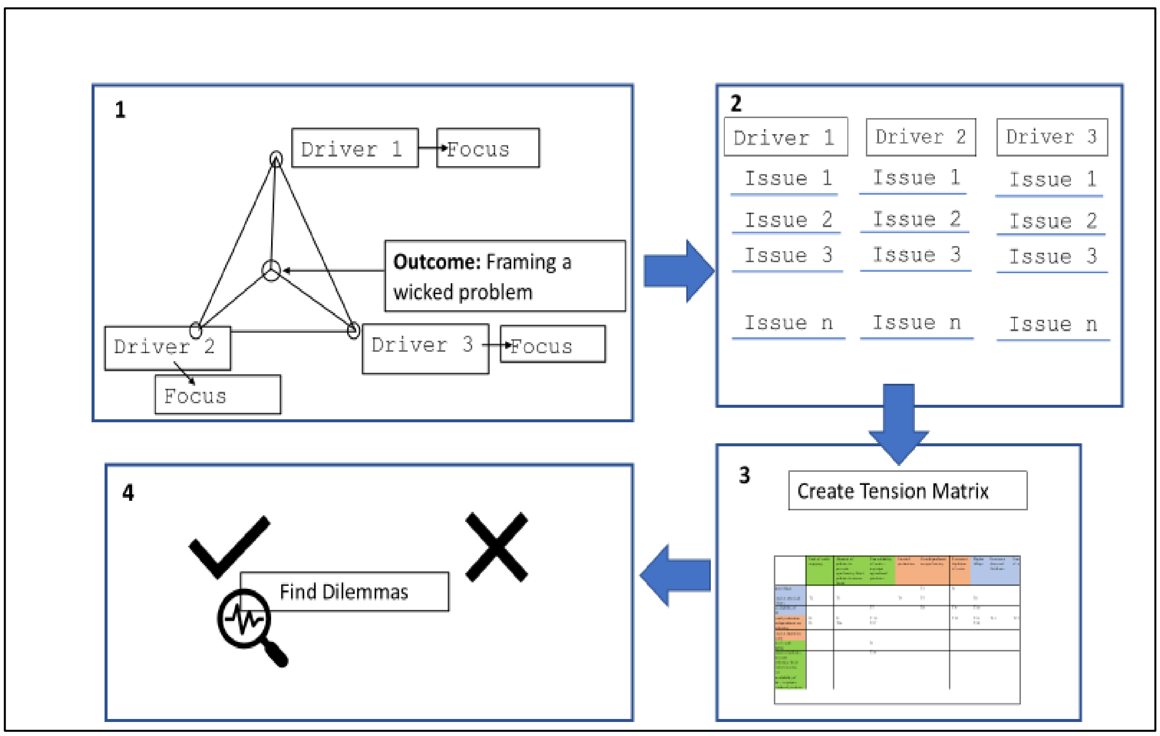

Figure 3.1: Generalized Dilemma Triangle Method

Driver: *These are the thematic areas that are key to framing a wicked problem and thence used in identifying an appropriate solution or way forward. There is no limit on the number of* Drivers *that can be considered.*

Focus: *A single statement used to define the goal that must be achieved for the* Driver*. There can be several* Foci *for each* Driver.

Issues: Issues *must be addressed to satisfy the* Focus *that must be achieved for the Driver.*

In the Dilemma Triangle Method, thematic areas that contribute to the wicked problem are selected followed by identifying the Drivers for each thematic area; see Figure 3.1. As shown in Block 1, Figure 3.1, three Drivers are identified for each thematic area. Further, the Focus is defined using experience and judgment each Driver that enables us to establish the boundaries This includes taking into account the perspectives of multiple stakeholders involved. Once we have the Focus for each Driver, the Issues are listed as shown in Block 2; Figure 3.1, that are key to achieving the specified Focus. Further the two important stages in the Dilemma Triangle Method which help in managing the dilemmas are creating Tension Matrix and identifying the Dilemmas.

A) Tension Matrix (Block 3; Figure 3.1)

A Tension Matrix is created to identify the relation between two Issues. This matrix is a foundational step in identifying Dilemmas. There are four relations between Issues which can be identified through the Tension Matrix:

a) *Tension:* A tension results when an Issue associated with one Driver negatively impacts an Issue associated with another Driver.

b) *Dependent:* A dependent arises when the Issue associated with one Driver positively impacts an Issue associated with another Driver.

c) Inter-Tension*:* When one Issue negatively impacts an Issue of a different thematic area.

d) *Inter-dependent:* When one Issue positively impacts an Issue of different thematic area.

B) Identifying Dilemmas (Block 4; Figure 3.1)

Dilemmas are identified based on the Tension Matrix constructed. Dilemmas, when correctly identified through combination of evidentiary and interpretive analysis help us to frame a wicked problem, the framework for which is described in this chapter.

For example, In several agricultural villages, relevant to this effort, the income of villages depends on the forest. If the villagers stop cutting trees and accessing the forest utilities their income will reduce. Thus, this happens to be a dilemma. Further, villagers who practice agriculture have over exploited water for their personal and agricultural use. They practice excessive tillage in farms which has other detrimental impacts on the planet. Thus, this is again a dilemma and precludes sustainable development. The three Drivers selected to promote sustainable development in such a village are People, Planet and Prosperity. This is anchored in the test problem used in this chapter. The use of the Dilemma Triangle Method to manage dilemmas in one thematic area for sustainable rural development of India is documented in Reference [96]. Further, the Dilemma Triangle Method is expanded to three thematic areas to provide a method for social entrepreneurs to develop value propositions [99].

The application of Dilemma Triangle Method along with systems dynamics to propose policies and value propositions is presented in [97-98] In the earlier papers the focus is on:

- Karkaria et al. [97] use the combination of Dilemma Triangle Method and System Dynamics to determine policies. Their main objective is to propose policies to ensure sustainable development. In this chapter, the focus is on framing wicked problems through iteration by incorporating evidentiary and interpretative analysis while maximizing synergy between computational capabilities and human abilities.
- Kamala et al. [98] focus on using System Dynamics to create value propositions for social entrepreneurs. Their objective is to aid social entrepreneurs to provide decision support to choose the right value proposition required for the intervention and evaluate its pre-impact. Whereas through the framework proposed in this chapter, a designer can identify the wickedness of the problem and frame wicked problems through interpretive and evidentiary analysis.

B. System Dynamics Modelling

System Dynamics is used to model the system and enable a designer to simulate and analyze the behavior of the system to gain insights that support decision making. Through simulation of system using System Dynamics, we understand the effect of variables on each other and gain insight on the interaction between variables and their impact on system model. Systems Dynamics necessitates constructing a causal loop diagram and a stock and flow diagram.

a) *Causal Loop Diagram*

Causal loop diagrams are an effective way of mapping the relationship among variables. These allow a designer to link the variables with one another and understand the interconnections of variables in a system. Further, causal loop diagrams help a designer understand the system as a whole and provides an opportunity to enhance the system structure. A causal loop diagram is an effective tool for story telling in order to communicate the understanding of the elements of system and system as whole.

b) *Stock and Flow Diagram*

The creation of stock and flow diagrams allows a designer to simulate the system and get insights on the interaction between variables. Through the simulations created through stock and flow diagram, a designer gains insight of the systems behavior by simulating the system which acts as an important tool for decision support when complex systems are involved. The two important elements namely stock and flow are defined as follows:

Stock: Stock is the accumulation of a quantity at any state of the system.

Flow: A flow is entity which increases or decreases the magnitude of stock.

3.2 FRAMEWORK FOR FRAMING WICKED PROBLEMS

In this section a framework that can be used by a designer to frame a wicked problem is described. We enable a designer to convert the early-stage heuristics into insights to frame a wicked problem through evidentiary and interpretative analysis with a human-in-the-loop.

3.2.1 Approach for Framing a Wicked Problem

In Figure 3.2, the proposed approach for framing a wicked problem is illustrated. Given a wicked problem, in the initial stages a designer has heuristics anchored in past experience. However, to frame a wicked problem a designer needs to generate evidence-based insight to augment what is currently known to him/her. Thus, based on the heuristics, a designer invokes the Dilemma Triangle Method. Using the information generated and deductive speculation a designer then constructs a Systems Dynamics model to model the system and thereby gain insight into the behavior of the system. With these insights a designer modifies the input to the Dilemma Triangle Method by considering the evidence-based insights gained through exercising the System Dynamics model. This process is repeated until a designer is satisfied with the outcome. In summary, a designer carries out interpretative analysis through the Dilemma Triangle Method and evidentiary analysis through System Dynamics. This process allows a designer to synthesize the heuristics and experiences into insights through deductive speculation to frame a wicked problem.

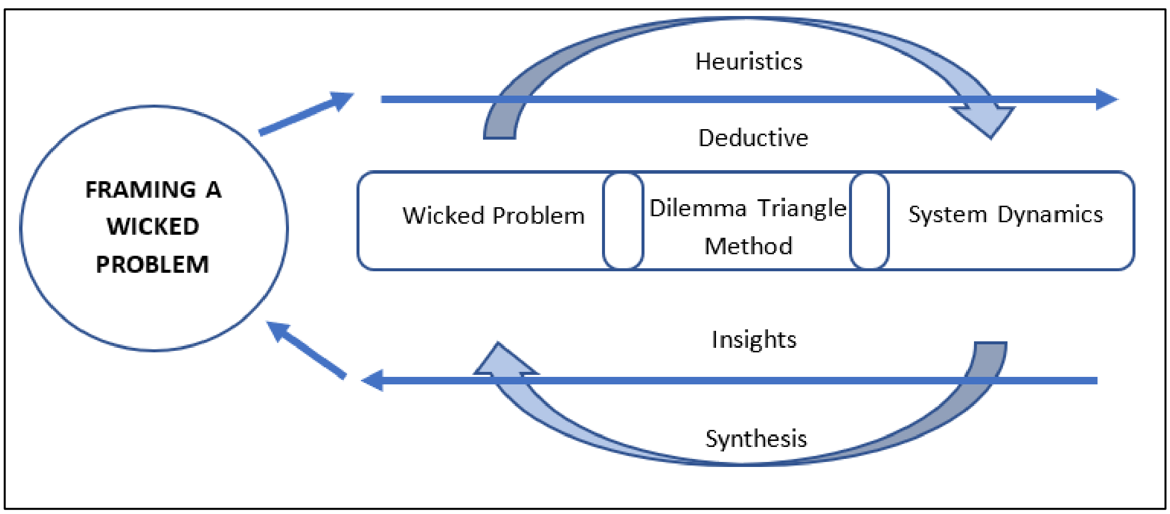

Figure 3.2: Overview of Approach

3.2.2 Features of the Proposed Framework

A framework is proposed to frame the wicked problems through a structured process. The features of the proposed framework are summarized in Figure 3.3.

Conversion of heuristics into insights

While dealing with wicked problems, it is evident that a designer has incomplete information

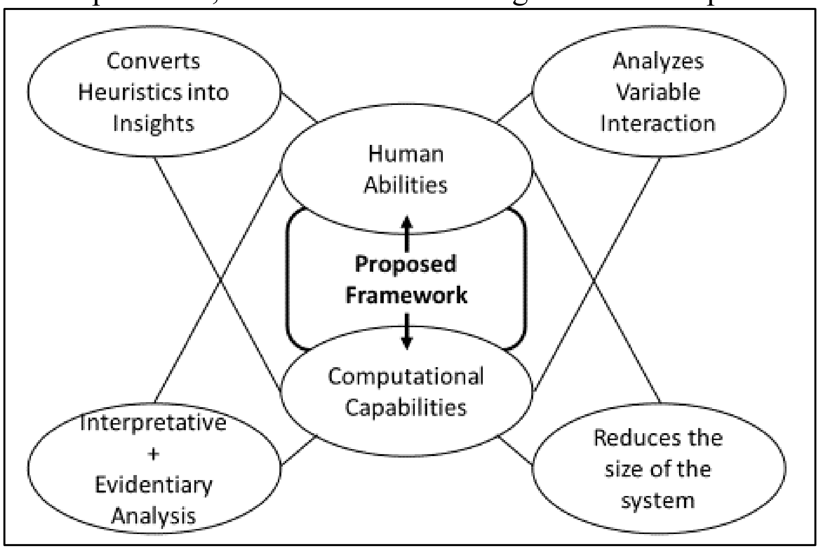

Figure 3.3: Features of the Proposed Framework

which is often confusing and conflicting. The value of this feature of the framework is to attain insights from the initial heuristics. As shown in Figure 3.2, the initial invocation of the Dilemma Triangle Method is based on the heuristics a designer has. Through the advancement from Dilemma Triangle Method to System Dynamics model, we create a foundation for having insights based on heuristics. The system behavior analysis as shown by Block 2A in Figure 3.4 is the stage where the heuristics are converted into insights.

Analyze interaction between variables and identify the correct size of the problem

When we consider a wicked problem, we have a plethora of variables that are of interest to a designer. However, some of these might not be significant. It is therefore important for a designer to understand the interaction among these variables and their overall effect on the wicked problem. This allows a designer to identify the variables that are significant which further emphasizes the third peculiar feature of the proposed framework, through which we enable a designer to identify the correct size of the problem. This anchors in Block 2 and Block 2A of Figure 3.4.

Maximizes synergy between human capabilities and computational abilities

Due to the characteristics of wicked problems, they can seldom be modelled alone with computational abilities. Human cognitive characteristics play a very important role in addressing wicked problems through judgements, perspectives, and experiences of humans. The value added through this feature is to maximize the synergy between human abilities and computational capabilities. Through the Dilemma Triangle Method a designer brings to bear his/her judgement (qualitative information) that is anchored in experience. By exercising the Systems Dynamics model, designer is able to transform judgment (qualitative information); see Blocks 1, 2 and 3 in Figure 3.4.

Integration of Interpretative and Evidentiary Analysis

Interpretative and evidentiary analysis play a very important role and have their own significance for addressing various types of problems. Through the proposed framework, authors provide an opportunity for a designer to have both; interpretative analysis through the Dilemma Triangle Method and evidentiary analysis by simulating the system by virtue of System Dynamics model.

3.2.3 Description of the Framework

The conceptual design of the framework is divided into three main building blocks is shown in Figure 3.4. Further, in Figure 3.5 the detailed framework is presented. In this section three steps in the context of their utility in the framework are discussed.

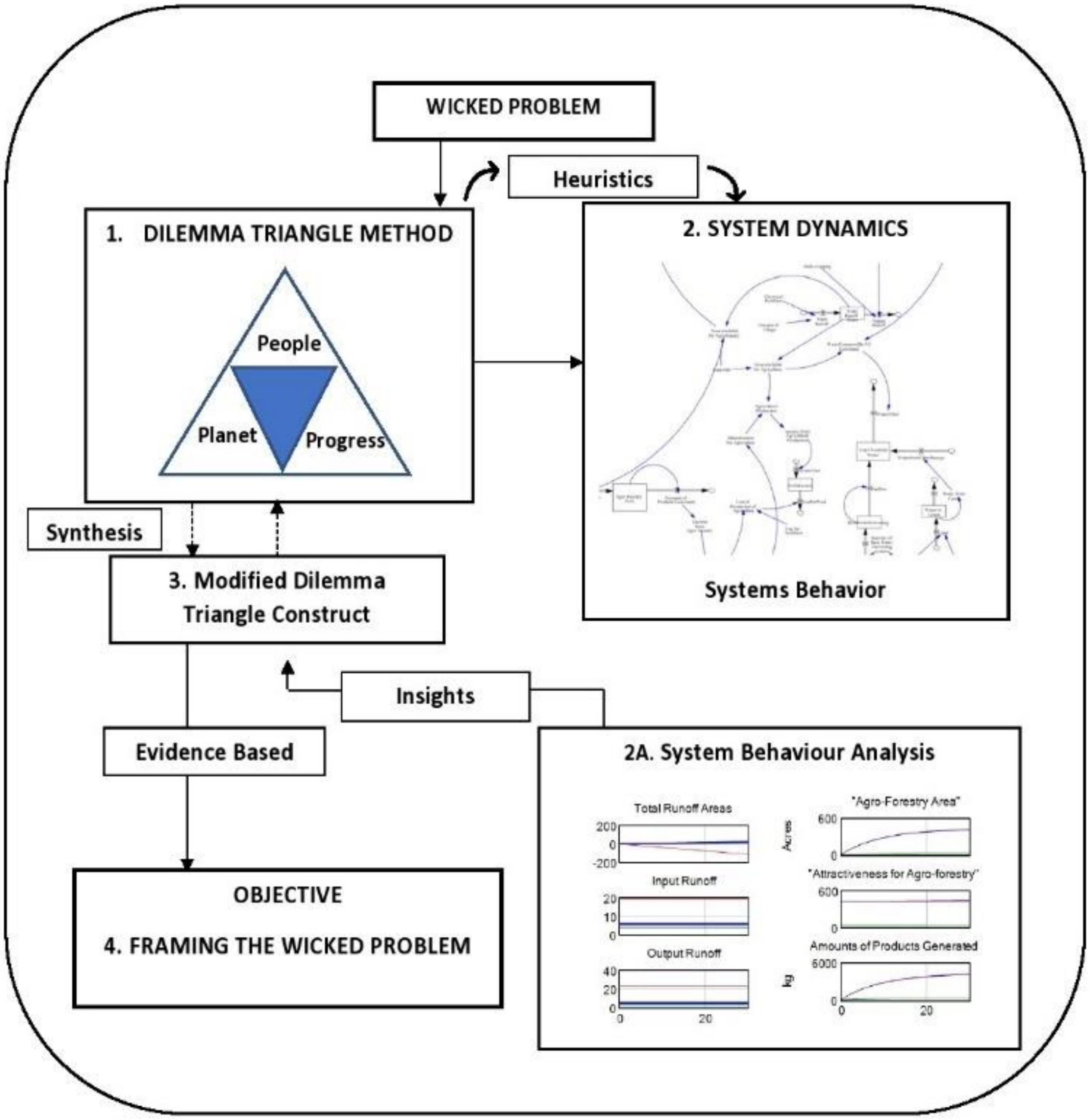

Figure 3.4: Mental Model for the Proposed Framework

Step 1: Dilemma Triangle Method

Identify the `Focus` and list the `Issues` that are key to attaining the `Focus`. This is based on heuristics and observations gained by the knowledge of the wicked problem we have. At this stage we do not create the `Tension Matrix` to arrive at `Dilemmas`. Through Dilemma Triangle Method we carry out interpretive analysis which allows us to incorporate the behavioral, cognitive, and social elements in the analysis to frame wicked problems. This interpretive analysis further helps a designer to analyze the qualitative data involving interpreting the data from the perspectives of actors involved. The information used is based on heuristics anchored in what the designer knows at this time.

Step 2: Systems Dynamics

Create a Systems Dynamics model to gain insights for framing a wicked problem. A designer develops causal loop diagrams based on the Dilemma Triangle construct from Step 1. Further, designer creates stock and flow diagrams and simulate the system. Through this structured process a designer is able to simulate and observe the behavior of the system. A designer analyzes the effects of interaction among variables and gains insight to the important variables the outcome and those that are not under a designer's control. This enables a designer to isolate the "wickedness" associated with the wicked problem and deal with it appropriately.

Thus, through System Dynamics a designer is able to carry out the evidentiary analysis by gathering insights and evidence by simulating the system and observing the interaction between variables. Through the framework, a designer have the opportunity to collect, evaluate and examine data by incorporating the interpretive analysis as well to provide decision support to frame wicked problems.

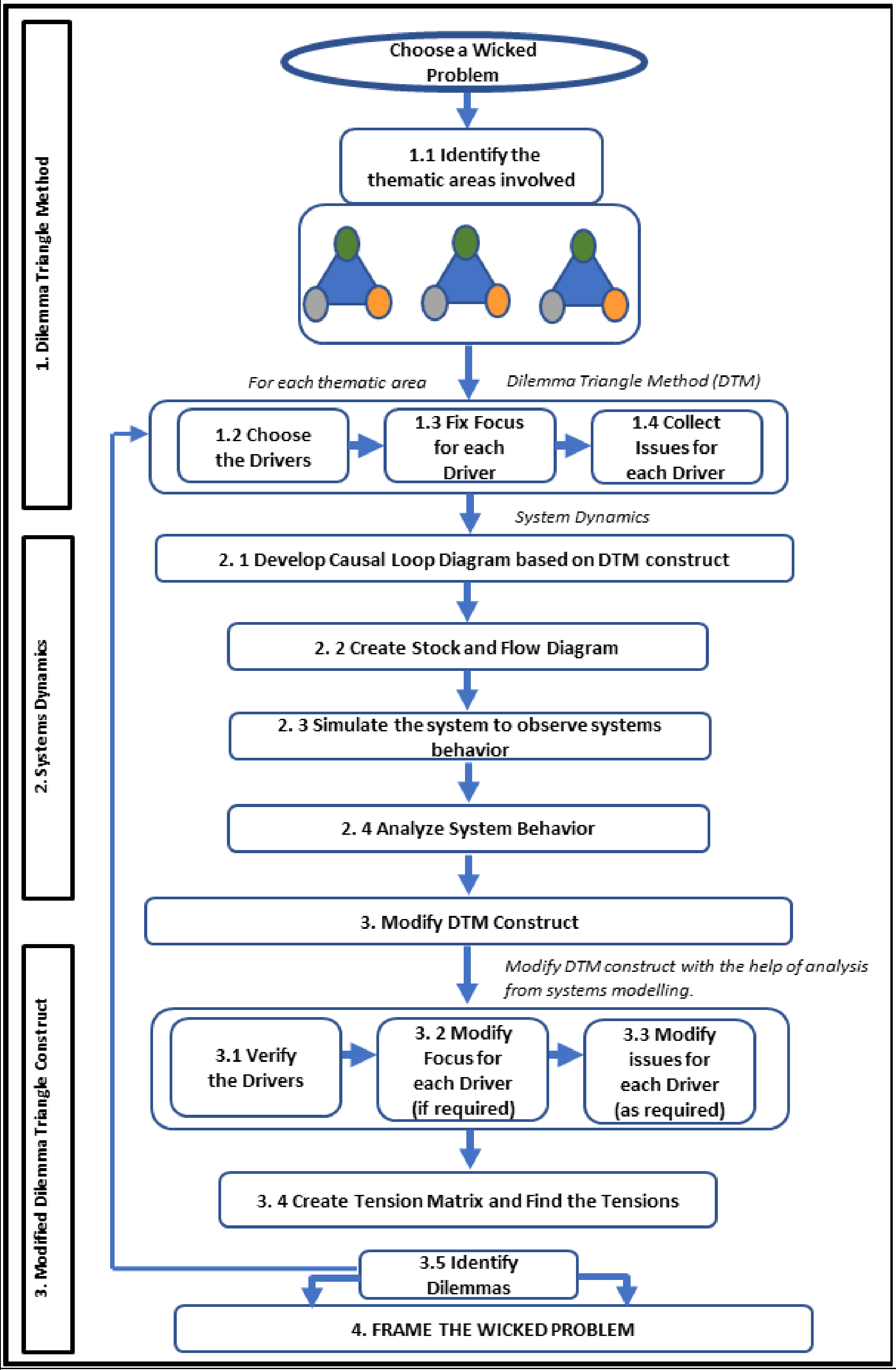

Figure 3.5: Proposed Framework to Frame Wicked Problems

Step 3: Modified Dilemma Triangle Method

As discussed in Step 2, at this stage a designer has gained insights from the System Dynamics model through the simulation of the system. The designer leverages the insights gleaned and modifies the Dilemma Triangle created in Step 1. This enables a designer to modify the `Tensions` and `Dilemmas` and add observations based on insights which impact the system. The `Dilemmas` constitute the framing of the wicked problem. Each `Dilemma` needs to be resolved. The resolution will typically involve some combination of technical, regulatory, policy, financial and social consideration.

Through this framework, designers utilise the interpretative analysis through the Dilemma Triangle Method compounded with the evidence-based analysis through System Dynamics to frame wicked problems. Thus, a designer who uses this framework, can convert the heuristics into insights and frame the wicked problem through a structured process to ensure correct identification of the problem and a way forward.

3.3 TEST PROBLEM OF KANTASHOL VILLAGE TO DEMONSTRATE THE EFFICACY OF THE FRAMEWORK

To illustrate the efficacy of the framework data for Kantashol village in Jharkhand, India is sued which is provided by Dr. Ashok Das and his colleagues at SunMoksha Power Pvt. Ltd. The average rainfall is around 60-65 days in a year with an annual count of 800-1310 mm, due to which villagers use excessive amount of ground water which happen to be one of the reason of overexploitation of the ground water. Villagers are overly dependent on the forestry for their livelihood and the practice of agriculture is limited due to various reasons. The average temperature in the village is around 40-45 degree Celsius. The village has marginal road transport. Since the income of villages depends on forestry, if the villagers stop cutting trees and accessing the forest utilities their income will be reduced. Thus, this happens to be a dilemma. Further, villagers over exploiting the water for their personal and agricultural use exacerbates challenges. The local practice of excessive tillage in farms which has various detrimental impacts on the planet including erosion which, in time, reduces the acreage of available land to the villagers, affecting the planet adversely. The situation is a wicked problem due to the incomplete, conflicting, and confusing information.

- Since the income of villages depends on forestry, if the villagers stop cutting trees and accessing the forest utilities their income will be reduced. Thus, this happens to be a dilemma.
- Villagers over exploiting the water for their personal and agricultural use exacerbates challenges. The local practice of excessive tillage in farms which has various detrimental impacts on the planet including erosion which, in time, reduces the acreage of available land to the villagers, affecting the planet adversely.
- The situation is a wicked problem due to the incomplete, conflicting, and confusing information.

Approach

Having identified this as a wicked problem based on insights from various stakeholders, we begin to assess the situation borrowing heavily from the expertise from the SunMoksha team. SunMoksha is an international partnership between scholars and local industry in India that strives to develop and field-deploy clean and sustainable technology solutions and provides consulting services for rural development and urban sustainability. The SunMoksha team consists of experts and professional with a passion for sustainable development, and decades of experience in technology, engineering and management across Asia, Africa and the USA including team members working on the ground which grants us real-time insight on problems faced at individual and community level in terms of people, planet, and prosperity.

The framework illustrated in Figure 3.5 is systematically exercised for the Kantashol village problem. A discussion on the efficacy of the framework through the test problem is presented in Section 4. The following steps are explained with respect to the test problem and are tied with the steps illustrated in Figure 3.5.

Step 1 Figure 3.5: Dilemma Triangle Method

Step 1.1: Identify the thematic areas involved

Initially the selection of important thematic areas involved based on the lifestyle and situations of the village is done. The thematic areas selected are water, forestry, and agriculture. However, to illustrate the framework all three thematic areas are combined in the Dilemma Triangle Method. The system dynamics model, however, has all three thematic areas involved to ensure accurate insights are obtained.

Step 1.2: Define the `Drivers`

We select the three `Drivers` with the goal of improving the progress of the people and at the same to ensure sustainable development. The three `Drivers` selected are People, Planet and Prosperity.

Step 1.3: Fix `Focus` for each `Driver`

Based on the situation in Kantashol the `Focus` of each `Driver is` defined. This is based on taking perspectives of various stakeholders and the data collected from the SunMoksha team.

Various factors affecting the livelihood and progress of the people of the village at an individual-level as well as community-level are considered, as well as ensuring that the development is sustainable.

Step 2 Figure 3.5: Systems Dynamics Modelling

Step 2.2: Create Causal Loop Diagram

This first step in System Dynamics modeling anchors with creating causal loop diagram. These causal loops help designers to map relationship between different variables. The interpretive analysis carried out during the Dilemma Triangle Method in Step 1 forms the foundation for constructing causal loop diagrams.

Step 2.2: Create Stock and Flow diagram

Once the relationship is mapped and dependencies amongst variables are known, a stock and flow diagram is created through which the system is simulated. To create the stock and flow diagram we specify the relationship among variables by inserting the mathematical equation and values, the data for which is acquired from the SunMoksha team. Based on the qualitative and quantitative data and survey, variables are as objective variables and decision variables. This allows us to categorize the variables in to simulate the system.

The information that cannot be quantified is incorporated in the framework through the Dilemma Triangle Method. While applying Dilemma Triangle Method we use heuristics that are judgements anchored in experience. This is where the interpretative analysis is executed. The information rather than being made up is anchored with deductive reasoning followed through the steps in the framework. Dilemma Triangle Method forms the foundation for the information that is fed in stock and flow diagram.

Step 2.3: Simulate the system to observe systems behavior

At this stage the system is simulate by conducting various experiments. For example, the amount of tillage and multi cropping is changed in order to understand its effect on the profits incurred and the runoff areas. This step helps us to simulate the system and understand the behavior of the system by analyzing the effects of interaction between variables and on the system.

At this stage we have the interpretations based on the initial Dilemma Triangle construct and evidence based on the system dynamics modelling. Simulating the Kantashol village based on the system dynamics model and critically analyzing the behavior, we gather insights. Through this analysis variables which do not affect the outcome are understood, as well as attain insights to identify the problem correctly.

Step 3 Figure 3.5: Modified Dilemma Triangle Construct

Based on the insights and evidence attained through Step 1 and Step 2, we modify the Dilemma Triangle. This allows us to identify the wicked problem based on interpretations that are based on expert views, and judgements, by inclusion of all the stakeholders as well as on the evidence gathered based on computational simulations. The interpretative analysis is compounded through evidentiary analysis by the aid of System Dynamics.

Accordingly, there is opportunity to modify the `Focus` and `Issues` through Steps 3.1, 3.2 and 3.3. Further, we construct the `Tension Matrix` for the `Issues` that ties with Step 3.4. The `Tension Matrix` allows us to find the `Dilemmas` thereby help us frame the wicked problem.

Step 4 Figure 3.5: Frame the Wicked Problem

After creating the tension matrix, we identify the dilemmas which enable us to frame the wicked problem which is our main objective in this chapter.

With the application of framework, we have a perfect reconciliation of interpretative analysis and evidence-based analysis thus ensuring the fidelity of the framing of the wicked problem through human abilities compounded through computational capabilities.

3.4 RESULTS AND DEMONSTRATION OF THE EFFICACY OF THE PROPOSED FRAMEWORK

In this section, the efficacy of the proposed framework is detailed. The results are discussed in three parts, namely, Initial Dilemma Triangle construct, System Dynamics Modelling, and Modified Dilemma Triangle construct.

3.4.1 Dilemma Triangle Method (Step 1; Figure 3.5)

a. People

`FOCUS`: To improve the quality of life of people by providing them with adequate nutritious food, water for various purposes, and promote sustainable agroforestry for the sustainable development of the village.

`ISSUES`

1. Lack of agriculture and crop diversification
2. Absence of policies to promote agroforestry and strict government policies to access the forests.
3. Unavailability of water due to lack of facilities, excessive runoff, less rainfall, etc.

b. Planet

FOCUS: To preserve forest and its biodiversity, prevent runoff, preserve fertility of the agricultural land, and utilize water resources wisely.

ISSUES

1. Excessive tillage for agriculture
2. Overdependence on agroforestry and lack of sustainable agricultural practices.
3. Excessive depletion of water and lack of awareness to maintain the quality of the water.

c. Prosperity

FOCUS: To enhance the sources of income for the farmers, to ensure progress in the income of villagers, and to provide reliable and feasible sources of water for varied purposes.

ISSUES

1. Excessive runoff due to high tillage resulting in large barren lands in the long term.
2. Lack of awareness of appropriate agricultural practices resulting in high reliance on agroforestry.
3. Unavailability of water due to limited access and an unstable power supply accompanied by unknown wastage of water.

For the initial Dilemma Triangle construct, we define the `Focus` and list the `Issues` encountered to achieve the `Focus` for each `Driver`. This is based on the information from various sources

and includes data, experiences, and judgements. Based on the `Issues` and `Focus` for each `Driver`, we create a System Dynamics model and simulate the system to help us understand the interaction between variables.

In this chapter two types of variables are used, namely, objective variables and decision variables. Decision variables are defined as the variables which a designer can assign a value or a set of values to achieve a goal or assess its effect on desired outcome, whereas the variables that represent the objective or goal and measure the effectiveness of the solution are defined as objective variables.

The effect of decision variables on objective variables through System Dynamics is assessed.

Based on the information gained, we recognize that for the development to take place it is required to increase the disposable income of the villagers without adversely affecting the planet. Thus, in order to ensure this, the utility of the proposed framework is demonstrated by selecting the following objective variables which are of significance to the villagers:

1. Overall Profit
2. Total Runoff Areas

Following decision variables are used to assess their effects on above mentioned objective variables:

1. Amount of tillage
2. Multi-cropping

(**Note:** *The significance of these variables is explained in the following section*)

The results presented are specific to the case of the village selected due to the intricacies of various social factors. The main objective of the authors is to demonstrate the efficacy of the proposed framework in order to provide decision support for a designer to identify variables that impact the outcome of a wicked problem which has a plethora of variables under consideration.

This helps us to identify the core of the problem and frame the wicked problems with maximum fidelity. The levels of decision variables are kept as per the judgements and experiences of the authors and may vary for every case. The system is simulated multiple times to understand the system's behavior and interaction between variables in order to make decisions on the levels of decision variables to assess profit and total runoff areas.

3.4.2 System Dynamics – Results and Analysis (Step 2; Figure 3.5)

Values of Input Variables to System Dynamics Model (Data Obtained from SunMoksha Pvt. Ltd.) are presented in Table 1.

The stock and flow diagram of the System Dynamics model is shown in Figure 3.6. System is simulated in order to analyze the interaction between variables. The magnitude/level of the decision variables is changed in order to understand the effects of each decision variable on the objective variables. The total area available is kept as the highest value considering that we have the entire area for utilization.

The control volume is defined by the thematic areas which a designer selects during the Step 1 of the framework. With the thematic areas defined (in our case Forestry, Agriculture, and Water) we define the external boundaries of the control system. The drivers for these

Table 3.1: Values for Input Variables of the System Dynamics Model

Input Parameter	**Value**
Storage Parameter	6 facilities
Transportation	50 vehicles
Amount of Tillage	5000 acres
Cost of chemical fertilizer	310 rupees per acre
Cost of organic fertilizers	150 rupees per acre
Multi-cropping	Normal – 2.5 crops/year – (Variable)
Number of post processing equipment	50 machines
Irrigation cost	5000 rupees per acre
Animal Labor Cost	33 rupees per acre
Cost of Seeds	2000 rupees per acre
Manure cost	150 rupees per acre
Human Labor Cost	5000 rupees per acre
Electricity cost	181 rupees per acre
Diesel Cost	520 rupees per acre
Total Area	20000 acres
Number of canals	5 canals
Amount of rainfall per month	1800 mm per annum
Number of Rain Water Harvesting systems	10 systems

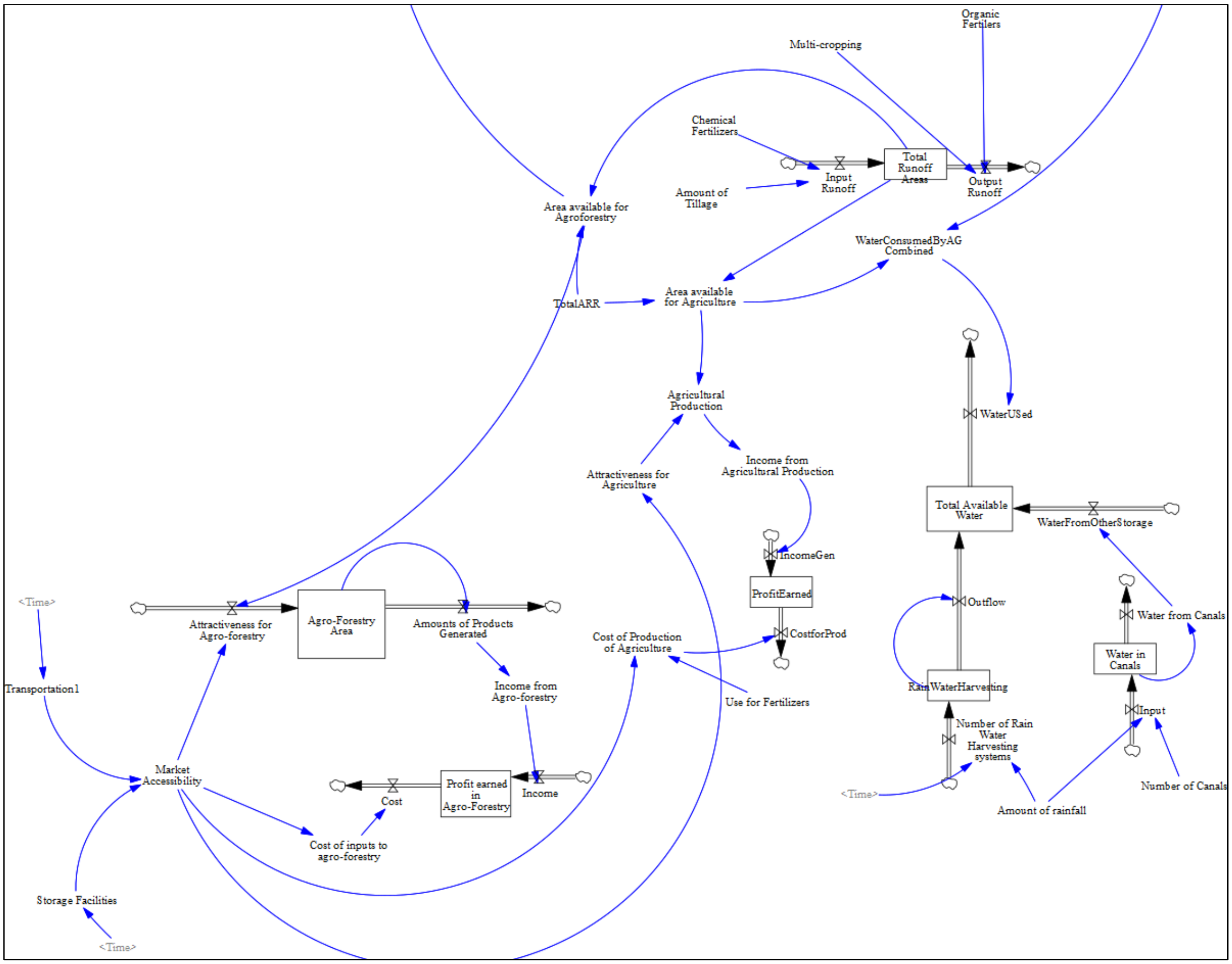

Figure 3.6: Stock and Flow Diagram of the Kantashol Village

thematic areas enable a designer to mark the internal boundaries of the control volume. The consensus on this decision anchors with the experiences and judgements taken during interpretive analysis through Dilemma Triangle Method.

While framing wicked problems we do not model the uncertainties, instead observe, and analyze them through simulation of systems. This analysis is then used to make modifications by iterating through the Dilemma Triangle Method and System Dynamics model to frame wicked problems. The insights gleaned through the simulations can then be utilized to synthesize information and mitigate uncertainties to identify the correct size of the problem, concentrate on core of the wickedness subsequently aiding in framing the wicked problems.

Results of System Dynamics Modelling

The effect of amount of tillage on profit earned and the total runoff areas is presented in Figure 3.7 and Figure 3.8. The effect of multi cropping on profit earned and total runoff areas is presented in Figure 3.9 and Figure 3.10. The results presented are with low tillage, medium tillage, and high tillage. The value of multi-cropping and the rest of the variables are maintained at medium level.

While considering the multi cropping decision variable, we consider the maximum tillage being done in order to be sure that the effect of multi cropping overcomes tillage. Two independent variables are considered in the System Dynamics model. The first being amount of tillage and the second being the multi cropping. The effects of these variables are assessed on two objective variables, namely, the total profit earned and total runoff areas.

Initially the system is simulated the by changing the level of amount of tillage. Three levels/cases are considered. One when no tillage is done, another when we simulate moderate tillage and the third with high levels of tillage. As seen through Figure 3.7, the amount of tillage does not drastically affect the overall profits. The profits remain relatively equal for all the levels of tillage. Thus, the progress of the village does not hamper due to the amount of tillage. However, when we assess the effects of the amount of tillage on the runoff areas, we find that the higher the amount of tillage the larger are the runoff areas.

Runoff is a deleterious factor for the productivity of the agricultural land in the long term. Moreover, the soil loses its fertility which affects the Planet. Larger run-off areas results in the

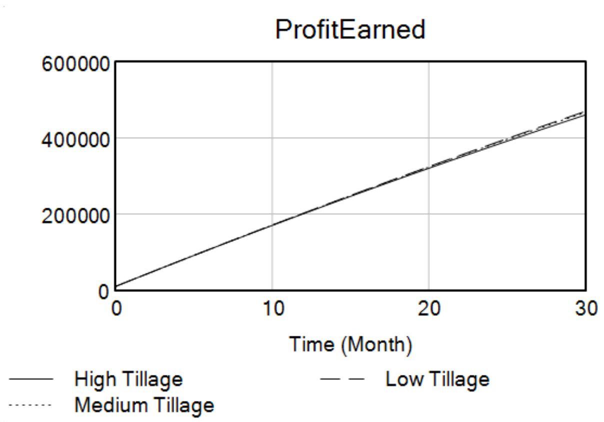

Figure 3.7: Effect of Amount of Tillage on Profit Earned

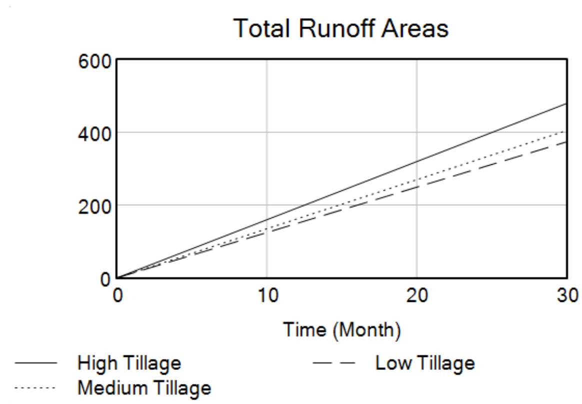

Figure 3.8: Effect of Amount of Tillage on Total Run off Areas

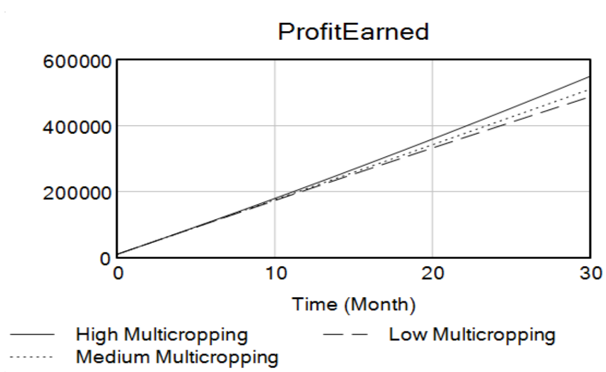

Figure 3.9: Effect of Multi Cropping on Profit Earned

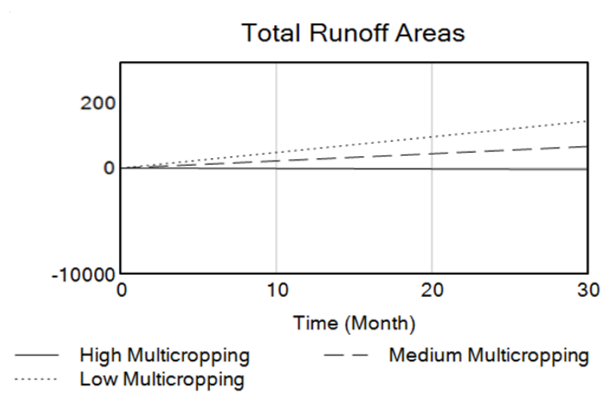

Figure 3.10: Effect of Multi Cropping on Total Run off Areas

decrease in the level of water absorption levels in the soil. To avoid any bias in the results, other factors are maintained at their moderate level during the simulation to analyze the system behavior with respect to change in the quantity of tillage. With the results as shown in Figure

3.7 and Figure 3.8, it is evident that the amount of tillage has a significant impact on the total run off areas. Further, in order to assess the impact of multi-cropping on

the entire system model, we simulate the system by changing the intensity of the levels of multi-cropping. The impact of change in multi cropping is assessed on two factors, namely, the 'overall profit' and the 'total runoff'. The results are presented in Figure 3.9 and Figure 3.10.

Analyzing the behavior of the simulated system, it is observed that with the increase in multi-cropping there is an increase in the overall profit. Further, on comparing Figure 3.7 and Figure 3.9 it is observed that the magnitude of decrease in profit due to high tillage is less than that of the magnitude of increase in profits by increasing the levels of multi cropping.

The effect of multi-cropping on runoff areas is observed through the results presented in Figure 3.10. With increase in the multi cropping, the runoff areas decreases. While simulating the system for multi cropping decision variable the levels of amount of tillage are kept at the highest levels in order to confirm the efficacy of multi cropping for increase in profits and decrease in runoff areas. Through the behavior of the simulated systems, following conclusions with respect to the decision variables and the objective variables are derived as shown in Table 2. The effect of interaction between decision variables and objective variables considered to demonstrate the framework is summarized in Table 2.

Table 3.2: Effect of Decision Variables on Objective Variable

Decision Variables	**Objective Variables**	
	Overall Profit	Total Run off areas
Amount of Tillage (↑)	Slightly decreases	Increases considerably
Multi Cropping (↑)	Increases	Decreases considerably

With the results obtained by simulating the system and the explanation provided it is identified that the multi-cropping decision variable impacts the outcome. This helps us to identify the core of the problem by eliminating the amount of tillage decision variable. With the results through systems dynamics and the justification provided above, multi-cropping is a significant decision variable while the amount of tillage, though a contributing variable to us is not of significance to the model and, thus we eliminate it. Through this we identify the correct size of the problem by identifying the variables which have significant impact on the model/outcome. The utility of this framework comes along with the framing of the wicked problem through evidence based structured process by converting heuristics into insights.

Framing the problem has great significance in order to get robust solutions especially when dealing with wicked socio-economic-technical problems that involve many variables (quantitative and qualitative) that need to be dealt with. Problem framing requires correctly identifying the problem by simulating the system in order to understand its behavior with respect to the variables of interest. In order to model a system and arrive at robust solutions it becomes important to initially frame the wicked problems with high fidelity. The efficacy of the solutions proposed for wicked problems depends on how well the problem is framed.

To achieve this, it becomes important to gain insight on variables which affect the problem to identify the core of the problem where wickedness lies so that it is modelled to provide decision support to the decision makers. This allows us to redefine the `Focus` and `Issues` in the Dilemma Triangle Method in order to understand the exact problem and frame it by revisiting the initial Dilemma Triangle construct (Step 1; Figure 3.5) that is developed in the initial stages of the framework. Further, Dilemma Triangle constructed in the initial phase is modified in order to enhance it with the insights gained on the interaction between variables through the behavior of the simulated system.

3.4.3 Modified Dilemma Triangle (Step 3; Figure 3.5)

After gaining insight to behavior of the simulated system through System Dynamics as shown in Step 2 of the framework presented in Figure 3.5, those insights are utilized to modify the Dilemma Triangle in order to frame the wicked problem. These insights are discussed in the Section 3.2.1

The `Drivers` of the Dilemma Triangle remain the same as before: People, Planet and Prosperity. We modify the `Focus` (if required) and `Issues` (as required) based on the results of system dynamics model. Heuristics are converted into insights to frame a wicked problem through the integration of evidentiary and interpretative analysis.

a. People

FOCUS: To improve the quality of life of people by providing them adequate nutritious food, water for various purposes, and promote sustainable agroforestry for the sustainable development of the village.

ISSUES

1. Lack of crop diversification and multi-cropping practices in agriculture leading to limited production of nutritious food.
2. Absence of policies to promote agroforestry and strict government policies to access the forests.
3. Unavailability of water due to lack of facilities and improper management in agricultural practices.

b. Planet

FOCUS: To preserve forest and its biodiversity, prevent runoff, preserve fertility of the agricultural land, and utilize water resources wisely.

ISSUES

1. Lack of multi-cropping practices in agriculture contributes to the soil losing its fertility and restricting water to be soaked in the ground leading to the unavailability and depletion of ground water in a village.
2. Overdependence on agroforestry and lack of sustainable agricultural practices.
3. Excessive depletion of water due to mono cropping in agriculture requiring high tillage which enables the soil to lose its fertility.

c. Prosperity

FOCUS: To enhance the disposable income for the farmers, to ensure progress in the income of villagers, and to provide reliable and feasible sources of water for varied purposes.

ISSUES

1. Lack of multi-cropping practices in agriculture. Monocropping results in higher tillage of land which affects the water holding capacity of the soil as well as degrading its fertility.
2. Excessive use of chemical fertilizers to enhance the production in mono cropping resulting in degradation of land in the long term and thus affecting prosperity.
3. Unavailability of water due to limited access and unstable power supply accompanied by prevailing monocropping practices leading to affect the quality of soil and water holding capacity of soil.

With the modified Focus and Issues in the dilemma triangle we now proceed with the further steps of dilemma triangle method. The Tension Matrix is shown in Table 3. In the context of Tension Matrix Tensions are enumerated (which are denoted by 'T' in Table 3) to demonstrate the framework and then proceed to find dilemmas which helps a designer frame the problem through the proposed framework.

The efficacy of the framework is observed from the Dilemmas identified. The Dilemmas are presented in Table 4. The correct size of the problem and the associated Dilemmas using insights gained from system behavior through system dynamics are identified. For example, instead of concentrating on the amount of tillage to prevent runoff areas which was initially considered by most of the stakeholders, we could reframe it through identifying the correct alternatives by studying its interaction with other variables. Agriculture requires tillage and thus taking steps to stop it affects the agriculture adversely.

TABLE 3.3: TENSION MATRIX *(T – Tension, D – Dependent)*

	Lack of multi cropping	Absence of policies to promote agroforestry/ Strict policies to access forest	Unavailability of water – improper agricultural practices	Limited production	Overdependence on agroforestry	Excessive depletion of water	Higher tillage	Excessive chemical fertilisers	Unavailabi-lity of water
Higher tillage					T1	D			

Excessive chemical fertilisers	T2	T3		T4	T5		T6		
Unavailability of water			T7		T8	T9	T10		
Limited production	D	D	T 11			T12	T13	T14	T15
Overdependence on agroforestry	D	T16	T17				T18		
Excessive depletion of water									
Lack of multi cropping			D						
Absence of policies to			T19						

promote agroforestry/Strict policies to access forest										
Unavailability of water – improper agricultural practices										

Table 3.4: Description of Dilemmas			
Sr. No.	**Dilemma- *Framing Wicked Problems***	**Dilemma arrived from**	**Justification**
1	How can we promote multi-cropping by reducing the use of chemical fertilizers and promoting organic fertilizers by ensuring decent production levels?	T2 and T4	Through the systems behavior it is evident that multi-cropping has a significant role to play for the planet and prosperity of the village. Further, through simulation we realize that organic fertilizers play an important role in the development of planet. Monocropping comes with excessive use of chemical fertilizers (to increase production and gain profits) to match with the nutrients that soil has lost. Thus, it is important to promote multi-cropping to reduce the use of chemical fertilizers whilst ensuring that the production through agriculture is decent.
2	How can we ensure higher production and progress of the village by promoting eco-	T4 and T11	The use of fertilizers in mono cropping not only affects the overall progress of the village but also degrades the planet. However, villagers are unaware about efficient and proper methods of agriculture. With the introduction of new methods there are high chances of exploitation of natural resources like

	friendly methods of agriculture without exploiting the available water?		water. Thus, it is very important to ensure that we preserve the planet and also help people and ensure prosperity by adopting eco-friendly methods of agriculture.
3	How can we reduce the overdependence of farmers on agroforestry and enable them to get decent production and sources of production through agricultural practices without making them overly	T1, T5, T15, T17	Reducing overdependence of agroforestry comes with excessive agriculture. Increased participation in agriculture results in exploitation of resources and degradation of planet due to excessive monocropping, high tillage, improper use of water, etc. Excessive monocropping and high tillage results in loosening of the soil's water holding capacity which results in waste of available water. Thus, it is important to reduce the overdependence of farmers whilst also ensuring that their participation in agriculture does not harms the planet.

	relied on chemical fertilisers?		

It is known that excessive tillage causes increased runoff areas which hampers the water absorbing capacity of the soil Through the framework, it is understood that it is the agricultural practices which are more important to Focus than emphasizing directly on stopping tillage which is not a viable solution knowing its necessity in agriculture. The dilemmas which anchor with framing the wicked problem are presented in Table 4. Further, knowing its interaction with other variables helps to eliminate the variable in modelling the system further to identify the dilemmas/frame the problems. This demonstrates the efficacy of the framework provided.

Thus, through the proposed framework, a designer can:

1. Convert heuristics into insights to frame a wicked problem through the integration of evidentiary and interpretative analysis.
2. Understand the interaction between variables through behavior of the simulated system by the virtue of System Dynamics.
3. Identify the correct size of the problem by eliminating the variables which do not impact the outcome/model and are not relevant to the wicked problem.

These three aspects together help in efficiently framing of the wicked problem.

In this chapter the key issues accounted are italicized in the ten characteristics of wicked problem recognized by Rittel and Weber [6] which is discussed in Section 1. We summarize how we address these key issues by the application of our framework in Table 5.

3.5 DISCUSSION

In this section discussion on the bottlenecks, verification of the framework and few limitations observed while applying it to frame a wicked problem are detailed.

The bottlenecks in the framework include undertaking interpretive analysis through Dilemma Triangle Method. This requires judgement and heuristics to be incorporated at the initial stage of the analysis. This includes exploring and interpreting data from the perspective of individuals which requires a designer to have experience with Dilemma Triangle Method. Further, the iteration from System Dynamics model back to Dilemma Triangle Method requires analysis of interaction of variables to modify the initial exercise of the Dilemma Triangle Method. This requires a designer to move back and forth and iterate in order to identify the wickedness of the problem.

Table 3.5: Summary of Key Issues Addressed

Wicked Problem Characteristics	**Contextualization**
There is no definitive formulation of wicked problems.	The framework provides a holistic approach to frame and identify correct size of wicked problems.

They are difficult to frame.	
Wicked problems have no stopping rule.	An opportunity to iterate through the framework. This augments the combination of interpretive and evidentiary analysis to understand the nature of the problem. This allows a designer to do better with every iteration until reaching a certain point. By iterating, a designer can identify the finer details and relationships between variables which result in appropriate framing of wicked problem.
Solutions to wicked problems are not true or false, but good or bad.	Through the combination of Dilemma Triangle Method and System Dynamics we approach to getting better insights for every iteration we have, enabling us to frame problems correctly which is the first step to find better solutions.
There is no immediate and no ultimate test of a good solution to a wicked problem.	Through the framework designers have the opportunity to involve human intelligence and cognitive abilities which augment computational capabilities in order to enhance the fidelity of framing wicked problems. Through this we give a designer a frame to enhance test-ability.
There are numerous explanations for a wicked problem.	With this framework the problem becomes concrete assisting designers to identify the focus without making foregone conclusions about prior explanations.

The planner has no right to be wrong.	Through the framework there is an opportunity for designers to analyze the dilemmas and the causal relationships between different elements (variables). Through the framework a designer can carry out analysis to interpret and compare a variety of conflicting scenarios resulting in improvement of the characteristics and 'corroboration' of results with the wickedness of the problem. Thus, through the framework there is an opportunity to 'improve' rather than aiming to find the truth.

Verification of the Proposed Framework: In Steps 1, 2, and 3 as shown in Figure 3.5, and further discussed in detail in Section 3.4, we gain input from the SunMoksha team of experts. After demonstrating the efficacy of the framework for the test problem, we confirm the results obtained through the proposed framework with the experts in SunMoksha Team as well as the villagers. It is informed that more such insights can be gained by modifying the thematic areas and modifying the System Dynamics model. The verification of the proposed framework comes through multiple trials and experimental simulations. These experimental trials are carried out with multiple scenarios and verified accordingly in accordance with the SunMoksha team and the authors. The validation of the framework is yet to be carried out.

Limitations of the Proposed Framework: The framework is based on the assumption that the Dilemma Triangle Method is executed rationally without any bias. Further, it is assumed that all the stakeholders act rationally which ideally should be the case, however, it might not happen. Further, the evolution of variables is not considered in this work, and it is assumed that variables are proportional with respect to time. This brings us with the following limitations:

i. The efficacy of the framework depends on the expertise, judgement, and interpretations of humans. Inclusion of bias by human cognitive capabilities make the results obtained through the framework futile and it negatively impacts the framing of wicked problems.
ii. System Dynamics used to simulate the system through *predefined data*.

What is the impact of a predefined set of rules and data? When we create a model (even at an initial level) we are explicitly defining the relations between different variables. For example, in stock and flow diagram we specify the causal relations between variables and define it through equations, which is essentially training the model on how it should behave. This implies that we are training the variables on how they should behave with any change which is done through simulations or changing the equations.

3.6 SYNOPSIS OF CHAPTER 3

RG.2 How can wicked problems be effectively framed through the combination of interpretative and evidentiary analysis, incorporating human-computer synergies?

In response to the question, in this chapter, a framework to frame wicked problems is proposed through interpretative analysis by utilizing the Dilemma Triangle Method and evidentiary analysis through the System Dynamics modelling. With the proposed framework, an opportunity for designers to frame any wicked problem is provided. The framework is designed to convert heuristics that a designer has in the initial phase, to insights by the analysis of interaction between variables through systems simulation by using System Dynamics. The framework consists of three stages, the first being the Dilemma Triangle Method, (Step 1; Figure 3.5) which is used to identify the `Drivers` and define the `Focus` of these `Drivers`. At this stage we do not identify the dilemmas. The second stage (Step 2; Figure 3.5) includes analyzing the system behavior and the variable interaction through System Dynamics. Through this stage we get insights on behavior of the simulated system and the interaction between variables. This analysis enables us to identify variables which impact wicked problems and thus identify the correct size of the problem by identifying its core. Further, the third stage (Step 3; Figure 3.5) is revisiting the Dilemma Triangle constructed in Step 1 and modifying it with the insights gained through System Dynamics. This allows us to modify the tensions based on insights gained through the behavior of the simulated system and then identify dilemmas to frame wicked problems.

To illustrate the efficacy of the framework, an example of Kantashol village is used that is considered a wicked problem, which is in Jharkhand, India. In Kantashol, villagers are overdependent on forestry for their livelihood and the practice of agriculture is limited due to multiple reasons including lack of water, insufficient yields due to improper methods of agriculture etc. Villagers have overexploited the ground water, and there is excessive runoff due to excessive tillage for agriculture. There are three thematic areas that need to be considered, namely; Forestry, Agriculture, and Water. This is classified as a wicked problem due to the incomplete and conflicting information available, conflicting perspectives of the villagers in Kantashol, multiple explanations of the existing problems in the village, and the existence of multiple tensions between the `Drivers`. Initially we attain heuristics from the expertise of the SunMoksha team and experiences of the villagers. We define `Drivers`, `Focus` for each `Driver`, and `Issues` for each `Drivers` through the heuristics attained.

Further, we create a System Dynamics model to convert the heuristics into insights through the qualitative and quantitative data from SunMoksha team. The results we get from System Dynamics model help us to gather insight on the interaction among variables. This is demonstrated in Section 3.5 by eliminating the ‘amount of tillage’ decision variable by showing its interaction with ‘multi-cropping’ decision variable. It is demonstrated through the System Dynamics modelling that ‘multi-cropping’ is a significant variable that affects the problem, and which suppresses the negative effects caused by ‘amount of tillage’. Moreover, it is demonstrated that its effect on the objective variables, namely, ‘total runoff areas’ and ‘overall profit’ is insignificant in comparison to the ‘multi-cropping’ variable. Thus, we identify the variables which impact the core of the problem leading us to gain insights on the correct size of the problem. Thus, through the proposed framework, a designer can:

iv. Convert heuristics into insights to frame a wicked problem through the integration of evidentiary and interpretative analysis.
v. Understand the interaction between variables through behavior of the simulated system by the virtue of System Dynamics.
vi. Identify the correct size of the problem by eliminating the variables which do not impact the outcome/model, are not relevant to the wicked problem, or not under a designer’s control.

The utility of the proposed framework for framing a wicked problem are:

iv. Enhancing the synergy between human-computer interaction by allowing human-in-the -loop to enhance framing of the wicked problem through computational capabilities and human abilities.
v. Enables a designer to convert the heuristics into insights through a structured process.

vi. Perfect integration of interpretative and evidentiary analysis to frame the wicked problems which forms the fundamental step of modelling a public policy.

The proposed framework can be extended in various domains to frame wicked problems. In the following discussion the possibility of application of the proposed framework is expanded in different research areas for varied problems. Problems (i) and (ii) are presented by NSF-NASA in a workshop with an objective to provide the context to a designer on wicked problems and extreme design problems whereas Problem (iii) anchors in the way forward as described in Chapter 6.

i. ***Revitalizing Rural Communities that Depend on One Industry***

Many regions in industrialized countries:

- Remain isolated and lack access to goods, services, and resources that are vital to thriving.
- Often suffer from single-industry economic dependencies that limit growth opportunities and upward, both individually and regionally.

Goal: For rural communities to thrive and become resilient outside of single industry infrastructure.

ii. ***Democratizing Medical Supply Delivery***

- Current medical supply transport is plagued by losses, including a relatively high temperature excursion rate.
- Delivery includes a diverse supply chain.
- Access to medical supplies is limited in some communities in the U.S. and abroad.

- Current U.S. regulatory and liability frameworks do not account for medical transport by non-traditional vehicles such as a drone.

iii. ***Environmental Justice in Oklahoma City***

Urban atmospheric pollution is driven by policy decisions negotiated by competing interests including local and regional governments, industry, and citizen's groups. Policy goals may greatly impact exposure to pollutants harmful to health and wellbeing, exemplified in extrema by historic redlining of minority groups in dense clusters near industrial emitters, generating urban canyon effects which further trap already significant pollutants with known health impacts. As the environmental sensor revolution quietly takes place in our urban centers, an opportunity arises to inject cyber system infrastructure data into extant social decision-making frameworks which shape our physical future by helping planners make better informed design decisions for uncertain policy futures. We have identified a sample region in Oklahoma City which meets the historic context above and presents a growth opportunity for a prototype framework to integrate with current policy-`Drivers`, including growth of sensing infrastructure in the region.

CHAPTER 4

EVOLVING CYBER-PHYSICAL-SOCIAL SYSTEMS (E-CPSS): A PERSPECTIVE FROM DECISION BASED DESIGN SUPPORT

Research Gap(s):

RG2 - What is the fundamental knowledge required in terms of key characteristics, requirements, and principles underlying design of Evolving CPSS, and how do they impact decision support in complex situations?

Objective:

i. Explore and establish the relationship between fundamental and application sides of the E-CPSS paradigm by exploring the design characteristics and requirements. ***(O2)***

ii. Establish a list of requirements of E-CPSS characteristics to guide designers. ***(O3)***

iii. Put-forth a cognitive map for E-CPSS.***(O4)***

New Knowledge:

i. Establishing the definition of E-CPSS and providing a fundamental model to address decision-making through E-CPSS. ***(K2)***

ii. Establishing the characteristics and outlining requirements that designers should consider to design an E-CPSS.***(K3)***

iii. A fundamental and foundational cognitive map to design E-CPSS. ***(K4)***

The study of human behavioral and cognitive features along with the inclusion of social and cultural aspects in the social environment necessitates the inclusion of social space in systems. This is addressed through the shift of cyber-physical systems to cyber-physical-social systems (CPSS) by incorporating the social space as an independent entity which interact with the cyber and physical space. The inclusion of social entity primarily focuses on the aspects of Human Reliability Assessment (HRA) to incorporate human cognition, coordination, and other behavioral factors; where the social space makes it continuously evolve owing to the nature of human behavioral characteristics and the social environment. However, the idea of evolving CPSS (E-CPSS) is relatively unexplored and a new paradigm to delve into. This involves assessing the impact of time on the CPSS and further addressing the dynamic social environment to support decision making in E-CPSS. The underlying gap that lies in this paradigm anchor in providing a well-constructed and thought-out definition of CPSS and E-CPSS and furthering it to provide the characteristics of an E-CPSS along with the generalized requirements that a designer should consider for addressing decision making in E-CPSS.

Evolution of intelligent systems is a key characteristic of systems that enables them to self-adapt and self-organize based on external changes in the environment to achieve a steady state. The evolving nature of such systems plays a critical role to enable dynamic changes in the structure and behavior of entities and their relationships to carry out an efficient decision-making process. CPSS is a system of interconnected cyber, physical, and social spaces with an aim to make intelligent and interactive human centric systems to deal with complex situations by adapting a decentralized decision-making process. An E-CPSS refers to a system that undergoes continuous change and improvement over time through self-adaptation and self-organization in response to changing stakeholder requirements and environmental factors.

Through this chapter the focus is to establish the foundation for E-CPSS by outlining essential requirements for achieving key attributes in terms of function, behavior and structure of the system. The research gap that is addressed through this chapter is:

What is the fundamental knowledge required in terms of key characteristics, requirements, and principles underlying design of Evolving CPSS, and how do they impact decision support in complex situations?

The contribution emphasizes recognizing CPSS's evolving nature and the crucial role of social entity in the decision support. The key features and attributes of E-CPSS are detailed with an objective to demonstrate their utility in the decision-making process in a complex environment. Furthering this, proposed is a cognitive map of an E-CPSS depicting the identified attributes and their importance in the overall decision-making process owing to provide designers an overview of the evolutionary mechanism that the system goes through to achieve the steady state when subjected to an uncertain and a complex environment.

Keywords: Cyber-Physical-Social System (CPSS), Decision Support, Design, Evolution, Human Reliability Assessment (HRA), Self-Organization, Self-Adaptation, Social Environment

GLOSSARY

1. Decision-Support: Leveraging methods to aid decision-makers in enhancing system's performance, adapting to changes, and effectively managing risks throughout the system's lifecycle.
2. Cyber-Physical-Social Spaces: Integrated environment where the cyber, physical, and social entities intersect and interact.
3. Interactions: Refers to the dynamic relationships, exchanges and interactions such as communication, coordination, and influence that occur among various components within the system.
4. Autodidactic systems: Autodidactic systems refer to systems that have the ability to learn and acquire knowledge autonomously, without explicit programming or external intervention.
5. Stakeholders: Stakeholders are individuals, groups, or entities that have an interest or concern in the success and outcomes of the CPSS
6. Endogenous social space: It involves the internal or inherent social dynamics and interactions that emerge from the system itself.
7. Exogenous social space: It involves the external influences on the social dynamics of the system that may not be directly controlled or governed by the system itself.
8. System Behavior: Dynamic and observable aspects of how an E-CPSS operates and responds to various stimuli or inputs over time.
9. System Structure: The architecture, composition, and arrangement of the components that make up the system.

10. Scenario Recognition: The process of identifying and understanding different scenarios or situations by analyzing data from various sources to identify patterns and anomalies that indicate the occurrence of specific scenarios
11. Self-adaptability: The ability of a system to adjust or modify its behavior, structure, or function autonomously in response to changing conditions or requirements to adapt to the changing scenario and context in a dynamic environment.
12. Self-organizability: The ability of the system to autonomously and collaboratively organize its components and resources to achieve desired system behavior or function.
13. Collective decision-making: The process by which decisions are made collaboratively and often distributed among multiple entities, subsystems, or stakeholders within the system.

4.1 FRAME OF REFERENCE

In the last decade, an increased discussion on the role of the social element in engineered systems is seen. The profound effect of human behavior and cognition on systems whether they are manufacturing systems, automotive systems, or social systems, is evident [100,101]. The research in Industry 4.0 and the utility derived from it reached its zenith in the last decade, ushering in Industry 5.0 which "provides a vision of industry that aims beyond efficiency and productivity as the sole goal, and reinforces the role and the contribution of industry to society." Through the study of Industry 5.0 paradigm, the aim is to complement the existing Industry 4.0 paradigm by highlighting research and innovation as drivers for a transition to a sustainable, human-centric and resilient industry. Industry 5.0 strategically redirects its focus from shareholders to stakeholders, prioritizing the values, objectives, and preferences of people [102]. This shift allows the fifth Industrial Revolution to adopt a human-centric approach, transcending the sole consideration of business perspectives. This heralds a monumental shift in the design paradigm of cyber-physical systems (CPS) to cyber-physical-social systems (CPSS) which are characterized by the incorporation of human behavioral, cognition, social, and cultural aspects along with the external environment.

4.1.1 Integrating Human Factors

A CPS combines computation, sensing, communication within the cyber entities and actuation of the physical systems to accomplish time sensitive functions with varying levels of interaction between the cyber and physical entities and the associated environment [103]. The CPSS differs from CPS by inclusion of social entities as an independent space. The CPSS provides a new perspective of the expanding relationships and interaction among humans, computers, and the physical environment in the context of human behaviors. In CPSS, the social system is an independent entity construct which can interact with the cyber- and physical- worlds where the humans act as resources (sensors in providing information, services, knowledge, etc.) or consumers (end-users of information, services, knowledge, etc.) [104].

There are various other paradigms that incorporate the human element, namely, Internet of People, Human in the loop, Cyber-Physical-Social Thinking, Social Internet of things, etc. These paradigms fail to incorporate human "factors" such as cognition, coordination, motivation, emotions, behaviors, and societal norms, etc. which leads into the existence of the cyber-physical-social system paradigm. The critical distinction may be modeled by the class of techniques called "Human Reliability Assessments" [105].

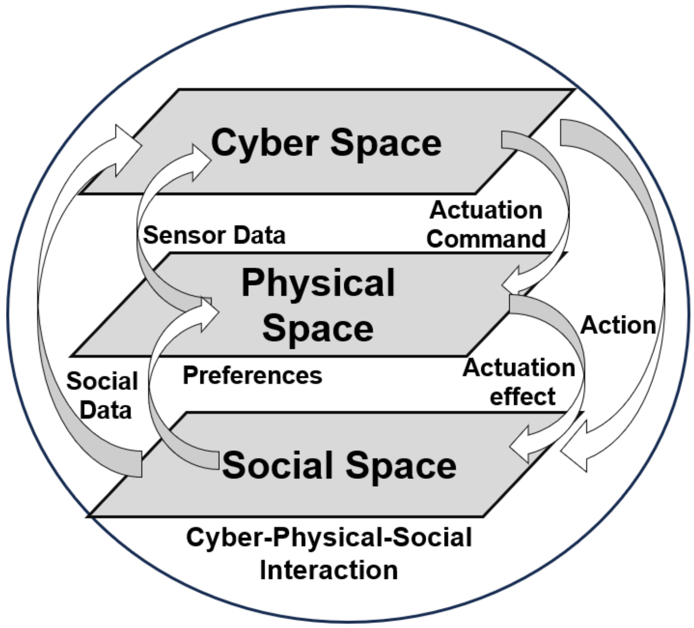

Figure 4.1 Cyber-Physical-Social Spaces and Interactions

4.1.2 Addressing the Entities: Cyber, Physical, and Social

The CPSS is the integration of cyber, physical, and social spaces. The cyber space is pivotal for system computation and control, fostering the generation, analysis, and exchange of data within and between the social and physical spaces. It facilitates seamless interaction and data sharing among social agents, incorporating human features like judgment, experience, cognition, decision-making, and behavior. This makes it evident that the introduction of social space introduces an untapped dimension of integrative mental space comprising the human knowledge, sociocultural elements, and mental capabilities [106].

The physical space anchors in the actuation medium as well a source of data producing entities through tangible entities that exist in the physical world such as sensors, robots, infrastructures, devices, etc. Preferences emanating from the social domain, specifically through social agents, serve as an informational source that triggers actions in the physical space. For a CPSS to exist each space must interact with all other spaces as binaries: Physical-Social, Physical-Cyber, and Cyber-Social. These interactions define a CPSS in terms of its functionality subject to relationship analysis to deliver high quality services for stakeholders [107]. This mirrors human decision-making between conflicting and contradicting objectives in terms of varied goals, preferences, opinions, beliefs, etc. and its effect on the underlying problem structures.

4.1.3 E-CPSS Foundations – Objectives and Organization

System designers must take into consideration the evolution and the integration of the social space in complex systems such as the CPSS. The evolving nature of the systems anchor in the time varying environment. The primary idea behind evolution of systems is the change in the information at any time instance. These instances at any particular time period are referred to as ‘states’ [108]. There can be any number of states in an evolutionary cycle and its selection depends on the exploration the designer desires which aligns with the system design. Every system changes over time in order to adapt itself to the dynamic environment. In this chapter, the focus is on addressing the relatively underexplored paradigm of evolving CPSS (E-CPSS). With the advent of real time decision making, it is necessary to develop predictive capabilities in order to understand the past states of the system to speculate on the future states. This will enable the system designers to identify the evolving states of the system and speculate on the future to make better informed decisions.

The significance of evolution from the design perspective comes from the necessity of systems to be responsive to the social environment. Designers must speculate on and inform a system about how it should respond to a change in the external stimulus. The growing complexities of intelligent systems makes it critical that the systems be contextually aware. As an autodidactic system gathers context data it may intelligently reassess its own behavior in response to a constantly changing environment with minimal human intervention [109].

In this chapter the objective is to establish foundations of an E-CPSS by laying emphasis on the social space: stakeholders holding individual preferences, objectives, and goals. The interests and objectives of stakeholders are constantly changing with the progression of time (states), influenced by the external environment. The problem here is threefold: (a) a CPSS will evolve, (b) a social entity will evolve and induce change in the CPSS, (c) interests in social space constantly change with states. This paradigm will enable designers to design effective systems in engineering, manufacturing, automotive, etc. while also addressing grand challenges such as environmental justice, climate adaptation, equitable allocation of resources, food insecurity, healthcare, etc.

The foundational knowledge with respect to E-CPSS is relatively underreported in the state of art. To advance fundamental research from the perspective of design systems engineering, it is imperative to carry out a systematic study to explore, identify, and analyze the characteristics/attributes of an E-CPSS. Further, it is critical to identify promising frameworks, methods, and approaches which can be adapted to E-CPSS, further establishing the computational capabilities. The goal of this systematized review is to establish a of requirements list to guide system designers in effectively addressing the complexities and demands inherent to E-CPSS. The organization of this chapter is discussed in the following section, elucidating the connectivity between various sections of the chapter to bring value to the study of designing an E-CPSS from the decision-making perspective.

4.1.4 Organization of Chapter 4

The objectives through this systematized, exploratory study presented through this chapter are:

i. Explore and establish the relationship among fundamental and application sides of an E-CPSS paradigm by exploring the design characteristics and requirements.
ii. Identify the gaps in the current state of art of E-CPSS.
iii. Establish a list of requirements of E-CPSS characteristics to guide designers.
iv. Define CPSS and E-CPSS
v. Put-forth a cognitive map for E-CPSS

A systemized review of the literature is conducted focusing on the design aspects of an E-CPSS. This comprehensive review comprises of a broad array of scholarly works concerning CPSS evolution, systems design, modeling paradigms, system characteristics, Function, Behavior, and Structure (FBS) ontology, and decision-support mechanisms. Employing a methodical approach, the authors navigated various databases and publications, adhering to predefined protocols and keywords such as CPSS, evolution, decision-support, computational strategies, and evolving characteristics to identify and analyze pertinent literature. Through this examination, the authors synthesize insights into the dynamic nature of the E-CPSS, elucidating the intricate interplay between system components, evolving functionalities, various modeling approaches and decision- making mechanisms through a cognitive map. Key characteristics of evolving CPSS are presented and decision-support frameworks essential for addressing dynamic changes within these complex systems are delineated. Through the review, the authors have leveraged the existing knowledge of the literature to present further avenues for exploration and put-forth critical research findings.

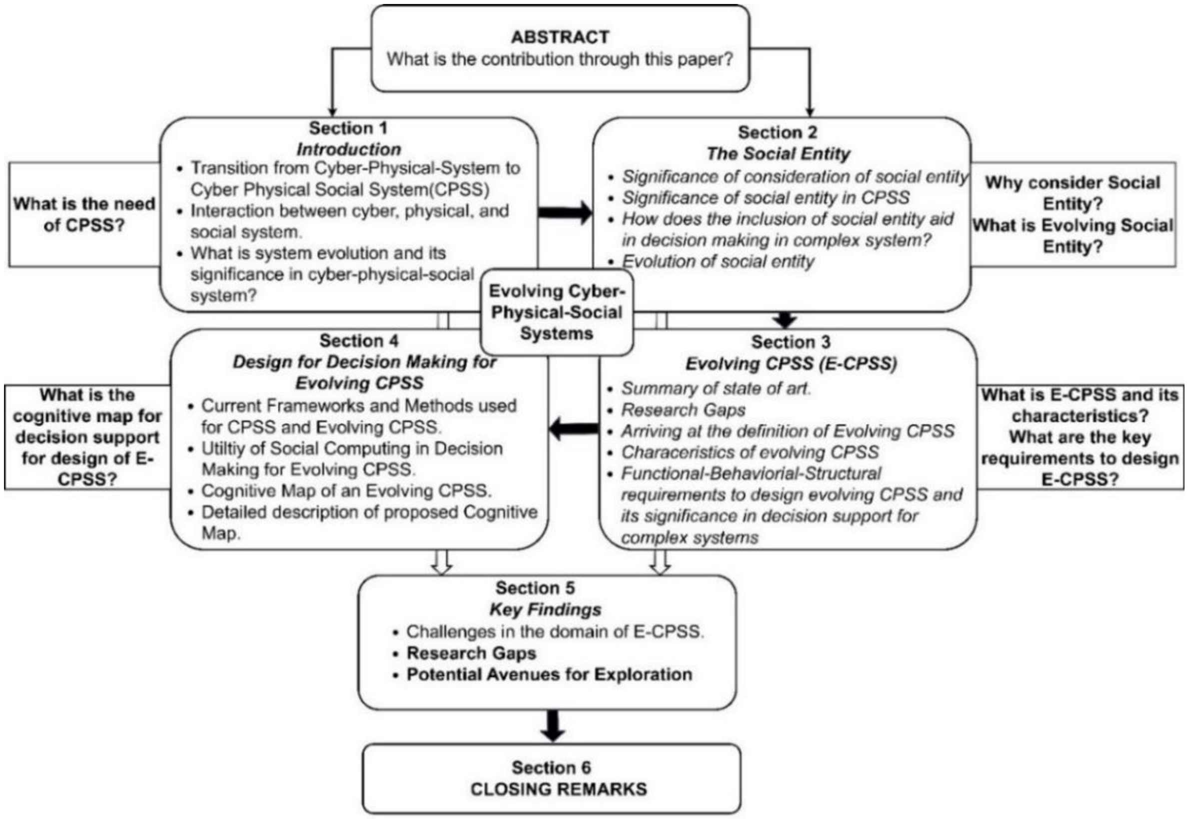

Figure 4.2 Organization of the chapter

The organization of the Chapter is summarized in Figure 4.2. The objective in Section 4.1 is to provide the readers the foundational knowledge required to understand the necessity of CPSS and the hierarchical evolution of CPS to CPSS. Further, through Section 4.1 a brief but essential knowledge required about evolution of systems is provided which further delves into understanding the fundamental idea of E-CPSS. Followed by the preceding as described, the objectives are explicitly mentioned. In Section 4.2, a detailed description of social space is provided to address its significance to E-CPSS. Furtherthe utility is of social space is addressed for decision support in complex systems and how social entities evolve. Section 4.3 deals with the E-CPSS state of art and the most significant research questions discussed in the literature as we arrive at a definition of E-CPSS. This is followed by establishing the characteristics of E-CPSS as shown in Table 4.3 and further classified into a detailed requirements list based on Function, Behavior, and Structure. This is followed by Section 4.4 where utility of design for E-CPSS decision-making is presented where the focus is on promising frameworks, models, and methods based on the state of art. This is followed by proposing the cognitive map of an E-CPSS based on the knowledge attained from the state of art and the characteristics and the requirement list established in Section 4.4. In Section 4.5 the goal is on presenting the key findings and describe a few challenges in modeling E-CPSS. This is followed by closing remarks which describe the takeaways for the paradigm of decision-based design support for E-CPSS.

4.2 SOCIAL ENTITY IN THE E-CPSS

The social space in CPSS is relatively less explored than the cyber and physical spaces. This includes defining the social entity, addressing the role of and effect of social entity on the system, as well as advances in the computational capabilities to address the social entities. There are various systems like Internet of People (IoP), Human in the Loop (HiTLCPS), SIoT (Social Internet of Things), etc. [101, 105] which incorporates the role of a social entity, however, the role of human in the social entity is not clear. In the context of integration of human in the decision-making process, HiTLCPS [110, 111] is a promising framework, however, there are problems in identifying the role of human. Factors such as human cognition, intents, emotions, behavioral predictability, etc. are loosely fixed in the HiTLCPSS framework. Thus arises the human reliability assessment (HRA) “the science disciplines dealing with the human factor assessment, especially in view from its reliability” as defined by Jirgl and co-authors [105]. This principle entails the scope of examining human performance in diverse operational scenarios, modeling human behavior, and evaluating its reliability and other attributes.

Factors such as trust, coordination, cooperation, and confidence form an integral part of the social space and human behavioral factors which are relatively unexplored in the state of art. Trust is a vital component to incorporate in systems [112] and its significance is discussed by Gharib. et. al. [113] through an example of ambient assisted living. They discuss remotely extracting and analyzing elderly patients' health status to facilitate the ease of communication and information transfer between physicians and the patients. However, for the development and implementation of such systems, trust between different stakeholders becomes a crucial factor. The need for trust arises when human and social agents depend on one another, as risks entail in the presence of dependencies between different human (agents) [114]. Apart from the preceding discussion of incorporation of human cognition and behavioral aspects, the social space also consists of sociocultural elements and the and social environment.

In the field of social science, Turner [115] defines a social interaction as a "situation where the behaviors of one actor is consciously reorganized by, and influence the behaviors of, another actor, and vice versa which can be extended to the process whereby there is a mutual influence between behaviors of multiple individuals". In accordance with the social action theory proposed by Weber [116], a social interaction involves accommodating the actions of others which, in essence, requires a compassionate comprehension of varied interests, perspectives, opinions, and behaviors. This forms the fundamental aspect of the significance of social space. Most of the social problems like environmental justice, equitable distribution of resources, and healthcare involve of humans as the core of social space and in the external social environment. For problems like these it is critical to interpret and understand the behavioral and cognitive aspects in the forms of preferences, opinions, interests, and beliefs of various stakeholders involved and incorporate these elements in the systems design.

4.2.1 Utility of Social Entity in Decision Support

Complex systems like a CPSS are characterized by the presence of multiple stakeholders having varied goals, interests, preferences, etc. which affect any given problem at both component level and system level. The presence of social space including the human behavioral and cognitive aspects as well as the social environment makes the system dynamic. Addressing them in a complex system enables designers to obtain robust design solutions. Models are abstractions of reality. For social problems, normal optimization methods will often fail due to the presence of confusing and conflicting information [117]. This is further exacerbated with the presence of multiple actors (in the forms of stakeholders). It is critical to consider the interests of the number of possible stakeholders to arrive at design options which are satisficing rather than optimal. The inclusion of social entity allows for the decision makers to interpret and analyze various scenarios for the social problems which will accommodate the preferences of maximum number of actors involved. It further allows consideration of diverse preferences in order to explore a broad range of feasible solutions for any given problem. Further, the inclusion of social entity enables the real time feedback through the interaction among the cyber-physical and social spaces. This enables in understanding the changing conditions, sharing information, and make decision support more dynamic and responsive further aiding to address evolving social entities.

The social space is categorized into endogenous social space and exogenous social space that helps in differentiating social space while at the same time addressing it holistically. The details of this categorization are as follows.

*(**Note:** The assimilation of endogenous and exogeneous social space is problem specific however a general description is provided below.)*

i. Endogenous Social Space

Endogenous social space refers to the internal dynamics of a social system, shaped by the interactions, behaviors, cognitions, and relationships that emerge organically from within the system. This space is self-contained, with its development and transformation being driven by the inherent characteristics and actions of its members. In the context of CPSS, endogenous social space can be influenced by several factors:

*(**Note:** These are few of the factors to provide a basic understanding)*

- **Cognition and Behavior:** The collective and individual cognitive processes, decision-making behaviors, and psychological factors of the individuals within the system play a crucial role. This includes how trust, privacy concerns, and social norms evolve from the interactions within the system.
- **Internal Communication and Interaction Patterns:** The ways in which information is shared, how communication channels are established, and the nature of interactions among participants within the system contribute to the shaping of the endogenous social space.

- **Social Structures and Hierarchies:** The internal organization, including social hierarchies, group formations, and networks, influences how individuals and groups interact within the CPSS.
- **Cultural and Normative Practices:** Shared values, beliefs, and practices that develop over time within the system guide behavior and expectations, further shaping the endogenous social space.

ii. Exogenous Social Space

Exogenous social space, on the other hand, encompasses the external factors and influences that impact the social dynamics of a system. These influences are outside the direct control of the system's internal mechanisms and can significantly affect its structure, functionality, and evolution. In the realm of CPSS, the exogenous social space is influenced by:

*(**Note:** These are few of the factors to provide a basic understanding)*

- **Technological Advancements:** New technologies and platforms can alter how individuals interact with the CPSS and with each other, introducing new behaviors and expectations.
- **Socioeconomic Factors:** Economic conditions, education levels, and access to resources outside the system can influence participation within the CPSS and impact its social dynamics.
- **Regulatory and Policy Environments**: Laws, regulations, and policies that govern data privacy, security, and usage can affect how the system operates and how individuals engage with it.

- **Cultural and Social Norms:** Broader societal values and norms can shape the expectations and behaviors of individuals within the CPSS, influencing how it functions and evolves.
- **Global Events:** Incidents such as pandemics, economic crises, and political changes can have profound effects on social behaviors and attitudes, impacting the CPSS indirectly.

iii. Integrating Endogenous and Exogenous Perspectives

To fully understand a CPSS, it is crucial to examine both endogenous and exogenous social spaces. The interaction between these spaces can reveal how internal dynamics are influenced by external pressures and how the system adapts to or resists these influences. This integrated approach provides a comprehensive view of the CPSS, highlighting the complexity of interactions and the multifaceted nature of social spaces within these systems.

By considering both endogenous and exogenous factors, researchers and practitioners can design more effective, resilient, and adaptable CPSS that are responsive to both the internal needs of the community and the external environmental pressures. This holistic perspective is essential for fostering sustainable development and innovation in CPSS design and implementation.

The inclusion of a social entity as accounting human behavioral and cognitive factors with Human Reliability Assessment adds to making realistic decisions by incorporating interpretive analysis to enable realistic decisions in CPSS. For example; understanding the role of social entities and their objectives, preferences, etc. is a critical factor in designing policies which further aids in decision support. The term "social entity" is utilized with multiple interpretations and encompasses a wide spectrum of meanings in today's academic and research literature. A few examples of social entities (or related considerations) within current publications on CPSS are shown in Table 4.1. In Table 4.1, the columns describe the example of the social entity in various papers reviewed along with their corresponding papers number from the list of references.

TABLE 4.1: Examples of social entities

Social Entity	Paper
Workers and technicians and their interaction with one another and the CPSS object, that is, the Cobot	[100]
Interaction with inhabitants and other CPSS objects	[106]
Users and policy makers - plant in charge, consumers	[118]
Humans and their associated interaction with cobots. Feature of personalization and socialization imbibed in smart devices	[120]
Human beings as sensors and users of technology. Social media as source of information on traffic routes	[121]
Humans interacting and using the social network	[123]
Self-organizing capability through obstacle detection and collision prevention	[126]
Self-organizing capability according to environment.	[127]
Situation, humans as data sources	[129]
Customer and Community engagement	[140]
Social behaviour and social organizations	[145]

Passengers, drivers, government	[153]
Learning and training of workers, Change in roles and objectives of workers due to introduction of CPS.	[155]
Nurses, patients, doctors	[166]

While the preceding discussion in the Section 4.2 is focused on the social space from the perspective of the human cognition and behavioral factors, now some insights are provided on the integral part of social space that is the social environment under consideration. When considering social space from the endogenous and exogenous aspects; cognition and behavioral factors can be examined within the endogenous social space, while the social environment of the CPSS under consideration can be viewed as the exogenous social space, as shown in Figure 4.3. The external environment that evolves with time is a critical consideration for the robust design options for complex problems in CPSS. This can be seen in Figure 4.3 when the system changes from State 1 to State n. These considerations empower designers to assess the impacts of social entities on the system by incorporating both exogenous and endogenous social spaces. This approach fulfills the requirement of integrating system design with a holistic social space. The external continually transforming environment exerts a dynamic influence on the intricate dynamics of CPSS. Understanding and adapting to these external changes are critical in exploring robust design strategies that can effectively address the multifaceted challenges encountered within the CPSS. As the external environment shifts and adapts, it introduces both opportunities and threats to the stability and functionality of CPSS. Navigating these external forces strategically becomes paramount consideration for the social space.

4.2.2 Evolution in Social Space

As indicated in Section 4.2. A, social entity is dynamic, that is, it changes with time. Human cognitive and behavioral aspects undergo constant evolution in response to the requirements, preferences, and changing goals, influenced by the changing circumstances in the external social environment. The importance of taking evolution into account is to guide the consideration of how systems should adjust in response to changes in external stimuli. This forms the fundamental aspect to design E-CPSS. For example, in Figure 4.4, the effect of dynamic social endogenous and exogeneous environment is presented.

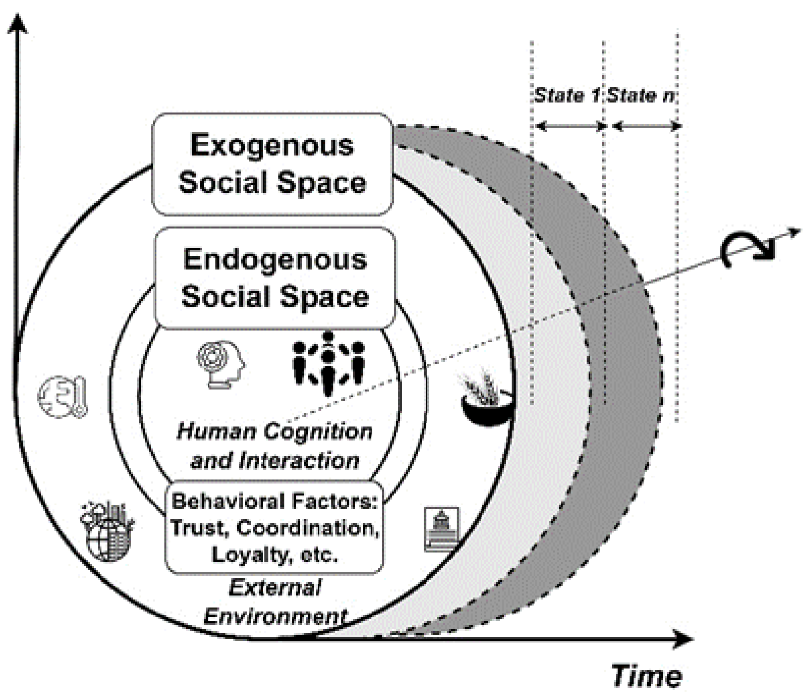

Figure 4.3 Holistic Social Space of CPSS

The inherent interconnected problem structure and different entities is sshown by network structures on the decision strategies. As the problems change through different states, the network structure evolves which inherently makes the decision strategies differ with respect to states of time. As the problem progresses across various states, designers need to recognize distinct decision strategies that are grounded in the diverse network structure corresponding to each facet of the problem, as illustrated in Figure 4.4. For example, Problem 1 will have a different set of network structures that includes uniqueness in terms of interaction of stakeholders and the social environment. This leads to the design of system that anchors in Decision Strategy 1. However, at a different states of time, as shown in Figure 4.4, Problem 1 that evolves to Problem 2 has a different decision strategy owing to a different network structure. Thus, the design of E-CPSS caters to the requirement of being self-adaptive. This anchors in the consideration of different aspects of social spaces as shown in Figure 4.3. Thus, the evolution of CPSS in general and the social entity in particular is critical for the decision support of the systems and provide predictive abilities to system design by leveraging the ability to make real time decisions for complex systems.

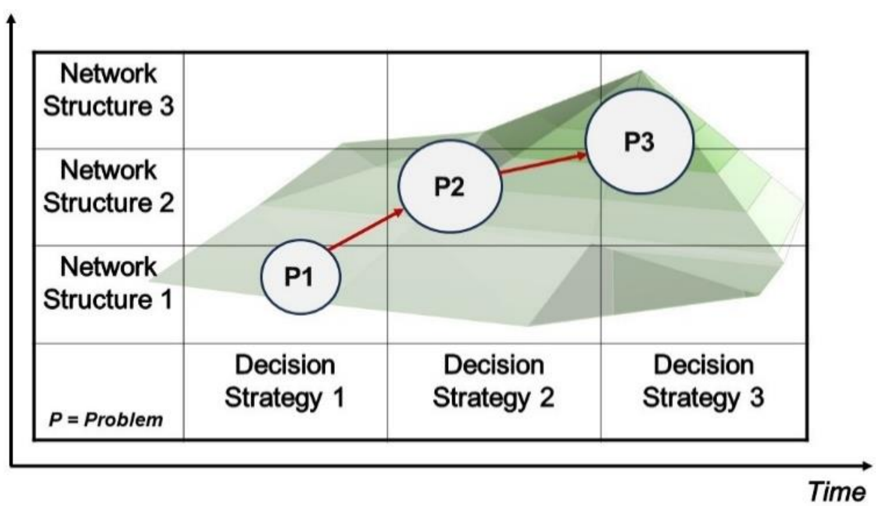

Figure 4.4 Evolving Problem Structures and Decision Strategies

	EVOLVING CHARACTERISTICS											MODELING AND FRAMEWORKS					CAUSES OF EVOLUTION					APPROACH/ METHODS					Social Entity	Evolut ion
Paper	Self-Adaptability	Self-Organisability	Robustness	Resilience	Emergence	Scalability	Flexibility	Interoperability	Decentralised Decision	Modularity	Context Awareness	Parallel World	ACP	Knowledge Automation	Force Field Control	MAPE-K	Changing Stakeholder Needs	Feedback/Closed Loop	Uncertainity	Risks/Disruptions	Unwanted Emergent Needs	Artificial Societies	Parallel Execution	Human Dynamics	Scenario Based	Social Computing		
Abera (2020)	*		*	*	*	*		*			*	*					*	*	*			*	*		*	*	Y	N
Wang (2010)	*	*	*		*		*	*			*																Y	N
Zhou (2022)	*		*	*	*	*		*							*			*			*						Y	N
Glasson (1989)	*		*		*																						Y	Y
Wang (2007)	*	*		*	*	*	*	*		*	*	*	*				*	*		*	*	*	*	*	*	*	Y	N
Yilma (2021)			*	*	*	*		*									*	*	*				*	*	*		Y	N
Zhang (2018)	*		*		*			*		*	*	*	*	*								*	*	*	*	*		
Rao (2022)	*		*	*	*	*	*	*			*	*					*	*						*	*	*	Y	Y
Smirnov (2015)		*	*					*			*														*		Y	Y
Assunta (2017)					*			*			*						*	*							*		Y	Y
Singh (2012)					*	*		*	*		*			*				*							*		Y	Y
Dao (2014)	*	*	*	*	*		*	*			*			*				*						*	*		Y	N
Peijun (2022)	*				*			*				*											*	*	*	*	Y	Y
Yin (2020)	*				*			*			*			*													Y	Y
Neves (2009)	*	*	*		*			*			*			*			*		*					*			Y	N
Zeadally (2019)	*	*	*		*						*																Y	N
Barbosa (2015)	*	*			*			*			*	ADACOR													*		N	Y
Pasandideh (2022)	*		*	*	*			*	*	*	*	*					*	*			*		*	*	*	*	Y	N
Hussein (2015)	*	*			*		*	*		*	*						*	*				*		*	*	*	Y	Y
Paulo (2016)		*			*		*	*				ADACOR					*	*		*							Y	Y
Francalanza (2018)	*		*		*			*			*	Azure Cloud Framework															N	Y
Agostinho (2015)	*											MBSE					*			*				*			Y	Y
Bhandari (2023)	*			*													*		*	*				*			Y	Y
Gero (2004)	*	*	*		*			*	*		*	FBS Design Model					*	*									N	Y
Lombardi (2022)	*	*			*			*	*		*																N	Y
Madni (2018)	*	*			*		*	*	*	*	*	CPHS					*								*		Y	Y
Arghandeh (2016)				*			*				*	STAMP							*	*				*			Y	Y
Colabianchi (2021)	*			*			*	*		*	*	Resilience assesment							*	*					*		N	Y
Dorst (2005)						*				*		FBS Design Model															N	N
Lee (1999)								*			*	Information Modeling													*		N	N
Tu (2001)							*	*			*	Stepping Structure IM					*							*	*		Y	Y
Smirnov (2014)		*			*			*	*		*													*			Y	Y
Wang (2021)a	*	*			*			*				VAR + GPR					*	*		*				*	*	*	Y	Y
Wang (2021)b	*				*			*			*						*	*		*				*	*	*	Y	Y
Bagozi (2021)	*		*	*	*			*	*	*	*						*	*									N	Y
Li (2018)		*			*			*	*			HBRGM						*		*	*			*			Y	Y
Van Beek (2022)			*	*	*			*	*		*	Group Value Concept						*	*	*	*			*			Y	Y
Ye (2022)				*	*			*	*		*		*				*	*	*	*	*		*	*	*		Y	Y
Sanderson (2019)	*		*	*	*		*	*	*		*	FBS Design Model						*		*							N	Y
Mukhopadhyay (2020)	*			*	*		*	*	*		*	GAN					*	*		*				*	*		Y	Y
Liu (2011)	*	*	*		*	*	*	*	*		*	Self-Synchornisation						*	*	*				*	*		Y	Y
Dustdar (2018)	*				*			*									*											
Gharib (2017)				*				*	*								*	*		*	*			*	*		Y	Y
Bennaceur (2019)	*				*		*	*			*													*	*		Y	Y
Gero (2003)	*			*	*		*	*	*		*	FBS Design Model					*	*	*					*	*		Y	Y
Chavhan (2019)	*			*	*			*	*	*	*	Agent Based Models						*							*			
Xiong (2015)	*		*	*	*			*	*		*						*						*	*	*		Y	Y
Tyszberowicz (2020)	*		*	*	*	*		*	*			Digital Twin						*			*		*				Y	Y
Leon (2012)	*	*			*	*	*	*	*		*	Agent Based Model												*	*	*		
Li (2006)	*				*		*	*	*		*	Agent Based Model					*		*	*	*	*		*	*			
Bucchiarone (2020)	*		*	*	*		*	*	*		*	Collective Adaptation															Y	Y
Mirta (2023)	*	*		*	*	*					*	Collective Adaptation					*	*	*		*			*	*	*	Y	N
Estrada-Jimenez (2021)	*	*			*	*	*	*	*																			
Angelo (2017)	*		*	*				*	*		*					*											N	Y
Xue (2023)	*	*	*		*	*	*	*	*		*							*	*		*	*	*		*	*	Y	Y
Li (2023)		*	*	*	*			*	*		*	Social Force Model													*		Y	N

4.3 EVOLVING CPSS

4.3.1 The State of Art and the Foundational Insights for an E-CPSS

In Table 2, the key findings and supporting references based on the systemized review process of the literature is presented. The goal is to provide foundational insights on an E-CPSS by discussing several factors and requirements that can help a designer design such systems. By furnishing a summary of the review, the research gaps in the state of art are identified that will be discussed in this section of the chapter. The findings are broadly classified into four categories, namely, Evolving characteristics, Modeling and Frameworks, Causes of Evolution and Approached/Methods. The evolving characteristics that are identified and summarized in this chapter are self-adaptability, self-organizability, resilience, robustness, flexibility, scalability, decentralized decision-making and emergent behavior. While these characteristics are defined in glossary, a detailed description of them in the context of E-CPSS is provided in Table 3, Section 4.3.2. To model such characteristics while designing an E-CPSS, potential models and frameworks are identified and categorized in Table 2. These models and frameworks are mainly ACP (Artificial societies, Computational experiments and Parallel execution), Parallel World, Knowledge Automation, Force Field Control and Mape-K and some models that do not fall in the above category are explicitly mentioned such as GAN (Genetic Adversial Networks), ADACOR (ADAptive holonic COntrol aRchitecture) and MBSE. Similarly, approaches and methods discussed in the state of art in context of the evolving nature of an E-CPSS are listed and categorized into Artificial societies, parallel execution, human dynamics, scenario-based, and social computing. Finally, the causes or the stimuli that brings about evolution in the system and for which the system needs to be designed are mentioned and these are mainly changing stakeholder needs, feedbacks, uncertainty, risks/disruptions and unwanted emergent needs. Based on the discussion in Section 4.2 highlighting the importance of the social space in bringing about evolution in the system, emphasis is made on the social entities and how systems evolve in response to the changing environment. Drawing from both, Table 2 and the literature review, the research gaps existing in the state of art are presented.

It can be inferred from Table 2 that among the various evolving characteristics identified and discussed; self-adaptability, interoperability, emergence, context awareness, robustness, resilience and decentralized decision making are addressed most frequently, leaving scope for exploration of other key characteristic such as self-adaptability, self-organizability, scalability and flexibility. With regards to the models and frameworks, the state of art lacks a uniform framework to model and design for E-CPSS and these include evolving characteristics in the system. This leads to establishing the first critical knowledge gap:

RG4.1. Lack of frameworks and models to design for evolving characteristics and the needs of all the stakeholders in an E-CPSS.

Cognition is an important capability of systems undergoing evolution to realize the system's current and evolving state. From table 2, it can be seen that the discussion of cognitive capabilities in the system is underexplored in the state of art which leads to the second research gap that is:

RG4.2. Lack of fundamental knowledge to realize collective advanced cognitive capabilities in a system causing evolution.

Changing stakeholder needs, feedback and interactions from social entities are inferred to be the most common factors responsible for causing evolving characteristics in the system which leaves the role of other factors in bringing about evolution underexplored. Additionally, the discussion of human dynamics and its role in bringing about evolution is insufficient in state of art which should be leveraged to explain the dynamic behavior in the system caused by the social entities. Additionally, a through discussion on different social integration strategies is missing in the state of art. This leads to the third and fourth research gaps as follows:

RG4.3. Role of social space and human dynamics in bringing about evolving characteristics in the system and the effect evolution has on the social entities.

RG4.4. Finding the different social integrations strategies to design for social dynamics in an E-CPSS.

In an E-CPSS, entities work in a synchronized manner to collectively adapt to the external environment. As a result of this adaptation, emergent behavior is observed that create uncertainties and risks for the system. It can be seen from Table 2 that the discussion in the area of collective adaptation and the corresponding uncertainties arising in the system is untapped which leads to the fifth research gap that is:

RG4.5. Dealing with uncertainties, disruptions, risks and emergent misbehavior as a result of collective adaptation and evolution.

The research gaps gathered after a thorough review of the state of art provide an area of enhancement in this field of fundamental research. These research gaps are summarized on the basis of the insights obtained from the Table 2 representing the sufficiency of various attributes in the state of art. The findings presented are used to address these research gaps (RG4.1 – RG4.5) and provide a depth to the current study on an E-CPSS. Drawing insights from the information presented in Table 2, definitions for CPSS and E-CPSS are provided in Section 4.3.2 These definitions take into account all the critical aspects derived from various papers and acknowledge the importance of social entities and evolution in complex systems. Additionally, we leverage the insights gathered from Table 2 to devise a cognitive map for the E-CPSS in Section 4.4 to explain its evolutionary mechanism when subjected to an uncertain environment and its evolving attributes.

4.3.2 Defining CPSS and E-CPSS

Humans, initially considered to be exterior entities of the system engaging with the CPS are now viewed as a diverse source of information. This trend has uncovered the importance of humans' centrality for the development of CPS which is recognized by the Human-in-the-Loop (HitL). Over the past decade, different researchers have used different terminologies to refer to this integration of the human aspect. For instance, a Cyber-Physical-Human System (CPHS), that is defined as "a system of interconnected systems 'talking' to each other across space and time, and allowing other systems, devices, and data streams to connect and disconnect" [118]. Alternatively, Human-cyber-physical system (HCPS) perceives human elements as separate physical entities, being controlled and coordinated by cyber systems. On the other hand, the term Social-Cyber-Physical-Systems (SCPS) is commonly used which are "complex socio-technical systems, in which human and technical aspects (CPS) are massively intertwined" [119]. Keeping the human not restricted only to a physical entity and taking into account the social intangibles has led to the existence of a separate 'social' space. The term "Social" carries a broader meaning as it reflects emotional, cognitive and behavioral aspects of a human. Moving forward towards a harmonious integration of social aspects, the CPSS research should take a holistic approach on the synergy between social aspects and CPS, looking for potential social integration strategies with a proper and uniform definition of the CPSS paradigm [120].

Abera and co-authors [100] define CPSS as “Cyber-Physical-Social system (CPSS) is a system comprising cyber, physical and social components, which exists or emerges through the interactions between those components. A CPSS comprises at least one physical component responsible for sensing and actuation, one cyber component for computations and one social component for actuating social functions” [100]. Humans in the social space of a CPSS act as both “sensors” and “users” of the system [121]. Humans act as “sensors” of the system by providing information consisting of preferences and needs with certain degree of personalization from every stakeholder. This information along with sensory information from the cyber-physical is further used by the system for understanding the context in which the decision has to take place to provide design solutions. On the other hand, humans act as “users” of the system as they tend to use the solutions provided by the system to formulate policies and take necessary action. Thus, looking for reliable integration strategies of the social space in a CPSS during the design process of a CPSS is vital. Concurrent designing and information modeling of a CPSS architecture is of immense importance along with social integration strategies to the designer to understand the stakeholder’s behavior, emotion and cognition before designing for CPSS to account for possible complexities and uncertainties that might arise in the system.

The inclusion of the social space in a CPS adds on complexity and uncertainty in the system which leads to bringing about dynamic changes in the structure and behavior of the system.

A CPSS operates and functions in an open, complex and a dynamic environment wherein uncertainties are a part of the process. The uncertainties in a system brought by system components and their corresponding environment can disrupt the functioning of the system thus compromising its performing capabilities. These uncertainties can be in the form of changing personal needs, preferences, external intended risks and unwanted emergent misbehavior. Integration of the social space allows for inclusion of the social entities and their perspectives and preferences in a decision-making process. As a result, the scope of uncertainties affecting the system state broadens. In response to this, the system must evolve over time by bringing about changes in its structure and behavior to adapt to these changes and achieve a steady state. Changing needs and preferences leads to the system evolving and adapting to the updated needs of the stakeholders to provide up to date design solutions. An E-CPSS has the capability to detect uncertainties and complexities and correspondingly adapt to the evolving environment mitigating and managing these uncertainties. This is done by bringing changes in the behavior and structure of the CPSS architecture and the associated network to achieve a steady state. In order to exhibit these changes, an E-CPSS exhibits various characteristics such as scalability, flexibility, resilience and interoperability. The literature is leveraged to explore and infer the key characteristics that are necessary for the system to evolve and adapt to the external environment to design an E-CPSS.

Some systems and entities with characteristics similar to that of an E-CPSS undergoing research in the state of art are “Collective Adaptive Systems (CAS)” and “Evolvable Systems”. These are a class of systems and entities that show evolutionary behavior over time by adapting to the external environment and accomplishing the objective that they are designed for [122, 123]. The entities in a CAS work in a synchronized manner to mitigate and manage any kind of uncertainty arising in the system. Though there exist various definitions of a CPSS, however a uniform definition of an E-CPSS is still lacking as research into the evolutionary and dynamic behavior of a CPSS is still in its infancy.

E-CPSS is defined as "*An E-CPSS is a system comprising of at least one cyber, physical and social component which exists or emerges due to the interaction between the tri-space leading to the changes in the behavior and structure over discrete states to achieve a defined function which may or may not change with respect to the states in an uncertain and a complex environment".* Thus, evolution in a CPSS is of immense significance, dealing with the rapidly evolving contexts by bringing about the necessary changes in the system's behavior and structure. We subscribe to the notion of decision-based design [156], which posits that the principal role of a designer is to make decisions. In this context, decision-based design serves as a framework for managing the complexities of E-CPSS, thus guiding designers in making better informed decisions that leverage the inherent self-adaptive and self-organizing characteristics of these systems. While we define the E-CPSS by incorporating knowledge about systems, evolution, and CPSS itself, the challenge remains for designers to understand and efficiently design systems by realizing the characteristics of the E-CPSS that help the system self-adapt and self-organize. These characteristics are discussed in detail in the following section as requirements list to design E-CPSS. The significant characteristics in the realization of designing an E-CPSS are shown in Table 4.3. In Table 4.3, the rows represent the characteristics that an E-CPSS must have which are identified from the review whereas the columns represent the description of each of these characteristics and their role in the decision-making process by the E-CPSS thereby helping the designer design such systems.

Through the review of the state of art, it is identified that a comprehensive study of the key characteristics of an E-CPSS is relatively unexplored. These features are critical in realizing evolving capabilities in cyber-physical-social systems to allow them to self-adapt and self-organize with respect to the changes in the external environment and cope up with the dynamic contexts.

TABLE 4.3: Characteristics of an E-CPSS

Characteristic	Description	Utility in decision-making
Scenario recognition	The process of identifying and understanding different scenarios or situations by analysing data from various sources, including sensors, social media, and other information streams, to identify patterns and anomalies that indicate the occurrence of specific scenarios	Multiple possible scenarios and their consequences are evaluated and the decision by an E-CPSS can be made allowing the system to adapt to the changing scenario
Context Awareness	The ability of the system to interpret the changes in the surrounding environment and adapt to it. Realization of the correct context	An E-CPSS shows context awareness by identifying the context in

	from the data and information sources is extremely important to interpret the needs and preferences of the stakeholders.	which the decision has to be made. In an evolving environment, the context updates dynamically allowing the system to evolve and adapt.
Organizability	The ability of the system to autonomously and collaboratively organize its components and resources to achieve desired system behavior or function.	System entities show structural and behavioral modification to organize themselves and perform functions to achieve the desired objectives.
Self-Adaptability	The ability of a system to adjust or modify its behavior, structure, or function autonomously in response to changing conditions or requirements to adapt to the changing scenario and context in a dynamic environment.	Systems having self-adaptability undergo a change in their behavior and structure to adapt to the external environment.
Modularity	Breaking down the system into smaller components that can be developed independently which can then be combined	Modular characteristics allow system entities to undergo structural

	or interconnected to form a larger CPSS architecture.	changes as part of the evolving process.
Scalability	The ability of a system to handle increased workloads, growing data volumes, or expanding requirements by scaling up or down while maintaining performance, functionality, and efficiency.	Interaction among the resources is managed on the basis of interaction between the system and the dynamic environment. E-CPSS carefully expends or saves resources based on the function.
Interoperability	The ability of systems entities to communicate, exchange information, and cooperate effectively in a seamless manner by the integration and interaction of heterogeneous technologies and subsystems allowing them to work together harmoniously to achieve common goals.	It ensures interaction and information sharing among system elements to allow the system to actively adapt to the evolving environment without compromising on system performance and helping in real time decision support
Robustness	The ability of a system to maintain stable and reliable performance even when	An E-CPSS subjected to a complex environment

	subjected to variations, uncertainties, disturbances, and changes that occur as the system evolves over time.	must possess robustness to manage the risks and disruptions with an objective to minimize the effect on decision-making process.
Resilience	The ability of a system to effectively adapt, recover, and continue effective functioning in the face of various challenges and disruptions that arise as the system evolves.	The ability to mitigate these external risks to allow the system to recover and perform effectively providing robust satisficing design solutions.
Emergent Behavior	Complex and unexpected system-level behavior that arise as a result of interactions and interdependencies among components within the system. These behaviors are not explicitly programmed or designed into the system but emerge as a consequence of the interactions and relationships among the components.	Unexpected emergent patterns can be harnessed for exploring new solutions and possibilities that might not be apparent through traditional, rule-based approaches.

Decentralized Decision Making	Decision-making approach wherein individual components or subsystems are empowered to make independent decisions based on local information and objectives. Each component has a degree of autonomy to react to its environment and make choices that support the system's goals.	This takes into consideration the individual decisions and interactions of all the nodes in the cyber, physical and social space allowing for improved resource allocation and distributed data handling.

Further as described in Table 3, it is critical for the systems to be have context awareness which inherently allows the designers to cater to the individual and emergent behaviors of the system. The significance of these characteristics is not restricted to only allowing the system to adapt to the environment but also aids the system in the decision-making process. Various models and frameworks can be used to design for realizing these characteristics in systems such as E-CPSS to ensure reliable system functionality. These models and frameworks to design for these characteristics based on computational capabilities of the system are shown in Figure 4.6. These can be further extended to design for an E-CPSS and complement the realization of these characteristics in an E-CPSS design. These characteristics are vital for systems designers to have a requirements list while designing an E-CPSS. These can be used to explain how the system can adapt, grow and continue to function effectively over time. By addressing these characteristics, organizations and institutions can ensure that they continue to meet evolving needs and maintain robust performance.

4.3.3 Requirements List to Design an E-CPSS from Functional, Behavioral, and Structural Perspectives

An E-CPSS undergoes behavioral and structural changes to adapt to the external environment and achieve the specific function that the system is designed for. Connecting the characteristics of a system with its function, behavioral and structural requirements for realizing these characteristics is essential for successful design and development of such systems. By categorizing the characteristics under the specific functional requirements, the system's purpose can be clearly established. Corresponding behavioral requirements can define how the system should adapt and respond to changing conditions to exhibit those characteristics effectively. Meanwhile structural requirements emphasize the structural characteristics of the system enabling it to evolve and reconfigure itself as required. Gero's Function-Behavior-Structure (FBS) framework [124] is a promising framework to study how the function, behavior and structure of an artefact interact and influence one another. The classification of the design requirements is done on the most recent and acceptable definition whose basis is formed by three classes of variables describing different aspects of a design object which can be extended to complex systems such an E-CPSS [124]:

1. **Function (F) Variables:** describe the teleology of the object, that is, what it is for.
2. **Behavior (B) Variables:** describe the attributes that are derived or expected to be derived from the structure (S) variables of the object, that is, what it does.

3. **Structure (S) Variables:** describe the components of the object and their relationships, that is, what it is.

The FBS framework of the situated world and the proposed definition devised by Gero is used as the basis for discussing and identifying key functional, behavioral and structural requirements of the system for realizing evolving attributes in an E-CPSS. This holistic approach ensures that the system's characteristics are not merely aspirational but are directly integrated into its design and development, enabling it to thrive and excel in real-world scenarios, even amid uncertainty and change. In Figure 4.5, the functional, behavioral and structural requirements are shown which are to be considered by a designer to design an E-CPSS. The significance of each characteristic and its alignment with the categorization is explained in the following section.

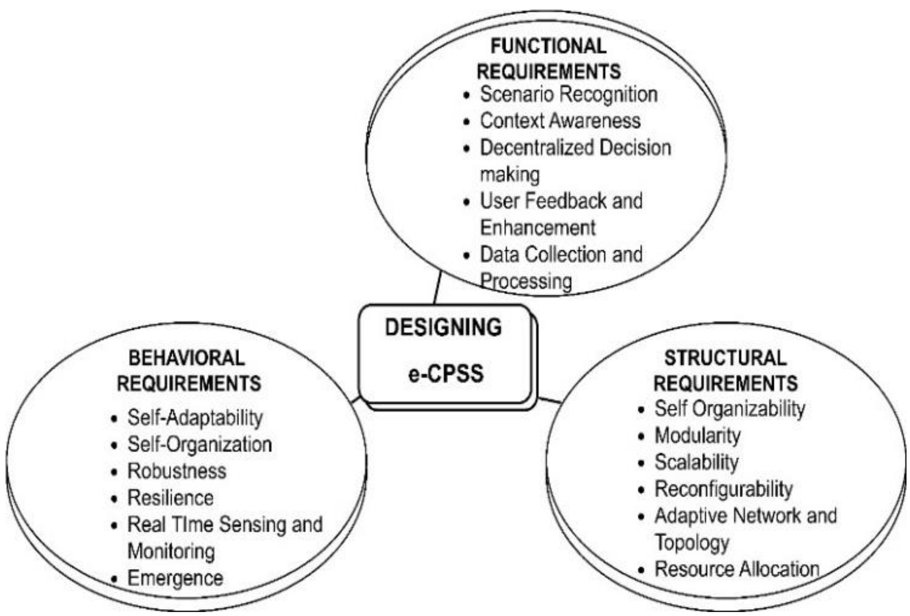

Figure 4.5. Classification of Design Requirements

1) Functional Requirements to Design E-CPSS

Functional requirements are the foundational requirements that a designer must consider while designing n E-CPSS as these would help establish and realize the purpose that the system would fulfill and is being designed for. This is moreover also critical to analyze the changes in the system characteristics with change in the system states over time. These requirements provide guidance to the designer to ensure that the system's core functions align with the evolving goals and attributes it needs to exhibit over time.

Scenario recognition is a critical functional requirement to ensure that the system recognizes the purpose it is designed for. Scenario recognition and context awareness allow recognition of specific scenarios and the context for decision-making on the basis of incoming information. Therefore, design rules and regulations for building frameworks to design for E-CPSS should be scenario-based [125]. Scenario based self-organization systems are discussed in the state of art with recognition of scenarios such as a disaster relief situation [126] and home cleaning robots [127]. Incoming data from physical and human sensors can be analyzed to look for patterns and understand the context and scenario [128]. Context awareness resulting in the realization of stakeholder needs can be used to design for E-CPSS by realizing the purpose it is to be designed for by considering needs of the social entities and comprehending the function of the system to be designed. A real-time complex event discovery platform for E-CPSS can be used to recognize and predict evolving scenarios [129]. Decentralized decision making followed by social interactions is another critical functional requirement a designer must consider to realize the true purpose of the system. A certain degree of autonomy to individual components or agents in an agent-based model allows the systems to make autonomous decisions based on changing conditions to fulfill the system's purpose. Evolving systems such as an ADACOR respond to internal and external changes by self-organizing and re-establishing system performance and functionality [130]. To provide the realistic scenario information, current and historical context information of entities is considered which is collected, analyzed and estimated to predict the realistic evolving scenario so that decentralized decisions can be taken [131]. Design of a context-aware E-CPSS carrying out a decentralized decision-making process utilizes interactions from the social entities to narrow down, expand or modify contextual factors to improve scenario recognition and system performance in subsequent iterations of the decision-making process [132]. Interactions with social entities in E-CPSS provides essential contextual information depending upon the objective of the stakeholder to realize and predict more precise function and purpose. The utility of social interaction in CPSS is shown in an airport situation using the Dynamic Social Structure Of Things (DSSOT) [133]. These functional requirements are essential for defining the core functionality of the E-CPSS and ensuring that it can fulfill its intended purpose while adapting to changing needs and environmental advancement.

2) Behavioral Requirements to Design E-CPSS

Behavioral requirements define the behavior of a system and are instrumental in realizing evolving characteristics, that is, attributes in a system. A designer should consider these requirements to design for key attributes in the system to allow the system to undergo behavioral changes to evolve and satisfy the function realized. Behavioral requirements provide the "how" by specifying how the system should behave and how does the designer want it to behave in various situations and changing conditions. The behavioral requirements are critical from the evolution standpoint as it allows the designer to predict and comprehend how evolutionary behavior affects system performance in the face of uncertainties and complexities in the environment. These requirements offer a roadmap for the dynamic behavior of the system, guiding it in adjusting its actions, making real-time decisions, and continuously adapting its responses to meet evolving goals and address uncertainties

The key requirements to realize evolutionary behavior in E-CPSS are self-adaptability and self-organizability. An E-CPSS subjected to an uncertain and a complex environment must self-adapt and self-organize in order to adapt to the changing environment with evolving scenarios and contexts. The cyber space and the network layer should support self-adaptation capabilities for ensuring reliable and predictable communication between the components of the E-CPSS and between the E-CPSS and its environment. The physical devices should adapt their operations based on context monitoring results and the self-assessment of their current state [134]. Social agents in the social space must exhibit self-organizability and self-adaptability against external disruptions and risks to mitigate and manage those risks. Designing for self-adaptability in E-CPSS also ensures providing agility and responsiveness [135]. Adaptation is also discussed between the humans and the CPS to reduce human cognitive load for decision making, back up malfunctions in CPS and respond to external disruptions [136]. The ability of an E-CPSS to evolve can be attributed to its property to deal with risks and disruptions. To deal with the same, an E-CPSS must possess and showcase robustness and resilience as its behavioral attributes. These act as key behavioral design requirements to ensure safe and efficient working of the system. Approaches such as DSSOT (Dynamic social structure of Things) are discussed in reference to E-CPSS that requires interaction with system entities and has a robust network to deal with heterogenous data that can potentially disrupt system functioning [133]. The concept of resilience is utilized in power systems and smart grids by ensuring system capabilities to evaluate grid operation exposed to unexpected extreme disturbances and hazards to leverage reliable and robust distribution of energy resources [137]. Agents in an E-CPSS collaborate with one another and collectively work in a decision-making process leading to emergent behavior in the system wherein the structure and behavior of the system is not what it is designed for, rather something unplanned and unprogrammed appears. Coordination with autonomy in a decision-making process may lead to providing design solutions different from the intended objective. Collective decision-making, synchronization and synergetic collaborations are important characteristics that should be realized by considering emergence as a behavioral requirement while designing for an E-CPSS as it allows for system to achieve goals that would be difficult to accomplish alone [138]. For instance, in a disaster response E-CPSS, emergency response teams might collaborate in unforeseen ways to effectively manage a crisis. In essence, behavioral requirements provide the flexibility and agility required for the system to evolve and maintain its performance in terms of fulfilling its objective, ensuring that it can navigate the complexities of an ever-changing environment while consistently embodying the desired characteristics. These requirements tie to the attributes that are derived or expected to be derived from the structural changes exhibited in an E-CPSS as a result of its evolutionary behavior over time.

3) Structural Requirements to Design E-CPSS

Structural requirements are indispensable in realizing evolving characteristics within a system as they define the underlying framework, architecture, and organization of the system, shaping its ability to adapt and evolve over time. These requirements will help the E-CPSS to realize the structural changes it must go through to evolve and satisfy the function realized. These requirements define the components and relationships among these components to support evolving attributes of the system effectively. Structural requirements dictate how the system can be realized to expand, modify, or reconfigure without causing disruptions, fostering its scalability and resilience in the face of uncertainties. Furthermore, they enable the integration of new technologies and components seamlessly, allowing the system to stay current and adaptable in an ever-changing environment.

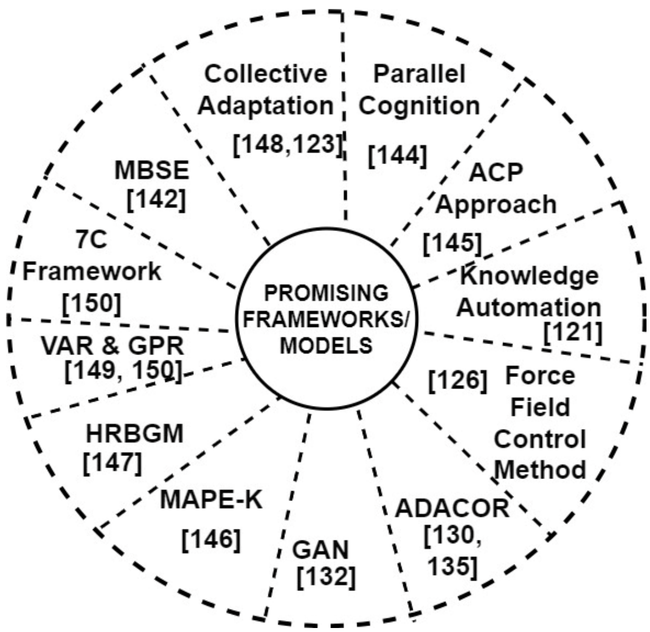

Figure 4.6 Promising Frameworks and Models

The key structural requirement to design for evolutionary behavior and address the changing relationships between the components in an E-CPSS is self-organizability that assumes the role of creating and maintaining a logical network structure on top of a dynamically changing physical structure topology wherein autonomous and dynamic structuring and re-structuring of components, context information and resources takes place [127]. Structural self-organizing mechanisms have to be considered as a key requirement to enable the system to deal with dynamic environment. Self-organization at various levels of the system allow for achieving evolutionary reconfigurable and modular systems such as in an ADACOR system [130]. Reconfigurability allows for the system to reconfigure and re-arrange its resources in response to external needs. On the other hand, modularity in complex systems allows for systems to add, remove, replace or reconfigure modules and resources to deal with the changing needs. Using the key requirement of designing for modular and reconfigurable characteristic, a designer can ensure the system portraying structural evolving attributes in the system architecture. Evolvable Assembly Systems (EAS) is a class of self-adaptive reconfigurable production systems that showcase modularity and reconfigurability wherein individual modules are able to cooperate with other modules creating new skills enhancing interoperability and emergent behavior to cope up with the constantly changing market demands and aims to promote efficient and economic production systems [135, 139]. Addition or removal of modules from the architecture of the system allows the system to showcase scalability to deal with the uncertain magnitude of data and uncertainties interacting with the system [133]. Scalability is seen as a key structural requirement to design for E-CPSS allowing it to deal with large amounts of heterogenous data and provide design solutions without comprising on computational complexity. Generative systems [140] and decentralized systems show scalable characteristics due to ubiquitous computing and connectivity [141]. Interoperability is another key structural requirement wherein entities in constant interaction with one another undergo structural changes collectively and in synchronization to adapt to the externally changing environment to accomplish system goals and objectives. Interoperability among network enterprises is an important requirement to keep network systems and architecture sustainable to deal with emerging challenges rising from evolution of enterprises and emerging information systems [142]. Adaptability in E-CPSS for resource and task allocation is a requirement designers must consider to leverage human cognitive abilities and respond to external disruptions by enabling synchronization between various entities of the E-CPSS. In essence, structural requirements serve as the foundation upon which the evolving characteristics are built, ensuring that the system's structure remains versatile and capable of fulfilling its evolving goals and attributes. A well-designed framework with the essential structural requirements allows the system to respond to changing user needs and seamlessly integrate new technologies ensuring the E-CPSS to evolve coherently and effectively over time.

4.4 E-CPSS COGNITIVE MAP FOR DECISION-MAKING

To coherently model an E-CPSS, it is critical to explore current frameworks and methods suggested use by others in CPSS and E-CPSS in the literature review. Ideally, models should describe and predict collective performance across different contexts of system behavior by realizing aspects along which different tasks, strategies, and network structures appear. Based on the state-of-the-art techniques found in the literature review, design tools for E-CPSS are summarized and coalesced. A selection of these in the context of modeling for evolving characteristics of a CPSS are discussed, explaining the decision-making process in an E-CPSS. The sample of techniques presented here are selected on the basis of a systemized form of review process wherein emphasis is laid on modeling techniques used to model and showcase evolving characteristics as mentioned in Table 2. The results of this sampling are summarized in Figure 4.6 with the perceived advantage of each framework with reference to designing for an E-CPSS. These frameworks, through their current utility as seen in the state of art have the potential to be leveraged to address E-CPSS. A more thorough discussion of each framework/model as presented in Figure 4.6 and its utility in the paradigm of E-CPSS can be found in the Appendix A.

To depict the E-CPSS' evolutionary mechanism and decision-making process in an uncertain and dynamic environment, a cognitive map of an E-CPSS based on context awareness is presented. A cognitive map is a mental representation or mental model created to organize and navigate understanding of physical spaces, environments, concepts, or information. It is a mental framework to store, process, and recall spatial or conceptual information to make sense of surroundings and make decisions. The cognitive map is a representation of an E-CPSS having evolving characteristics in the tri-space for sharing of information between the three spaces in real time. The various processes and working of the model are explained with the example of a water utility system wherein change in the environment external to the system brings about a change in user requirements causing the system to evolve. The interconnections of physical assets (pumps, pipes and valves), processes and social interactions (customer, community engagement, policy makers) with the emergence of digital technology adoption (software, data and network adaptation) are transforming water utilities into CPSSs for a collective decision-making process which is why it is chosen as an example to demonstrate the working of the cognitive map [143]. The interconnections and interdependencies between these components may enhance services leading to designing more robust systems and providing design solutions in application areas including water demand management, customer service and detection of contamination incidents to name a few.

The cognitive map shown in Figure 4.7 has been put-forth after understanding the entities and the interactions of the trispace as discussed in Section 4.1.2, the evolving characteristics as discussed in Table 3 and the requirements list as discussed in Section 4.3.4. The following subsections 4.4.1 and 4.4.2 discuss the features of the cognitive map, and the working of the cognitive map respectively.

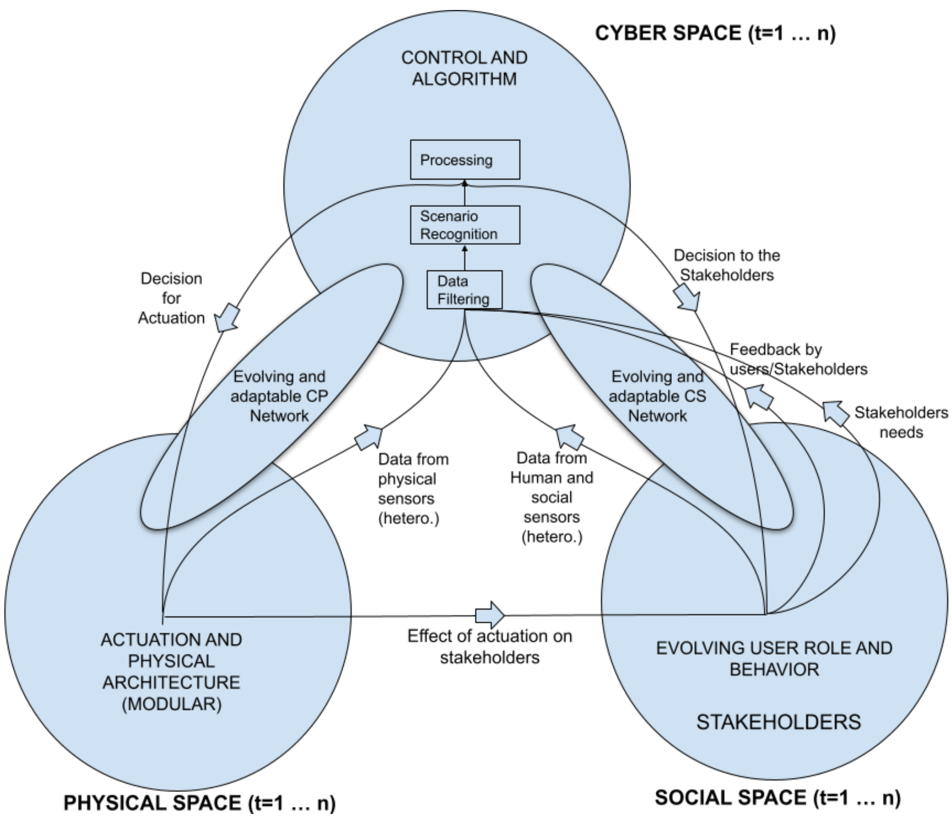

Figure 4.7 Cognitive Map for the E-CPSS

4.4.1 Features of the Cognitive Map

In the cognitive map, the three spaces, Cyber, Physical and Social spaces are shown in Figure 4.7. In the cyber space, heterogenous data from humans and physical sensors is homogenized, and patterns and similarities are observed in the homogenized data to recognize scenario and context to understand the requirements. Decisions are taken based on the context understood. The physical space encompasses the actuating capabilities and sensors for sensing and data generation. Components are modular in the sense that with the change in the demands of the stakeholder, the physical configuration can be rearranged, removed or added to satisfy the requirement, that is, the space can undergo structural evolution to achieve the updated state. The social space consists of humans and their interdependencies, social network and social analytics. The emotions, role and behavior of the humans are a part of the social space. The three spaces act as spatiotemporal zones being space and time dependent, that is, showing changes in the structure and behavior over time. With the changing environment over time, the spaces also get updated. The evolving behavior of the system is observed when system function updates due to changing context and recognizes updated scenarios. The network for sharing of information between the Cyber and the Physical space (CP) & Social and the Cyber space (CS) also evolves due to the dynamic sharing of a large amount of heterogenous information between the various spaces. The change in the user/stakeholder preferences in the social space and the interaction by the users/ stakeholders due to unsatisfactory decisions are responsible for changes in the context. Thus, the CPSS also evolves to counter this dynamic change caused by the change in its own social space in real time by self-adapting to suit the needs of the stakeholders and provide satisfactory solutions.

An urban city with proper resources and facilities has a developed water utility system in place however a rural city with minimal resources lacks a properly designed robust framework and hence is susceptible to a large magnitude of uncertainties causing disruptions in functioning of the system. For explanation of the cognitive map, we have assumed that the initial requirements of the stakeholders were to have simply "water supply access" for purposes such as drinking and cleaning. The requirements were well understood by the authorities and the system worked in a coordinated manner to ensure that every household has a "water supply access." Based on the interaction with social entities, necessary changes were made until every requirement is fulfilled and to achieve a steady state. However, with the change in the environment, the requirements of the stakeholders begin to change. Climate change, urban activities and differences in lifestyle resulted in stagnation of water and the requirements of the stakeholders is updated to "public health protection." This change in requirements results in corresponding decisions by the E-CPSS in collaboration with the policy makers and allocate required resources to meet the changing demand. Hence, with the change in requirement (the driver), the function, behavior and structure of the system (driven) changes. The mechanism of adapting this change is discussed through the cognitive map.

4.4.2 Working of the Cognitive Map

Initially, heterogenous data including multiple preferences and physical parameters from the physical and social sensors is sent to the cyber space. **For example**, in a water utility system, data from social sensors includes requirements of stakeholders such as clean water and a regular supply and data from physical sensors include pH level of water, temperature of water, etc. In the Cyber space, the heterogenous data is analyzed and processed to create a homogenous data by computational methods to utilize the necessary data based on stakeholder requirements and filter out rest of the data to ease computational complexity. The filtered-out data is stored in the databases of the servers which can be accessed for other decision-making situations and requirements. Computations take place on the homogenous data and scenario recognition takes place**. For example**, the requirement of having "water supply access" is recognized. Once the scenario is recognized, context awareness is observed through the cyber space with its evolved cognitive capabilities. Decisions for physical actuation and operation are sent to the physical space based on the context wherein actuation takes place. Modularity is observed here as change in requirement brings about repositioning, removal, replacing or addition of structural modules. **For example**, the electromechanical solenoid valves receive decisions as signals to maintain the flow and pressure of water supply to ensure water supply access until new signals with new commands and controls are not received. The decision can also be sent directly to the social entities if the requirement doesn't require physical actuation [Cyber-Social Interaction (CSS)] **For example**, Query of the duration and time of water during the day is provided by the cyber space directly. The effect of actuation in physical space is observed on the social space in terms of human behavior, cognition and emotion [Physical-Social Interaction (PSS)]. If the decision taken by the system is not satisfactory, the feedback due to social interaction is generated by the social entities and is sent to the Cyber space as input simultaneously with the existing heterogenous data incoming from physical and social sensors. This allows for new and updated scenario recognition and context awareness, thus showcasing an evolving attribute. **For example,** the supply of the water is not available to every stakeholder or potential user and a query is sent. Within the social Space, user role and behavior evolve in accordance with the different level of preferences by direct and indirect stakeholders and changes in the environment. Thus, a human acts as a user of the system. The changing preferences and objectives of the user makes the data dynamic as the information also evolves and subsequently the situation and context areupdated. **For example,** climate change and urban activities have now degraded the water purity level and the stakeholders are now concerned with the health of the users. Thus, the system objective updates from ensuring water supply access to providing clean water supply. The decision-making process is repeated until the final objective of the users/stakeholders is satisfied and the system achieves a steady state. Thus, the evolving nature of the CPSS can be observed from the above description of the working of the cognitive map. With changes in requirements of the users and stakeholders, the context updates which in turn brings about changes in the trispace of the system. The changes continue to take place until the requirements are met and, hence, the system achieves a steady state.

The utility of the cognitive map is to design and understand the complex interactions within systems such as E-CPSS. In terms of designing an E-CPSS, a cognitive map is of value to understand the interdependencies, identify key components and relationships, and interpreting characteristics of such systems. Designers can use such cognitive maps to support decision-making whether its modeling for social dynamics, incorporating user preferences or identifying potential risks and vulnerabilities in the system. In summary, the cognitive map presented provides a comprehensive and dynamic representation of an E-CPSS that supports design, analysis, and management of complex systems that can be leveraged to ensure that system components are working synergistically to satisfy stakeholder needs and achieve system goals.

4.5 KEY FINDINGS

In this section the findings and suggestions are highlighted, after a thorough review of the literature shedding light on the key insights for advancement of design engineering for E-CPSS. The key contribution of this chapter is to provide a pathway for system designers to effectively design an E-CPSS from the perspective of enhancing the decision-making process. This is achieved by addressing the various entities of the system and the relationships among these entities as done in the case of cyber, physical and social spaces of an E-CPSS, discussed in Section 4.1.2. From the discussion in Section 4.2 and Table 2, it can be concluded that the social space plays an integral role in the decision-making process. To effectively tackle and design an E-CPSS, a list of requirements is formulated in Section 4.3.3 encompassing perspectives catering to function, behavior, and structure of the system. The evolving characteristics shown in Table 3 provide an opportunity to further delve into the establishment of foundational frameworks, approaches, and methods by leveraging existing tools to address the E-CPSS. At last, various features of the models and frameworks from Figure 4.6, the requirements list from Section 4.3.3 and the characteristics from Table 3 are tied together to present a cognitive map of an E-CPSS as shown in Figure 4.7. The cognitive map presented will be of utmost value in the field of design engineering to help designers understand the working of an E-CPSS during the decision-making process when subjected to an uncertain environment while taking into account the interest of all the stakeholders involved. Based on the findings, here are the challenges that need to be addressed in order to advance design engineering for E-CPSS.

Challenge 1: Addressing evolving Cyber Physical Social systems.

E-CPSS possess immense computational, physical and cognitive capabilities to deal with external changes when subjected to uncertainties and complexities. Hence, addressing the evolving attributes of such systems along with frameworks, approaches and methods to model these characteristics becomes critical. The challenges associated with addressing E-CPSS include data security and privacy, dynamic resource management, human-centric design and ethical and societal implications.

Challenge 2: Uniform modeling of cyber, physical, and social spaces.

Through review of state of the art, different techniques, methods and frameworks for modeling the cyber, physical and social spaces in context of different scenarios and assumptions are presented. However, the literature still faces the challenge of uniform modeling of the trispace that can be used to model the functioning and behavior of a CPSS in every possible scenario. Challenges such as data heterogeneity, computational complexity, dynamic nature and interdisciplinary integration second the need for uniform and compatible modeling of cyber, physical and social spaces.

Challenge 3: Realizing the social dimension and with both endogenous and exogeneous social space to effectively design E-CPSS.

The role of social dimension and social interactions bringing about evolving characteristics in a CPSS is relatively untapped in the state of the art due to the challenge it puts forth for modeling and predicting emotions and behavior associated with the social dimension. The social space having an endogenous and an exogenous nature needs to be realized to address the social interactions that are caused due to evolving behavior of the system and understand how these interactions bring about evolutionary behavior in the system. Balancing the impact of internal social dynamics (endogenous) with external societal factors (exogenous) and understanding how they interact and influence each other is a challenge that needs to be addressed to seamlessly incorporate these into the design of E-CPSS.

4.6 SYNOPSIS FOR CHAPTER 4

In this chapter, the findings on the dynamic nature that an E-CPSS exhibits owing to the inclusion of the social space involving human behavior, emotions and cognition that differentiates it from a CPS are presented. The importance of the social domain in the decision-making process is discussed and the cause and effect of evolution in social space with a changing overall system architecture is put forth in Section 4.2. After a thorough review of the state of art, key research questions are identified as discussed in Section 4.3.1 that must be discussed to address the evolving nature of a CPSS in the decision-making process. These questions portray challenges in the research of E-CPSS that range from addressing the social dimension to identifying the key evolving attributes and approaches to model these attributes for designing an E-CPSS. To address these research questions, comprehensive definition of a E-CPSS is presented in Section 4.3.2 while describing the system's evolving features and the behavioral and structural changes the system undergoes as a result of this evolving nature. Various key features emerging in the system as a result of its evolutionary behavior such as self-organization, self-adaptability, resilience, interoperability, context-awareness and many more are presented in Table 3 to aid the designer design for an E-CPSS. Based on the preliminary review of the state of the art, it is inferred that modeling and framework resources for designing for E-CPSS is an area of untapped potential, therefore potential models and frameworks are summarized and presented in Figure 4.6 that are commonly used in numerous applications such as smart cities, intelligent transportation, water utility systems, etc. For this, Table 2 is put-forth identifying and classifying the study of state of the art to comprehensively categorize and summarize the findings. To realize these evolving attributes, various requirements are inferred and realized from the standpoint of Gero's FBS framework as shown in Figure 4.5 with the intention to contribute to the design research community with the concept of concurrent designing for such systems. This would help underline the critical functional, behavioral and structural requirements to realize and showcase evolving characteristics discussed in Section 4.3.3. Further, a cognitive map of an E-CPSS is put forth as shown in Figure 4.7 with reference to water utility systems to explain the decision-making process in an uncertain and a complex environment with constantly changing stakeholder needs and preferences. The map can be used by researchers and designers to understand the decision-making mechanism in an evolving environment which would help them to expand the model or revamp it according to their own objectives and problem statements. The purpose of presenting the cognitive map is to guide further research into the development of design procedures for developing frameworks for E-CPSS.

As CPSS' evolves, new security and privacy challenges emerge. Studying about system evolution helps in identifying potential vulnerabilities and designing measures to ensure the security and privacy of sensitive data and operations in a large adaptable network handling large volume of heterogenous data. An in-depth study of E-CPSS can foster innovation by identifying opportunities for new features, services, or applications that arise as the system evolves. As CPSS continue to evolve, models can be updated to reflect new requirements, technologies, and insights. This allows for continuous improvement and adaptation to changing needs. Emergent behavior commonly observed in Collective Adaptive Systems (CAS) is a distinctive and an important characteristic of an E-CPSS which cannot be predicted, controlled or accounted for. Future studies can expand into looking for modeling and computational techniques to control and predict emerging attributes to prevent misbehavior and unaccounted for, unplanned risks disrupting system performance.

CHAPTER 5

DESIGNING PUBLIC POLICIES FOR THE FUTURE: EMBRACING A SYSTEMS PERSPECTIVE

Research Gap(s):

RG3 - How can the collective adaptation construct be applied to facilitate policy design within Evolving CPSS?

RG4 - What common themes, theories, and frameworks emerge across the domains of public policy, and how can they be integrated to provide a comprehensive approach to design public policies?

Objective(O5): Propose an approach to design public policies by tapping into synergy between Collective Adaptive Systems as a cognitive map and Evolving Cyber-Physical Social Systems (CPSS) as the technological infrastructure.

New Knowledge (K5): An approach for designing public policies by establishing the utility of interaction between E-CPSS and CAS.

In today's rapidly evolving society, designing effective public policy requires a fundamental shift in perspective. Through traditional approaches designers struggle to capture the intricate tapestry of contemporary challenges. Public policy design demands a holistic approach that considers not only the immediate problem, but also the diverse perspectives, evolving preferences, and dynamic nature of the problem itself. This complexity underscores the need for an approach that can encompass this multifaceted landscape and inform the design of adaptable and responsive policies.

Existing public policy design frameworks often fall short by neglecting the interconnected and dynamic nature of the policy environment. While they acknowledge some elements like stakeholder involvement and problem context, they often fail to capture the interplay between these elements and their continuous evolution. This disconnect between policy design and the evolving realities of the social environment leads to policies that lack adaptability and struggle to effectively address complex societal challenges.

The primary research questions that are addressed in this chapter are:

RG.3 *How can the collective adaptation construct be applied to facilitate policy design within Evolving CPSS?*

RG.4 *What are the common themes, theories, and frameworks that emerge across the domains of public policy, and how can they be integrated to provide a comprehensive approach to design public policies?*

Through this chapter, an approach is proposed to bridge the identified gap by hypothesizing Public Policy as an Evolving Cyber Physical Social System (E-CPSS). The proposed cognitive map as Collective Adaptive System leverages CPSS as a technological infrastructure. By utilizing this approach, we recognize the dynamic interplay between social agents, social environments, and the problem structure. By adopting a holistic perspective informed by CPSS principles, this approach empowers designers to design comprehensive and adaptable public policies that are responsive to the ever-changing needs of society. The broader perspective illuminated by this chapter entails contributing to the improvement of informed decision-making among policymakers/decision makers, guiding them toward designing effective public policies.

Keywords: Public Policy, Collective Adaptive System, Cyber-Physical-Social System, Adaptability, Evolution, Preferences, Stakeholders

GLOSSARY

1. **Public Policy:** Public policy refers to government actions, decisions, and measures aimed at addressing societal issues, setting priorities, and achieving specific goals for the public welfare.
2. **Evolution:** Change in the time intervals defined as 'states' characterised by change in stakeholder needs, social environment and the problem structure itself.
3. **Stakeholders:** Stakeholders are individuals, groups, or entities that have an interest or concern in the success and outcomes of the design of public policy.
4. **Collective Adaptive System:** Dynamic interaction of social integration strategies, social environments, and problem structures in complex socio-cognitive systems
5. **Social Integration Strategies:** Stakeholders often have different beliefs, viewpoints, interests, etc. Social integration strategies relate to integrating various such viewpoints of stakeholders.
6. **Problem Structure:** A problem structure is conceptualized as any challenge encountered by stakeholders, whether originating externally or internally, that undergoes evolution over time.
7. **Social Environment:** Social environment is perceived as consisting of social networks as well as the external environment that the problem structure is based on.

8. **Adaptability/Self-Adaptability:** The ability of a system to adjust or modify its behavior, structure, or function autonomously in response to changing conditions or requirements to adapt to the changing scenario and context in a dynamic environment.

5.1 FRAME OF REFERENCE

From a broader perspective, policy design can be viewed as a facet of policy sciences that focuses on the examination of policy processes [170]. The objective through this domain of study is not just to obtain better solutions to address social problems, but it aims to develop more effective or enhanced methods for formulating policies. It has been observed from the observers of policymaking that some policy design efforts are well thought out and designed while others are considerably arbitrary [170]. In multiple situations it can be seen that designing public policies comes up with higher levels of heterogeneous actors as stakeholders who have conflicting and contradicting objectives and interests than commonly linked with a conventional design process and result [171], [172]. Policy design consist of multiple challenges including lack of information, conflicting and contradicting interests of multiple stakeholders involved, lack of integrity towards policy objectives, etc. [86], [90]. *(These characteristics anchor in the context of wicked problems discussed in Chapter 2 and 3)*. While considering the actors involved to be under best intentions in best circumstances, government in the process of decision making, frequently face intricate challenges in complex situations in the realm of designing public policies. These scenarios involve multiple actors with potentially conflicting ideas and interests that evolve making it challenging to secure or maintain agreement on the most likely successful policy alternatives. The existing gap lies in comprehending the process of effective policy design, particularly in terms of selecting the appropriate tools for optimal effectiveness [173]. This is explained in detail in [174], [175]. The importance of designing better informed policies that comes with the synergistic integration of human and technology compounded by a cognitive map for policy design through a technological infrastructure is evident. The essence of any policy design lies in comprehending diverse policy options to address a given problem. These policy options should be designed in a way where it takes into consideration the multiple views and preferences for the actors involved, the interactions between various stakeholders, and the problem structure. To ensure the effective design of policies, it is essential to consider the evolving nature of interests and the environment within which these landscapes are situated. We realize that public policy is an Evolving Cyber-Physical-Social System (E-CPSS) *(Refer Chapter 4)* This gives a holistic approach for the design of public policy for which we consider collective adaptive systems as a mind map and the paradigm of E-CPSS as out technological infrastructure.

With the growing complexities and wicked nature [2] of the grand challenges that the world is facing (environmental justice, food insecurity, etc.), the role of government (public administration) in the policy making has been of significance importance. On the other hand, the expectations that communities have through these policy initiatives have increased [176], [177], [178]. Herbert Simon who calls public administration as a design science states design 'is concerned with how things ought to be, with devising artefacts to attain goals' [30]. This emphasizes the idea of core of designing to be problem entered where the design is evaluated based on the ability to deal with situations that involves analysis of problem and methods to address them. While, this is the foundation of design, in the recent design methods there has been a larger utility of human centred approaches that focus on outcomes rather than solutions

[179]. Designing public policies necessitates the understanding of systems behaviour and the capabilities to engage in scenario-based modeling through artificial simulations. The availability of data should not limit any model based policy design with the view that it's not merely the data that needs to be evaluated but the anticipated systems behaviour under different scenarios. This comes through various artificial data generation methods [180], [181], [182]. To underscore, the focal point is the comprehension of systems (pertaining to model-based policy design) under varied conditions and scenarios, rather than solely focusing on the data. Through this chapter, however, the focus is not on proposing a design method, but utilizing the insights from the state of art and literature to propose an approach of designing policies to provide policy options to policy makers. We accord to the idea that performing experiments and proposing interventions results in attaining insights and knowledge that fits into the broader objective of policy making as a design science [180], [181].

Collectives are both influenced by and contribute to individual cognitions, patterns of interactions, and the problem structure they encounter and form [182]. The general definition of collective adaptation considered in this chapter is as proposed by Mirta Galesic et. al. [148] that defines collective adaptation as a "dynamic interaction of social integration strategies, social environments, and problem structures in complex socio-cognitive systems." Through collective adaptive systems we consider the differences in opinions, beliefs, interests, and objectives of various stakeholders through social integration strategies. When designing public policy, it is crucial to account for the interaction among various stakeholders and the emergent behavior resulting from these interactions in policy design. This aspect is addressed by the second building block of collective adaptation, which is the social environment. It is critical to note that the interests of various stakeholders evolve with respect to time. Moreover, in the design of public policy, it is critical to acknowledge both the external and internal environments that contextualize these circumstances. This recognition will influence how policies are formulated, considering the nuances of the associated problem in line with the environment. This aspect is simultaneously addressed by the social environment and the problem structure. The third pillar, namely problem structure, attends to the specific issues for which the policies are designed. This is explained in detail in Section 5.4 of this Chapter.

As we contemplate Complex Adaptive Systems (CAS) as the cognitive map for designing public policy, we advocate for the implementation of Evolving Cyber-Physical Systems (CPSS) as the technological framework. In the past decade, there has been a growing discussion on the influence of the social element in engineered systems. The significant impact of human behavior and cognition on diverse systems, [101], [120] is critical in the realization of design of public policy. While the traditional public policy designing recognizes the involvement of social factors, [183] the connection of a foundational cognitive map and the concurrent technological infrastructure is missing. The utility of designing public policy as an E-CPSS through CAS by incorporating the social element in the system is proposed through this chapter. The Cyber-Physical-Social System (CPSS) involves the integration of cyber, physical, and social spaces. The cyber space plays a central role in system computation and control, promoting the generation, analysis, and exchange of data within and between the social and physical spaces. It enables smooth interaction and data sharing among social agents, encompassing human attributes such as judgment, experience, cognition, decision-making, and behavior. In our perspective, public policy design entails defining the problem [184] and offering well-informed policy alternatives to policymakers. This process is guided by evidence, presenting the consequences of each option, enabling policymakers to make more informed decisions.

Organization of the chapter:

The objectives through this chapter are:

(i) Deliver pertinent literature and research gaps to explore the utility of "Design" in policymaking as a basis for proposing an approach for designing public policy.

(ii) Offer perspectives on the essential prerequisites and factors to be considered in the design of public policy.

(iii) To propose an approach for designing public policies by tapping into synergy between Collective Adaptive Systems as a cognitive map and Evolving Cyber-Physical Social Systems (CPSS) as the technological infrastructure.

(iv) Establish the utility of model based policy design for policy making in real world.

(v) Offer a pragmatic approach for policy designing that will assist policymakers/ decision makers to make better informed decision by designing effective policies.

In this chapter, our exploration unfolds across carefully delineated sections, each contributing distinct insights to the overarching theme of public policy design. In Section 5.2 the emphasis is on presenting a comprehensive understanding of the Policy Mix, setting the stage for our proposed integrated approach utilizing Evolving Cyber-Physical Social Systems through Collective Adaptive Systems. In Section 5.3 the focus is to provide diverse perspectives surrounding policy design, discussion on fundamental questions, research gaps, and acknowledging the limitations of conventional 'technocratic' approaches that underscore the complexities inherent in this field. In Section 5.4, the proposed approach to design public policies is described. Prior to the detailed exploration of this approach, Section 5.4 provides a concise overview of Collective Adaptive Systems and Evolving Cyber-Physical Social Systems. Finally, in Section 5.5 the closing remarks are provided, synthesizing key takeaways and encouraging readers to reflect on the implications of our proposed approach for the dynamic realm of public policy design.

5.2 UTILITY OF POLICY MIX IN DESIGNING PUBLIC POLICIES

In this section, we explore the concept of policy mix, recognizing its influential role in designing effective policies by considering its functionality and utility. This understanding aims to assist policymakers in making more informed decisions, especially in complex situations. The term “Policy Mix” has got growing interests from researchers in multiple areas including policy design, innovation studies, economics, etc. There have been multiple definitions and context for policy mix that are based on the field of studies [185]. We will adapt to the definition proposed by Kern and Howlett [186], that states “Policy mixes are complex arrangements of multiple goals and means which in many cases, have developed incrementally over years”. In a more general way policy mixes are the combination of several policy instruments [187]. The three general features that emerge from policy mixes that Rogge suggest are its close relation to the objective through the policy design, second that deals with different components of policy mix. The third feature that we believe is critical is the dynamic nature of policy mix referring it to have been evolved [188]. We believe that policy mix should present a detailed picture of the actions that were taken in the past that influence the processes of policy design in the present to predict policy options in the future. This requirement is influenced from the design of policy as a system to help policymakers to make better informed decisions. Flangan enunciates on the necessity of policy design as a verb and proposes to assimilate the policy processes “by which policies emerge, interact and have effects”. We specifically enunciate the importance of interaction of policies in policy mix that plays a vital role in designing public policies, this is further detailed in Section 5.4.

In this Section we primarily focus on understanding the building blocks of a Policy Mix with an objective to propose an integrated approach to design public policies as an Evolving CPSS through Collective Adaptive Systems. Meeting the complexities of real-world policy mixes necessitates three fundamental requirements: the inclusion of a strategic component, the incorporation of the associated policy process, and an enhanced consideration of the characteristics of policy mixes [185] These three requirements are critical considerations for the approach we suggest in this chapter.

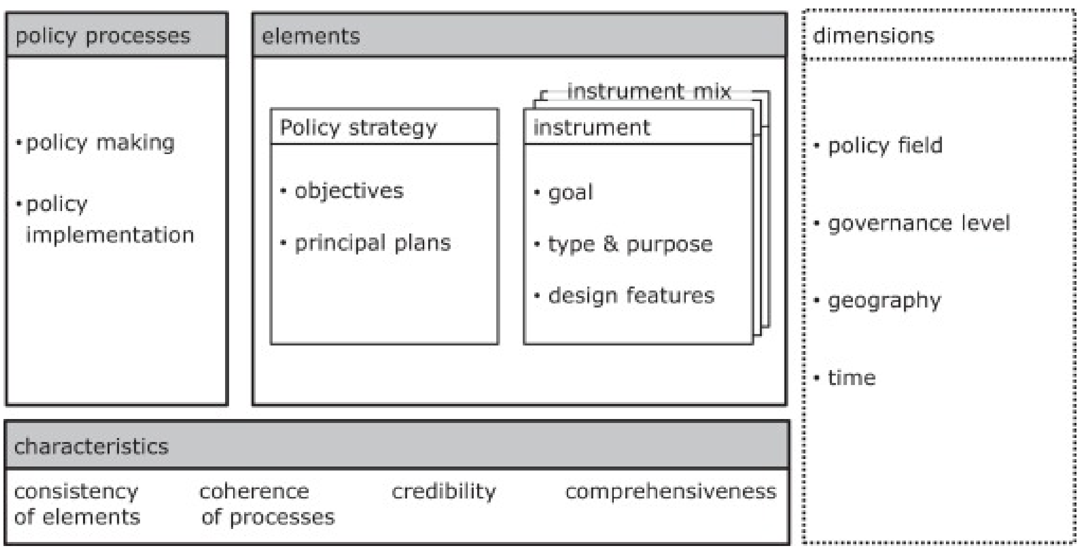

Figure 5.1: Policy Mix [185]

5.2.1 Elements of Policy Mix

As seen from Figure 5.1, elements primarily comprise of policy strategy and instrument mix. Policy strategy has its objectives and principal plans to achieve them. For the government to address grand challenges like environment justice, food insecurity, climate change, healthcare etc., it is critical that the policies are designed with long term strategic considerations by laying out clear plans to achieve them. We recognize that policies designed to address social problems are not a one shot process [190], [191]. The plans that constitute in the policy strategy are bound to meet with various uncertainties and risks. This calls for the design of policy to focus on outcomes rather than solutions. In such situations it is critical to create, think and analyze on various scenarios that could arise in the course of time. This deals with the idea of incorporating uncertainty and evolution in the design of policies to ensure its effective functioning throughout the intended course of time. Further, a parallel consideration that designers should make is the possibility of various objectives in a single policy. This is critical in situations where you have multiple stakeholders under consideration with conflicting and contradicting objectives. The diverging public and private interests are often visible in policy design. For policy makers, it is critical to integrate such interests and reach a shared agreement and objective to attain. Thus, the objectives are evolving and principal plans are bound to face uncertainties that need some space to adapt as per the scenarios, which calls for scenario based modeling of model based design of public policies.

The second element as shown in Figure 5.1 is Instrument. At a more general sense the policy instrument anchors in providing tools to achieve the underlying objectives from the policy strategy. Instruments define the tools [192] or techniques of governance [193] required to address the problem [185]. Instruments help policymakers to achieve the objectives and channels the plans through the strategic initiatives. Instrument type is critical to incorporate various constraints that a policy maker might face. Policy instruments interact with each other and the influence of one is modified by the coexistence of other policy instruments [187] The utility of instrument mix is important to address this. This plays a vital role in laying out considerations for designing policies in consideration of other policies having a varied level of objectives. Ideally in the real world the planner has no right to be wrong and thus in the traditional policy design considering, analyzing, and reflecting on the existence of other instruments and policies is often challenging. However, this can be attained by leveraging the capabilities of model based policy design and is one of the aspects that our proposed approach entails.

5.2.2 Policy Processes in Policy Mix

Policy strategy and instrument mix are anchored in design as noun, whereas, the utility of policy processes lies in design as verb [186] While to design a public both these forms are important as design as noun helps policymaker in shaping the framework and structure whereas design as verb aids in formulation, implementation, and refining. We carefully agree to the notion of policy process developed on the works of [194], [195], [196] and proposed by Rogge [185] as a "political problem -solving process among constrained social actors in the search of solutions to societal problems – with the government as a primary agent taking conscious, deliberate, authoritative and often interrelated decisions" While we accept this notion, at the same time we also want to underscore the fact social actors in the real world are not rational and the policies should be designed with this consideration.

Policy process can be viewed as a "cycle of problem solving attempts" [185] that results in policy learning. We propose a slight modification to this notion by adding that policy process can be viewed as a "cycle of problem addressing attempts by considering varied scenarios" This notion allows an effective way of policy learning. Another important aspect is "policy adaptation" that is equally important as policy learning in the policy making process. Though policies are made at a particular state of time we recognize that policy designing should be adaptive to the changes in the external environment. This is by incorporating evolution in the design of policy. This enables us to account for uncertainties associated with evolving states. Evaluating the impacts of policy mixes and thus policy design is of fundamental significance [197]. Evaluating the policies is critical, however it is often seen that policies are evaluated after they are being implemented, which is logical, however, the model based policy design could help us with predictive capabilities to evaluate and present the consequences of policy decisions for multiple policy options that can help in effective policy design in present.

5.2.3 Characteristics of Policy Mix

Characteristics form an important way to evaluate the performance of the policies. In our opinion characteristics connect the policy design to the outcomes through the policy process. From Figure 5.1 it can be seen that the important characteristics proposed by Rogge and Reichardt in the extended policy mix concept are (i) consistency of elements, (ii) coherence of processes, (iii) credibility, and (iv) comprehensiveness.

Consistency ensures the connectivity between different elements of a policy. This characteristic highlights the 'state of elements' of policy mix at a particular point in time [185]. We recognize the importance of this notion with the view that elements at one state of point when compared with other state should have careful consideration of evolution of states of system. This is difficult to speculate in policy design, however, the model based policy design could allow attaining this. The consistency in relative terms by differentiating it between time, geography, and governance highlights the complex interplay of factors shaping various societal dynamics. The underlying gap here is that how do you account for these differences by considering a dynamic and changing social environment and problem structure?

Coherence allows us to have synergistic policy building. It includes the incorporation of multiple views, interests, and opinions to reach a shared objective. This is often the case as seen in the interests of public and private interests. The presence of multiple stakeholders' necessitates policymakers to consider an approach that integrates multiple interests. Credibility as the name suggests, is to understand the reliability of designed policy. We argue that it is critical to have an approach to design policies that provide designers with the ability to make decisions based on an analysis of multiple scenarios consisting policy various policy options. We discuss further about this in Section 5.4. Comprehensive anchors in ensuring that the instrument mix considers the relevant market, system and institutional failures, and the constraints placed by various actors and stakeholders [185], [198], [199], [200].

5.3 DESIGN FOR PUBLIC POLICY

Policy design is a diverse concept, and various perspectives on policy design have been discussed by different researchers in the field. "Everyone designs who devises courses of action aimed at changing existing situations into preferred ones" as said by Herbert Simon [30] provides a generic view of design but aligns with the broader idea of policy design. Design, as contended by Jan Tinbergen, is an alternative to "decisions taken on the basis of general idea of progress and often somewhat haphazardly" [201]. We regard the questions posed by B Guy Peters [202] *"Are we yet able to produce policy designs that can indeed address social problems effectively and efficiently? And can we develop templates for interventions that can have utility beyond a narrow range of issues and a narrow range of contexts? Or should we be more concerned with specific designs for specific issues rather than assuming that we can develop generic designs? Does 'one size fit all' in policy designs, or do we need more finely tuned designs for each particular problem?"* While as these questions point to the fundamentals of policy design and its utility for policy makers, at the same time they also inherently question the availability of well thought out approaches for the policy design. We believe these questions not only cater to the need of "design engineering for public policy" but also point out at the void of systems thinking in this field. In our view, for policy studies, systems thinking should not be viewed as a distinct entity for policy design, but rather as an integral and crucial component of it. There is a growing need to develop approaches for policy design that can bridge the gap for government to make better informed decisions. While emphasizing the utility of policy design, we acknowledge an "upset" or, in more sophisticated terms, a "research gap" within policy studies, noting that the prevalent approach to design often leans towards the development of algorithms, as reflected in a substantial body of literature [203], [204], [205], [206], [207]. We suggest that while this aspect is crucial in policy design, it does not encompass the entirety of the process. In a broader context, algorithms serve as instruments, as elaborated in Section 5.2, constituting a part of the policy-making process. (refer Section 5.2).

We posit that policy design involves more than contemplating ways to address existing problems; it also encompasses 'speculating' as termed in traditional policy studies or, in our terms, predicting the consequences of the designed policies. In Vincent Ostram's [208] article on the intellectual crisis in American public administration, he stated "***An appropriate theory of design is necessary both to understand how a system will work and how modifications or changes in a system will affect its performance"***. This idea anchors in scenario based modeling for policy design. This is discussed in Section 5.4. We believe that public policy design should enable the designers to carry experiments with different scenarios, constraints, and considerations, which is not always possible in the real world. Thus, there needs to be an approach of designing public policy that should provide designers with these capabilities through suitable designing approaches. Unlike traditional designing practices that attempt to cut the available options to reach the best possible solution, in policy studies it is important that designers analyze various policy options arrived from different scenarios to understand consequences of different policy options.

Design Approaches in Public Policy

Despite numerous formal definitions of 'design' in the context of policy design, the interpretations and approaches differ among individuals that are shaped by contextual priorities. The three commonly observed design approaches are *design as optimization (bounded rationality)*, *design as exploration*, and *design as co-creation* [209]. We argue that Herbert Simon has carefully transitioned from optimization to '**satisficing**' to consider the complexities of real world. This holds paramount importance in policy design because, frequently, for social issues, we encounter incomplete and contradictory information. In 'The Sciences of the Artificial' Herbert Simon states "We must trade off satisficing in a nearly-realistic model against optimizing in a greatly simplified model." In accordance with this perspective, we argue that to design public policies we need satisficing strategy that helps designers to find good enough solutions by taking into account various uncertainties associated with design. We assert that the policy problem at one point in time may differ from that in another temporal state. This concept is rooted in the notion of evolution of systems, with social systems experiencing magnified impact due to the presence of stakeholders with changing interests and preferences, dynamic social environment and the emergent effects causing changes in the priorities of problems. This is further detailed in Section 5.4. **Design as exploration** anchors in the notion of 'learning by doing.' This design method is inclined towards designing by experimenting and making prototypes. While the effectiveness of design as exploration relies on reflection stemming from action or tasks, executing these processes can be challenging, particularly in dynamic or live environments. If the evaluation through 'learning by doing' is dependent on the actual implementation of policies, there remains a constant question about the opportunity to enhance the present situation. The third type that is commonly used as a form of design is **Design as Co-creation.** This approach primarily involves the inclusion of various stakeholders in the design process [210]. This approach involves participation from various stakeholders thus ensuring a more reasoned and deliberate approach of designing public policies. Further, this approach advocates 'human cantered' design by including a wide variety of actors [209].

The question that comes through is ***"How can we simultaneously explore the utility of design as satisficing, design as exploration and design as co-creation in designing effective policies?"***

These approaches though deal with different aspects (rational strand as design as method to find satisficing solutions, emphasizing on learning by doing, and inclusion of wide variety of actors), all these are critical to design public policies. The exclusion of any one of these will impact the policy design process by creating the void in design approach. By considering various aspects of design in the way it is perceived and pursued by various researchers of different fields, we propose an approach to design public policies by the integration of a cognitive model through Collective Adaptive Systems and technological infrastructure through the construct of evolving CPSS.

5.4 AN APPROACH TO DESIGN PUBLIC POLICY

In this Section we will discuss on the approach that is proposed. However, before exploring the approach we will explain Collective Adaptive Systems and Evolving Cyber Physical Social systems in brief to give readers an idea of the cognitive map and technological infrastructure used for our approach. While Section 5.4.1 and Section 5.4.2 will give the primary idea of the basic building blocks we recommend readers to refer [147] *(Refer Chapter 4)* to understand in details of both these constructs.

5.4.1 Cognitive Map - Collective Adaptive Systems

Collective Adaptive Systems are characterized by individual agents whose behavior exhibits coherence at a collective level, enabling the system to adapt in response to changes within the collectives. This is the fundamental idea of a Collective Adaptive System.

We refer to the cognitive map for designing public policy from [147] where the authors have proposed a framework for Collective Adaptive Systems, with some changes that we discuss in this section. Collectives are both influenced by and exert influence on individuals, cognitions, patterns of interactions, and the problem structures they encounter and create [182]

We consider the definition of collective adaptation as “dynamic interactions of social integration strategies, social environments, and problem structures in complex socio cognitive systems” [147]. We consider CAS as the cognitive map for designing public policies. The understanding of building blocks of collective adaptive system, namely, social integration strategies, social environment, and problem structure are critical in order understand our

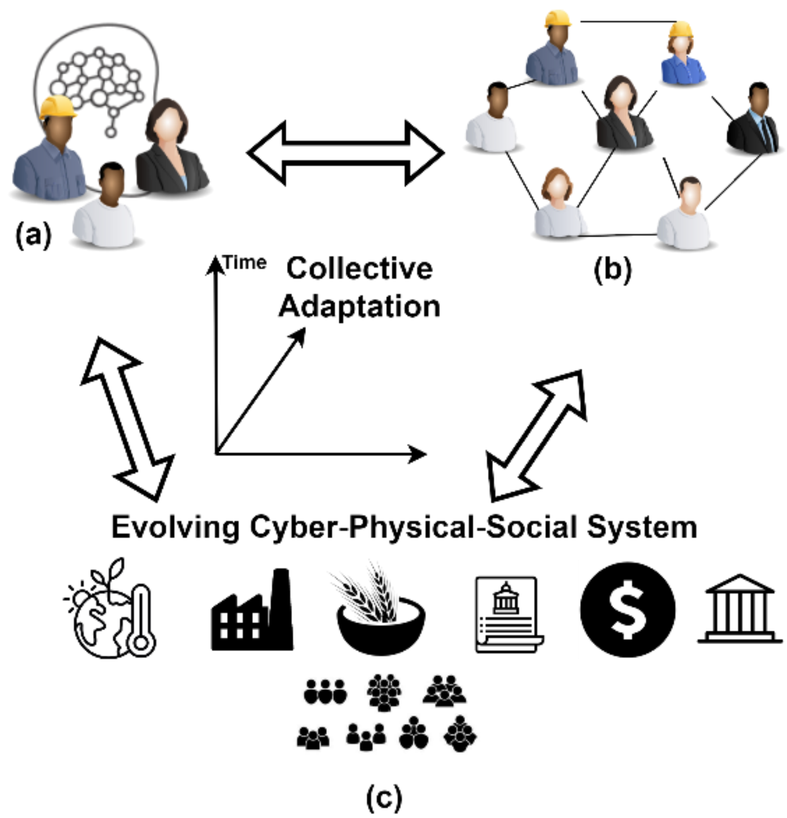

Figure 5.2: Collective Adaptation

proposed approach for designing public policies as an Evolving CPSS through Collective Adaptive Systems. Thus, we will explain these building blocks in the context of designing public policies.

Members of collectives entail varied preferences, interests, objectives, belief systems, and cultural values. They have different opinions and values on the states of world that are often aligned with their own goals. In Figure 5.2 (a), we depict social integration strategies that portray diverse stakeholders with numerous conflicting and opposing objectives, opinions, preferences, and goals. Social integration strategies are referred in various domains of studies as different terminologies. Social learning strategies in psychology, voting procedures in political sciences, aggregation procedures in computer science, etc. We consider the social environments as social networks characterised by patterns of interactions in social agents. These interactions shape opinions, form communities, and change the dynamics of the system. This gives new characteristic to the system owing to the emergence of interaction among agents. Social environments undergo continuous changes in response to current challenges, past experiences, social interactions, and individual cognitive strategies. This aspect is critical to address evolution in the design of public policy. The incorporation of technological infrastructure through E-CPSS helps us to address this, however, this is discussed in detail in the Section 5.4.2. In the context of designing public policies, Figure 5.2(b) represents the social environment influencing interactions among different stakeholders. Analyzing the impact of stakeholder interactions on the decision-making process is crucial, offering an effective approach for various jurisdictions or public entities to consider opposing perspectives. It is also essential to capture the emergence of complex system-level behavior resulting from the interactions of multiple stakeholders with diverse objectives in the process of policy design. Collectives encounter a multitude of challenges simultaneously, ranging from mitigating potential risks and devising technological solutions to organizing and coordinating social relationships [148], [123]. Figure 5.2 (c) depicts the problem structure, representing the issue in the public sphere that is being addressed. The dynamics of stakeholders' objectives and interests evolve with changing temporal states and the shifting nature of the problem structure. The central research concern in Figure 5.2 revolves around exploring an effective approach for policy design.

Internalizing Collective Adaptive Systems

Through the following subsection it is intended to illustrate an example of how Collective Adaptive Systems can be internalized by the designer. It is aimed to show one of the ways of how can CAS be used by the designers. This is in the context of Figure 5.2.

Note: *This example is intended to serve for understanding purposes only; designers may explore the utility of CAS in various ways.*

A. Social Integration Strategies:

Social integration strategies comprise various set of approaches adopted by stakeholders to navigate the complexities of collective decision-making. Designers can identify these strategies by closely examining the stakeholders involved in the policy-making process. These stakeholders, comprising individuals, communities, organizations, and institutions, bring forth a spectrum of preferences, interests, objectives, belief systems, and cultural values.

To identify social integration strategies, designers should:

- **Conduct stakeholder analysis:** Identify and categorize various stakeholders involved in the policy domain. Understand their motivations, goals, and the mechanisms they employ to influence decision-making.
- **Analyze stakeholder interactions:** Observe the patterns of interaction among stakeholders. Pay attention to alliances, conflicts, negotiation tactics, and consensus-building mechanisms employed during the policy formulation process.

- **Recognize decision-making procedures:** Study the methods through which stakeholders' aggregate preferences and make collective decisions. This could involve voting procedures, consensus-building mechanisms, or hierarchical decision structures.

B. Social Environment

The social environment within CAS comprises the intricate web of interactions, relationships, and dynamics among stakeholders. Designers can identify the social environment by examining the context in which policy decisions were made and the channels through which stakeholders communicate and collaborate.

To identify the social environment, designers should:

- **Map stakeholder networks:** Visualize the relationships and connections among stakeholders. Identify key influencers, opinion leaders, and clusters within the stakeholder network.
- **Analyze information flows:** Trace the flow of information within the policy ecosystem. Identify communication channels, information dissemination mechanisms, and the impact of media and digital platforms on shaping public discourse.
- **Monitor external influences:** Consider the broader societal, political, economic, and cultural factors that influence the social environment. Recognize how external events, trends, and crises shape stakeholder behaviors and attitudes.

While internalizing the social environment is one aspect, the other component lies in understanding the external environment. It's necessary to address this to comprehend the external influences affecting stakeholder preferences, viewpoints, etc., resulting in varied interactions that affect decision-making anchored in policy design.

C. Problem Structure

Through the problem structure we explore and specify the substantive issues and challenges that the designers aim to address by designing public policies. Designers can identify the problem structure by scrutinizing the underlying issues, goals, constraints, and complexities inherent in the policy domain.

To identify the problem structure, designers should:

- **Conduct policy analysis:** Evaluate the context, scope, and objectives of the policy initiative. Identify the underlying factors like socio-economic, environmental, and institutional factors, etc. contributing to the problem at hand.
- **Define policy objectives:** Clarify the desired outcomes and goals through the policy intervention. Understand the trade-offs, conflicts, and synergies between competing objectives and stakeholder interests.
- **Assess policy dynamics:** Recognize the dynamic nature of the problem structure, including how it evolves over time in response to changing circumstances, stakeholder dynamics, and external influences.

By meticulously identifying and understanding social integration strategies, social environment, and problem structure, designers can adopt a nuanced and context-sensitive approach to designing public policies within Collective Adaptive Systems.

We contend that model based designing of public policies requires a carefully planned integration of a cognitive map and technological infrastructure. While we have introduced the cognitive map to familiarize the readers with collective adaptive systems, in Section 5.4.2, we will delve into our technological infrastructure known as the Evolving Cyber Physical Social System *(Refer Chapter 4)*.

5.4.2 Technological Infrastructure - Evolving Cyber Physical Social System (E-PSS)

CPSS, as the name suggests comprises of three layers namely, cyber, physical, and social [50]. The existence of CPSS is confirmed by the interactions among Physical-Social, Physical-Cyber, and Cyber-Social. Designers of complex systems like the CPSS must consider both the evolution and the incorporation of the social space. The dynamic character of these systems is rooted in the ever-changing environment over time. The fundamental concept underlying system evolution is the alteration in information at any given moment. These specific points in time are commonly denoted as 'states.' Incorporating the social layer into the physical and cyber layer ensures seamless alignment of this infrastructure, making it practically useful for the design of public policies.

E-CPSS is defined as "*An E-CPSS is a system comprising of at least one cyber, physical and social component which exists or emerges due to the interaction between the tri-space leading to the changes in the behavior and structure over discrete states to achieve a defined function which may or may not change with respect to the states in an uncertain and a complex environment*" *(Refer Chapter 4).* The evolution within a CPSS is pivotal for coping with rapidly changing contexts, instigating necessary adjustments in system behavior and structure. As we define the E-CPSS, incorporating knowledge about systems, evolution, and CPSS itself, the challenge for designers extends to comprehending and proficiently crafting systems. This is especially pertinent in the realm of designing public policy, where understanding the characteristics of the E-CPSS becomes crucial. These characteristics play a vital role in enabling systems to self-adapt and self-organize, offering valuable insights for policymakers to develop adaptive and resilient public policies that effectively respond to dynamic societal needs and challenges.

We classify the social space into two distinct categories: endogenous and exogenous social space. Within the endogenous social space, the cognition and behavioral factors of stakeholders can be scrutinized, while the social environment of the considered Cyber-Physical Social System (CPSS) is regarded as the exogenous social space, illustrated in Figure 5.3. The external environment, evolving over time, emerges as a crucial factor influencing the robust design options for intricate problems within CPSS, exemplified in Figure 5.3 during the transition from State 1 to State n. These considerations provide designers with the capability to evaluate the impacts of social entities on the system by encompassing both exogenous and endogenous social spaces. This method fulfils the imperative need for integrating system design with a comprehensive social space. The endogenous and exogenous social space anchors in social integration strategies and social environment layers of the cognitive map.

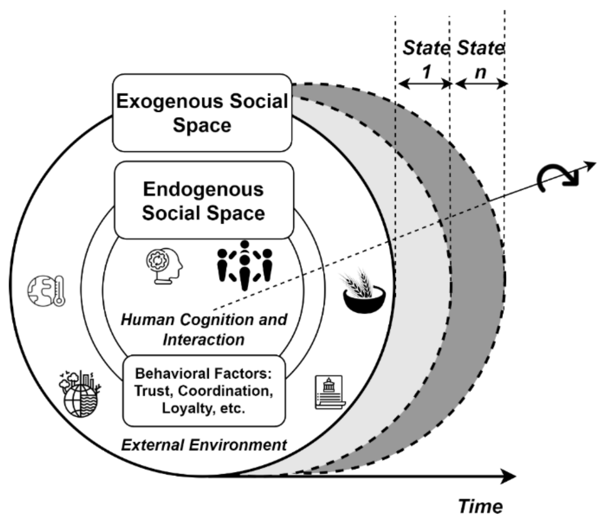

Figure 5.3: Social Space for Designing Public Policy (Chapter 4)

5.4.3 The Need for Holistic Policy Design Approach

The 'technocratic efforts' [203] to design policies have most of the times overlooked basic aspects of policy design. Unlike the industrial design that might involve prevalence of individual setting in design, policy design often caters to the need of *'collective'* activity [203]. One weakness or failure in designing public policies stems from the absence of mechanisms to adequately consider the actors influenced by the policy [211], [212]. The challenge for policymakers operating within the real political environment is to devise holistic designs that simultaneously incorporate a broad spectrum of values and ideas. The literature on policy design frequently emphasizes the importance of considering the political consequences of policy choices, not solely the process through which designs are formulated [213], [51], [214], [215], [216]. We believe this of critical importance for the success of policy design. The policy process should enable the exploration of various scenarios while providing a mechanism to anticipate the consequences of each policy option. This approach is crucial for designing policies that are informed by diverse scenarios.

The next critical aspect of designing public policy is that it involves 'humans' as the objects of policy [202]. The design should possess the capability to incorporate human behaviour and include mechanisms to integrate individual viewpoints, interests, objectives, and goals, (in the group of stakeholders) that might be contradicting. While designing public policy may appear daunting, there is a benefit to considering humans as artifacts, allowing policies to be crafted around the central concepts of 'behavioral studies.' In doing so, policymakers can guide society to align with their intentions, considering the greater social good. However, the critical question is ***whether we possess sufficiently effective mechanisms or approaches that enable the flexibility of designing public policies centred around humans, emphasizing the use of incentives to achieve social good rather than coercion.*** Lastly, before going to the proposed approach we underscore the importance of targeting and modulation [202]. For the effective functioning through the design of policy it is essential they act on the parts of society for whom they are meant. To achieve this, it is crucial for policy designers to comprehend the interactions between groups of stakeholders and understand the priorities of each group. This understanding is essential for crafting policies that align with the diverse needs and perspectives of the stakeholders involved. We present the fundamental considerations required to design public policies in Figure 5.4.

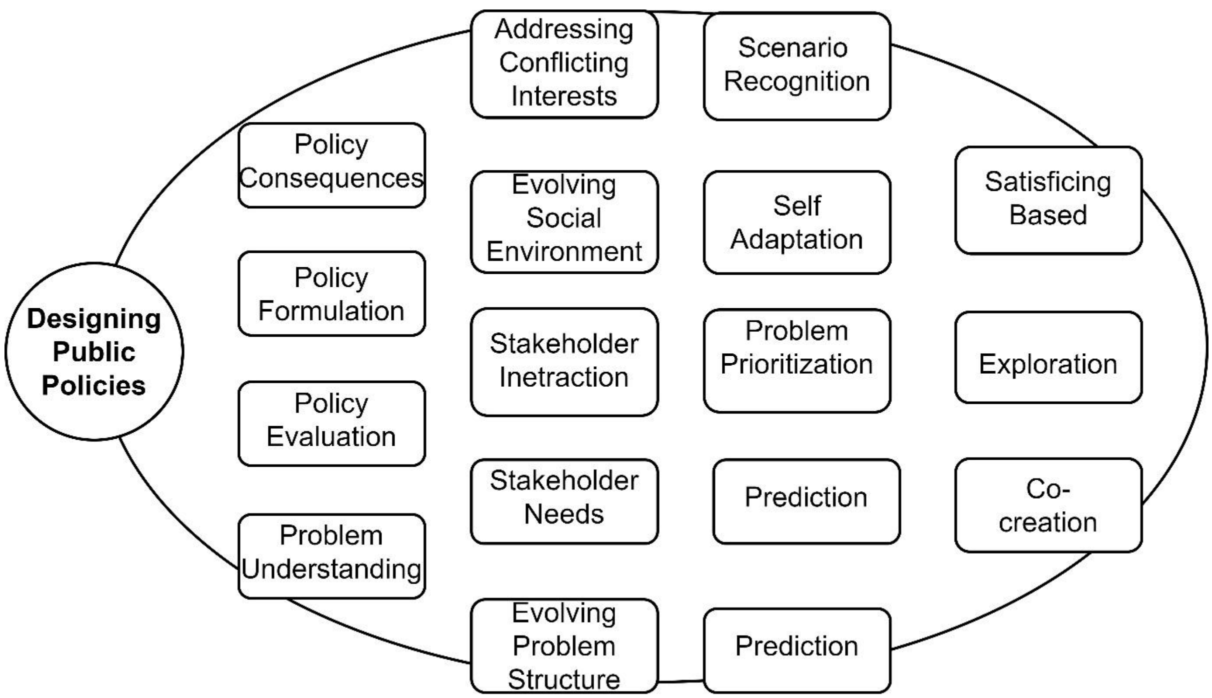

Figure 5.4: Considerations for Designing Public Policies

5.4.4 Proposed Approach to Design Public Policy

The dynamic nature of public policy design is constantly challenged by evolving issues. This dynamic environment involves the continuous evolution of various factors, including the problem structure itself. The problems being tackled can morph and transform over time, demanding constant revaluation and adaptation. Furthermore, the stakeholders involved in these challenges, with their diverse interests, objectives, and preferences, are also subject to change. Their priorities and desires can shift, creating a complex and ever-evolving landscape of needs and perspectives adding another aspect of complexity is the interplay among these stakeholders. The interactions they have and the effects they produce on each other further contribute to the dynamic nature of public policy challenges.

Despite the established understanding of system evolution within the broader academic sphere [108], [219], [220], its application in the design of public policy remains surprisingly underutilized. There's a potential overemphasis on technocratic solutions and algorithm development. This focus, as highlighted by scholars in the field [221], [222], [223], might inadvertently overshadow fundamental societal concerns. By prioritizing technical solutions, the inherent dynamism and evolution of social systems, with all their human complexities, might be overlooked. Further addressing the impact of evolution and its implications for policy design is inherently challenging. The difficulty lies in accurately predicting the long-term consequences of policy decisions. In practice, public policy design often relies on expert opinions and historical trend analysis to navigate this uncertainty. Predicting the long-term ramifications of complex policies is a daunting task, making it difficult to account for future changes and adaptations.

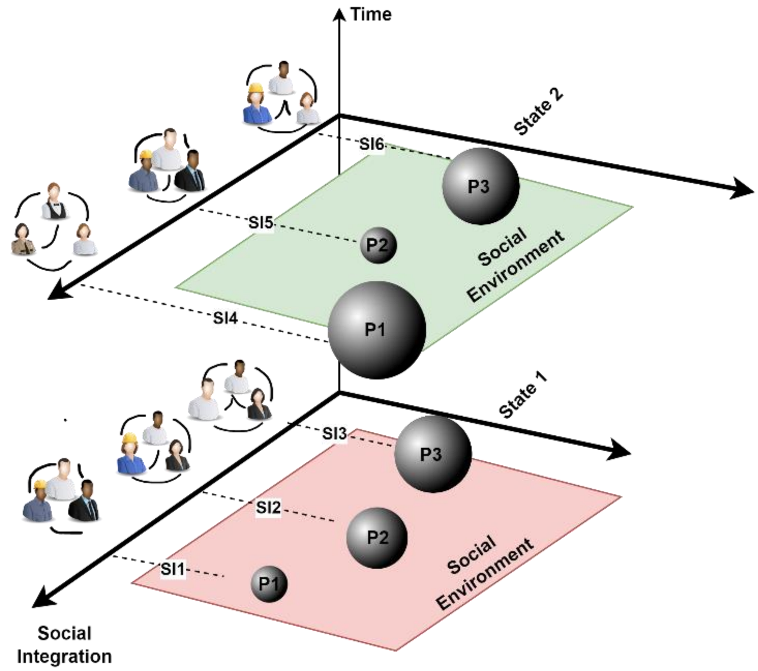

Figure 5.5: Dynamics for Designing Public Policies

Through the proposed approach we bridge this gap by explicitly incorporating the notion of evolution. We do this by considering discrete states within a defined time interval. We recognize that the priority of policy problems for policymakers varies across different states. In Figure 5.5, through Y axis, the changes in the intervals of time where State 1 and State 2 represent different time intervals is shown. Through the additional two axes Figure 5.5, the social integration strategies, which vary according to shifts in states, and the prioritization of the problem, which changes in the time interval is represented. The change in time cause the priority of problems (P) P1-P3 change as the time changes. Additionally, as illustrated by State 1 and State 2, the problem structure, social integration strategies, and the social environment continuously evolve across different states as time changes. It is shown form the example in the figure on how the priority of three problems (P1, P2, and P3) changes with states and the subsequent change in social integration strategies from SI1-SI6, as shown in Figure 5.5. Similarly, the social integration strategies employed by diverse stakeholders also evolve over time, influenced by stakeholder interactions and the current state's problem priorities. The consideration of evolution and the underlying principles are realized in the proposed approach to design public policies that is discussed in the following section.

Building Blocks of the Proposed Approach

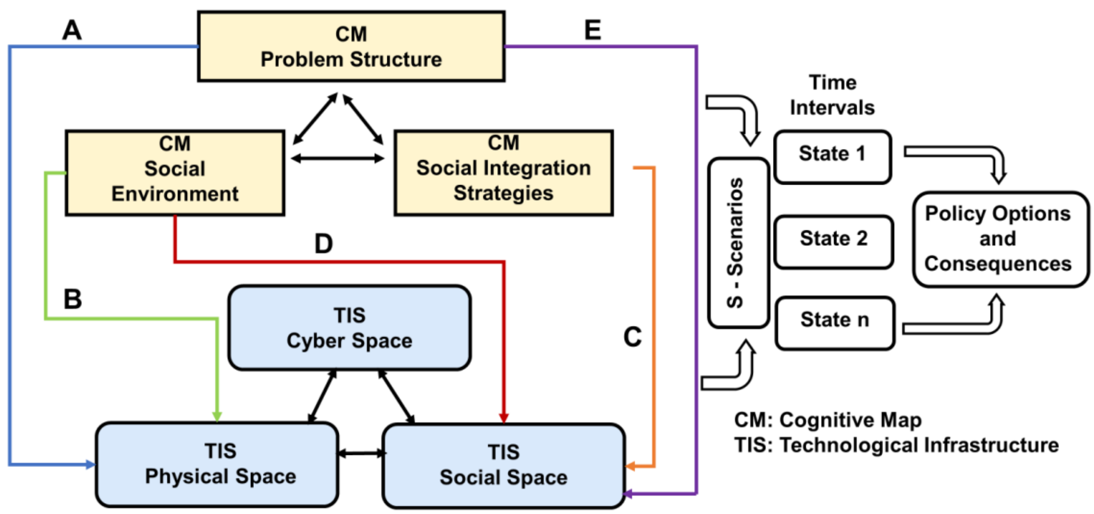

Figure 5.6: The building blocks of the proposed approach

In Figure 5.6 the building blocks of the proposed approach are shown. CM that stands for Cognitive Map that is Collective Adaptive Systems that is explained in detail in Section 5.4.3. The cognitive map is given its functional utility by integrating it with the E-CPSS construct that is the technological infrastructure of the proposed approach. The connectivity between the cognitive map and technological infrastructure is through the flow of information through connecting Arrows A-E, shown in Figure 5.6, which are described in Table 5.1. The different colors of Arrows A-E represent the distinct information that flows through them.

<table>
<tr><th colspan="3">Table 5.1: Description of arrows in Figure 5.6</th></tr>
<tr><th>Arrow</th><th>Connecting Elements</th><th>Information Flow</th></tr>
<tr><td>A</td><td>Physical Space (TIS) supporting the Problem Structure Space (CM)</td><td rowspan="2">Information on relevant constraints, regulations, and norms.
Information on context, scope, and objectives of the policy initiative.
Gathers data from entities associated with the problem structure, such as gadgets, vehicles, buildings, land, and sensors (emitting data like emissions, signals, etc.).
Information on majority of variables directly impacting the public policy.</td></tr>
<tr><td>B</td><td>Physical Space (TIS) supporting Social Environment (CM)</td></tr>
<tr><td>C</td><td>Social Space (TIS) supporting Social Integration Strategy Space (CM)</td><td>Information on differences in objectives of stakeholders including potentially conflicting goals and interests of various stakeholders.</td></tr>
<tr><td>D</td><td>Social Space (TIS) supporting Social Environment Space (CM)</td><td>Information on social interactions arising from stakeholder interactions
Information on interactions causing emergent behaviors.</td></tr>
<tr><td>E</td><td>Social Space (TIS) supporting Problem Structure Space (CM)</td><td>Information on social effects arising from the problem structure due to varying community norms and beliefs.
Information on trade-offs, conflicts, and synergies between competing objectives and stakeholder interests.
Information on stakeholder interactions, resulting effects like cooperation, coordination, and potential biases affecting problem structure.</td></tr>
</table>

The Cognitive Map for designers, along with data (as information – Table 5.1) gathered at specific time intervals such as State 1, facilitates the generation of diverse scenarios (as shown in Figure 5.6) corresponding to each state. The scenarios at different states are input to the computational model that will help designers to design policy options and their consequences. The design options and consequences are the output through this approach. This is done for the integration of different states under consideration to address evolution.

The further exploration of the proposed approach is through the following crucial steps:

I. Understanding the Cognitive Map in the context of Designing Public Policies.

II. Integrating the Cognitive Map with Technological Infrastructure – Exploring the information arrows in Table 5.1.

III. Understanding the proposed significance of scenarios, policy options, and consequences to design public policy.

Cognitive Map

In the context of Figure 5.6 and Table 5.1 the cognitive map is explained as follows.

(The explanation below is considered for one state, unless stated. The process followed for every state is same as explained below.)

- **Problem Structure:** Through this design stage the focus is on defining the problem for any given state (n). Here, we identify the stakeholders (social agents) impacted by the problem. These stakeholders possess distinct interests, objectives, viewpoints, and belief systems due to the structure of the problem. This establishes the requirement to handle these diverse viewpoints that is fulfilled by Social Integration Strategies.
- **Social Integration Strategies:** The utility of this space is to support the differences in objectives of stakeholders including potentially conflicting goals and interests of various stakeholders. The goal is to devise strategies for effective social integration.

- **Social Environment:** The focus through this space is to primarily emphasize on social interactions arising from stakeholder interactions (driven by social integration strategies). The objective here is to analyze how these interactions lead to emergent properties. Policy design necessitates understanding and incorporating the social networks that govern relationships between stakeholders, encompassing cultural norms and legal frameworks [218], [219]. The Social Environment Space considers all aspects of social agent and stakeholder interactions during policy design.

Integrating the Cognitive Map with Technological Infrastructure

E-CPSS and its Functional Spaces

E-CPSS comprises distinct spaces that support various aspects of the cognitive map (Refer Figure 5.6 and Table 5.1).

- **Physical Space:** This space has a crucial role in supporting both the problem structure and social environment (Arrows A and B; Figure 5.6, Table 5.1). The data is gathered from entities associated with the problem structure, such as gadgets, vehicles, buildings, land, and sensors (emitting data like emissions, signals, etc.). The objective through this space is to provide the majority of variables directly impacting the public policy. Understanding the individual and combined effects of these variables is crucial for effective policy design.
- **Social Space:** Through this space the functioning of the social integration and social environment spaces of the cognitive map (Arrows C and D; Figure 5.6, Table 5.1) is facilitated. Through this data pertaining to stakeholders, including their objectives, perspectives, preferences, and evolving interests is addressed.

Recognizing that models are abstractions of reality and traditional optimization techniques may not be suitable for complex systems, we propose a "satisficing strategy" (as outlined in [30]) to establish a problem space that meets the diverse requirements of stakeholders. (*Through this approach we acknowledge that finding an optimal solution might not always be appropriate, and seeks solutions that are "good enough" to address the complexities of the problem.*) The Social Space incorporates the interactions among heterogeneous stakeholders and their impact on public policy. It encompasses all stakeholder interactions, resulting effects like cooperation, coordination, and potential biases. Additionally, a connection from the problem structure space feeds into the Social Space (Arrow E; Figure 5.6, Table 5.1), reflecting the incorporation of social effects arising from the problem structure due to varying community norms and beliefs.

Cyber Space: When data encompassing all spaces of the cognitive model, namely the physical and Social Spaces, is consolidated, the Cyber Space of E-CPSS comes into play. Cyber Space interacts with the Physical and Social Spaces for two critical functions:

I. **Data Extraction and Integration:** The data is extracted from each respective space, combines it, and integrates it with relevant functionalities within the E-CPSS. This combined data serves as the foundation for further analysis and decision-making.

II. **Data Conversion:** The heterogeneous data collected from various sources is converted into a unified format suitable for further processing and analysis. This ensures seamless integration and exploration of the diverse data points.

Scenarios, Policy Options and Consequences for Designing Public Policies

Following the crucial data preparation steps explained in the Cyber Space, we propose utilizing the integrated and processed data to generate multiple scenarios for each state as shown in Figure 5.6. These scenarios serve as the foundation and input for designing effective policy designs. Analyzing multiple scenarios is crucial for understanding their potential effects and the overall behavior of the system under consideration. For **Identifying Effective Scenarios,** we propose leveraging deep learning and predictive analytics, incorporating a "satisficing strategy" [30], to identify suitable scenarios through multiple simulations. These Scenarios are then used as the basis for designing initial policy designs. By mapping various scenarios to corresponding policy designs, designers gain a stronger ability to formulate "**what-if**" questions based on computational evidence. This approach allows for a wider range of possibilities to be explored. By **predicting policy consequences,** utilizing the model's predictive capabilities based on the designed policies, we can further create different policy consequences. Understanding the potential consequences of near-future policies is vital not only for addressing system evolution but also for improving existing policy designs to more effectively address the problems at hand. **Understanding the Response of Policies,** The researchers have extensively explored the concept of response to policies and policy analysis that aligns towards reaction to policy [51], [224], [225], [226], [227]. Predicting and analyzing the potential consequences of designed policies closely aligns with comprehending the response to each policy option. While generating scenarios facilitates the creation of "what-if" questions, generating consequences effectively answers them.

The consequences of each **"Policy Option" (Refer Figure 5.6)** are then analyzed to arrive at the Policy Recommendation; see Figure 5.6. Implementing this approach provides another benefit: the ability to incorporate the considerations of other existing policies when designing new ones. This is facilitated by integrating relevant constraints, regulations, and norms guided through the Physical and Social Spaces within the E-CPSS. The interaction between these spaces allows policymakers to consider the effect of existing policies when designing new ones, a concept often referred to as "policy mix" in policymaking literature [185]. The proposed approach offers the advantage of being generalizable [212] to various policy issues, thus addressing several identified research gaps in policy design literature.

By embracing this framework, policy designers gain the opportunity to approach policymaking through the lenses of satisficing/optimization, exploration, and co-creation *(Section 5.3).* By allowing designers to analyze various scenarios and their consequences we facilitate the design to be seen from a *satisficing* (as contextualised with optimization in literature) perspective where designers can make good enough choices considering uncertainties and constantly evolving environment. Designers can utilize various computational methods and attain a wide variety of functionalities including finding robust solutions to analyzing various scenarios and consequences. Further, our main objective is to provide policy options to decision makers in order to design a policy, which advocates the idea of *design as exploration*. We intend to provide robust solution space to decision makers that provides better scope for decision makers to select policy options. Further, by considering a vast region of social space we bring various stakeholders together in the design and account for their interaction. This facilitates collaborative design and thus advocates *design as co-creation*. Further, we provide an opportunity to speculate on the consequences of policy design that jointly supports Design as exploration and co-creation. Thus, the approach we have proposed enables designers to design policies with holistic considerations.

We started Section 5.3 of this chapter by stating the questions posed by B. Guy Peters [202] *"Are we yet able to produce policy designs that can indeed address social problems effectively and efficiently? And can we develop templates for interventions that can have utility beyond a narrow range of issues and a narrow range of contexts? Or should we be more concerned with specific designs for specific issues rather than assuming that we can develop generic designs? Does 'one size fit all' in policy designs, or do we need more finely tuned designs for each particular problem?"*

We have explored and proposed the utility of Collective Adaptive Systems as our cognitive map which is leveraged with E-CPSS as the technological infrastructure of our approach. We believe the incorporation of cyber, physical, and social elements provides a peripheral perspective in effective and efficient design of policies. This addresses the notion of 'human as object,' a significant challenge in design of public policies. Through the approach we have provided we not only consider human as object but also highlight the importance of interaction among different stakeholders. We have put forth this approach with the aim of ensuring its applicability in designing public policies that can be generalized to any problems. In this era of information, we advocate for considering system characteristics that generate an abundance of data, recognizing that problems are interconnected and nested, rather than approaching them in silos. Rather than outlining specific steps of a particular design method, the provided approach offers directional inputs, guiding the consideration of policy design within the broader public sphere to advance model based policy design. On one hand, this permits a structured approach, while on the other hand, it enables the accommodation of the specificities inherent in the issues and problems of policies tailored for individual domains. Further, in policy design, diverse problems demand unique solutions tailored to their specific features. However, a common thread that emerges is the need for an approach that focuses on essential objectives. Despite the individual nuances, a shared set of principles guides effective policy formulation, emphasizing a strategic focus on core objectives. Hence, a comprehensive strategy is essential, as proposed in Figure 5.5, encompassing the requirement of finely-tuned designs proposing specific policy options for individual problems, alongside a more generalized approach to designing public policies, as outlined in this chapter. In Table 5.1 comments on the incorporation of characteristics of policy mix (discussed in Section 5.2) through proposed approach is presented.

Table 5.1: Addressing Characteristics of Policy Mix through Proposed Approach

Characteristic of Policy Mix	**Incorporation with the proposed approach**
Consistency of Elements	Consideration of variables with respect to time. Consideration of different states of system at varying time intervals to address evolution.
Coherence of Processes	Through the proposed approach we can incorporate multiple viewpoints, preferences, goals, and objectives, of stakeholders. This is achieved by considering the social integration strategies. This is further expanded in the proposal presented in Chapter 6.
Credibility	This characteristic relates to the Verification and Validation of the proposed approach and model. This will be accomplished by taking the policy options attained through this model to policymakers who will assist in further modifying the model. The plan is explained in Ph.D. proposal presented in Chapter 6.
Comprehensiveness	This is ensured by considering the proposed approach to design public policies. This is addressed by considering social integration strategies, social environment, and problem structure through which designers can consider the relevant market, system and institutional failures, and the constraints placed by various actors and stakeholders.

5.5 SYNOPSIS OF CHAPTER 5

Through this chapter we propose a holistic approach to designing effective public policies, building upon the established literature in the field. The major objective through this chapter anchors in establishing a foundational model for designing public policy that will assist policy makers decision makers in making better informed decisions. The research gaps that we address through this chapter are:

- *How can the collective adaptation construct be applied to facilitate policy design within Evolving CPSS?* ***(RG3)***
- *What are the common themes, theories, and frameworks that emerge across the domains of public policy, and how can they be integrated to provide a comprehensive approach to design public policies?* ***(RG4)***

***Elevating the Role of Collectives in Policy Design* -** As highlighted in Section 5.2, the concept of "collectives" holds immense importance in policy development. We delve into the concept of "Policy Mix" and its fundamental building blocks, such as policy processes, elements, and characteristics (Sections 5.2.1-5.2.3). These sections not only present relevant literature but also incorporate our insights and arguments, emphasizing the importance of considering the broader framework of model-based design when designing policies for "collectives." We believe this shift from individualistic to collective-centric design methodologies is crucial for tackling complex societal challenges.

***Aligning Literature with the Broader Picture* -** Moving forward, Section 5.3 explores existing literature on public policy design, aligning it with our thoughts and suggestions that advocate for a broader view encompassing model-based design principles. Notably, we incorporate insightful questions posed by B. Guy Peters on "Designing Public Policy" that challenge the fundamental assumptions of traditional design approaches. Furthermore, we discuss three key design approaches, emphasizing our support for "satisficing" over pure optimization. This critical distinction acknowledges the inherent limitations of models as simplified representations of reality and recognizes the value of practical solutions even if they are not theoretically optimal.

***Introducing the Cognitive Map* -** Section 5.4 introduces our proposed approach to public policy design, leveraging Collective Adaptive Systems (CAS) as the core cognitive map. We emphasize the importance of the three fundamental layers within this map: social integration strategies, social environment, and problem structure. The success of this approach hinges on integrating this cognitive map with a multi-layered technological infrastructure known as an Evolving Cyber-Physical-Social System (E-CPSS), depicted in Figure 5.4. Section 5.4.4 details this crucial integration, demonstrating how the proposed approach leverages technology to support and inform policy decisions.

Embracing the Impact of Evolution - One of the overarching themes highlighted throughout the chapter is the importance of **evolution** in successful policy design. We consistently emphasize the **dynamic nature** of the interests of stakeholder, problem structure and the social environment, underscoring the need for policies that can adapt and evolve over time. Figure 5.5 in Section 5.4 visually demonstrates how the problem structure and social environment change across different states, highlighting the necessity for adaptable policy designs. By embracing and acknowledging this dynamic nature, we can create policies that are more responsive to the ever-evolving needs of society.

Revisiting the Fundamental Questions - After presenting our proposed approach and highlighting its key features, we revisit the fundamental questions posed by B. Peters Guy in Section 5.3. We believe that our proposed framework, which incorporates social data, embraces a "satisficing" approach, and leverages the power of E-CPSS, offers valuable insights and perspectives on these crucial questions. By engaging in further discussion and collaboration, we aim to stimulate progress in the field of public policy design, paving the way for creating policies that are more effective, adaptable, and responsive to the complex challenges of the contemporary world.

CHAPTER 6

CLOSURE: CONTRIBUTIONS AND Ph.D. PROPOSAL

The principal goal through this thesis is to establish fundamental and foundational models for designing public policies as an evolving Cyber-Physical-Social System. The thesis includes three major avenues that align with the broader perspective: (i) An approach to frame wicked problems through evidentiary and interpretive analysis, (ii) Cognitive map for Evolving CPSS that is established by identifying key characteristics and requirements that a designer must consider while design an evolving CPSS, and finally providing a definition of E-CPSS and (iii) Establishing a foundational model for designing public policy that will assist policy makers/ decision makers in making better informed decisions.

The primary motivation through this Thesis is to define my Ph.D. proposal that will be submitted to National Science Foundation. This chapter primarily consists of summary of the thesis and the way forward as the Ph.D. proposal. The research gaps, objectives, and the new knowledge presented through this thesis are summarised in this Chapter.

6.1 SUMMARISING CRITICAL ASPECTS OF THESIS

In this section the summary of critical aspects in Chapters 1-5 is discussed. The objective behind this is to provide a summary and discuss on the research gaps, objectives, and new knowledge through this thesis.

6.1.1 Framing Wicked Problems

Rittel and Weber define wicked problem as a class of social system problems which are ill formulated, where the information is confusing, where there are many clients and decision makers with conflicting values, and where the ramifications in the whole system are thoroughly confusing', which is considered as one of the earliest definitions of wicked problem; see editorial by Churchman. Rittel and Weber who enunciate the importance of correctly identifying and framing the wicked problem by stating "In that structural framework it has become less apparent where problem centres lie, and less apparent where and how we should intervene even if we do happen to know what aims we seek."

In Chapter 1, a framework to frame wicked problems is provided that taps into the synergy between human abilities and computational abilities by allowing the interpretation of multiple perspectives, preferences, issues, etc. that is backed by evidence generated by analyzing systems behaviour. We present a conceptual framework aimed at framing wicked problems by integrating interpretative and evidentiary analysis methods, utilizing the Dilemma Triangle Method for the former and System Dynamics for the latter. We emphasize the importance of framing wicked problems and underscoring their essence, allowing designers to comprehend the intricacies and systematically approach their resolution. By incorporating both interpretative and evidentiary analyses, we empower individuals involved in the process to consider human cognition, mental capacities, and socio-cultural factors. We contend that involving humans in the decision-making loop enhances the effectiveness of framing wicked problems, leveraging the synergies between human abilities and computational capabilities.

Analyzing the literature that is presented in Chapter 2 and Chapter 3, we cater to fill in the research gap to frame wicked problems by catering to various issues. These issues are addressed by the features of the framework. The features of the proposed framework are:

1. *Conversion of heuristics to insights.*
2. *Analyze interaction between variables and identify the correct size of the problem.*
3. *Maximizes synergy between human capabilities and computational abilities.*
4. *Integration of Interpretive and Evidentiary Analysis.*

The test problem that is used as a wicked problem anchors in an example of a village in India, named Kantashol in the state of Jharkhand. The test problem is presented in Section 3.3

By employing this framework and simulating the system to analyze its behavior, we identify the wickedness in the problem by closely examining the interaction among variables.

Framing wicked problems aligns with the broader vision of designing public policies. We hypothesize that public policy is an evolving cyber physical social system. We recognize that the social problems are wicked problems and they cannot be addressed or designed by traditional systems practices and methods.

6.1.2 Evolving Cyber Physical Social System (E-CPSS)

In the literature of Cyber Physical social systems there is ambiguity for the meaning and various considerations of social space. This confusion is owing to the fact that CPSS is a relatively new field. We tap a relatively recent paradigm of Evolving CPSS. As presented in Chapter 4, we define E-CPSS as *"An E-CPSS is a system comprising of at least one cyber, physical and social component which exists or emerges due to the interaction between the tri-space leading to the changes in the behavior and structure over discrete states to achieve a defined function which may or may not change with respect to the states in an uncertain and a complex environment."* We present the foundational model to design an Evolving CPSS in Chapter 4. We define the characteristics of E-CPSS and enlist the key requirements that a designer should consider to design an E-CPSS. The requirements are from the perspective of function, behaviour, and structure. This will be the foundational considerations for designing E-CPSS. Further, there are various frameworks that are briefed that have the potential to be leveraged to be utilized in evolving CPSS.

The fundamental model established and presented in Chapter 4 will further open up various research avenues in this domain of research. We pose important challenges and potential avenues of exploration.

CHALLENGES

Challenge 1: Addressing evolving Cyber Physical Social systems.

Challenge 2: Uniform modeling of cyber, physical, and social spaces.

Challenge 3: Realizing the social dimension and incorporating endogenous and exogeneous social space to effectively design E-CPSS.

POTENTIAL AVENUES OF EXPLORATION

1. Modeling public acceptance for design options for the social problems prevailing in the society as an E-CPSS?
2. What is the method to model human judgement (and other human reliability assessment factors) in order to enhance the social capabilities for decision support for an E-CPSS?
3. How can you enhance the real time decision-making by enhancing the predictive capabilities while designing an E-CPSS?
4. What are the computational capabilities required to establish scenario-based modeling techniques for addressing the social space in an E-CPSS?
5. What foundational knowledge is necessary for predictive analysis, enabling the anticipation of different states within an E-CPSS by examining past states and forecasting future states, which holds critical importance for E-CPSS?
6. What is the new knowledge required to propose the FBS design model for an E-CPSS to account for the evolving system behavior and structure for the desired function?
7. What are the mathematics required to address E-CPSS and subsequently design it for decision support of complex systems?
8. What effect will trust, cooperation, coordination, etc. have on effectively designing for a robust E-CPSS?

6.1.3 Towards Designing Public Policies

To design effective public policies, it is essential to grasp the foundational principles of policy-making and incorporate the multifaceted nature of 'design'—both as a noun and a verb. In Chapter 5, we present an approach and a foundational model to design public policies by tapping the synergy between Collective Adaptive Systems as a cognitive map and Evolving Cyber-Physical Social Systems (CPSS) as the technological infrastructure. This chapter builds on previous chapters through which the focus was on framing wicked problems and establishing foundational models for Evolving-CPSS. In this chapter insights on design as satisficing, design as exploration, and design as co-creation is presented. The model presented in Chapter 5 aligns to incorporate these fundamental approaches of designing, thus allowing designers to design policies to find solutions, explore a solution space, and systematically speculate about multiple scenarios and its consequences.

6.2 SUMMARISING THE RESEARCH GAPS AND OBJECTIVES

The principal goal in this thesis is to establish foundational knowledge to design a public policy as an evolving cyber physical social system. Aligning with the broader picture, the primary interest is to assist decision makers in making better informed decisions by designing effective policies for the grand challenges the world is facing. Through this thesis, the objective is to propose and establish an approach to design policies that takes into consideration various factors that are discussed in Chapter 3 and Chapter 5. In order to provide a solid foundation in terms of the hypothesis – *Public Policy is an Evolving Cyber-Physical-Social System*, a detailed model including cognitive map, characteristics, and functional, behavioral, and structural requirements, of an E-CPSS is provided. This is critical to fill the gap in the literature in the context of basic knowledge of Evolving CPSS and a cognitive map that anchors in decision support for designers to design evolving Cyber-Physical-Social System. The models that are established in this thesis will be further utilised in my Ph.D. to design public policies, the details of which are given in my Ph.D. proposal that is described in Section 6.5 of this chapter. The research gaps addressed in this thesis are as follows:

Primary Research Gap: What foundational knowledge is essential for designing an evolving cyber-physical-social system to address significant societal challenges by expanding the scope of design engineering to previously uncharted social domains (like wicked problems) through a systems lens, with a focus on designing public policy?

The research gaps presented in Chapter 1 that are discussed in this thesis are as follows:

RG.1 How can wicked problems be effectively framed through the combination of interpretative and evidentiary analysis, incorporating human-computer synergies?

RG.2 What is the fundamental knowledge required in terms of key characteristics, requirements, and principles underlying design of Evolving CPSS, and how do they impact decision support in complex situations?

RG.3 How can the collective adaptation construct be applied to facilitate policy design within Evolving CPSS?

RG.4 What common themes, theories, and frameworks emerge across the domains of public policy, and how can they be integrated to provide a comprehensive approach to design public policies?

The research gaps, objectives and new knowledge is summarised as follows.

Research Gap 1: How can wicked problems be effectively framed through the combination of interpretative and evidentiary analysis, incorporating human-computer synergies?

Objective: *To frame wicked problems with the integration of human cognition, experience, and judgments through human-in-the-loop, and to comprehend system behavior by simulating the system and analyzing the interaction between variables.*

New Knowledge:

i. *An approach and a framework to frame wicked problems through* ***evidentiary*** *and* ***interpretive*** *analysis.*

Research Gap 1 aligns with the broader picture of designing public policies by understanding an approach to frame wicked problems. Public policies often involve social problems that are wicked in nature. Various approaches and viewpoints of perceptions of wicked problems are presented in Chapter 2. In Chapter 3, a framework to frame wicked problems through interpretive and evidentiary analysis is presented. Interpretive analysis is supported by utilising the Dilemma Triangle Method (Section 3.1.2.1). Through the Dilemma Triangle Method we carry out interpretive analysis which allows us to incorporate the behavioral, cognitive, and social elements in the analysis to frame wicked problems. This interpretive analysis further helps a designer to analyze the qualitative data involving interpreting the data from the perspectives of actors involved. This analysis engages ***human-in-the-loop*** that provides an opportunity to include insights and experiences in the framing of the problems. The second component of the framework focuses on establishing an approach to support interpretations with evidence, as suggested by the principles of system dynamics. Through this structured process a designer is able to simulate and observe the behavior of the system. A designer analyzes the effects of interaction among variables and gains insight into the important variables that affect/govern the behavior of the simulated system and also those variables that a designer is unable to control (Section 3.1.2). Thus, through the proposed framework, a designer can:

i. Convert heuristics into insights to frame a wicked problem through the integration of evidentiary and interpretative analysis.
ii. Understand the interaction between variables through behavior of the simulated system by the virtue of System Dynamics.
iii. Identify the correct size of the problem by eliminating the variables which do not impact the outcome/model, are not relevant to the wicked problem, or not under a designer's control.

The utility of the proposed framework for framing a wicked problem is:

i. Enhancing the synergy between human-computer interaction by allowing human-in-the -loop to enhance framing of the wicked problem through computational capabilities and human abilities.
ii. Enables a designer to convert the heuristics into insights through a structured process.
iii. Perfect integration of interpretative and evidentiary analysis to frame the wicked problems which forms the fundamental step of modelling a public policy.
iv. (Section 3.2)

This anchors in the ***Research Gap 1*** to provide a framework to frame wicked problems through evidentiary and interpretive analysis, by incorporating ***human abilities and computational capabilities.***

Research Gap 2: What is the fundamental knowledge required in terms of key characteristics, requirements, and principles underlying design of Evolving CPSS, and how do they impact decision support in complex situations?

Objectives:

ii. *Explore and establish the relationship between fundamental and application sides of the E-CPSS paradigm by exploring the design characteristics and requirements.*

iii. *Establish a list of requirements of E-CPSS characteristics to guide designers.*

iv. *Put-forth a cognitive map for E-CPSS.*

New Knowledge:

ii. *Establishing the definition of E-CPSS and providing a fundamental model to address decision-making through E-CPSS.*

iii. *Establishing the characteristics and outlining requirements that designers should consider to design an E-CPSS.*

iv. *A fundamental and foundational cognitive map to design E-CPSS.*

The importance of the social domain in the decision-making process is discussed in Section 4.2 and the cause and effect of evolution in social space with changing overall system architecture is put forth in Section 4.2.2 and Section 4.3. A comprehensive definition of an E-CPSS is provided in Section 4.3, alongside describing the system's evolving features and the behavioral and structural changes the system undergoes as a result of this evolving nature. This anchors in one of the elements of new knowledge through Chapter 4. Various key features emerging in the system as a result of its evolutionary behavior such as self-organization, self-adaptability, resilience, interoperability, context-awareness and many more are presented in Table 3 to aid the designer design for an E-CPSS. Based on the preliminary review of the state of the art, it is inferred that modeling and framework resources for designing for E-CPSS is an area of untapped potential, therefore potential models and frameworks are summarized and put-forth in Figure 4.6; Section 4.3.3, that are commonly used in numerous applications such as smart cities, intelligent transportation, water utility systems, etc. For this, Table 2 is put-forth identifying and classifying our study of state of the art to comprehensively categorize and summarize the findings. To realize these evolving attributes, various requirements are inferred and realized from the standpoint of Gero's FBS framework as shown in Figure 4.5; Section 4.3.3 with the intention to contribute to the design research community with the concept of concurrent designing for such systems. This would help underline the critical functional, behavioral and structural requirements to realize and showcase evolving characteristics discussed in Section 4.3.3. We also put-forth a cognitive map of an E-CPSS as shown in Figure 4.7 with reference to water utility systems to explain the decision-making process in an uncertain and a complex environment with constantly changing stakeholder needs and preferences. The map can be used by researchers and designers to understand the decision-making mechanism in an evolving environment which would help them to expand the model or revamp it according to their own objectives and problem statements. The purpose of presenting the cognitive map is to guide further research into the development of design procedures for developing frameworks for E-CPSS.

As CPSS evolves, new security and privacy challenges emerge. Learning about system evolution helps in identifying potential vulnerabilities and designing measures to ensure the security and privacy of sensitive data and operations in a large adaptable network handling large volume of heterogenous data. An in-depth study of E-CPSS can foster innovation by identifying opportunities for new features, services, or applications that arise as the system evolves. As CPSS continue to evolve, models can be updated to reflect new requirements, technologies, and insights. This allows for continuous improvement and adaptation to changing needs. Emergent behavior commonly observed in Collective Adaptive Systems (CAS) is a distinctive and an important characteristic of an E-CPSS which cannot be predicted, controlled or accounted for. Future studies can expand into looking for modeling and computational techniques to control and predict emerging attributes to prevent misbehavior and unaccounted, unplanned risks disrupting system performance.

***Research Gap 3* -** What common themes, theories, and frameworks emerge across the domains of public policy, and how can they be integrated to provide a comprehensive approach to design public policies?

***Research Gap 4* -** How can the collective adaptation construct be applied to facilitate policy design within Evolving CPSS?

Objective:

v. Propose an approach to design public policies by tapping into synergy between Collective Adaptive Systems (CAS) as a cognitive map and Evolving Cyber-Physical Social Systems (CPSS) as the technological infrastructure.

New Knowledge:

v. An approach for designing public policies by establishing the utility of interaction between E-CPSS and CAS.

In Chapter 5 a foundational model is presented to design a public policy by utilizing Collective Adaptive Construct as the cognitive map and E-CPSS as infrastructure. A detailed account of E-CPSS is provided in Chapter 4, where the Collective Adaptive System is briefed as one of the potential models that can be utilized in designing E-CPSS. Research Gap 3 is addressed in Chapter 5, where the discussion is laid in understanding pertinent principles and approaches of designing public policy. This is further expanded by providing a holistic approach to design public policies that addresses **Research Gap 3** and **Research Gap 4**, facilitating the objective and new knowledge in providing an approach to design public policy.

6.3 VERIFICATION AND VALIDATION

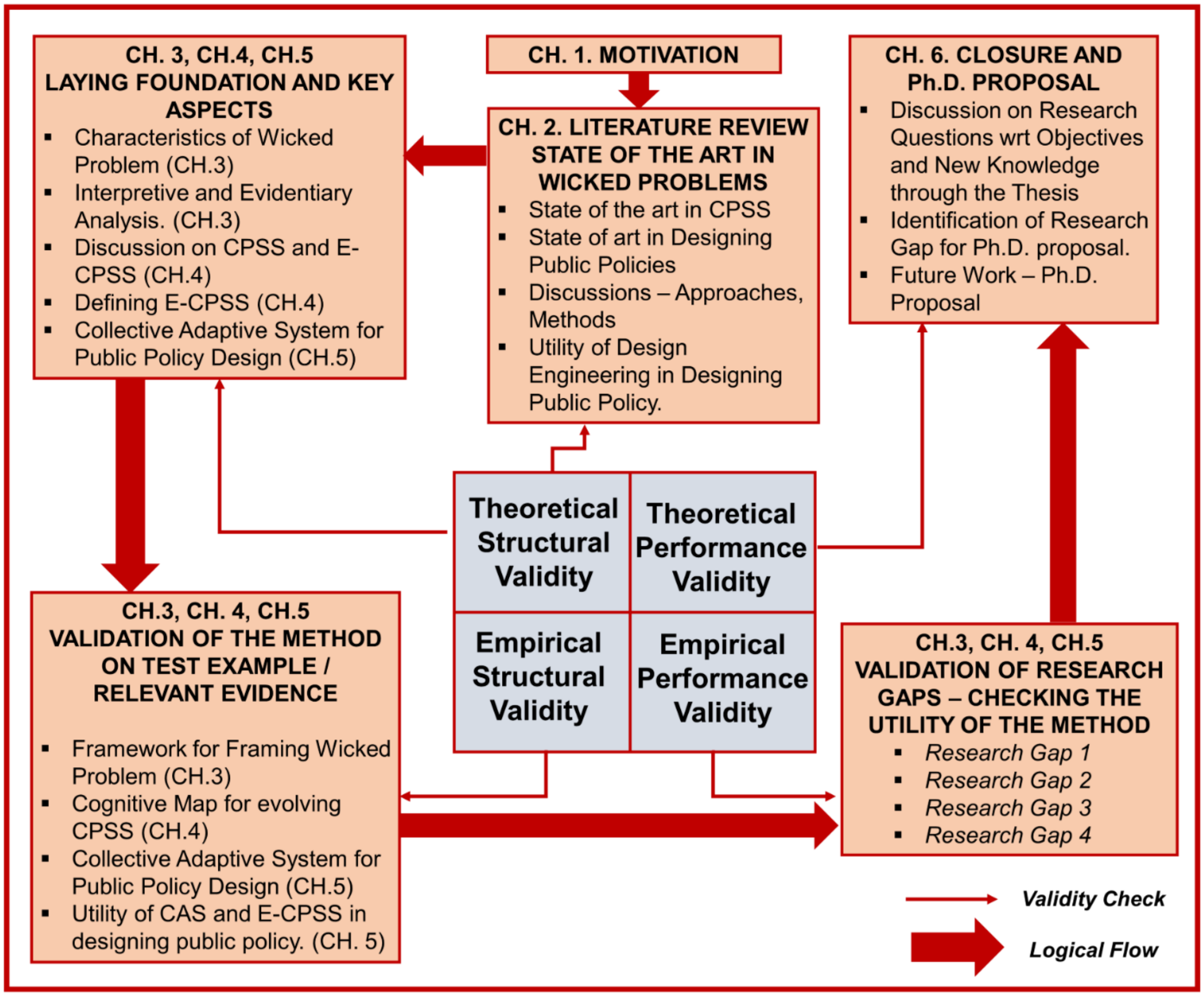

Figure 6.1 Validation Square

In Chapter 1, a detailed view of verification and validation is provided that outlines the tasks anchoring in each of the quadrant of verification and validation square. In the following section some light on verification and validation with respect to this thesis is shed.

6.3.1 Theoretical Structural Validation

The theoretical structural validation of the research method employed in this thesis is paramount for ensuring the internal consistency and logical soundness of its constructs, both individually and when integrated. In this quadrant, the focus lies on establishing the theoretical structural validity of the research method, encompassing its logical soundness, construct integration, and the development of hypotheses within the context of addressing complex social problems.

Critical Literature Review and Research Gaps

To make sure the ideas behind the research are strong, we first start by thoroughly checking what others have already written about similar social problems. Chapter 2, Chapter 3, Section 3.1; Chapter 4, Section 4.1, 4.2, and Chapter 5, Section 5.1, 5.2 and 5.3 systematically delve into the existing body of knowledge, outlining the intricacies of social problems. This literature review not only provides a foundation but also identifies research opportunities within the context of addressing social problems as complex systems. By the way this thesis is written, the relevant literature is provided at the start of each chapter owing to its transdisciplinary nature that makes it easy for readers to understand the logical flow of the chapter and back ground required to understand the accomplishments of objectives by addressing respective research questions. Thus, in Chapter 2 the relevant literature on wicked problems is presented, through Section 2.3 relevant literature on framing wicked problems and its importance is presented. The literature in Chapter 4, Section 4.2 makes case for the utility of consideration of social space and evolution in systems that is anchored in Evolving Cyber-Physical-Social Systems. The literature presented in this Chapter 4 is critical to establish the cognitive map for E-CPSS accompanied by its definition, characteristics, and functional, behavioral, and structural characteristics.

Logical Formulation of Research Gaps

Chapter 2, Chapter 3(Section 3.1) Chapter 4 (Section 4.1, 4.2), Chapter 5(Section 5.1~5.3) contribute to the theoretical structural validation by justifying the logical formulation of the research gaps. These gaps are meticulously crafted to encompass the identified research opportunities, ensuring that they appropriately cover the multifaceted aspects of complex social problems. The logical coherence of these hypotheses is crucial for establishing a robust framework for addressing the identified challenges.

Merits, Limitations, and Application Domains

Moving forward, the theoretical structural validation extends to Chapters 3, 4, and 5, where we delve into the merits and limitations of the developed research framework. Identification of these aspects contributes to the overall validation, offering insights into the strengths and potential shortcomings of the proposed method. This includes proposing a framework to frame wicked problems, providing a requirements list through FBS and Cognitive Map for evolving CPSS, and proposing a new approach for designing public policies.

Through this examination across chapters, the objective is to ensure the theoretical structural validity of the research method. This encompasses not only addressing the internal consistency and logical soundness of individual constructs but also verifying their integration within the broader framework. The thorough exploration of literature, formulation of logical hypotheses, and the assessment of merits and limitations collectively contribute to a robust foundation for the subsequent phases of validation and performance evaluation.

6.3.2 Empirical Structural Validation

Empirical structural validation in this research scrutinizes the efficacy of the research method in generating practical results for comprehensive issues within evolving cyber-physical-social systems and public policy design.

It is worthy to note that, in this thesis, the main goal is to develop fundamental and foundational models that are used to define the Ph.D. proposal. This anchors in bridging the gap in foundational knowledge. These models will be used in PhD. research and thus play a crucial role in deriving analytical results throughout the Ph.D. research. Additionally, beyond this objective, there are several critical aspects that correspond to empirical structural validation.

Challenging Aspects for Testing Research Gap 1 and Objective 1 (Chapter 3)

RG.1 How can wicked problems be effectively framed through the combination of interpretative and evidentiary analysis, incorporating human-computer synergies?

Objective (O1): *To frame wicked problems with the integration of human cognition, experience, and judgments through human-in-the-loop, and to comprehend system behavior by simulating the system and analyzing the interaction between variables.*

Chapter 3 confronts the challenging aspects of framing wicked problems, asserting their relevance to Research Gap 1. The framework is tested through an example of wicked problem, in Kantashol village, in Jharkhand as described in Section 3.3 and further the utility being demonstrated in Section 3.4 defends the appropriateness of these aspects, forming a crucial step in validating the first objective to provide an approach and a framework to frame wicked problems.

Challenging Aspects for Research Gap 2 and Objective 2,3,4 (Chapter 4)

Research Gap 2: What is the fundamental knowledge required in terms of key characteristics, requirements, and principles underlying design of Evolving CPSS, and how do they impact decision support in complex situations?

Objectives (O):

- ***i.*** *Explore and establish the relationship between fundamental and application sides of the E-CPSS paradigm by exploring the design characteristics and requirements.* ***(O2)***
- ***ii.*** *Establish a list of requirements of E-CPSS characteristics to guide designers.* ***(O3)***
- ***iii.*** *Put-forth a cognitive map for E-CPSS.* ***(O4)***

In Chapter 4, the focus shifts to challenging aspects of addressing evolving systems, aligning them with the requirements of Research Gap 2, thus, getting a step closer to the big picture of designing public policy as an evolving CPSS. Rigorous deliberation and argumentation establish the suitability of these aspects for testing the second hypothesis.

Through this a logical method to address evolving CPSS is proposed that is backed by a water utility system example as demonstrated in Section 4.4. This method will be further leveraged in Ph.D. research as planned in Ph.D. proposal, Section 6.5.

Challenging Aspects for Research Gap 3 and Research Gap 4 (Chapter 5)

***Research Gap 3* -** What common themes, theories, and frameworks emerge across the domains of public policy, and how can they be integrated to provide a comprehensive approach to design public policies?

***Research Gap 4* -** How can the collective adaptation construct be applied to facilitate policy design within Evolving CPSS?

Objective (O5): Propose an approach to design public policies by tapping into synergy between Collective Adaptive Systems (CAS) as a cognitive map and Evolving Cyber-Physical Social Systems (CPSS) as the technological infrastructure.

In Chapter 5 the focus is to navigate through the intricate elements of collective adaptation for public policy within evolving CPSS. The aim is to understand and address the dynamic interplay among social agents, technological advancements, and policy frameworks. By justifying the relevance of these challenges to Hypothesis 3, the research demonstrates its effectiveness in facilitating informed decision-making in complex socio-technical systems.

Challenging Aspects for Research Gap 4 (Chapter 4, 5, 6)

In Chapters 4, 5, and 6, a comprehensive analysis of the complexities involved in designing public policy is provided. With a specific focus on Research Gap 4, the aim is to incorporate human behavior, social dynamics, and technological advancements into policy frameworks. Through in-depth analysis and argumentation, the research highlights the importance of these facets in validating the fourth hypothesis, showcasing its practical relevance in shaping effective public policies.

6.3.3 Empirical Performance Validity

The assessment of empirical performance validity involves evaluating the research method's effectiveness in producing valuable and practical outcomes that contribute to a deeper understanding of complex issues.

Validation of Research Gap 1 and Objective 1 in Framing Wicked Problems (Chapter 3) (RG1, O1)

Discussing the results obtained from demonstrating the framing of wicked problems (Section 3.5). This is validated by the logical correctness of the results through System Dynamics and framing of the problem, while getting inputs from the actual team working at the ground. This is further explained in Chapter 3, Section 3.5

Validation of Research Gap 2,3,4 and Objectives 2,3,4 in Evolving CPSS and Public Policy Design (Chapter 4, 5) (RG2, RG3, RG4)

The foundational models are developed and presented in Chapters 4 and 5 that will be validated in Ph.D. However, the models are developed by critical review of literature, analysis of gaps, ensuring appropriate connectivity and logic between the elements of the model. Thes models in future will be validated not just through computational simulations, but also by gaining feedback from the policymakers, as described in detail in the Ph.D. proposal.

6.3.4 Theoretical Performance Validity

The establishment of a leap of faith is intricately woven into the process of building confidence in the general utility of the design method, encompassing the strategic steps outlined from in 6.3.1-6.3.3.

Evaluate Logical Coherence and Internal Consistency (Chapter 1)

In Chapter 1, a meticulous evaluation is undertaken to scrutinize the logical coherence and internal consistency of this thesis.

Theoretical performance validation serves as a critical component in this research endeavor, aimed at evaluating the logical coherence and internal consistency of the developed theoretical framework for addressing multifaceted issues. Chapter 2 further examines the alignment of research questions with the overarching objectives of the study and the theoretical underpinning, ensuring a cohesive and purpose-driven approach. Chapters 3 delves into how theoretical constructs are employed to frame wicked problems and understand evolving cyber-physical-social systems, demonstrating the practical application of the theoretical framework in addressing real-world complexities. Chapters 4 and 5 play a crucial role in bridging the knowledge gap concerning evolving Cyber-Physical-Social Systems (CPSS) and public policies, which are then integrated into Chapter 5. This anchors in the gaps identified in Chapter 2 followed by the literature provided in each of Chapters 3, 4, and 5 of this thesis.

Further, when discussing the opportunities and constraints of the theoretical framework in Chapters 3, 4, and 5, its applicability in the context of designing public policy and addressing complex societal challenges is acknowledged. It is imperative to note that the approaches provided in Chapter 4 and 5 will serve as foundational knowledge for further utilization in future research endeavors, particularly in the pursuit of a Ph.D. This thesis aims to establish a foundational gap of knowledge, paving the way for the development of fundamental and foundational knowledge to address evolving socio-technical challenges comprehensively.

6.4 ACHIEVEMENTS AND CONTRIBUTIONS

The major contribution through this thesis is to provide fundamental and foundational knowledge to design public policy as an evolving cyber physical social system. The achievement through this thesis is to cater to the void of assist decision makers in designing public policies to make better informed decisions. While this anchors in the broader accomplishments through this thesis, more specific contributions through this thesis include in providing fundamental frameworks, approaches, and methods in designing public policies. Through this thesis, an effort is put forth to provide an example of transdisciplinary research, thus, showcasing the integration of diverse fields including comprehending social problems that are wicked in nature, establishing fundamental knowledge in the paradigm of evolving cyber-physical social systems, and strategically designing public policies, that builds on the first two domains. This includes contemplation of cognitive maps as well as the technological infrastructure required to design systems that are anchored in policy-making. The specific contributions through this thesis are outlined as follows.

6.4.1 An Approach and a Framework to Frame Wicked Problems by Evidentiary and Interpretive Analysis (Chapter 3; New Knowledge 1)

The initial contribution of this thesis revolves around the development of a framework to assist designers in framing wicked problems, thereby enhancing understanding of these complex issues. This framework enables the integration of human capabilities and computational resources to effectively address wicked problems. The significance of this new knowledge lies in its practical functionality and effectiveness, as encapsulated in the following key points.

6.4.2. Definition of Evolving Cyber Physical Social Systems (E-CPSS) (Chapter 4; New Knowledge 2)

A notable gap in the state of art anchors in the void in clear definitions and perspectives for evolving cyber physical social systems. Through this thesis a clear definition of E-CPSS derived from the state of art is established that happens to be a new knowledge in the state of art. This contribution not only provides clarity and direction but also paves the way forward for establishing comprehensive frameworks and methods essential for designing systems that are responsive and adaptive to the complexities of ever evolving society. By bridging this gap, through this work it is aimed to contribute to the broader advancement of design and systems knowledge, facilitating the development of fundamental methods to address evolving societal challenges.

6.4.3. Establishing Foundational Knowledge on Evolving Cyber Physical Social Systems (E-CPSS) (Chapter 4; New Knowledge 3, 4)

Through meticulous examination of the literature, in this thesis, the essential features and characteristics of Evolving CPSS (E-CPSS) are established, thereby highlighting their practical significance in navigating evolving decision-making environments. Additionally, the introduction of a cognitive map delineates these identified characteristics, offering designers a comprehensive understanding of the system's evolutionary trajectory amidst uncertainties. This contribution not only provides valuable insights but also identifies potential avenues for further exploration and addresses research gaps within the field.

6.4.4. A foundational approach to design public policies by establishing the utility of interaction between E-CPSS and Collective Adaptive Systems (Chapter 5; New Knowledge 5)

The primary objective through this thesis is aimed at establishing fundamental models required to design public policies as an Evolving Cyber Physical Social System. Thus, one of the major contributions through this thesis revolves around establishing fundamental models and approaches in designing public policies.

Through this contribution a method and an approach are proposed by conceptualizing Public Policy as an Evolving Cyber-Physical-Social System (CPSS). Through this approach Collective Adaptive System (CAS) is utilized as the cognitive map and CPSS as its technological infrastructure. Employing this method, allows designers to grasp the dynamic interactions among social agents, social environments, and the structural facets of a given problem. By adopting a comprehensive perspective rooted in CPSS principles, through this approach it is aimed to empower the design of holistic and flexible public policies that adeptly respond to the ever-evolving societal needs. The broader implication of this contributions lies in enhancing the decision-making abilities of policymakers, guiding them towards the development of adaptive and responsive public policies.

6.4.5. Foundation for Future Research

As explained in Section 1.6 of Chapter 1, the primary motivation behind this thesis is to lay the groundwork for a Ph.D. proposal. Through this research, the intention is to extend and build upon the fundamental and foundational models established within this thesis. The major contribution of this work lies in defining the Ph.D. proposal that is to be submitted to the National Science Foundation.

This contribution not only involves defining the research for my Ph.D. but also establishes a direction for my research after completion of my Ph.D., aiming to chart a course for further advancements in the design and engineering of complex systems. The goal is to address societal problems more efficiently by pioneering innovative approaches in system design and engineering.

6.4.6. Towards Generalizability

While public policy serves as a prominent application domain, the methods and insights developed are inherently generalizable, with broad relevance across various domains. Through meticulous investigation and foundational approaches, the goal is to provide methods for the design of complex systems, offering invaluable tools for tackling multifaceted challenges across diverse contexts. Specifically, the research delves into the intricacies of designing Evolving Cyber-Physical-Social Systems (E-CPSS), addressing the evolving landscape of technological integration and its implications for society.

Furthermore, by advancing design engineering principles, this work not only enhances our understanding of complex systems but also empowers practitioners with practical frameworks to navigate and innovate within increasingly intricate environments. Thus, while rooted in the context of public policy, the emphasis is placed on transcending disciplinary boundaries, thus, offering transformative insights with far-reaching applicability and significance.

6.4.7. Scholarship Achieved Through the Thesis

The academic scholarship achieved through this thesis is summarized in Table 6.1.

Table 6.1: Academic Scholarship through Thesis

Sr. No.	Title	Thesis Chapter	Journal/Conference
1.	**Conference Paper:** Framing Wicked Problems through Evidentiary and Interpretive Analysis	Chapter 3	ASME IDETC
2.	**Journal Paper:** On Designing Evolving Cyber-Physical-Social Systems (E-CPSS): A Decision-Based Design Perspective	Chapter 4	Under Review: IEEE Transactions on Systems, Man, and Cybernetics: Systems
3.	**Journal Paper:** Designing Public Policies for The Future: Embracing A Systems Perspective	Chapter 5	TBD
4.	**Proposal:** Integrated Policy Design for Public and Private Interests	Chapter 6	National Science Foundation

One of the significant outcomes through this thesis is to define a Ph.D. proposal that is submitted to NSF. Through this proposal an elaborate technical definition of the conceptual models developed in this thesis is provided, that is further augmented by a plan of action and research stages during Ph.D. The details of this proposal are described in Section 6.

6.5 Ph.D. PROPOSAL

Eager: Integrated Policy Design for Public and Private Interests

"The Engineering Design and Systems Engineering (EDSE) program supports fundamental research that advances design science and/or systems science through the creation of new knowledge about the design of engineered artifacts. Engineered artifacts include, but are not limited to, devices, products, processes, platforms, materials, organizations, systems, and systems of systems."

In our case, the artifacts to be designed are "policy options."[1]

Government, Industry, and the Community are major stakeholders addressing grand challenges such as climate change and healthcare. We recognize the need to discover an approach to help policymakers understand how decisions involving multiple public and private interests can be integrated. We **hypothesize** that such problems can be modeled computationally as Evolving Cyber-Physical-Social systems (CPSS). We **recognize** that computational models are abstractions of reality and of differing fidelity. We **suggest** that researchers in the design community have developed theories and tools to address problems associated with grand challenges, typically from a cyber-physical perspective. In this proposal, we **propose** to address the following question:

What are the fundamental theories and principles needed in the model-based design and systems engineering to facilitate decision-making in public and private entities to consider concurrently competing and conflicting objectives, opinions, and preferences of the

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[1] NSF EDSE - https://new.nsf.gov/funding/opportunities/engineering-design-systems-engineering-edse

Note: A different numbering system "P.X" is adopted within the proposal in Section 6.5 to navigate the complexities of subsection numbering. The proposal is an integral part of Chapter 6 of this thesis, ensuring clarity and coherence in its structure.

stakeholders and understand their effects to generate, adopt and evolve policy decision options for the problem structure of the social problems to be addressed?

Why is this Research Appropriate for an EAGER Proposal?

We seek funding to support an exploratory and untested construct, namely, public policy that can be designed as an evolving cyber-physical social system. If successful, it could lead to transformative outcomes. Some of the untested issues in the design of public policy include:

- Understanding the interconnections and interactions among human behavior, problem structure, and possible public policy engineering solutions required to design public policy. The stakeholders in public and private entities are characterized by discrete and often conflicting objectives, opinions, and preferences.
- Public officials are often motivated by votes; they see the large picture and have distinctive constraints [246]. Members of the public often focus on factors affecting daily life, such as jobs, clean air, excellent infrastructure, and services. For industry, of course, the focus is usually economic. We propose to explore methods for integrating the CPSS anchored in design theory and principles that allow us to identify the consequences of implementing proposed policies.
- To establish the efficacy of our approach we plan on focusing on Environmental Justice in Oklahoma City and Houston, TX. If successful, we envisage laying the foundation for transdisciplinary, convergence research that is of current interest to NSF, for example, Environmental Stressors and Equity, Health Equity, and Climate Change.

P1. GAPS AND UNTESTED CONSTRUCT FOR RESEARCH

In Table P1, we identify the papers that have allowed us to identify the gaps and propose a way of advancing design engineering to a new domain, namely, integrated policy design for public and private interests, Figure P1.

Table P1. Gaps in designing public policy

Category	Paper No.
Considerations for Designing Public Policy	Added in the submitted version
Cyber-Physical-Social Systems	
Social Integration and Stakeholder Modelling	
Collective Adaptive Systems	
Design Models, Methods, and Approaches Reinforcement Learning and related	

In Figure P1, based on our critical evaluation of papers, we propose an untested construct for how stakeholders can make decisions for designing public policy. The construct proposed in Figure P1 is logical but untested. Embodied in Figure P1 is our contention that addressing decision-making in public and private entities with different objectives and constraints requires exploring approaches to frame the problem and explore alternative solutions. This includes providing multiple scenarios to the stakeholders that can be analyzed from individual stakeholder and collective stakeholder perspectives. Being able to propose underlying scenarios for decision-making, together with the capability to demonstrate impact, adds transparency to the public policymaking process.

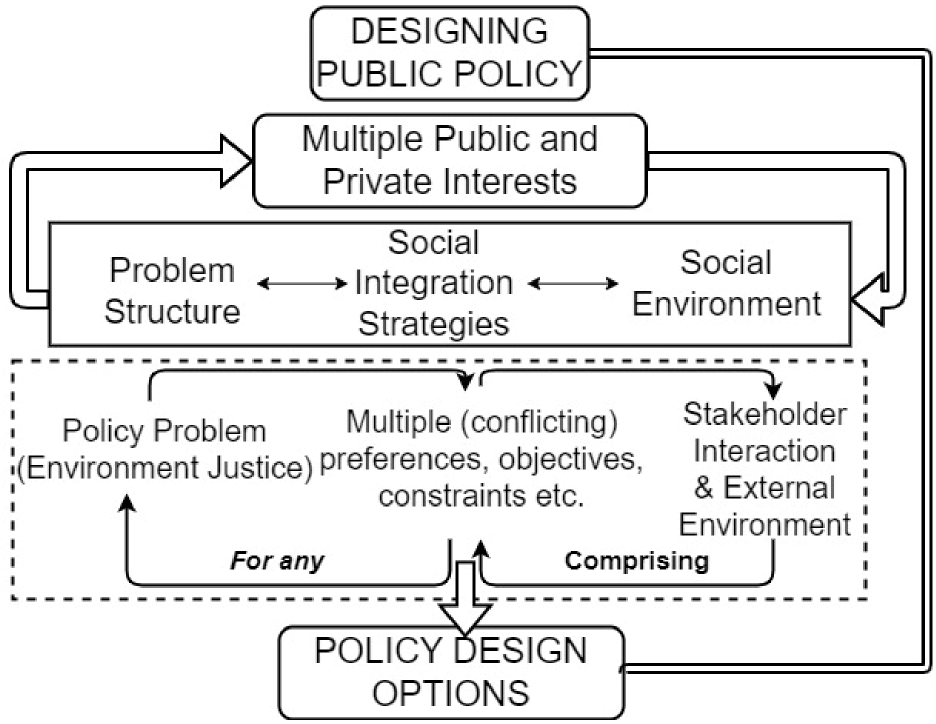


Figure P1: Untested construct for designing public policy as an evolving cyber-physical-social system

P2. PROPOSED APPROACH

To discover an approach for guiding policymakers and understanding how decisions involving public and private interests can be integrated, we study the interactions among *social integration strategies, the social environment, and problem structure,* see Figure P1.

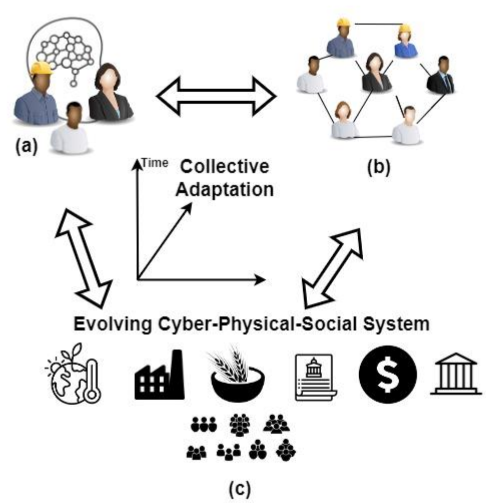


Figure P2: Collective adaptation for CPSS

To design public policy as an Evolving CPSS [296], we propose using the collective adaptation construct [123,148,236,237]. In Figure P2(a), we illustrate social integration strategies representing various stakeholders with conflicting objectives, opinions, preferences, and goals. The social environment influencing the interactions among various stakeholders is represented in Figure P2(b). This is critical to analyzing the effect of stakeholder interactions on the decision-making process and proposing an effective approach for various jurisdictions or public entities to consider accommodating opposing views. It is also important to capture the emergence of complex system-level behavior resulting from the interactions of multiple stakeholders pursuing multiple objectives in policy design. P2(c) represents the problem structure, which is the problem in the public sphere we are addressing. The dynamics of stakeholders' objectives and interests change over time. The research issue central to Figure P2 is rooted in the exploration of an effective approach to policy design by integrating public and private interests in the context of our demonstration problems: Environmental Justice in Oklahoma City and Houston.

In addressing decision-making in public and private entities, we propose to explore the integration of decisions involving multiple interests, recognizing the presence of multiple agents and objectives. We explore a method that can handle multiple conflicting objectives and preferences from multiple agents (stakeholders) without using conventional optimization techniques, which are inappropriate in practice, as models are just abstractions of reality [286,287]. Thus, we propose taking a Reinforcement Learning (RL) [247] based hybrid approach of Multiobjective RL (MORL) [248,249] and Multi-agent Reinforcement Learning (MARL) [250,251], namely, Multi Agent-Multi Objective Reinforcement Learning [252] by employing satisficing strategy. MORL is used to address multiple conflicting objectives, while MARL is effective in handling multiple stakeholders (who might or might not be decision-makers). The proposed approach is one of the underlying intellectual properties established through this thesis. We recognize three major stakeholders, namely, government, industry, and community, with multiple conflicting objectives.

The adopted hybrid approach enables us to address the inherent complexities involving multiple agents and conflicting objectives. Through this approach we will account for stakeholder goals and enable us to understand the collective outcomes through interactions and cooperation. It is critical to explore an approach to understand how policymakers can take opposing views into account to reach a shared solution. This necessitates coordination and collaboration among heterogeneous agents. Through this strategy we propose to address scenarios where trade-offs among conflicting objectives need to be reconciled. Further, this enables us to capture the emergence of complex system-level behavior. Employing these capabilities we will provide various integrative options to decision-makers to make better-informed decisions by considering the stakeholders' constraints, interests, and viewpoints. This approach fits the required functionality to provide policy options; however, it must be leveraged to cater to the need for practical utility to address the multiple conflicting objectives of the system's multiple agents. Using optimization techniques [253] in the learning algorithm [254] to find the best solutions using multiobjective optimization (e.g., Pareto front) [255], compounded by the learning processes in reinforcement learning, makes standard techniques unfit for practical uses. Instead, we plan to use techniques anchored in a satisficing strategy [288].

The inherent uncertainties that real-world decision-making often involves, which are characterized by evolving environments and incomplete information, makes the use of optimization inappropriate [286]. To reach shared solution spaces for decision-making, compromise and agreement is needed when public and private entities have disparate preferences. Optimization techniques emphasize a single solution, potentially neglecting the need to compromise. Thus, considering the practicality of consensus, optimization techniques will often give results but their utility to policymakers is questionable. The design challenge here lies in exploring methods anchored in a satisficing strategy in the reinforcement learning models. If this is shown to be successful, it will give the research community a unique method that is practical to use in designing public policy.

The building blocks of the proposed approach (Figure P4) is explained in Figure P3 to provide background of the proposed approach and the computational model. The basic idea of multi agent multi objective reinforcement learning by employing satisficing strategy is shown in Figure P3. Parts A, B, C, D and notations as provided in Figure P3 and P4 will further ensure.

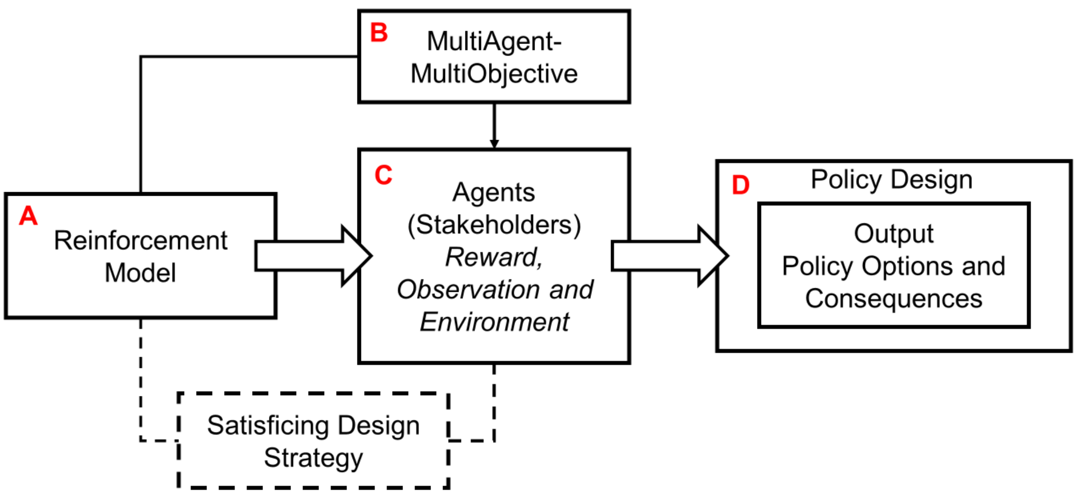


Figure P3: Basic Building Blocks of the Proposed Method

The utility of Reinforcement Learning to design public policy by considering multiple agents having multiple objectives by designing reward function for the environment in which the policy is designed is show in Figure P3. The building blocks are explained as follows.

Agents (Stakeholders): *(Refer B in Figure P3 and P4)* This refers to the various entities with a diverse interest, goals, and preferences in the policy being designed. The major stakeholders considered here are Government, Industry and Community (Refer Figure P4).

Reward, Observation and Environment: *(Refer C in Figure P3 and P4)* The environment refers to the context in which the policy will be implemented. The reward function determines the signal or feedback provided to the agents based on their actions within the environment. Observations are the perceptions that the agents receive about the environment.

Reinforcement Model: *(Refer A in Figure P3 and P4)* This model is a representation of the environment and how the agents interact with it. The reinforcement model is used to train the agents through a process of trial and error, allowing them to learn which policies are most effective in achieving their goals.

Policy Options and Consequences: *(Refer D in Figure P3 and P4)* The output through this model is integrated policy design that is obtained by offering policy options and their consequences. The policy design process takes into account the reward function, the environment, and the agents' objectives.

Satisficing Strategy: This is the strategy that will be employed to design policy that seeks to find a solution that is “good enough” rather than trying to find the absolute optimal solution.

In Figure P4, the detailed approach to design public policy by presenting policy options is presented.

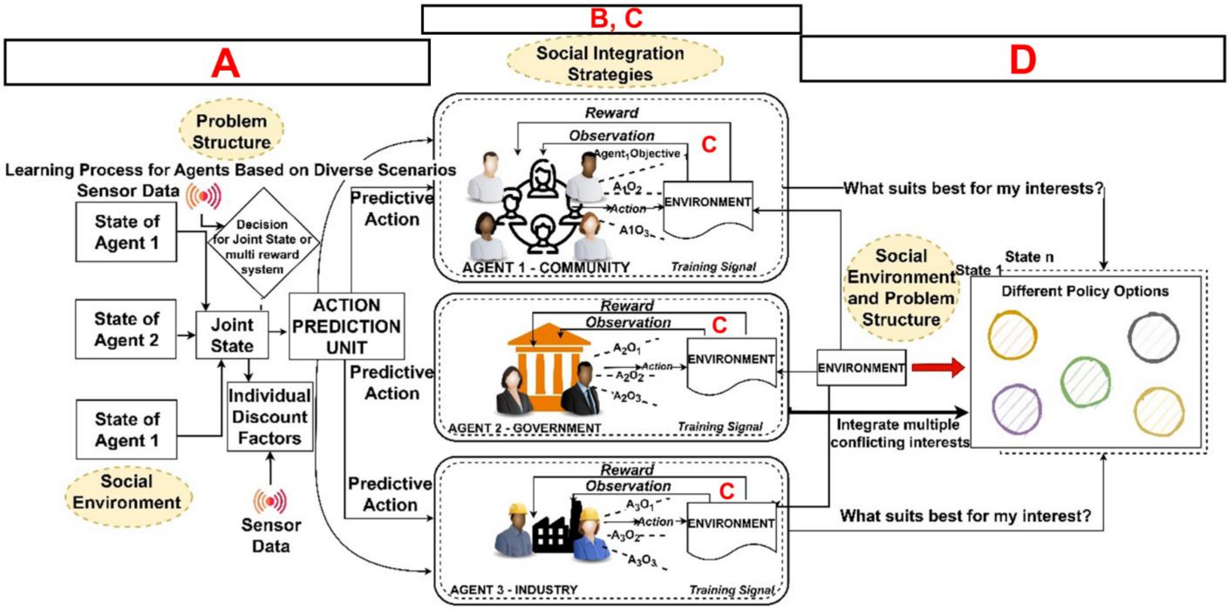


Figure P4: Cognitive Map - Multi Agent-Multi Objective RL for integrating public and private interests

As shown in Figure P4, through the proposed approach (to be developed as the algorithm) we accommodate the myriad objectives of individual agents, representing stakeholders such as Industry, Government, and Community (*Refer B in Figure P4*). The connection between the collective adaptive construct and the proposed method is shown in yellow dotted objects in Figure P4 (Refer Section 5.4.4 for details). Each agent is driven by multiple objectives. This is represented by A_1O_1, which signifies Agent 1 - Objective 1 and so on for A_2O_2 – A_nO_n. Given that every agent is in a specific state , as shown by State of Agent 1 - n, (*Refer A in Figure P4)*, it is intended to utilize this information to design reward factors both, for individual agents and the joint reward considering multiple agents to account for collectives of the system. To address this, we introduce a reward system *(Refer C in Figure P4*) based on the data (both-sensor and social) and then suggestions from the policymakers, that carefully balances the achievement of each objective against the others. The reward system *(for* *objectives)* will be further validated at the end of Year 1, as documented in the Research Plan. In the training phase, agents learn to make decisions by observing the outcomes of their actions. Further, based on modeling of agents and the action prediction unit (as shown in Figure P4) that is guided by the social data and the sensor data the predictive action is observed for a given reward function to understand the consequences of proposed policy design option. The iterative feedback loop refines their strategies over time. We envision discovering the utility of this approach by employing the principles of satisficing strategy, encouraging agents to make decisions that compromise between multiple objectives [286]. This strategy is encapsulated in a reward system *(for actions)* that fosters a balanced approach, ensuring no single objective dominates the decision-making process.

As discussed, in a multi-agent setting, through the proposed method, we will consider the joint policy states, considering the collective impact of agents' decisions. The training processes for each agent involves a discounted reward mechanism, where the temporal consequences [256] of decisions to design public policy as an evolving CPSS are considered. The algorithm will be designed to capture immediate rewards and long-term implications, promoting strategic decision-making. The introduction of discounted rewards for individual agents, based on their specific objectives, ensures a nuanced understanding of the consequences of their actions. Agents (here, stakeholders) engage in collaborative decision-making to reach integrated policy design options. This involves a sophisticated joint policy state consideration, where agents collectively assess the impact of their decisions on the overall system. Through this framework it is intended to encourage agents to find common ground, promoting synergy and compromise among stakeholders with diverse objectives. This collaborative approach ensures that the resulting policies align with the shared interests of

Industry, Government, and Community, fostering a holistic policy design process. Based on the results and performance of the algorithm, we will modify our approach, including incorporating other tools and techniques. This approach aligns with the broader objective of integrating public and private interests for policy design, where stakeholders, including Government, Industry, and Community, are represented as agents in the model. The hybrid satisficing-based Multi-Agent-Multi Objective Reinforcement Learning (MAMORL) framework thus becomes a powerful tool for holistic policy design, accommodating the intricate interplay of diverse objectives among multiple stakeholders, thus, integrating and satisficing public and private interests in designing public policy.

P3. TEST PROBLEMS FOR VERIFICATION OF EFFICACY OF MAMORL FRAMEWORK

P3.1 Test Problems – Urban Pollution

Urban atmospheric pollution is driven by policy decisions negotiated by competing interests, including local and regional governments, industry, and citizen groups. Various policies impact exposure to pollutants harmful to health and wellbeing, exemplified in extreme cases by the historic redlining of minority groups in dense clusters near industrial emitters where urban planning generates urban canyon effects, which further trap pollutants with known health impacts. As the environmental sensor revolution quietly takes place in our urban centers, an opportunity arises to use cyber-system infrastructure data in social decision-making frameworks. This will shape our physical future by helping planners make better-informed decisions and increasing transparency of the decision-making process. We will consider "Challenges" from two cities with very different environments, stakeholder needs, and buy-in levels for our public policy design goals. However, these challenges run parallel to each other. Both of our example cities, Oklahoma City and Houston, have similar atmospheric flow conditions as part of the central US flow stream, making many meteorologic conditions directly comparable in specific wind-fetch context.

P3.1.1 Test Problem 1 – Oklahoma City, OK (OKC)

Land use designations in Oklahoma City, OK (OKC) bisect commercial and residential areas with a belt of industrial zoning along the Oklahoma River, including emitters of CO_2, CO, and PM2.5. The residential zones in OKC were historically segregated by home loan risk associated with non-white populations prior to the Fair Housing Act of 1968. However, those racially distinct neighborhoods exist somewhat today, with denser populations nearest the river [258]. Gentrification has partially redistributed these neighborhoods, notably through the Metropolitan Area Projects (MAPS) in 1993 [259,260], to increase green space access to disadvantaged communities [261]. Instead, efforts outpaced residents' wealth through the updated 2017 MAPS Act that promises to create an "Innovation District" in a historically black neighborhood, moving more of the population and shifting the urban terrain [262].

P3.1.2 Test Problem 2 – Houston, TX

Houston, TX, has unique mixed zoning regulations, allowing industry and residential zones to intermingle, a paradigm acknowledged as a potential strategy for equitable urban design [263]. A high industrial load in the La Porte, TX region near the "Houston Shipping Channel" means that wind sources coming from the sea often carry emissions. This polluted upwind fetch often manifests as a stable boundary layer of dark brown smog during the early summer prior to a layer inversion, which mixes the pollution with low-level air. Similarly to OKC, racial "redlining" by home loan risk was reduced in 1968. However, traditional communities either persisted in rapidly gentrifying regions like "Freedmen's Town," increased housing density due to increased costs as in the second and third wards, or completely relocated as in the case of the disappearance of the original Houston "Chinatown" [264, 265, 266]. Unlike OKC, Houston has a mature Environmental Justice movement through groups like the Air Alliance Houston, which performs assessments and legal action [267, 268].

P3.1.3 Description of Work for the OKC and Houston Challenges

To study ways to model the impacts of policy decisions, we will study potential impacts on pollution in urban canyons when various policy options are implemented in a cyber reality. We will acquire data for this simulation using PM2.5 and CO_2 sensing devices by modifying equipment developed by Co-PI Honeycutt [269] in addition to analysis of meteorological data for individual test sites, including an equipment validation test prior to field experimentation at OU AQTLab as noted in a Letter of Support from Prof. Lee Fithian. Social data concerning the relationships between stakeholders for MAMORL analysis will be acquired through sentiment analysis of local reporting on policy decisions, e.g., the newspaper *The Oklahoman* for OKC, using search strategies developed in partnership with supporters at OU Libraries (see Letter of Support from Dean Denise Stephens). Finally, policy options derived from the analysis of the MAMORL algorithm will be considered by stakeholders such as the Council of Governments group represented in a Letter of Support, acting as "human sensors" for iterative assessment of the model. We will not directly poll or evaluate residents of traditionally redlined districts: we believe it would be unethical to apply the results of this model study without implementation preparedness and broader community support. In situations where observational data are unavailable, e.g., when sentiment analysis fails to assess a required relationship, simulated data will be generated as explained in Section P4.

Our project timeline prioritizes the OKC study with partners who already promised support in Y1. Example data streams described here or included via Letter of Support reflect OKC only. We will leverage Y1 progress to obtain equivalent partners and datastreams for Houston. Further details are included in the Research Plan.

P4. DATA ESSENTIALS

In Table 2, we summarize the essential data required from each stakeholder for our proposal. Acknowledging the potential data acquisition risks, we resort to Synthetic Data Generation methods in the instances of unavailability/missing of data. This is detailed in Table 2.

Table P2: Summary of data required from each stakeholder			
Gov: Government; Ind: Industry; Com: Community			
Gov	**Policy Documents**	**Historical Decision Data**	**Resource Allocation**
Utility	To provide the foundational principles and guidelines set by the government. **Source:** *This is a static variable during initial simulations, existing policy for Oklahoma is available through the public record.*	Insights from past decisions and their outcomes will provide a valuable context for understanding the decision-making landscape. **Source:** *The Oklahoman, using sentiment analysis to determine how votes were cast on a public policy decision.*	Data on budget allocation and resource distribution will help us understand government priorities and the allocation of resources towards environmental initiatives. **Source:** *We will use broad categories from the OKC budget [290]*

			as quantification of allocation, especially for special projects like MAPS [259,260]
Use in Model	Initialization: Initializing the model	Train the model to learn from past successes and failures.	Inform MORL model's objectives based on resource allocation.
	Reward Design: Existing policies can be used to design a reward structure in the MORL model.	Policy Evaluation: Use historical decisions to evaluate the impact of different policies and identify patterns in decision-making.	-
Ind	**Emission Data**	**Stakeholder Engagement Records**	**Compliance Data**
Utility	Information on emissions, resource usage, and operational parameters will help gauge the environmental impact of industrial activities.	Records of communication and feedback will provide insights into industry concerns, priorities, and willingness to engage in collaborative decision-making.	Records of compliance will demonstrate adherence to environmental regulations and policies.

	Source: *We will interpolate yearly emissions estimates from [291] and [292] with daily PM2.5, ozone, and pollen levels available from meteorology to estimate emissions background.*	**Source:** *Sentiment analysis of local reporting on policy decisions, e.g., the newspaper The Oklahoman for OKC, using search strategies developed in partnership with supporters at OU Library.*	**Source:** *Direct data are difficult to obtain, so we will simulate a range of compliance states (complete non-compliance, 10%, 50%, 90%, and total compliance) with respect to values reported in ACOG's Cost of Nonattainment Study [293]*
Use in Model	Reward Design: Emission levels and operational efficiency can contribute to the reward structure in the MORL model. To align objectives with environmental impact considerations.	Communication Channels: Use this data to simulate. communication channels in the MARL model. Also, this is useful to define how agents representing the industry engage with other stakeholders.	Incorporate compliance with environmental regulations as one of the objectives in the MORL model.
Com	**Public Sentiment Analysis**	**Community Concerns**	**Feedback on Past policies**

Utility	Extracting sentiments from relevant platforms will help gauge perceptions and concerns related to environmental justice. **Source:** *Initial values will come from sentiment analysis of local reporting in The Oklahoman in "man on the street" interviews.*	Understanding the community's specific concerns, preferences, and priorities is crucial for addressing EJ issues. **Sources:** *We will simulate concerns based on those frequently observed by other researchers e.g., NIMBY-ism, asthma reduction, employment rates, etc. Initial values will be based on OKC satisfaction surveys [294].*	Insights into how past policies have impacted the community help shape future policy considerations. **Source:** *Starting with simulated seed values, iterative meetings with ACOG will tune this portion based on their outreach experience.*
Use in Model	Reward Design: Public sentiment can influence the reward structure in the MORL model. Align objectives with community preferences.	Objective Definition: Reflect community concerns in the multi-objectives optimized by the MORL model.	Learning Objective: Train the hybrid model using feedback data to adapt policies based on community responses.

In Table P3, we have briefed the utility of the data in the proposed method to design public policy.

Synthetic Data Generation: As we recognize the risks and uncertainties associated with the collection and availability of data, we have crafted a comprehensive plan to address potential imbalances in the data and mitigate challenges related to data unavailability. We reviewed multiple synthetic data generation methods that primarily include various Generative Adversarial Networks (GAN), including Conditioned GAN [270], Information Maximizing GAN [271], GANs for tabular data including Tabular GAN [272], and CTGAN [273], Bayesian Networks [274, 275], Autoencoders [276], to highlight a few. These models are useful for generating synthetic data based on preliminary assumptions (Stage1) and then on real data, which will further aid us in verification and validation. We also acknowledge that there may be imbalances in the collected data. This can be seen in classification tasks. To create a concrete plan, we have reviewed methods including Random Oversampling [277], Synthetic Minority Oversampling Technique [278] and its multiple variants described in [279, 280, 281], ADASYN [282], Cluster-Based Oversampling [283], Gaussian Mixture Models [284]. The inclusion of social entities in research necessitates a careful selection of data generation methods. Due to the difficulties in finding preferences within public and private interests, we are restricted from using certain methods to address these issues. Other intricacies are associated with the characteristics of data. For example, non-gaussian and

Table P3: Data Usage in the Proposed Model

Learning Objectives	Policy Evaluation	Decision Support
Integration: Train the hybrid MARL and MORL model with government, industry, and community data.	**Scenario Testing:** Use the model to simulate different policy scenarios based	**Alignment:** Ensure that the model's LOs align with the principles outlined in policy documents, reflecting the

Policy Initialization: Use historical data to initialize the model and learn from past decisions and their outcomes.	on government data and evaluate their impact on industry and community objectives.	priorities of government stakeholders. **Continuous Learning:** Use ongoing data collection and feedback loops to refine and adapt the model over time.

multimodal distributions are often noticed and must be considered when generating synthetic data. It is often observed to have highly imbalanced categorical variables. This might result in mode collapsing and insufficient and inaccurate training for the minority classes. Considering the challenges outlined, we choose Conditioned Tabular GAN (CTGAN) for synthetic data generation. This method enables us to assess the correlation between any two columns and maintain the integrity of the joint distribution across all columns [273]. This will primarily be used in Stage 1 with iterative modifications. To address data imbalances arising from factors such as inherent class distribution, rare events, and data collection constraints, we will use Safe-Level SMOTE [280, 285]. This approach does not randomly generate a data point with respect to any point in the minority class but also considers the distribution of similar minority data points within the dataset.

P5. RESEARCH PLAN

Over the next two years, our research plan, as shown in Figure P4, will unfold in three stages, each strategically designed to contribute to the initialization and use of a Multi-Agent-Multi Objective Reinforcement Learning (MAMORL) algorithm based on a satisficing strategy. Our plan entails 3 major stages in 2 years as shown in Figure P4. In Year 1 - Stage 1, the focus is on data collection and synthetic data generation anchored in establishing the proposed algorithm, setting the foundation for subsequent stages to use the actual data collected in this stage. The expected output from this stage is on verifying if a MAMORL algorithm based on satisficing strategy is capable of handling diverse decision scenarios to consider multiple conflicting interests of the stakeholders in public and private entities is the appropriate way forward, thus enabling us with our objective to explore the untapped construct shown in Figure P1.

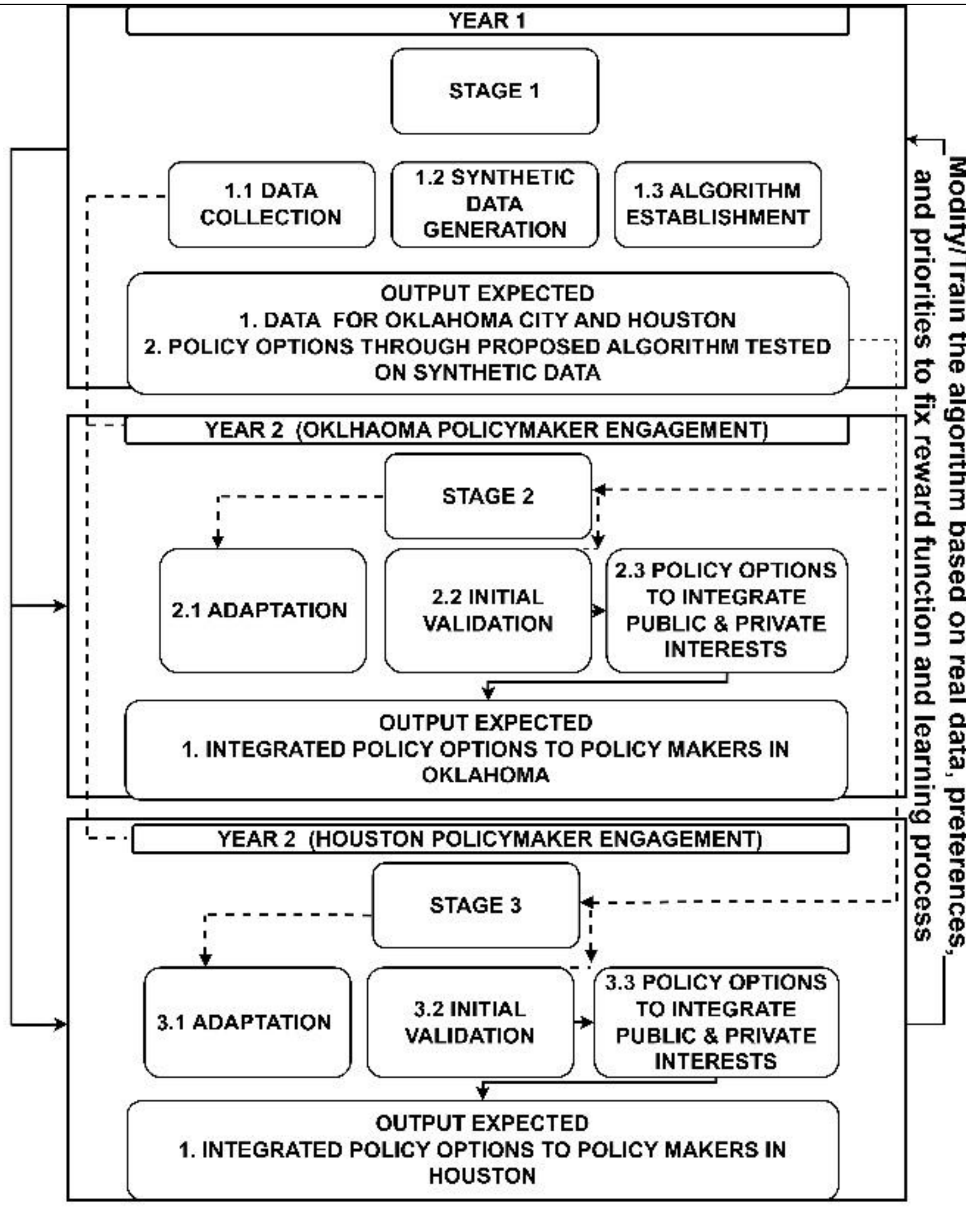


Figure P4: Research Plan

TASKS (T)

1.1 Data Collection

T1. Begin collecting actual data from stakeholders in both Oklahoma and Houston, focusing on public and private interests, preferences, and decision scenarios.

T1.1 Preprocessing of Data

1.2 Synthetic Data Generation

T2. Generate synthetic data representing various stakeholders' (Government, Community, and Industry) objectives, goals, constraints, interests, and preferences.

1.3 Algorithm Establishment

T3. Develop underlying principles to incorporate satisficing design theory into a hybrid multi-agent multi-objective algorithm.

T4. Develop a proposed algorithm using synthetic data.

T5. Define the initial reward structure and learning mechanisms.

T6. Implement the developed algorithm using synthetic data and learning mechanisms.

2.1. & 2.2 Adaptation and Initial Validation

T7. Present the initial algorithm and policy option landscape output to policymakers. Gather feedback on algorithm and policy options.

T7.1 Attain ranking for policy options from policymakers.

T7.2. Revise the learning process and policy reward structure in the algorithm.

T8. Run the algorithm with revised policy reward structure & learning mechanism &with the data collected in Y1.

T9. Present policy options to OK Policymakers.

T10. (3.1, 3.2, 3.3 – Stage 3) Follow Task T7-T10 for Houston. **T11. and T12.** Verification and Validation

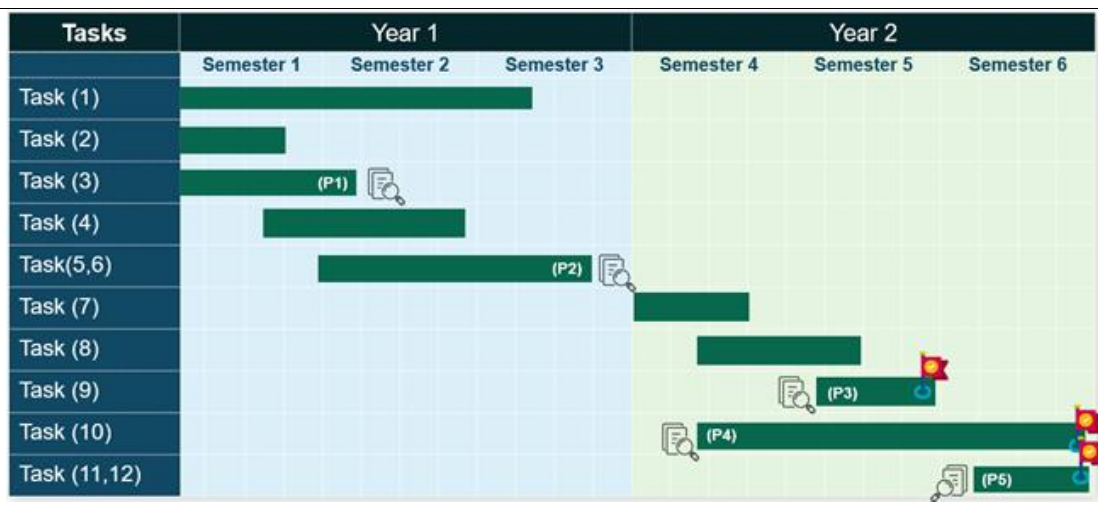
Stage 2 of our research plan, beginning in the second year, involves engaging with the policymakers in Oklahoma, presenting the algorithm and the results obtained from the synthetic data. This is an intricate process of obtaining feedback on the landscape of policy options in addressing conflicting objectives and preferences. We plan to provide policymakers with generated design options, incorporating their unbiased rankings to refine our model. This input is critical in deciding discounted rewards for crafting policy options within the evolving CPSS.

This ranking system is crucial input for the revision of policy rewards, ensuring that the algorithm aligns with local priorities and reflects the policymakers' option rankings. This is critical to provide integrated policy design options for public and private interests in Year 2. This iterative feedback loop enhances the algorithm's precision, reinforcing its utility to address environmental justice challenges.

P6. PROJECT MANAGEMENT AND TIMELINE

P= Planned Publications

Table P4: Project Timelines



Farrokh Mistree is responsible for the overall direction of the project. Both Farrokh Mistree and Janet K. Allen will supervise the graduate student who will develop the models and work with Dr. Honeycutt who will be responsible for designing the two test problems, data collection and interpretation and will take the lead in interactions with the communities involved.

P7. RISK MANAGEMENT PLAN

With the risk management plan, we ensure a resilient and adaptive framework.

Table P5: Risk Management Plan

Activity	**Risk Identification**	**Risk Mitigation**
Stage 1 Data Collection and Fundamental Algorithm Development (Tasks 1, 3, 4)	▪ Stakeholder non-cooperation or reluctance to share information ▪ Incomplete or biased data ▪ Difficulty in satisficing design principles ▪ Unavailability of data for some attributes for various reasons	▪ Establish clear communication channels with stakeholders ▪ Ensure data anonymization for transparency ▪ Involve domain experts in process development ▪ Crete synthetic data based on the logical and real-world appropriateness
Stage 1 Synthetic Data Generation and Initial Algorithm Implementation	▪ Inaccurate representation of real-world scenarios ▪ Algorithm may not perform as intended	▪ Validate synthetic data against actual data/attain feedback on synthetic data from stakeholders ▪ Implement algorithm iterative refinement

(Task 1- Task 6)		▪ Involve experts for reinforcement learning for guidance
Stage 2 and 3 Algorithm Presentation, Revision and Policy Option Presentation (Tasks 7, 8, 9, 11)	▪ Lack of stakeholder understanding or acceptance ▪ Algorithm may not converge or produce desired results	▪ Conduct regular feedback sessions to address concerns ▪ Clearly communicate the benefits of the algorithm ▪ Implement iterative testing and refinement ▪ Change policy rewards and alter learning process
Stage 2 and 3 Algorithm Validation in Oklahoma and Houston (Task 10)	▪ Inability to validate algorithm's effectiveness with real data	▪ Use multiple validation metrics ▪ Collaborate with external experts for third party validation

P8. INTELLECTUAL MERIT

The Intellectual Merit embodied in the successful completion of this EAGER is:

- Information models (mathematics) for the integration of social theory (collective adaptation, social computing, predictive analytics) and engineering theory.
- A foundation for transdisciplinary, convergence research through two types of generalizations [290]

    - Analytical Generalization: This involves abstracting a theory based on results to understand the design principles for public entities.
    - Case to Case Translation: The use of findings from research to different settings and populations and identification of a specific treatment to produce similar results in different situations.
- A computational framework for public policy design that can be extended to other problems.
- If successful, we will also develop a different method of approaching machine learning problems.

In summary, if successful, we will have provided a theoretical and computational foundation for transdisciplinary, convergence research to address issues embodied in programs such as the *Analytics for Equity Initiative* co-sponsored by NSF and the White House Office of Science and Technology Policy. Issues include Environmental Stressors and Equity, Health Equity, and Climate Change.

P9. BROADER IMPACTS

The test problems are designed to address Environmental Justice by understanding how economic growth and air quality disproportionally impact historically marginalized communities. By studying traditionally redlined districts of OKC and Houston, outcomes from this study will apply directly to those communities. This meets or exceeds the mandate at NSF to evaluate "Environmental Stressors and Equity" and "Health Equity in the Wake of Climate Change" per "The Analytics for Equity Initiative." This work will also allow policy makers to address governance democratization as an equitable distribution of federal investment per the Justice40 Initiative. We hypothesize that a generalized method for public policy decisions capable of responding to updated information democratizes access to governance and allows traditionally underrepresented groups to assess future action. Further, we will generate a database – containing both real and synthetic that will be useful to other researchers. We will also disseminate our research outcomes through standard academic channels – seminars, publications, and presentations at conferences as well as interaction with affected communities.

6.6 “I” Statement

Reflecting back to August 2022, a pivotal moment stands out vividly in my memory. I sought guidance from my mentors Professor Janet K. Allen and Professor Farrokh Mistree, grappling with the weighty question, "*What should I do*?" in the context of my research. Their response, delivered with profound simplicity and deepness, echoed a truth that has since shaped and stimulated my thinking, becoming a guiding principle of my academic journey. In their wisdom, they imparted not a prescriptive answer, but a timeless directive that resonates deeply within me to this day. They said *"We might tell you now about what you can do, but in the future, you are the one who has to do independent research, take responsibility of your life, and lead your life your own way.”* And from that day forward, those questions never troubled my thoughts again. This moment has great impacts in shaping my thinking and transitioning towards the journey of an independent researcher while establishing my own identity.

In August 2022, I embarked on a transformative journey as a member of the Systems Realization Laboratory at the University of Oklahoma. Over the course of 20 months, I have had the privilege of co-authoring five research papers (4 submitted; 1 yet to be submit), three of which comprise the individual chapters of this thesis. This invaluable experience has been instrumental in honing my ability to identify research gaps and effectively address them by establishing foundational research methods. Furthermore, it has provided me with a profound understanding of research competencies, structured writing, and the collaborative research transcending disciplinary boundaries. During this time, I have served as a mentor/co-mentor to five undergraduate students. These interactions have greatly enhanced my interpersonal abilities and mentoring skills. Through these experiences, I have been able to delve into the nuances of effective communication, the art of providing constructive feedback, and the importance of fostering a supportive learning environment.

Further, I was engaged in writing a proposal that is submitted to NSF, which also serves as my Ph.D. proposal. This undertaking proved to be a transformative experience, illuminating not only the systematic approach to proposal writing but also deepening my appreciation for the exploratory research. Through this process, I internalized the crucial steps involved in germinating the initial seed of an idea and nurturing it into a fully-fledged research endeavour. Moreover, drafting the proposal granted me profound insights into research, nurturing a mindset that breaks traditional limits and drives me towards innovative strides in design engineering in unexplored domains.

Research Oriented

The research I have pursued which is presented in this thesis anchors in providing fundamental and foundational perspectives to design public policy by utilising systems engineering and design engineering. I believe the foundational insights provided through this thesis are going to be of great utility to design complex systems where the social entity is of utmost importance. The research I pursued and that is presented in this thesis holds promise for addressing pressing social problems, thereby contributing to societal well-being. Moreover, its intellectual contributions extend beyond the realm of social impact, advancing the fields of design engineering and systems engineering. It gives a sense of fulfilment knowing that the foundational perspectives established in this thesis will be used to design public policies for greater social good, contributing to making the world a better place. The idea that anchors in designing public policies expands in addressing the grand challenges the world is facing. The new knowledge presented in this thesis anchors in establishing foundational approaches and method to design public policies in particular and designing complex systems at a broader level. This has enabled me to implement a systematic process in developing foundational models, which will serve as the basis for integrating model-based system design with the necessary technological tools. This research represents a holistic integration of fundamental and applied research, laying the groundwork for further expansion in my Ph.D. journey.

The broader vision involves establishing a method for developing information models tailored to address social challenges, with potential applications across diverse complex systems. In today's landscape, cutting-edge research fields like digital twins, predictive analytics, and deep learning hinge on understanding the flow of information among various entities, a pivotal aspect in designing complex systems. Embracing this has broadened my research horizons, laying the foundation for further refinement and exploration. This will be pursued and demonstrated in my Ph.D. dissertation for which the foundational knowledge is established in my thesis. I am also inclined to explore the integration of moral and ethical principles within model-based systems design, with a focus on their application in designing public policy.

Therefore, throughout this period, I have not only gained proficiency in various tools and technologies but have also internalized the fundamental principles of scholarly inquiry. This deep comprehension of the researcher's mindset and the art of conducting research has become integral to my academic development. I am confident that this profound insight will not only propel me through the subsequent stages of my Ph.D. journey but will also be invaluable in nurturing my unique identity throughout my life.

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APPENDIX A – Relevant Frameworks and Models from Chapter 4

For modelling of an E-CPSS, techniques, methods, and frameworks were selected by the authors based on criteria discussed in Section 4 and the results are summarized in Figure 4.7. Since a lengthy discussion of technique definitions and characteristics was not germane to the article, we offer this detailed supplement for context.

An E-CPSS functions in parallel to Popper's three worlds, the physical, mental, and artificial [106]. Several distinct techniques leverage this parallel:

Parallel Cognition — It comprises of two systems, the artificial and the real human cognitive system. Each interacts with the other in three stages: descriptive, predictive, and prescriptive cognition. The framework functions by integrating existing psychological models into a virtual agent then exploiting Artificial Intelligence (AI) to build equivalent machine learning surrogates to draw parallel between the real and the artificial (computational) world. The needs of social entities in the real world are realized as possible design solutions and to address these needs, computations are performed in the artificial world that allows the system to predict possible behavior [144].

ACP Approach — The ACP approach comprises of a) modeling with Artificial societies utilizing agent-based simulations involving human behaviors and social organizations; b) analysis with Computational experiments, that is, finding an effective way to conduct experiments for further development in social computing c) control through Parallel execution by running one or more artificial systems in parallel with a real system to provide a mechanism for control and management through comparison, evaluation, and interaction with the artificial systems [145]. Artificial systems emulate the real system such that while designing for an E-CPSS, designer can use emulated behaviors to improve and optimize the real system processes performance in real time. This creates a parallel world of dual artificial entities to analyze and evaluate for better decision-making [106].

Knowledge Automation — A data-driven advancement of the ACP approach which is agent-based and AI oriented is Knowledge Automation. This method performs computation on cyber-physical and social data while taking into consideration various uncertainties, redundancies and inconsistencies in the system [121]. For instance, the social space in the social energy system of an energy grid adds on complexity in the system. Therefore, an artificial system that is derived from the social and the energy system could play a central role in processing the big data and information which is where Knowledge Automation can be used.

Beyond parallels with Popper's philosophy lay techniques with a "designer first" approach. Since CPSS and E-CPSS exhibit self-organization and self-adaptability to external environmental uncertainty, techniques must also handle unpredictable and unplanned changes. Certain modeling techniques aid the designer to design for CPSS with such characteristics:

Force Field Control Method —The Force Field Control Method is commonly used to enable self-organizing capabilities in swarm robots. It is comprised of two parts: the Inner and Task Force Fields. Inner Force Fields enable robots to maintain operating distance with proper directionality. The Task Force Field determines the group behavior to perform the system's specific task while interacting with the environment. The combination of the two force fields allows the system to self-organize while continuously interacting with the environment to achieve system objectives [126].

Since this method controls and designs for scenarios involving quasi-social behavior, it may be applied to CPSS. Since both structural and behavioral self-organization characteristics are observed to adapt to environmental stimuli across changing states, it applies to E-CPSS as well.

ADACOR — The ADACOR (ADAptive holonic COntrol aRchitecture) system uses an adaptive production control approach to adaptively balance static and transient states in normal and unexpected conditions, respectively. The two-dimensional self-organization at micro (behavioral self-organization) and macro level (structural self-organization) allows the system to respond to internal and external changes over-time and re-establish system performance and functionality [130]. For instance, in case of an uncertainty in a distributed manufacturing system, the holons self-organize, providing agility and responsiveness to the emergency. The system should remain in the transient state as shorter as possible and return to the stationary state when the disturbance is recovered.

GAN (Genetic Adversial Networks) — Models such as GAN can be used for modelling the design characteristics of an E-CPSS. It is used to generate mixture models, that allow appropriate fusion of existing designs and knowledge of human interactions as obtained from IVE (Immersive Virtual Experiments). IVE experiments are conducted based on models obtained in physical experiment facilities and the feedback obtained is used for narrowing down, expanding or modifying the set of specific influential contextual factors that should be considered to improve predictions of the performance of the system under design. [132]

MAPE-K — The importance of cognition is discussed in the Parallel Cognition framework which led to an evolved version of the MAPE known as the MAPE-K (Monitor-Analyze-Plan-Execute-Knowledge) [146]. Knowledge is useful for modeling self-adaptive systems to implement system functionalities, maintain steady and reliable flow of relevant information for other components and system nodes, and implement the adaptation logic by means of Monitor, Analyze, Plan and Execute components. Cognition builds up in form of constructive memory and the system becomes capable to adapt, adjust and compute changing needs in real-time and based on historical data.

HRBGM — Understanding the importance of cognitive features of a system to adapt to external environment, a Hierarchical Bayesian Risk Graph Model (HBRGM) is studied which includes a hybrid risk analysis model, in which a hidden Markov model (HMM) is introduced to model the dynamic user activities [147]. The HMM and the BRG model takes into account influences of activities of neighboring nodes to analyze potential risks caused by dynamic user activities [148].

VAR & GPR — These are used to model information dynamics and for the fluctuating decision-making and predicting capability of the nodes in a CPSS network. Each node in a CPSS has sensing and predictive capabilities quantified with the prediction probability. These information dynamic models can be used in an E-CPSS design to predict the evolution of node behavior as a result of information exchange between the various system entities. Thus, VAR and GPR can be used to model for interoperability in an E-CPSS and also ensure resilience by predicting and defining allocation of resources to nodes that ensure system resilience and robustness [149,150].

The 7C Architecture — A 7-level framework can be used for modeling E-CPSS [151]. The Collective intelligence level of the 7-level framework is involved in inducing self-adaptive capability in the system. Complementary inputs in the data to information level, cyber level and cognition level can also potentiate the process self-organization by analyzing and learning from user preference [151]. The knowledge level and the

"Knowledge-to-wisdom" levels are the ones where the system evolution might take place due to the dynamically changing cognition of the components involved [152].

MBSE — Model-based systems engineering (MBSE) can be used to model complex dynamic relationships and dependencies among system entities, and facilitate to reduce the complexity of EIS (Enterprise Information Systems). MDSEA (Model Driven service engineering architecture) as discussed in [142] uses principles to model and guide the transformation from requirements/objectives to detailed specification of function and features of the system's components such as Human, IT and Physical which correspond to the social, cyber and physical spaces of the E-CPSS respectively. The promising framework addresses system dynamics that arise due to interoperability among enterprises, a characteristic shown by E-CPSS as well [142].

Collective Adaptation Framework — The behavior of collectives using different integration strategies and network architectures to adjust to developing problem structures in an unpredictable and complex social environment is the focus of the collective adaptation framework [148]. In social contexts, social integration strategies integrate beliefs, behaviors, and intentions. The paradigm is applied to CAS, a distributed cyber-physical system made up of entities that can change their behavior in response to various internal or external stimuli and interact with one another. The framework enables the system to demonstrate collective behavior, or coherent behavior at the collective level as well as the adaptive behavior, that is, the capacity to modify its control rules in response to external or internal stimuli [123].