Assessing Information Complexity Through Bio-inspired Systems Thinking Approach

Thesis

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<u>THESIS ACCEPTANCE CERTIFICATE</u>

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Date: ______________________________

I dedicate this thesis to my family, friends and teachers who have supported me in this challenging journey.

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Abstract

Information generation, transfer, and management have been a key part of any industry. In the construction industry, information plays a very key role in the success of any project. Primary areas of information generation are either construction site or design office. However, key decisions are usually made in the project management office. Due to this, information transfer and decision implementation depend upon multiple interdependent factors. Due to the complexity of the information system, to understand the interdependencies and its effects, systems-thinking and system dynamics approach become an obvious choice.

Nature has been dealing with such complex systems since its creation 4.5 billion years ago. It has perfected its system by evolution, resilience towards sudden changes, and extinction of unadaptable and outdated species that are no longer fit for the environment. Nature has been accommodating the changing factors and handling complexity forever. Humans have started to look at their natural counterparts for inspiration and solutions for their problems. This study aims to assess complexity in information management in the construction sector by providing a guideline, inspired by nature with a systems-thinking approach, using system dynamics as a tool.

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Chapter 1

Introduction

1.1 Brief Description / Abstract

Biomimetics is an emerging field in the world. It is portmanteau from the words ‘Biology’ and mimesis (imitation). Essentially, it means to copy natural phenomena into man-made designs and processes (Gleich et. al., 2010). Biomimetics is the realization of technical application based on insights from fundamental biological research and is not direct carry-overs from biology. In other words, it does not work on “Blueprints from nature” but rather is a creative technological implementation (Spech et. al. 2008).

Humans have taken many benefits from biomimetic implementation in various fields. Bullet train used to create a sonic boom when coming out of a tunnel, due to the difference in air pressure in and out of the tunnel. It was solved by imitating the beak of a kingfisher, after the observation that when the kingfisher dove to catch the fish, disturbance in water was negligible (Primlani, 2013). Swiss inventor, George de Mestral found that, upon returning home for a walk with his dog one day, his pants and the canine’s fur were covered with cockleburs. He studied the burs under a microscope, observing their natural hook-like shape, which ultimately led to the design of the popular adhesive material, Velcro. It is a two-sided fastener – one side with stiff ‘hooks’ like the burrs and the other side with the soft ‘loops’ like the fabric of his pants (Benyus, 1997). Similarly, a dialysis machine was inspired by the functions of a kidney (Lee, 2011), and windmill’s propeller wings imitated from humpback whale’s fins (Miller, 2010).

In addition to phenomenal design, nature has been generating, transferring, and managing a lot of information regularly. One of the best examples is the transfer of information as a song by a tropical bird. It is a combination of the process of natural selection (Hauser et. al., 2002) and adaption to the chaotic process of species evolution (Grant and Grant, 2002). Long and short-range frequencies and the restriction of receivers are all complicated processes, carried by a single song with a very simple structure (Mathevon et. al., 2008). This is one of many examples of nature handling complex information but transmitting it seamlessly between receivers with little complexity. The system, which controls the generation, storage, flow, and utilization of information, is called the Information Management System (IMS). The synthetic information management systems created by humans have failed in the past (Liebowitz, 1999). Postponing the information system restricts the benefits, which are to be gained from any project (Sanchez et. al, 2018), while its absence can be catastrophic. Since Guptara (1999) pointed out the inefficiency of IMS, numerous attempts have been made to manage information in a better way, each solution proposing a solution for individual problems. As multiple interlinked factors affect information management systems and natural phenomenon, a complex system's approach is a better-suited approach to improve the IMS. In this research, multiple IMS and their factors will be explored by the causal loop technique, which will further help in generating a system dynamics approach towards an improved bioinspired IMS.

1.2 Problem Statement

The current construction industry of Pakistan is lagging from its research counterpart by decades. Projects face over-costing and over-time on regular basis. Information management in Pakistan is still paper dependent in many places. Wherever technology is being used, it is inefficient at best. The absence of a proper information management system in our construction industry is one of the key factors for project failures. This study provides an insight into the currently used information management systems and their objective comparison with themselves and their natural counterparts. It will provide an insight into the flaws in our systems and provides direction to overcome the observed flaws.

In this research, multiple IMS and their factors will be explored by the causal loop technique, which will further help in generating a system dynamics approach towards an improved bioinspired IMS.

1.3 Level of research already carried out on the proposed topic

Guptara (1999) pointed out the inefficiency of information management systems, there have been attempts to identify improvement areas and propose solutions for the said problem. Chua and Lam (2005) reinforced the idea by pointing out the inefficiencies using a multi-case analysis. Since then, multiple solutions have been presented to make information management systems effective. Butler et al (2007) laid out a theoretical model and framework for understanding the information management system and its implementation. Hayes (2011) explored the information sharing possibilities by the use of information technology.

Currently, knowledge and information management are divided into multiple categories, which include but are not limited to Organization IM, Enterprise IM, and Archive IM, etc. This diverse classification generated multiple parallel systems for information management, each one tailored for a specific type of use, but still far from efficient. Khazieva et al. (2018) again pointed out multiple loopholes in the IM strategies currently implemented in the industry. Biomimetics shows promise in terms of improving existing systems by copying the practices used in nature as mentioned above. Ogiela (2016) opens a gateway towards bio-inspired information management techniques and its applications.

1.4 Reason / Justification for selection of the topic

Biomimetics has been adopted as one of the most efficient techniques for improvement of current systems or reduction in their complexity, or both. It can be used to compare multiple information management solutions, factors affecting such solutions, and their efficiency.

Loermans, Fink (2005), and many others explored the road to a better information management system by various theories and management techniques. This resulted in several solutions for each problem identified but are still far from being efficient. To better understand these solutions, a system thinking approach should be used for accurate results. Nature has its simple yet effective IM systems, tailored for every species. There is a need to not only standardize and compare various present IM systems in use. This study attempts to analyze these systems from the systems thinking approach and improve its efficiency by using the latest biomimetics approach.

1.5 Objectives

The objectives of this study are listed below:

- To identify the benefits and applications of biomimetics in the construction sector.
- To improve the information complexity using various biomimetics techniques through causal loop diagrams.
- To develop a system dynamics model to address information complexity using biomimetics.

1.6 Advantages

This is an exploratory study that will provide a fresh look at the existing problems in the construction industry. This study will be advantageous in the following streams, but are not limited to them:

- Benchmarking the current state of the information management system
- An exploratory study towards the biomimetics in management systems, and it's future in the construction management sector.
- Marks possible improvement areas in the current information management systems.

1.7 Areas of Application

This study will improve the body of knowledge and combine the following streams, but are not limited to these:

- Project Communications Management
- Information Management
- Biomimetics
- Complexity, Systems Thinking, and Dynamics

Chapter 2

Literature Review

2.1 Construction Industry

"Everything prospers when construction industry prospers", is a very common French saying. This is based on the key role the construction industry plays in the economy of the country as it is the largest employment generating industry in the country (Isa et al., 2013, Maqsoom et al. 2013). Despite being so important, it faces major challenges including low-profit margin, leading to claims and counter-claims due to continuous overruns in budget and schedule (Yeo and Ning, 2002).

2.2 Information Management in Construction Industry

The construction industry has a substantial contribution to a country's gross domestic product (GDP), but it has never achieved its full potential (Nawaz et al., 2013). Participants from different disciplines collaborate to deliver competitive construction design services (Oloufa et al., 2004). Time constraints have increased the popularity of fast-track projects in today's world as they overlap the design and construction phase. Due to this overlap, the logical order of project execution is disturbed which amplifies the reliance on sub-contractors, increasing the complexity of planned activities (Baldwin et al., 1998). This has increased the importance and impact of communication and it has become a fundamental component of the design process (Sonnenwald, 2006).

The construction industry includes fragmentation, with separation in design and construction, communication gaps, and poor collaboration amongst stakeholders (Albaloushi and Skitmore, 2008). A framework of computer-supported collaborative design technique with computer-aided design tools was introduced by Duan and Zhou (2006), improved by Chen and Tien (2007) by improving accessibility and flexibility. Despite many efforts, poor communication is still a problem in today's construction industry and has negative effects on project success (Gamil and Rehman, 2017). Cooperation between stakeholders is not adequate and changes occurring during the project increase complexity (Kardes et al., 2013, Capka, 2004). Multiple contributors to complexity have been identified and documented in the construction sector through the primary stakeholders' perspectives (Kermanshach and Safapour, 2019). To understand and tackle the complexity in a better way, communication in process of innovation has been remodeled by the systems thinking approach (Leeuwis and Aarts, 2011). This approach has been applied in various places, like the corporate business model (Moellers, 2019), and has the potential to be applied in the construction industry as well.

2.3 Complexity and System Dynamics

Multiple interdependent factors form a system and the outcome is very sensitive to the initial conditions, known as the "butterfly effect" (Gleick, 2011). This has been commonly used to link unpredictability and complexity (Boffetta et al., 2002). Communication is complex, having multiple factors that enhance or suppress each other (Alviar et al., 2019). This complexity increases as the number of contact points (people) increase. To address this complexity, the system dynamics approach is used. System dynamics (SD) is an iterative modeling approach that is used to visualize and simplify complexity using feedback mechanisms (Morecroft, 2020). This approach provides a comprehensive analysis of a complex system (Xu and Coors, 2012) by using stocks, flows, feedback loops, time delays, and table functions (Coyle and Coyle, 1977). Causal loop diagrams are developed showing relationships and interdependencies of variables (Nguyen and Bosch, 2013), and interprets changes occurring in the system over time. (Forrester, 1997).

2.4 Bio-Inspiration, an Introduction

Bioinspiration (i.e., biomimicry, bionics, biomimetics, etc.) is an innovative approach, which seeks inspiration from nature for design and innovation in the human-made world. The natural world offers a lot of potential solutions for sustainable solutions to human problems (Benyus, 1997). There are three stages of bio-inspiration: design, process and ecosystem (Kennedy et al., 2015). Singh and Nayyar (2015) documented some of the most prominent innovations include the modern design of bullet train inspired by kingfisher, penguin, and owl, bacteria resistant coating from shark skin, self-cleaning paint from lotus leaf, and HVAC from termite nest. In the field of management, multiple bioinspiration has been applied, such as swarm intelligence in operations (Bonabeau & Meyer, 2001), sustainability-oriented innovation (Neves and Francke, 2012), strategic planning (Baumeister and Herzlich, 2015), and RM (Anderson, 2010). Human communication is dynamic and complex (Johansson and Persson, 2009) but the natural world might have a fitting model.

2.5 Sociality in Animals

Nature holds a very vast and diverse spectrum of species. As far as sociality is concerned, some animals prefer to live most of their life independent, self-sufficient, and without forming any social connection except mating and fighting. Platypus (Griffiths, 1988, Grant and Temple-Smith, 1998), Jaguars (Schaller, 1980), Puma (Hansen, 1992, Anderson, 1983) are a few examples of such species. However, it was observed that most species live as a group. Wolves prefer to live as packs (Zimem, 1976, Mech et al., 2010), lions prefer to live as pride (Packer et al.,1990, Packer et al., 2005) and orcas prefer to live in pods (Brault and Caswell, 1993, Denkinger, 2020). Living in a group can have many benefits such as defense against infanticide (Pusey and Packer, 1994), communal foraging (Orsdol et al., 1985, Schaller, 1972, Bertram, 1978, Van Orsdol, 1981, 1984), defense of prey’s carcass (Mosser and Packer, 2009, Cooper, 1991, Mills and Biggs, 1993) and resting (Rook and Penning, 1991, Wechsler and Brodmann, 1996). “Alpha” role is observed in some animal groups, such as alpha wolves in wolfpacks (Mech, 1999), the alpha dog in African wild dogs (Creel, 1997), and alpha lioness in a pride of lions (Velzen, 2016). This behavior precedes in some colonial species such as bees (Abou-Shaara, 2014) but despite having a queen in the colony, an absence of central control is observed in most colonial species such as ants (Gordon, 1999), wasps (Premnath, 1995) and termites (Kipyatkov, 2006). Although the group animals can be a closer example of a management team (Johnson, 2000), the colonial system is a better depiction of the whole organization. However, there is a difference of opinion in the roles of alpha animals, their hierarchy and dominance order (Mech, 1999), but, the colonial management system of ants without queen domination or central control has been extensively documented by DM Gordon (1999).

2.6 Collective Behavior of Ants

Ants inhabit different habitats. Cataglyphis (Fent and Wehner, 1985) and Pogonomyrmex (MacMahon, 2000) live in deserts, Leafcutter ants (Swanson et al., 2019) reside in rainforests, and Pharaoh ants (Wetterer, 2010) are native to urban developments of tropical areas. A detailed study has been carried out on fifty species out of fourteen thousand discovered. They provide the opportunity to study the interactions in diverse environments to generate collective behavior (Gordon, 2019). Animals evolve to better adapt to their environment (Schmidt-Nielsen, 1997). The collective behavior of ants emerges from feedback through interactions among individuals, based on a combination of three basic factors: Patchiness of resources in time and space, operating cost, environmental stability, and the threat of rupture (Gordon, 2014). Gordon (2016) further explained the response behavior associated with these factors. If resources appear in patches through time and space, the response is accelerating and non-linear, and if resources are scattered, the response follows a linear pattern. If the acquisition of energy through food is faster than energy spent to get it, the default is to continue with an activity unless it is halted for some reason. If the energy spent is rather higher than getting it, the default changes to stay put, unless activated. Finally, if the environment is stable and the threat of rupture is low, the activation and amplification rate is slow but steady. Otherwise, it is fast and sporadic. To further study the effects and to eliminate the environmental bias, the behavior of four different ant species were studied, as mentioned below:

- Red Harvester ants – Pogonomyrmex Barbatus
- Argentine ants – Linepithema Humile
- Turtle ants – Cephalotes Goniodontus
- Leafcutter ants – Genus: Atta

2.6.1 Pogonomyrmex Barbatus (Red Harvester ants)

This species is native to semi-arid regions of North America and is among the largest harvester ant in the Chihuahuan Desert (Whitford et al., 1976, Cole, 1968). Their social interaction among individuals generates collective behavior (Sumpter, 2010, Leonard, 2014). This species collects seeds, scattered by wind and flooding (Beverly et al., 2009, Gordon, 1993) rather than appear in patches, which diminishes the need for spatial information. This activity is regulated through feedback loops based on local interactions (Prabhakar et al., 2012) like many other species such as schools of fish and flocks of birds (Gautrais, 2012). Patroller ants start the day by patrolling the areas in the nest's vicinity, and their safe return initiates foraging (Greene and Gordon, 2007).

The rate of forager ants returning with food stimulates and regulates the foraging activity throughout the day (Greene et al., 2013, Pinter Wollman et al., 2013). It is regulated by managing the tradeoff between obtaining food and water and spending water. Ants going out to lose water in the dry air and gain water by metabolizing fats in the obtained seeds (Lighton and Bartholomew, 1988, Marler and Moore, 1989). These are identified through antennal contact by the ants, ready to go out for foraging (Greene et al., 2003). The rate of returning foragers correlates with the local density of ants. (Davidson et al., 2016). Pagliara et al. (2018) established the foraging activity regulation as a closed-loop excitable system.

Although living in a hot and harsh desert, the environment is stable with a low threat level, scattered resources and low intake-to-outflow ratio leads to a collective behavior with slow amplification and information distribution at the nest. The default behavior is to wait at the nest till instigated (Gordon, 2019).

2.6.2 Linepithema Humile (Argentine Ants)

Linepithema Humile (Argentine Ants as they are usually called) is an invasive species that are native to the Mediterranean climate. Due to high variation in temperature, they restrict themselves to a single nest in winters (Abril et al., 2008, Markin, 1970). To gain the maximum advantage of the warm weather of summer, they become polydomous (form multiple nests) to increase the trail network to amplify their response to a food source (Flanagan et al., 2013). Distribution of L. humile is restricted as competition affects the temporal patchiness of nutritional consumable resources (Vonshak and Gornon, 2015, Crist and MacMahon, 1991). The food obtained is then distributed among multiple nests (Heller et al., 2008). Like most ant species, Argentine ants also regulate their foraging activity by interactions among individuals (Gordon, 2010). They are continuously on the lookout for new spaces (Gordon, 1995) and keep going unless instigated to stop.

2.6.3 Cephalotes Goniodontus (Turtle Ants)

Turtle ants are arboreal ant species living in a rapidly changing environment of tropical dry forest (Gordon, 2017). They provide a system of feedback with the default to continue unless inhibited. They use pheromone trails and chemical interactions to maintain the activity (Gordon, 2016). The trails consist of vines and branches. Turtle ants form loops, different paths emerging with the same start and endpoint. Over time, all paths are trimmed out except one (Gordon, 2017). Loops decrease the efficiency in networks (Alwan and Agarwal, 2009, Chouikhi et al., 2015), but it increases robustness and coherence. It appears as if turtle ants prefer coherence along the path rather than going for the most efficient and shortest path. Although exploration is done to find new resources and repair broken paths, that comes at a cost of "waste of ants and time" if the path explored is fruitless (Chandrasekhar et al., 2019).

2.6.4 Genus: Atta (Leaf-cutter Ants)

Leaf-cutter ants are dominant herbivores, arboreal species in the neotropical forest ecosystem (Hölldobler & Wilson, 1990). They harvest and bring leaves from canopies to create gardens of symbiotic fungus within their nests, which they feed to their larvae (Aylward, 2012, Swanson et al., 2019). Leaf-cutter ants live in an unstable environment with patchy resources distribution. They save energy by bringing in the largest leaf fragments possible and have a very high energy intake-to-spent ratio. Hence, they and adjust their activities rather than halting them (Gordon, 2019). They travel on pheromone trails and local interactions depend upon crowding and width of the trail (Bruce et al., 2012). Local antennal interactions amplify the response and affect the number of ants traveling on the trail (Bouchebti et al., 2015, Farji-Brener, 2010, Dussutour, 2007). Since the intake to spent ratio is relatively high, tasks are adjusted in response to various variables such as the speed of ant increases in case of an attack by a predator (Bedoya Cochet et al., 2017), number of ants increases if smaller pieces of leaves are being brought in (Dussutour, 2007), workers drop the current task to remove obstacles (Bruce et al., 2017) and if dropped leaves are found, foragers, pick them up rather than cutting more leaves (Röschard and Roces, 2003). The threat of disturbance depends on the nest to nest and varies from medium to very high (Norman et al., 2017, Barrera et al., 2015).

2.7 Interdependent Factors from Ant Behavior

Factors identified from the literature are classified into three groups as shown below:

Table 2-1: Factor Classification

S. No	Factor Name	Frequency	References
Primary Factors (Related to information)			
1	Interaction Rate	20	Buhl and Rogers, 2016; Carmazine et al., 2003; Davidson et al., 2016; Flanagan et al., 2013; Friedman et al., 2018; Gordon and Mehdiabadi, 1999; Gordon, 2013; Gordon, 2016; Gordon, 2016; Gordon, 2019; Gordon, 2019; Greene and Gordon, 2007; Hirsh and Gordon, 2001; Jandt and Gordon, 2016; Naug, 2009; Pagliara et al., 2018; Pinter-Wollman et al., 2011; Pinter-Wollman et al., 2013; Prabhakar et al., 2012; Prabhakar et al., 2012
2	Quorum	13	Carmazine et al., 2003; Davidson et al., 2016; Friedman et al., 2019; Friedman et al., 2018; Gordon and Mehdiabadi, 1999; Gordon, 2013; Gordon, 2014; Gordon, 2016; Gordon, 2019; Gordon, 2019; Jandt and Gordon, 2016; Pagliara et al., 2018; Pless et al., 2015
3	Interaction Type	20	Beckers et al., 1989; Burford et al., 2018; Carmazine et al., 2003; Chandrasekhar et al., 2018; Chandrasekhar et al., 2019; Chu et al., 2004; Davidson et al., 2016; Friedman et al., 2019; Flanagan et al., 2013; Friedman et al., 2018; Gordon and Heller, 2014; Gordon, 2012; Gordon, 2016; Gordon, 2017; Gordon, 2019; Gordon, 2019; Greene and Gordon, 2007; Hirsh and Gordon, 2001; Pagliara et al., 2018; Prabhakar et al., 2012
4	Decision Making	19	Buhl and Rogers, 2016; Burford et al., 2018; Carmazine et al., 2003; Chandrasekhar et al., 2019; Davidson et al., 2016; Flanagan et al., 2013; Friedman et al., 2019; Gordon and Heller, 2014; Gordon, 2012; Gordon, 2013; Gordon, 2016; Gordon, 2017; Gordon, 2019; Gordon, 2019; Greene and Gordon, 2007; Hirsh and Gordon, 2001;

S. No	Factor Name	Frequency	References
			Pagliara et al., 2018; Prabhakar et al., 2012; Prabhakar et al., 2012
5	Amplify	15	Beckers et al., 1989; Burford et al., 2018; Carmazine et al., 2003; Chandrasekhar et al., 2018; Flanagan et al., 2013; Gadagkar et al., 2019; Gordon and Heller, 2014; Gordon, 2012; Gordon, 2014; Gordon, 2016; Gordon, 2017; Gordon, 2019; Gordon, 2019; Pinter-Wollman et al., 2011; Prabhakar et al., 2012
6	Default Behavior	9	Burford et al., 2018; Carmazine et al., 2003; Gadagkar et al., 2019; Gordon, 2014; Gordon, 2016; Gordon, 2017; Gordon, 2019; Gordon, 2019; Pagliara et al., 2018
Internal Factors (Colonial Factors)			
1	Colony Size	16	Beckers et al., 1989; Buhl and Rogers, 2016; Burford et al., 2018; Carmazine et al., 2003; Gordon and Heller, 2014; Gordon and Mehdiabadi, 1999; Gordon et al., 2013; Gordon, 2016; Gordon, 2019; Gordon, 2019; Greene and Gordon, 2007; Hayakawa et al., 2020; Hirsh and Gordon, 2001; Naug, 2009; Pinter-Wollman et al., 2011; Prabhakar et al., 2012
2	Density	21	Beckers et al., 1989; Buhl and Rogers, 2016; Carmazine et al., 2003; Chandrasekhar et al., 2019; Davidson et al., 2016; Friedman et al., 2019; Gordon and Heller, 2014; Gordon and Mehdiabadi, 1999; Gordon, 2014; Gordon, 2016; Gordon, 2016; Gordon, 2017; Gordon, 2019; Gordon, 2019; Greene and Gordon, 2007; Hayakawa et al., 2020; Hirsh and Gordon, 2001; Naug, 2009; Pagliara et al., 2018; Pinter-Wollman et al., 2011; Prabhakar et al., 2012
3	Additional Cost	18	Carmazine et al., 2003; Chandrasekhar et al., 2019; Friedman et al., 2019; Friedman et al., 2018; Gadagkar et al., 2019; Gordon, 2013; Gordon, 2013; Gordon, 2014; Gordon, 2016; Gordon, 2016; Gordon, 2019; Gordon, 2019; Greene and Gordon, 2007; Pagliara et al., 2018; Pinter-Wollman et al., 2013; Pless et al., 2015; Prabhakar et al., 2012; Prabhakar et al., 2012

S. No	Factor Name	Frequency	References
4	Benefit to Cost Ratio	18	Carmazine et al., 2003; Chandrasekhar et al., 2019; Friedman et al., 2019; Friedman et al., 2018; Gadagkar et al., 2019; Gordon, 2013; Gordon, 2013; Gordon, 2014; Gordon, 2016; Gordon, 2016; Gordon, 2019; Gordon, 2019; Greene and Gordon, 2007; Pagliara et al., 2018; Pinter-Wollman et al., 2013; Pless et al., 2015; Prabhakar et al., 2012; Prabhakar et al., 2012
5	Search Time	17	Carmazine et al., 2003; Friedman et al., 2018; Friedman et al., 2019; Gordon and Heller, 2014; Gordon et al., 2013; Gordon, 2013; Gordon, 2013; Gordon, 2014; Gordon, 2016; Gordon, 2016; Gordon, 2019; Gordon, 2019; Hirsh and Gordon, 2001; Pagliara et al., 2018; Pinter-Wollman et al., 2013; Pless et al., 2015; Prabhakar et al., 2012
6	Volatility	9	Burford et al., 2018; Carmazine et al., 2003; Gordon, 2012; Gordon, 2017; Gordon, 2019; Greene and Gordon, 2007; Hirsh and Gordon, 2001; Pagliara et al., 2018; Pless et al., 2015
7	Coherence	1	Jandt and Gordon, 2016
External Factors (Environmental influence)			
1	Competition / Neighboring Colony Distribution	18	Buhl and Rogers, 2016; Burford et al., 2018; Carmazine et al., 2003; Fitzgerald et al., 2012; Gadagkar et al., 2019; Gordon and Heller, 2014; Gordon et al., 2013; Gordon, 2013; Gordon, 2014; Gordon, 2016; Gordon, 2017; Gordon, 2019; Gordon, 2019; Gordon, 2019; Jandt and Gordon, 2016; Prabhakar et al., 2012; Prabhakar et al., 2012; Sturgis and Gordon, 2013
2	Death Risk	10	Burford et al., 2018; Carmazine et al., 2003; Chandrasekhar et al., 2019; Friedman et al., 2019; Gadagkar et al., 2019; Gordon et al., 2013; Gordon, 2017; Gordon, 2019; Gordon, 2019; Pinter-Wollman et al., 2013
3	Climate	16	Burford et al., 2018; Davidson et al., 2016; Friedman et al., 2019; Fitzgerald et al., 2012; Friedman et al., 2018;

S. No	Factor Name	Frequency	References
			Gadagkar et al., 2019; Gordon and Heller, 2014; Gordon et al., 2013; Gordon, 2013; Gordon, 2016; Gordon, 2016; Gordon, 2019; Gordon, 2019; Jandt and Gordon, 2016; Pagliara et al., 2018; Pinter-Wollman et al., 2013
4	Food Carried	13	Carmazine et al., 2003; Davidson et al., 2016; Friedman et al., 2018; Friedman et al., 2019; Gordon, 2013; Gordon, 2013; Gordon, 2014; Gordon, 2016; Gordon, 2016; Gordon, 2019; Gordon, 2019; Pagliara et al., 2018; Pinter-Wollman et al., 2013
5	Resource Availability and Distribution	25	Burford et al., 2018; Carmazine et al., 2003; Chandrasekhar et al., 2019; Davidson et al., 2016; Friedman et al., 2019; Fitzgerald et al., 2012; Flanagan et al., 2013; Friedman et al., 2018; Gordon et al., 2013; Gordon, 2012; Gordon, 2013; Gordon, 2013; Gordon, 2014; Gordon, 2016; Gordon, 2016; Gordon, 2017; Gordon, 2019; Gordon, 2019; Gordon, 2019; Jandt and Gordon, 2016; Pagliara et al., 2018; Pinter-Wollman et al., 2013; Pless et al., 2015; Prabhakar et al., 2012; Prabhakar et al., 2012
6	Stability of Environment	13	Burford et al., 2018; Chandrasekhar et al., 2018; Friedman et al., 2018; Gadagkar et al., 2019; Gordon, 2014; Gordon, 2016; Gordon, 2017; Gordon, 2019; Gordon, 2019; Gordon, 2019; Hirsh and Gordon, 2001; Pagliara et al., 2018; Pinter-Wollman et al., 2013

Content analysis was carried out to study the identified factor's impact on the system. The impact of each factor was assessed based on a 3-factor Likert scale (high, medium, and low), through a detailed review of the literature. A quantitative number was assigned to each impact (5 for high, 3 for medium, 1 for low) as described in the respective literature document. The highest frequency impact was selected for each barrier. Literature score was calculated using the following equation:

$$\textit{Literature Score} = \textit{Impact Score} \times \frac{\textit{Frequency}}{5 \times \textit{Total No. of Papers}}$$

Equation 2-1

The literature score assigned to each factor was divided by the sum of the literature score to calculate the normalized score for each factor. The list of factors was then arranged in descending order of the normalized score and the cumulative score was calculated. The obtained list of factors was arranged in the descending order of their relative significance (Ullah et al.,2017). The result is shown in table 2-2:

Table 2-2 Normalized Score - Factors

S. No	Category	Identified Factor	Literature Score	Normalized Score	Cumulative Score
1	External	Food Availability and Distribution	1.25	0.1057	0.1057
2	Internal	Density	1.05	0.0888	0.1944
3	Primary	Interaction Rate	1	0.0845	0.2790
4	Internal	Additional Cost	0.9	0.0761	0.3550
5	Internal	Benefit to Cost Ratio	0.9	0.0761	0.4311
6	External	Climate / Weather	0.8	0.0676	0.4987
7	Primary	Quorum	0.65	0.0549	0.5537
8	External	Stability of Environment	0.65	0.0549	0.6086
9	Primary	Interaction Type	0.6	0.0507	0.6593

S. No	Category	Identified Factor	Literature Score	Normalized Score	Cumulative Score
10	Primary	Decision Making	0.57	0.0482	0.7075
11	External	Competition	0.54	0.0456	0.7532
12	Internal	Search Time	0.51	0.0431	0.7963
13	External	Death Risk	0.5	0.0423	0.8385
14	Internal	Colony Size	0.48	0.0406	0.8791
15	Primary	Amplification	0.45	0.0380	0.9172
16	Internal	Volatility	0.45	0.0380	0.9552
17	External	Food Carried	0.39	0.0330	0.9882
18	Primary	Default Behavior	0.09	0.0076	0.9958
19	Internal	Coherence	0.05	0.0042	1.0000

The factors mentioned in table 2-1 are interrelated with one another. These interrelations give rise to the specie's collective behavior. Behavior of observed species depict a set pattern based on similar factors but diversify their response to better adapt to their surroundings. They follow an iterative feedback loop to regulate day-to-day activities (Pagliara et al., 2018). That feedback is stimulated by information transfer through physical interaction through antennal connections or by chemical interaction from cues of pheromone (Gordon, 2019, Deneubourg et al., 1986). Pheromone trail only provides spatial information and pheromone type dictates the response reaction by the colony. Since the interaction is with the chemical trail laid by the ant rather than the physical ant, the response reaction is fast and sporadic (Gordon, 2014). If the resources appear in patches through time and space, profit is maximized by rapid recruitment and quick response (Flanagan et al., 2011). Physical interaction is when an ant meets another one, it detects the food carried, its contents and the current hydration level present in the ant through antennal connection (Gordon, 2019, Greene et al., 2013). This information provides a ratio between water evaporated while searching for food and water present inside the collected food. Spatial information has not been proven yet, but it was observed that some spatial information is transferred as the red harvester forager ants only forage the areas which have been scouted earlier that morning (Greene and Gordon, 2007, Gordon, 1991). Although physical interaction provides more information, but the response is comparatively slower than chemical interaction (Gordon, 2016). The response for any interaction can be vastly classified into three types: To start a new activity (Gordon, 2019), follow a new trail or go to a new nest; To stop an existing activity such as foraging due to any factor i.e. predator attack, harsh climate etc.; To amplify the current response, stop or start, throughout the ants in local vicinity, or in some cases, the whole colony. The information given is forgotten in a leaky integer method. The pheromone trail laid is volatile and is lost in the environment and the information through physical interaction is also forgotten unless it is reinforced by another ant with the same information. Thus, the response for any information, whether to start or to stop, is not initiated till they reach "quorum", a requirement of number of ants providing the information. Once the quorum is reached, the response is then amplified throughout the interaction rate of ants present in the local vicinity, and sometimes throughout the whole colony depending upon the information. This process can be graphically represented as:

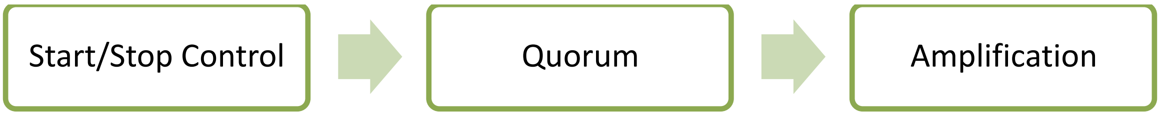

Figure 2-1: Activity Regulation Process

The default behavior for an ant colony is dictated by the environment (Gordon, 2019). If the environment is stable and disturbance is not frequent, the default response amplification is slow, but steady. If the environment is unstable and disturbance is frequent, the default response amplification is fast and sporadic. If the environment is harsh i.e. high temperature and low humidity, the evaporation rate in ants outside the nest is increased (Quinlan, 1999), thus the activities are coordinated at the nest and the default is to stop unless quorum is reached to maintain the benefit to cost ratio and avoid desiccation. If the environment is humid and the ratio of water intake to evaporate is high, the recruitment is done on the trail rather than at the nest as desiccation is not a threat. In this case, the default behavior is to continue the activity unless quorum is reached to stop the activity. The climate, specifically humidity and temperature, are causing the water evaporation rate to increase (Friedman et al., 2019). In other words, climate is the cause of additional resource consumption than what is required for performing an activity. High amplification rate also increases the cost of activity as quick response is required. It also depends upon the density of ants present in the local vicinity, as the number of ants increase the rate of interaction (Buhl and Rogers, 2016). The number of ants present outside the nest depends upon the size of the respective colony. When the ants of one colony meet the ants of another colony, they are usually hostile towards one another (Gadagkar et al., 2019). This is one of the factors that restrict the size of the colony. Ants adapt to the resource distribution and risk of disturbance in the environment. If the resource appears in patches in terms of space or time, the response must have spatial information about the source of food, which reduces the search time for food. If environment is unstable, it is paired

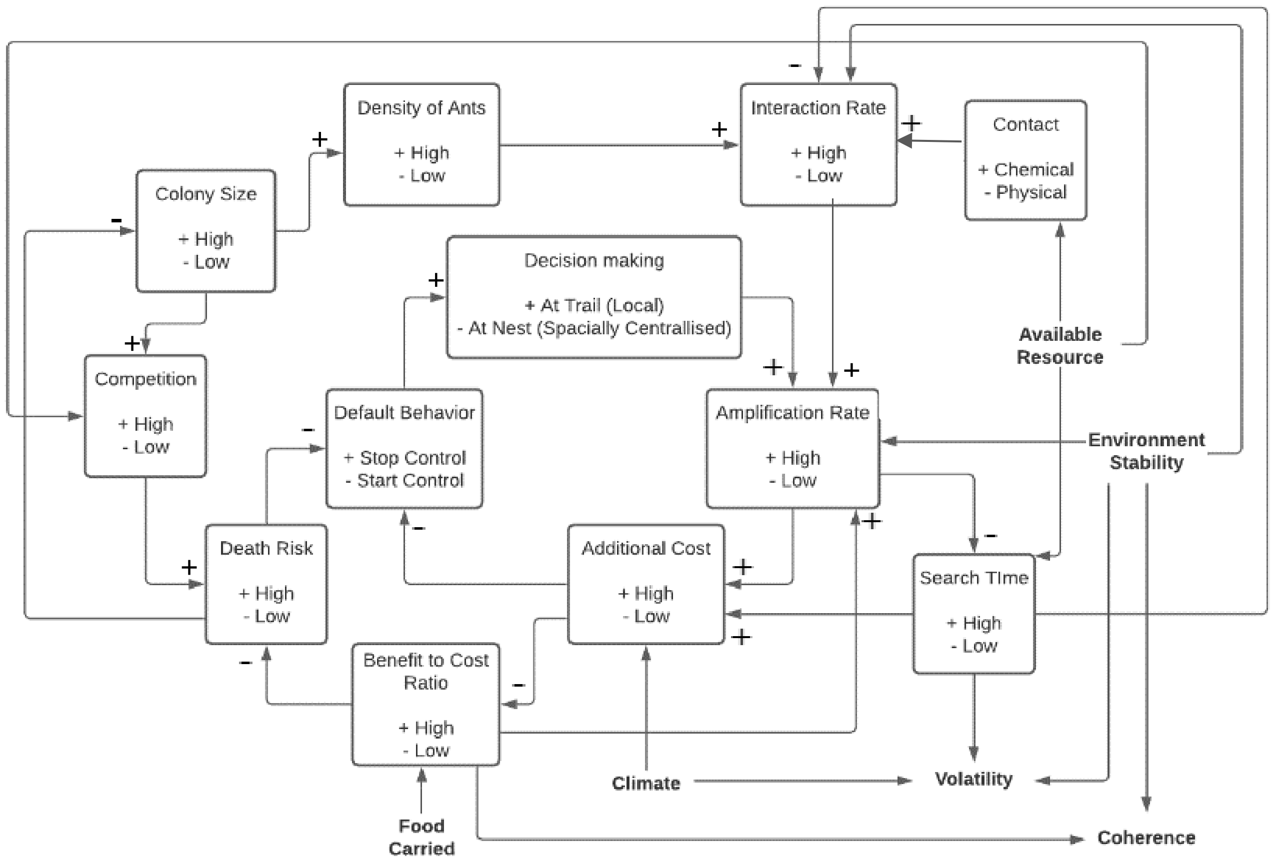

Figure 2-2 – Factor Mapping – Ant Behavior

with fast amplification (Gordon, 2016). However, if the environment is stable and frequency is of disturbance is low, then the amplification is slow. Frequency of disturbance is countered by adjusting quorum and volatility of the pheromone. Turtle ants also depict a behavior of coherence on trails rather than following the shortest path (Chandrasekhar et al., 2019). A factor mapping diagram depicting the interdependencies between factors is shown in figure 2-2:

Chapter 3

Research Methodology

3.1 Introduction

This study is an attempt to improve information management in the construction industry by comparing it with its natural counterpart, following the concepts of complexity by using a systems-thinking approach and system dynamics modeling technique as a tool. Various phases of this study are depicted below:

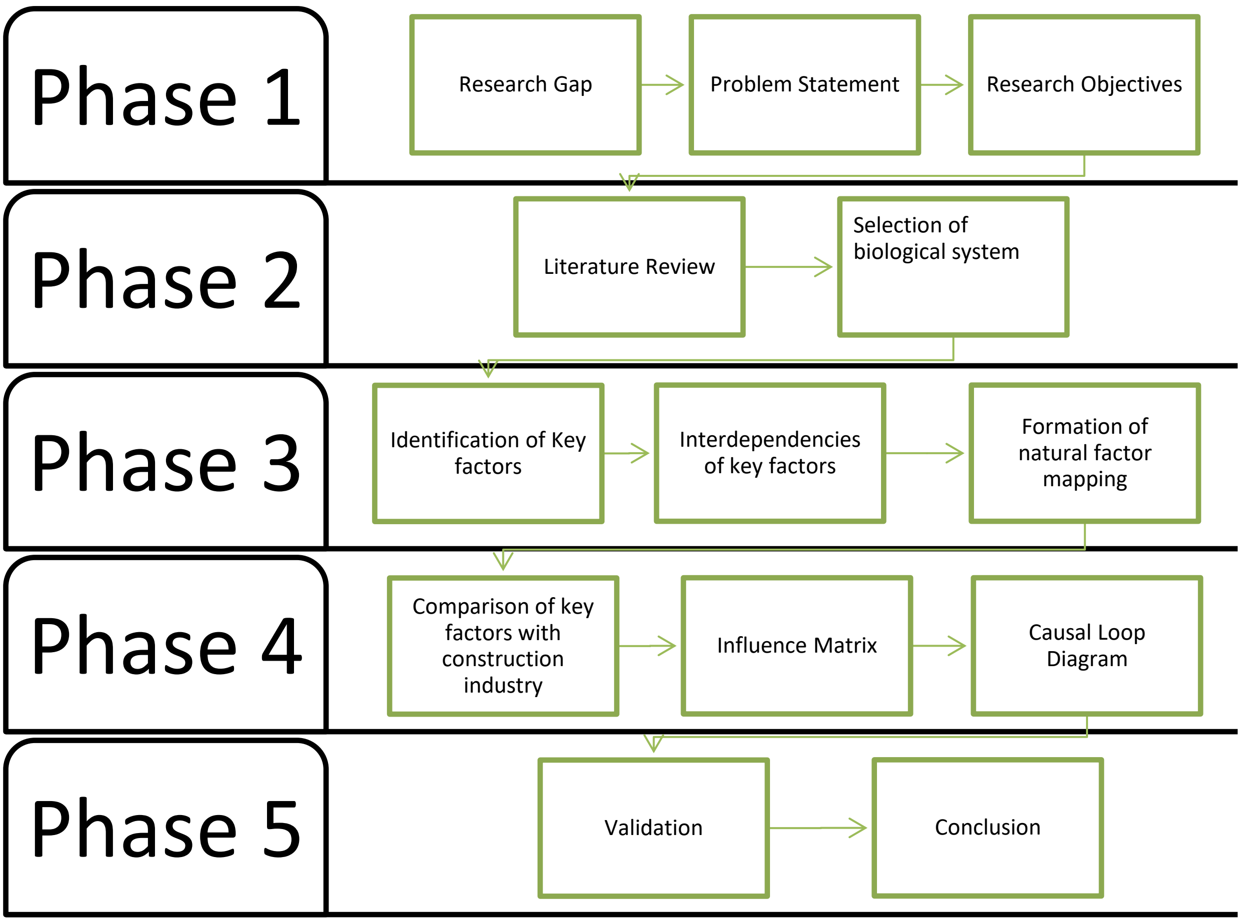

Figure 3-1: Research Methodology

3.1.1 Phase 1: Identification of Research Objectives

Research articles, books, and conference papers we studied in this phase to identify the research gap and research topic. After developing the problem statement, research objectives were identified to define the scope of work. In addition to defining the scope, the scrutiny of articles gave a preview of the research work already done on this topic, the reason for conducting a research study in this field, its relevance to national needs, and its benefits to the construction industry and the existing body of knowledge.

3.1.2 Phase 2: Selection of Biological System

The literature review was carried out to study various natural and ecological systems focusing on their communication, information generation, and transfer. 3 different biological specie systems were analyzed depending upon their social connections, mentioned below:

- Solitary animals such as Jaguars, Arctic Fox, and Sand Cats
- Social animals such as wolves, lions, and monkeys
- Colonial species such as termites, ants, and bees

The basic characteristics of each set of species were reviewed to select the best fit model for information transfer and management.

3.1.3 Phase 3: Literature Review

The behavior of four different ant species was studied in detail with a combination of nature documentaries, books, and 40 research articles. To eliminate the environmental and random bias, a total of 20 factors we identified that were common in all the four species under study and were related to information generation and its transfer. Each factor with their effects on the behavior of the individual and colony was documented. These identified factors were divided into three different categories:

- 6 Primary Factors: mode and way of information generation, transfer, and management
- 7 Internal Factors: Factors related to the colony itself and its behavior
- 6 External Factors: Environmental factors influencing the behavior of the colony

Content analysis was carried out to study the factor's impact on the system. The impact of each factor was assessed based on a 3-factor Likert scale (high, medium, and low), through a detailed review of the literature. A quantitative number was assigned to each impact (5 for high, 3 for medium, 1 for low) as described in the respective literature document. The highest frequency impact was selected for each barrier. Literature score was calculated using the following equation:

$$\boldsymbol{Literature\ Score} = \boldsymbol{Impact\ Score} \times \frac{\boldsymbol{Frequency}}{\mathbf{5} \times \boldsymbol{Total\ No.of\ Papers}}$$

Equation 3-1

The literature score assigned to each factor was divided by the sum of the literature score to calculate the normalized score for each factor. The list of factors was then arranged in descending order of the normalized score and the cumulative score was calculated. The obtained list of factors was arranged in the descending order of their relative significance (Ullah et al.,2017).

In addition to the impact of each factor, the interdependencies between the identified factors we also extracted from the literature. These interdependencies were drawn in the form of a mind-map, which was later converted into a preliminary causal loop diagram.

3.1.4 Phase 4: Field Study

The field survey was divided into two parts. The first part was a preliminary interview session with field and academic experts. The objective of this preliminary field survey was to translate the factors taken from the ecosystem of ants and find their equivalent factors in the construction industry. After these interviews were documented, a detailed survey was designed following a hybrid approach of interviews and questionnaires to validate the impact of each factor on one another which was previously obtained from the literature and formed the initial causal loop diagram. After the results of the field survey were compiled, two influence matrices were developed. One was based on the interrelationships obtained from the literature and the other one was based on the responses collected from the field. The two influence matrices were then compared, and a weightage ratio of 50/50 was used to combine the two matrices into a final influence matrix.

3.1.5 Phase 5: Development of System Dynamics Model

In this final phase, the final influence matrix was used to model a final causal loop diagram, which was further converted into a System Dynamics Model by determining the equations by which each factor was influencing the other. This model addressed the rate of information transfer, the level of detail in each transfer, and the level of decision-making authority to be given to the site team by considering various factors and their changes with time.

Chapter 4

Results and Discussions

4.1 Pilot Survey

An initial pilot survey was conducted to translate the external and internal factors identified in nature. Semi-structured interviews were carried out to find out the closest meaning of the natural factors in construction industry. For each factor, an expected converted factor was given. The reason and expected factor were asked from the respondents if they disagreed with the given factor. If only one respondent disagreed with any factor, that disagreement was neglected, for more than one disagreement, the reason was incorporated in the conversion of factors. A total of 10 interviews were collected and their summary is as shown below in table 4-1:

Table 4-1: Pilot Survey results

S. No	Factor in Nature	Factor Translated	Agree	Disagree	Reason for Disagreement
1	Environment Stability	Stable market and construction policies	10	0	N/A
2	Risk of disturbance	Unforeseen Delays	8	2	Call it "Force Majeure"
3	Water intake to spent ratio	Benefit to Cost Ratio	9	1	N/A
4	Climate	Additional Resource consumption/ Wastage	9	1	N/A

S. No	Factor in Nature	Factor Translated	Agree	Disagree	Reason for Disagreement
5	Desiccation Tolerance	Tolerance Towards Loss	7	3	Tolerance towards “additional cost”
6	Offspringing Colony	Firm with Vision	7	3	Non-offspringing is “Dead-end Firm”
7	Risk of Death	Risk of Loss	10	0	N/A
8	Neighboring Colony Distribution	Competition	10	0	N/A
9	Colony Size	Size of Firm	9	1	N/A
10	Density	Size of Team	9	1	N/A
11	Food Availability	New Project	10	0	N/A
12	Food	Revenue	10	0	N/A
13	Search Time	Activity / Project Time	10	0	N/A

Table 4-1 indicates that the factors in ant kingdom and in construction industry are very closely related. Because of their close relation, causal loop diagram in generated from one ecosystem has the potential to be applied in another. Thus, the causal loop diagram generated from the factors of ant kingdom as shown in figure 2-2 was updated according to the responses of pilot interviews. The resultant updated factor mapping diagram is shown in figure 4-1:

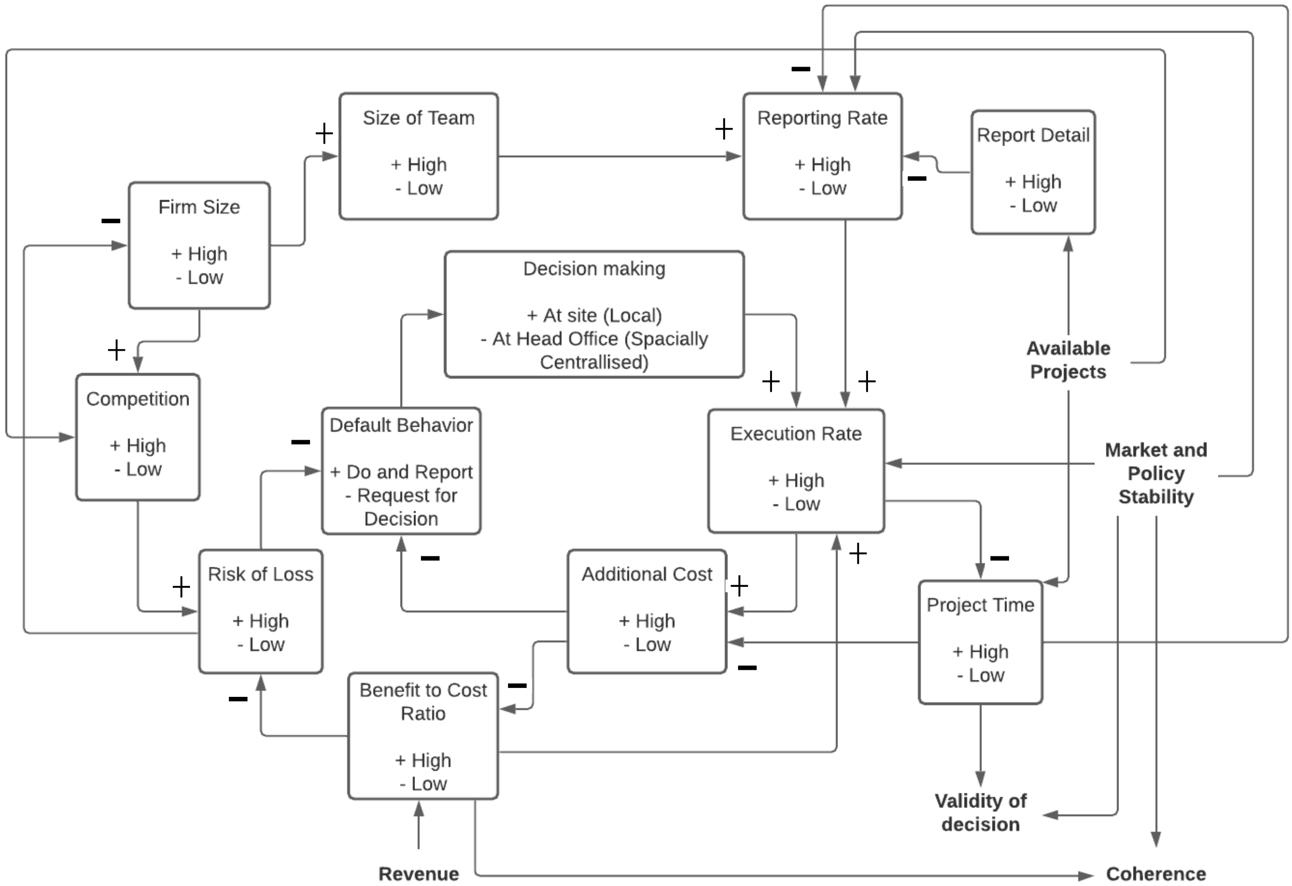

Figure 4-1: Factor Mapping – Construction

4.2 Final Survey

Based on the causal loop diagram mentioned in figure 4.1, a bi-section questionnaire survey was developed on Google® Docs (Shen et al., 2017) to determine the impact of each factor on the other, as well as to further confirm the nature on the relationship, direct or indirect. The head section had personal information of the respondents such as qualification, experience, nature of job etc. The second section had a list of relationships and were rated from 0-5, as well as the polarity of the relationships. A total of 96 responses were obtained dominantly from Pakistan. The demographics of respondents are shown in tale 4.2:

Table 4-2: Respondent Demographics

Respondent Demography		Frequency	Percentage
Qualification	Less than 1	27	28.13
	1 to 5 years	32	33.33
	6 to 10 years	10	10.42
	11 to 15 years	6	6.25
	Greater than 15 years	21	21.88
Qualifications	Undergraduate	24	25
	Bachelors	18	18.75
	Masters	41	42.71
	M.Phil.	12	12.5
	Ph.D.	1	1.04
Nature of Job	Academia	38	15.63
	Client	21	21.88
	Consultant	15	12.5
	Contractor	12	39.58
	Others	10	10.42

4.2.1 Influence Matrix

The factors and their affects obtained were organized and summarized. The external factors were ignored for further study as polarity agreement did not reach any significant satisfaction. The summarized table is shown below:

Table 4-3: Survey Results

Relationship	Polarity	Average Impact
B/C with sensitivity to Risk of loss	Indirect	2.875
Revenue to B/C	Direct	3.531
Additional Cost to B/C	Indirect	3.438
Additional Cost to Site team authority	Indirect	3.031
Risk of loss to Site team authority	Indirect	2.885
Site team authority to Execution rate	Direct	2.562
Rate of Reporting to Execution Rate	Direct	2.823
Execution Rate to Additional Cost	Indirect	2.708
Project Time to Additional Cost	Direct	2.937
Project Duration to Reporting Rate	Direct	2.614
Report Detail to Reporting Rate	Indirect	2.729
Project Team to Reporting Rate	Direct	2.719
Firm Size to Team Size	Direct	3.021
Firm Size to Competition	Direct	3
Competition to Risk of Loss	Direct	2.615
Risk of Loss to Firm Size	Indirect	2.417

An Influence Matrix was developed based on table 4-3. Positive value shows direct relationships while the negative shows indirect ones. Influence matrix generated is as under:

Table 4-4: Influence Matrix

Relationships	Firm Size	Competition	Team Size	Risk of Loss	Site Team Authority	Report Detail	Reporting Rate	Execution Rate	Project Time	Additional Cost	Benefit to Cost Ratio	Revenue
Firm Size		3	3.02									
Competiti				2.62								
Team Size							2.72					
Risk of	-2.42				-2.88							
Site Team Authority								2.56				
Report							-2.73					
Reporting								2.82				
Execution										-2.71		
Project							2.61			2.94		
Additional					-3.03						-3.44	
Benefit to Cost Ratio				-2.88								
Revenue											3.53	

4.2.2 Reliability Test

The responses collected were first checked with the Fleiss Kappa test to check the inter-rater reliability of agreement. The factors on the influence matrix shown above, achieved the kappa value of 0.533 with S.E. value of 0.0037. This shows moderate agreement on the factors (D Zuehlke et. al., 2009). Only the selected ones were chosen for final causal loop diagram.

4.3 Causal Loop Diagram

The final causal loop diagram developed had 4 loops in total, three reinforcing loops and one balancing loop, described below:

4.3.1 Balancing Loop (B1)

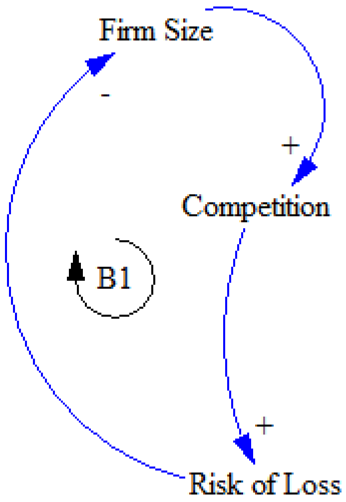

Figure 4-2: Balancing Loop B1

Increase in the size of the company means that more projects are being executed, thus increasing the competition. Increasing the competition will increase the risk of loss, which will restrict the company size.

4.3.2 Reinforcing Loop (R1)

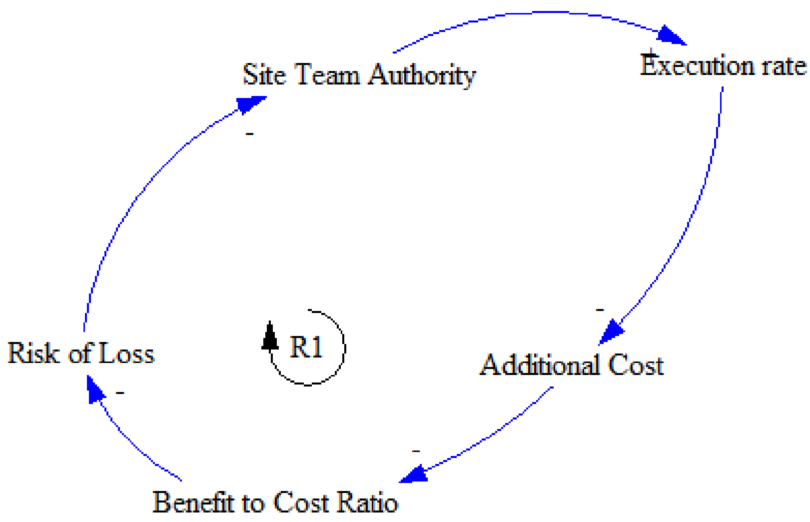

Figure 4-3: Reinforcing Loop R1

By increasing the additional cost, benefit to cost ratio is reduced, which increases the risk of loss. As the risk of loss is increased, the site team is given restricted decision-making authority, which also reduces the rate of execution. This increases the additional cost incurred.

4.3.3 Reinforcing Loop (R2)

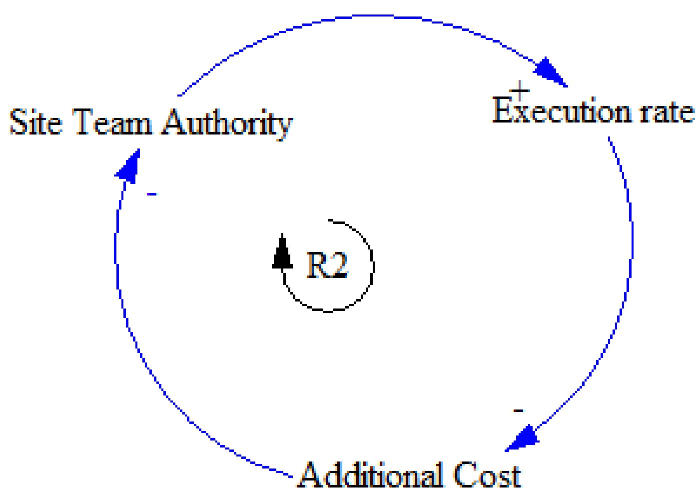

Figure 4-4: Reinforcing Loop R2

An increase in the execution rate will reduce the additional cost incurred due to reduction of time. This will increase the site team authority which will further increase the execution rate.

4.3.4 Reinforcing Loop (R3)

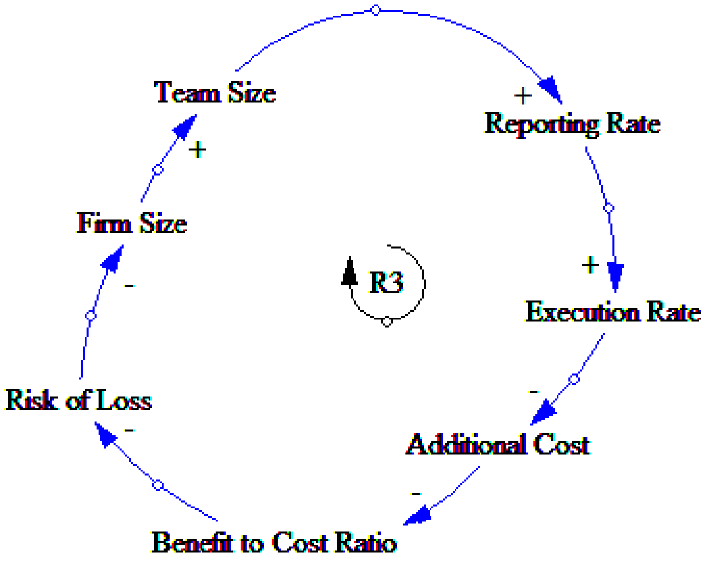

Figure 4-5: Reinforcing loop R3

An increase in the execution rate will reduce the additional cost incurred due to reduction of time. This will increase Benefit to Cost ratio which will decrease the risk of loss. That reduction will increase the firm size as well as ream size, which will reduce rate of reporting, and increasing the execution rate.

4.3.5 Feedback Causal Loop Diagram

In addition to the above-mentioned loops, some external factors were also added which were agreed upon by more than 90% of the respondents. The resultant causal loop diagram is as follows:

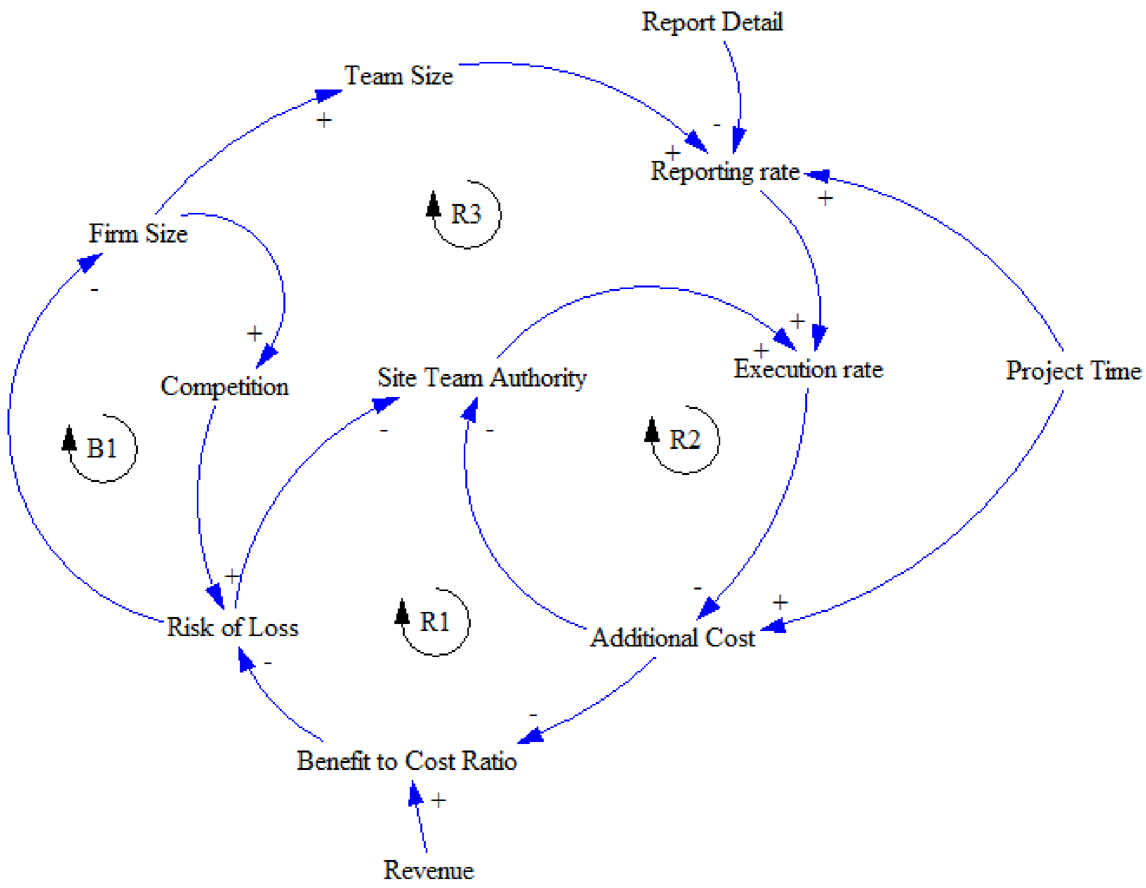

Figure 4-6: Feedback Causal Loop Diagram

Chapter 5

Conclusions and Recommendations

It has been observed that changing the decision-making authority can affect the rate of execution of the project. If it is kept at the head office, the execution is slowed, and if it is moved to the site office, the execution rate is increased, also increasing the additional cost incurred. Thus, if the benefit to cost ratio is above required target, “Do and Report” method should be followed rather than “Request for Decision”. Ideally, some things should be kept for the latter method despite the benefit to cost ratio.

Bioinspiration shows a promising solution to the problems currently being faced. It is a relatively new technique, even in the domain of research, which has its own risks and complexities. But it should be adopted not only in the field of information management, but in other aspects of management as well. Human race might not readily accept the management practices evolved from “lesser species”, but the fact of the matter is that they are managing their systems way better than we are. This opens a lot of horizons for creating more efficient and sustainable systems. Nature provides a repository full of solutions, for the problems we currently face, irrespective of the domain of the problem, and is ready to be exploited.

This research primarily focuses on the internal factors of the system. External factors, although some are identified, are yet to be determined properly. Some factors such as “Market stability”, “Coherence in Information” and “Validity Period” have shown that they do influence the system, but the nature of influence is yet to be determined. Bio-inspiration, although a new and difficult approach, but it holds a lot of promise in terms of upgradation and finding solutions of problems across all engineering platforms and management techniques. In addition to the factors identified, it has been observed that site team authority not only depends upon the cost and risk of loss, but various other factors also contribute, such as motivation and company bias. These are yet to be determined completely.

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