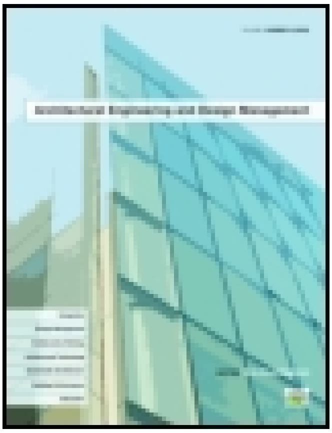



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# General contractor's project of projects - a meta-project: understanding the new paradigm and its implications through the lens of entropy

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# General contractor's project of projects – a meta-project: understanding the new paradigm and its implications through the lens of entropy

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Why do Koskela and others argue that the underlying theory of project management (PM) is obsolete? Project management works for the manufacturing industry, and for the construction industry at both the physical production level and the subcontractor level. Stakeholders, including the owner (along with due diligence, and O&M teams), architect (and the design team), general contractor (and its subcontractor team) create, transmit, process, manage and use information. The boundary between information (creation and transmission) and physical production is where PM controls and predicts cost and schedule and where quality controls fail to work as intended. This paper argues that subcontractors give project numbers for the physical part of the project, while general contractors' project numbers are actually a *project of projects* (those of the subcontractors). The general contractor manages a meta-project (term and definition, as related to building construction, coined by Fernandez-Solis). The meta-project paradigm has significant consequences and is the key to a novel understanding of the general contractor role. Lean construction's percent (or promise) plan complete (PPC) gages the reliability of promises made, is a useful and viable indicator of the quality of the schedule, and serves as a surrogate measure of project flow – how smoothly or chaotically a project runs. The PPC is operationalized as an index that meta-project stakeholders can use to calibrate the reliability of work in progress and provide feedback on the predictability/variability of logistic plans. The methodology of this paper uses conceptual analysis, the metonymic mapping of key concepts from the thermodynamics domain to the construction domain and showcases the concepts through PPC case studies. Information entropy theories are discerned in the PPC reports. In conclusion, scientific information theories, principles and characteristics of flow, in contrast to managerial principles, provide a clearer background for visualizing a novel understanding of the state of the project flow at the meta-project level. It could be argued that this paper is about defining a reference discipline and construed as "construction science viewed through the lens of entropy" but this is not the focus of this paper but the topic of the next.

**Keywords:** asymmetric information; game theory; lean construction; meta-project; paradigm; percent plan complete; project management body of knowledge

## Introduction

Project management (PM) and PM Body of Knowledge (PMBOK, 2013) are successfully applied in manufacturing companies, such as Toyota and Boeing, among others.

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Likewise, PM, as taught and practiced in the construction industry for cost, schedule and quality control, is successfully applied by subcontractors and suppliers close to the manufacturing and fabrication production process. In other words, subcontractors' application of production management tools generally results in controllable, predictable and reliable performance, in large part because they are close to the on-site work, materials, methods, fabrication and assembly. Fernandez-Solis (2008) treats in greater detail the similarities and differences between manufacturing and construction. However, space limitation prevents the exploration of the differences between construction management and construction Science in this paper, a task relegated to a future paper.

However, Ballard and Howell (1994), Koskela and Howell (2002a, 2002b), Koskela and Vrijhoef (2001) and Ballard (1994) state that while PMBOK works in manufacturing, it does not produce the same reliable results in construction, specifically in terms of stabilizing workflow, reducing inflow variance and improving downstream performance. When the same PMBOK theories, principles and tools taught by universities are practiced by general contractors in estimating, scheduling and project controls, the expected results, predictability and reliability are not consistently achieved (Ballard, 2000; Christodoulou, Ellinas, & Aslani, 2009).

Gaps in information creation, communication transfer and management and integrity are found due to three main reasons: First, information transfer across phases and stakeholders is prone to gaps due to incomplete, incorrect, untimely and/or ambiguous information.

Second, asymmetric information (game theory, GT; Davis & Morgenstern, 1997) is prevalent in construction (more on this later). Third, gaps are created by broken promises that are endemic in construction. To counteract these deficiencies, buffers and contingencies are put in place by each stakeholder because there is no confidence (trust) in the reliable performance of other stakeholders (players) (Nash, 1951). Figure 1 showcases gaps in information (Gleick, 2008) as the dark

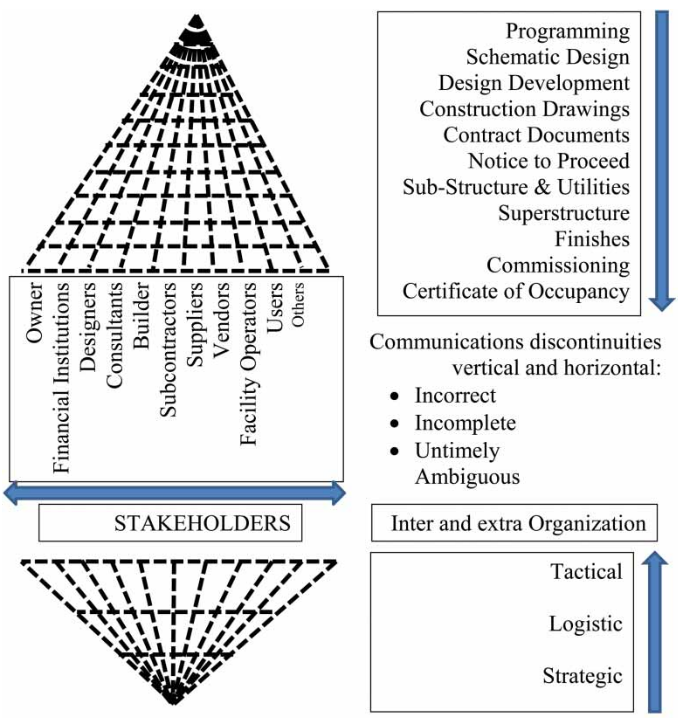


Figure 1. Stakeholders and information flow (arrows).

lines in the diagonal and horizontal grids. These gaps increase the non-performance risk at the tactical level; for example, when information is transferred from the team that does programing, to the design team, to the general contractor team, and finally, to the subcontractors for action.

In addition, three macro-reasons at the strategic, logistic and tactical levels have been advanced for the lack of concordance between plans and execution reliability: At the strategic level, the systematic nature of the construction industry (Fernandez-Solis, 2008) is radically different from that of other industries. At the logistic level, a tight coupling of logistics planning and tactical execution does not exist. At the tactical level, the application of management tools has not yielded a consistent, reliable and predictable performance.



## Strategic level

The officers at the strategic level of each stakeholder are the owners, presidents, board of directors, vice presidents, leadership group and principals. Their function is to identify and implement the mission, vision and objectives of the organization, establish the history and culture, leadership and ethics of the organization internally and as it relates externally to other stakeholders. One universal strategic mission is to promote growth and plan for survival in adverse times and make the organizational decisions such as hiring, firing and promotion of personnel. In general, this level answers the questions of how we came into being, what is our mission and vision, where are we going and how are we going to get there and stay out of trouble (i.e. court). Strategic level adds value through service.

Note: The definition of strategic as tactical is not the one we use here. Rather, this paper differentiates strategic, logistic and tactical as the construction industry and other institutions, such as the military, do.

## Logistic level

The personnel at the logistic level of each stakeholder organization includes planners, architects, engineers, project managers, office personnel, human resources, accountants, estimators, schedulers and IT personnel. The role at the logistic level relates to planning, organizing, documenting, creating, coordinating and disseminating information to stakeholders and keeping financial records of all transactions. In general, the logistic level of any organization is charged with carrying out the mission, vision and objectives of the organization to fulfill strategic directives. Logistics adds value through service (i.e. almost exclusively by handling information).

## Tactical level

The personnel at the tactical level of each stakeholder organization are the boots on the ground, those close to the physical execution of the logistic plans, of interpreting the information provided. In general, the tactical level of any organization is charged with execution: creating a final product that is accepted by the owner (public or private) for its intended use. Even at a mostly service organization, such as an architectural firm, the Contract Administrator meets the boots on the ground, where the contract documents are delivered to the next organization (the owner delivers to the general contractor in most project delivery cases), and interfaces between the owner's representative in the field and the builder make the project a reality. Another major function at the tactical level is to capture lessons learned – actual cost, schedules, obstacles, project flow, performance – and pass them to the logistics level for assimilation into future best practices, which, in turn, are filtered up to the strategic level as it affects the direction of the organization and its objective of growth and survival. Tactical adds value through the life experience of how it has and can be done and solving problems that arise in the field.

### Logistic – tactical disconnect

The logistic and tactical disconnect has led Koskela and others (Puddicombe & Johnson, 2012) to argue that the underlying theory of PM is obsolete and is a hindrance to innovation (Koskela's, 1992, 2000, 2002, 2003a, 2003b; Koskela & Ballard, 2003; Koskela, Ballard, & Howell, 2003; Koskela & Howell, 2002a, 2002b; Koskela & Vrijhoef, 2001; Vrijhoef & Koskela, 2005). PM works for the manufacturing industry but not for the construction industry. Why? This question has not been squarely formulated and properly answered. The building construction industry operates on an average of 3% profit and has an average of 3.1% work recall (i.e. reworking costs money, time, warranty calls and indirectly the goodwill that becomes repeat business; DPR Construction, 2012). Work recall is attributed to a Pareto mix of reasons such as communications failure (missed communication, missed understanding, misidentification and misalignment of expectations) between stakeholders, a real disconnect on information creation, transmission and use between the strategic, logistic and tactical stakeholders (Nalebuff & Dixit, 1991).

In spite of the remarkable systemic differences between manufacturing and construction, general contractors stubbornly apply manufacturing management theories, principles and techniques to construction (such as the metrics of cost, schedule and quality).

The application in construction of current management practices is not impressive when compared to manufacturing (Fisher, 1993). Any gains in construction production practices are due to the shifting of prefabrication offsite, thus making on-site activities even less efficient (Gann, 1996). The need to find a better method of production in construction has led to Six Sigma and now, lean construction, which is taking the industry by storm.

In order to reduce variability and create better controls, lean, an outgrowth of Six Sigma used in manufacturing and industrial engineering, has devised theories of value and waste in applicable formats (Linda, 1995). However, lean approaches are thought by most practitioners to be simply another set of tools for the PM tool kit available to builders, one more PMBOK fad that will come and go, and eventually be ignored by the construction industry, like Six Sigma "we can put construction into Six Sigma but we cannot put Six Sigma into Construction" (AGC's Lean Construction 101 – Online).

At the strategic level, construction is indeed different from manufacturing. However, at the logistic level the same operationalized metrics are employed as in manufacturing: cost, time and quality. The strategic level of construction is really a meta-project that requires a different set of operationalized metrics, with PPC being one of them. The metaphors of strategic, logistic and tactical functions permeate all types and forms of organizations, from the macro level of the construction industry to the mezzo level of organizations to the micro level, if you please of the project. Previous paper treats this fractal nature of these functions in greater detail; see Fernandez-Solis, Lü, and Ryoo (2012).

As such, this paper advances a new paradigm: general contractors do not manage "a project". Rather, they manage a *project of projects* (those of the subcontractors), which requires a novel understanding of the tools needed to visualize productivity or lack thereof, due to gaps in information (Koskela & Kazi, 2003) created by the above-mentioned reasons. We develop this new paradigm through the methodology and discussion that follow.

### Methodology

The methodology section presents the research rationale, the data collected, the tools used to interpret it and a glimpse of the results. At the heart of Science resides a conceptual metaphor that is foundational for meaningful explanations of phenomena. Thermodynamics and construction are presented through abstract concepts that are largely a literal core extended by metaphors (Lakoff & Johnson, 1999). Metaphors can be either structural inferences or dynamic. Blending theories indicate that in the neural theory of languages (Glaser & Strauss, 1967) there exist:

- Metaphorical mappings
- Image schemas
- Force-dynamic schemas
- Frames
- Prototypes
- Metonymic mappings.

This paper creates a new framework for understanding macro-projects using force-dynamic schemas, metonymic mappings, conceptual analysis and case studies as prototypes of the construction industry.

Palmer's (2000, 2001, and 2003) force-dynamic nesting of schemas shows that systems are synergistic, while meta-systems (system of systems) are the opposite – anti-synergistic, entropic or dissipative. This translates into a novel construction schema of subcontractor projects and contractor meta-projects with the attending synergistic and dissipative results. This novel schematic approach results in a new paradigm with implications that have not been fully explored, understood or measured. That is, a new field of studying construction as a science and not as pure management is opened up. The field of management science more closely approaches the new paradigm required for a better understanding of meta-projects and strategic, logistic and tactical relationships of project controls. However, thermodynamics offers better developed and parallel schemas with information entropy (Ding & Shi, 2005; Lam, Tang, & Lee, 2005; Zhou, Fan, & Zhou, 2010) in construction and therefore, presents a closer metonymic mapping opportunity.

Metonymic mapping (Shannon & Weaver, 1949) is used to indicate similarities between two domains. In our case, we map the thermodynamics domain into the construction domain. The thermodynamic concepts at hand are energy, work, waste, entropy, chaos and flow and the construction concepts include information, work and waste.

We use the PPC construct to operationalize our meta-project paradigm. A PPC is a broad, mutual fund-like indicator of the quality of the project flow and of the reliability of the logistic schedule tracking promises made at the tactical level. The PPC construct will be explained and elaborated later in this paper. Eighty-five (85) PPC case studies are presented, described and analyzed using Lyapunov exponents (Stewart, 2002), also defined later on. One PPC case in particular is analyzed in two ways: regular PPC data are compared with the same PPC data but with the subcontractor's share of the cost as a loaded ratio.

The comparative analysis focuses on how complex all production organizations are, how they are prone to chaos due to the information gaps between stakeholders, as well as between phases, but most importantly, how the contract is enforced through promises to deliver. When tracked, the analysis illuminates how gaps in promises show in the project production flow. The point is made that while a subcontractor tracks schedule, cost and quality, the general contractor at the meta-project level should be tracking the flow, the rate of promises to deliver work, that includes information gaps, and asymmetric information that is manifested in broken promises.

Asymmetric information exists when one party has more or better information than the other (this concept is further explained later). Asymmetric information (information GT; Kotarbinski, 1965; Roth & Kagel, 1995) often occurs because each stakeholder belongs to an organization with many other projects, each of which may affect the actual performance of this project. The particular project team is not privy to all the issues and relevant background history that a stakeholder brings to the table affecting his performance on the team. Asymmetric information is a major force in information gap and information loss (Zhou et al., 2010), as well as a strategic tool. In fact, deliberate asymmetric information is prevalent in construction, a tool of the survival/growth game, as we shall further explore later in this paper.

"We have to remember that what we observe is not nature itself but nature exposed to our method of questioning" (Heisenberg (1958, p. 356). We translate and apply this quote to construction as follows: with the new framework of a general contractor managing a meta-project, the method of questioning project flow and performance changes from monitoring schedule, cost and quality to an emphasis in the presence, quantity and type of information gaps as manifested in broken promises captured in the PPC. What we observe through this different method of questioning construction reality is the project flow, energy, entropy and presence of chaos. Meta-project information is based on science; project information is based on management of data. The approaches are radically different as the first one is based on entropy, the tendency toward dissipative energy and the second one is synergistic. This approach is, according to Palmer (2003) and Gunderson and Holling (2002), the way nature operates.

## Data validation

The PPC data are validated from two sources, one is Lean Construction Institute (LCI) and the other is the International Group of Lean Construction (IGLC). Also included are data gathered by the research team from projects in the area using lean construction practices, including PPC monitoring along with reasons tracking, five whys, last planner practices and other customary lean practices. The research team was allowed to visit and monitor these projects on a regular basis.

### *Force-dynamic schemas*

Johnson (1987) and Lakoff and Johnson (1999) have hypothesized that schemas are essential for human's reasoning capacity, with image schemas as well as force-dynamic schemas (Talmy, 1988) at the center. An image schema is a recurring structure within our cognitive processes which establishes patterns of understanding and reasoning. Image schemas are formed from our bodily interactions, from linguistic experience and from historical context. Force dynamics is a semantic category that describes the way in which entities interact with reference to force. The force group of schemas include: compulsion, counterforce, diversion, removal of restraints, enablement, attraction, link and scale. Force-dynamic schemas are a good fit for understanding construction project organization systems as the elements of this schema are thematic in construction.

## Project production organization system

Construction in general and building construction in specific, is an information intensive service that creates, transmits, processes, manages and uses information to identify opportunities, anticipate difficulties and resolve problems by creating the contract documents that comprise what is generally known as the design intent used by supervised workers for the production of a building project (from now on "project"). The purpose of including the following discussion of project numbers is to illustrate how a general contractor actually handles the subcontractors' projects; hence the general contractor is operationalizing a meta-project.

The production of a project is organized around two key information data: the project name and the client's project number. The project name is a surrogate of the virtual project, and eventually the physical project, that includes location, type, cost, size and quality; it is tracked by the client's project number. The design team, whether led by an architectural or an engineering firm, will keep the project name but assign their own project number for tracking among other firm projects. Each stakeholder at the owner due diligence level exclusively deals with information creation, processing, management and transmission.

The stakeholders at the design phase preparing the contract documents also exclusively deal with information. These stakeholders create a temporary system organization for the period that encompasses the project design and construction. The project life extends beyond this period but is not in the scope of this study.

The contractor inherits the information contained in the contract documents as the design intent and assigns a project number that distinguishes the project from other projects of its organization. The general contractor selects a set of sub-contractors who likewise assign its own organization's project number. Their numbering system is independent of all other numbering systems from the owner and other stakeholders as their portion of the work has to fit within their established subcontractor production organization system.

Taking this reasoning a step further, all suppliers and vendors likewise will give their portion of the work a unique project number that works within their own organizational system. Project physical activity takes place at the general contractor tactical level (superintendent, project manager, site trailer personnel) and at the subcontractor and vendor tactical level (foremen, supervisors, crew leaders, workers, delivery persons and plant personnel). Figure 2 shows a graphical representation of two activities: field work (circled) and all others. Field work is where the boots are on the ground value is added by physical activity and material objects, all others add value through manipulating information.

The rules of engagement in construction production require that no owner, designer, consultant and even general contractor or general contractor's superintendent can direct the work of the field, the foremen, supervisors and its crews (Rounds & Segner, 2011). Only the foremen or subcontractor supervisors can issue on-site work orders, direct the labor, means, and methods and direct all aspects of the physical production that corresponds to their trade and contract, therefore assuming and managing the risk. In other words, at the tactical level, especially the subcontractor,

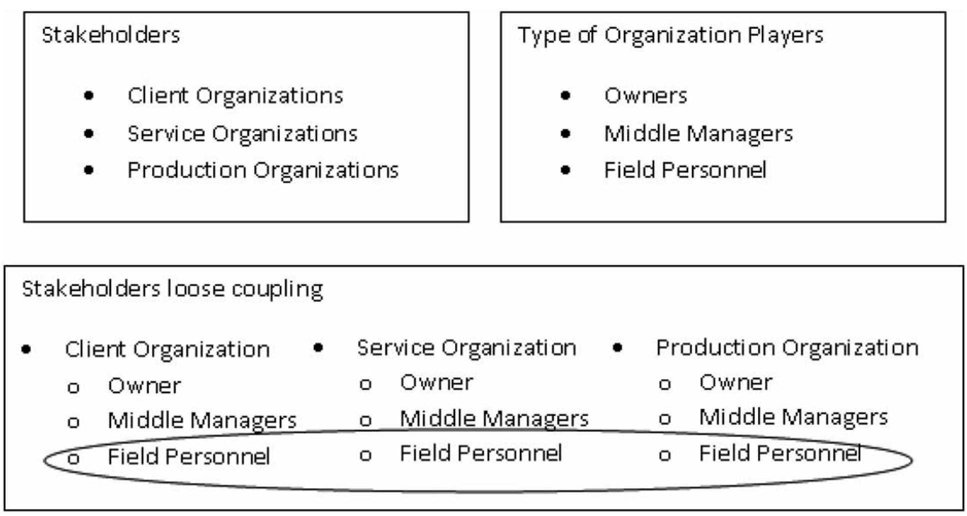


Figure 2. Stakeholders and type of organization players (field work is circled).

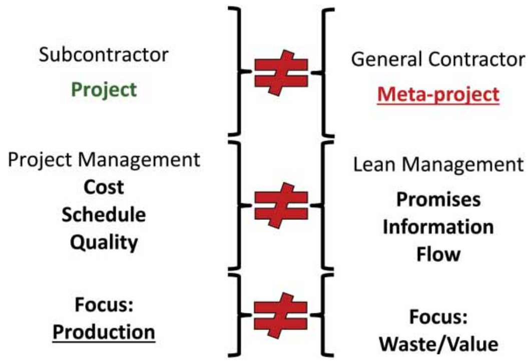


Figure 3. A new metaphor distinguishing subcontractor and general contractor understanding of the concepts of project and meta-project. Caveat: Lean Management is PM with lean theories, tools and techniques.



suppliers and vendors, there is direct control of the assembly, fabrication, material placement, labor, erection, movement and transportation, and parts that becomes the physical building. This proximity with the physical world grants the subcontractor at the tactical level a magnitude of control in cost, schedule and quality that eludes other stakeholder at the informational (strategic and logistic) levels, including the general contractor.

In summary, the subcontractor, supplier and vendor project numbers are the real players of the physical project; the general contractor and owner project numbers are virtual projects, and represent a *project of projects*. The project of projects, like a system of systems, is the definition of an entity called a *meta-project* or meta-system (Figure 3).

## Definition of a meta-project as a project of projects

Meta-projects require different metrics (scale, type and complexity) to visualize and understand flow patterns. Palmer (2003) observed that systems are synergetic in nature. That is, one plus one is more than two, or in construction, the work, labor, material effort at the end has a value that is greater than the work, once completed and used for its intended purpose. This is the project's economic utility (Buchen & Kelly, 1996; Choi & Jeffrey, 2005).

Palmer (2003) also observes that a system of systems or a meta-system is the opposite of synergistic; they are entropic. That is, handling the complexity (Frizelle & Woodcock, 1995) of a meta-system, we can expect an increase in the possibility and probability of disorder, variability, chaos, and therefore, of entropy in the production process (McClean, 1986) of work.

Work is the force marshaled with and through correct, complete, timely and unambiguous information against this pervasive tendency toward an increase of entropy at the meta-project level due to the strategic fact of its systemic nature, the logistic fact of the existence of information gaps and the tactical fact of autonomous agents with asymmetric information.

The concept of *asymmetric information* comes from GT, the formal study of strategic situations and interactions (games) among agents (players) who are fully rational (maximize payoffs without concern for the other players), aware of each other, and aware that their decisions are mutually dependent and affect the resulting payoffs (Myerson, 1991; Nash, 1951; Roth & Kagel, 1995; Smith, 1984). In construction, the building process is the game and the subcontractors are the players. GT is characterized by five elements:

(a) Players: how many and who they are;
(b) Strategies: what players may rationally decide to do given known circumstances;

(c) Payoffs from each outcome: what the players expect to gain from their moves;
(d) Sequence of the actual moves or state: the players' position at certain stages of the game;
To this given set we add:
(e) External influences: how other games in which the player is involved affect the strategies in this game.

This is new and a contribution to GT since in construction the players' organization is open to external circumstances that prevent the one game from being isolated from external influences.

On item (e) above, imagine that you have a franchise of teams that are all playing on a given Saturday. However, team (A) is doing poorly so you call players from other teams (C, F, H) to shore up the performance of team A. Or imagine that there is a delay in starting the game for team (B) and the players are then sent to help with the effort of team (G) affecting the temporary performance of team (G) when the players are inserted and then extracted to go back to team (B) because they are ready to start. This happens in construction all the time (the porosity of one team's performance to externalities) due to the fact that each franchise (i.e. subcontractor) is an autonomous agent looking after its best interest, as prescribed by GT.

Players in construction have asymmetric information (incomplete information about at least one of the features (a)–(e), specially (e). Conversely, one player has relevant information that other players miss. Puddicombe (2009) provides additional information on dealing with potential opportunism in contracting and information asymmetry. Because of a known asymmetry in information, under-informed players tend to over-react with additional buffers and contingencies. Asymmetric information is overcome through signaling and screening. Signaling can be described in terms of derivative information as prescribed and required in contract theory. Screening can be seen as the converse of signaling; the under-informed players induce informed players to disclose their information by offering a menu of options (Last Planner System – LPS®, stickies-on-the-wall) such that the choices of the informed agents reveal their (asymmetric) information (e.g. buffers, contingencies, fears, strategies, biases). Keep in mind that information as a resource has the following characteristics:

- Availability (timeliness)
- Accessibility (clarity, unambiguous)
- Accuracy (correct, complete).

In the physical world, entropy is the tendency to move from a system of order to one of disorder. Similarly, information entropy (Ding et al., 2009; Zhou et al., 2010) is the destruction, corruption, pollution and depletion of information objects, the opposite of the information characteristics and in general "an impoverishment of reality".

Incomplete information games are also known as Bayesian games, where a source of randomness and uncertainty is introduced as a player. Whenever information is incomplete or imperfect, there is a general need to be able to gain as much as possible of the missing information through what is known as reverse inference or Bayesian reasoning.

Building construction experience and management practices indicate that the general contractor at the meta-project level does not have internal control of all the interactions within the project or external control of all the players in the subcontractor, supplier and vendor sectors. Each player also intersects with all the other projects at hand and each project is pulling, pushing and demanding attention beyond what the logistics plan calls for. In other words, at the phase where all the action is taking place, there is no tight coupling of actors, materials and methods that are under the control of the general contractor.

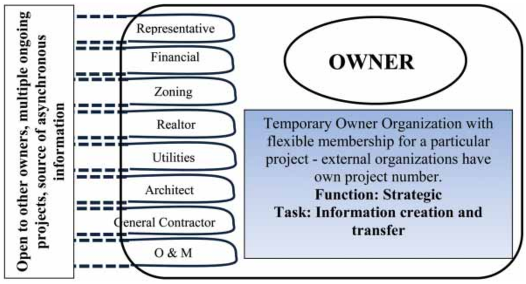


Figure 4. Owner's meta-project.

As an owner handles a meta-project (Figure 4), the architect or designer similarly handles a different form of meta-project (Figure 5). Likewise, a general contractor project is not a project as such, but a project of projects (Figure 6).

The projects, plural, reside at the subcontractor level, where the physical activity of production actually takes place. When we transfer our knowledge of how systems and meta-systems work, we find that at a system level, synergies are achieved while at the meta-system level, the system of systems, we have entropy, chaos, variability – the opposite of synergies, with work dedicated to mitigating that tendency toward entropy and chaos.

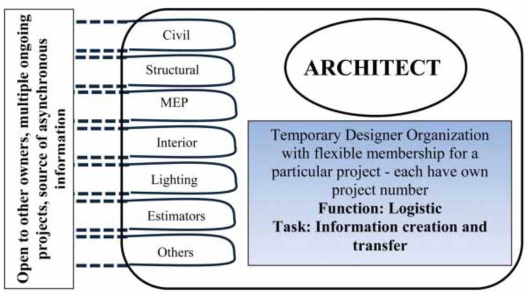


Figure 5. Architect's (designer's) meta-project.

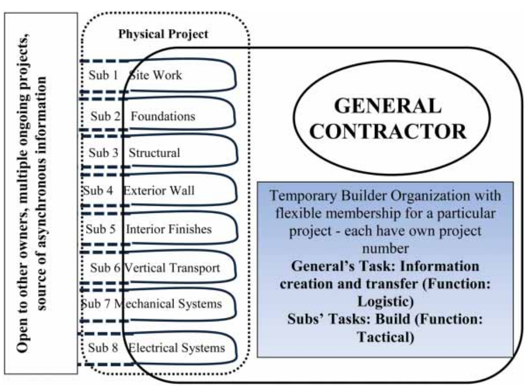


Figure 6. General contractor's meta-project.

***Metonymic mappings***

Metonymy is understood as a mapping with the same domain of experience and metaphor as a mapping between two different domains (Barcelona, 2003; Goossens, 1995; Lakoff & Turner, 1989), the verification of this hypothesis would indicate that the metaphorical leap (Goossens, 1995) from one domain to another must be previously prepared or aided by an internal mapping. In this paper, we map the domain of thermodynamics into the domain of building construction by introducing an internal mapping of this leap through the use of entropy and chaos theories. What is understood in one domain (thermodynamics) is then visualized in the other (construction).



## Work generally opposes spontaneous change (entropy)

Thermodynamic laws have touched a wide range of phenomena such as the field of information theory where the content of a message is closely related to the statistical thermodynamic definition of entropy. But is thermodynamics or dynamic the right way to approach construction? Dynamics (Pesin, 1998) deals with the behavior of individual bodies, thermodynamics deals with the average behavior of a vast number of bodies. In construction, a relatively vast number of stakeholders create and communicate data and information across phases and between stakeholders. Then, in the field, another relatively vast number of actors perform the act of construction supported by another relatively vast number of players in many industries that mine, transport, refine, create and assemble all the materials, parts and pieces that, along with labor, go into the finished product. Classical thermodynamics grew from the observations of bulk material; therefore, we have found a parallel, a ready transference of knowledge domains between thermodynamics (in lieu of dynamics) with the field of building construction and by extension, with construction in general. However for the purpose of this paper we are limiting this study to building construction read as "construction".

The center of attention in thermodynamics is the system. In construction (building as an act, a verb), it is the project "production system". The final product, the building (as a noun) itself is also a physical system but is not the subject of this research.

As in thermodynamics, the universe in which the project production system occurs is the construction industry that exists within the Pluriverse of the general economy.

A system is defined by its boundary. If matter can be added or subtracted from the system, it is said to be open. Construction is an open system. The final product, the building, may be considered a closed system; however, this discussion is not part of this research.

The properties of a system depend on prevailing conditions. Properties are divided into two classes:

- An extensive property depends on the quantity of matter in the system – its extent. This encompasses all the information created, transmitted, managed and used or discarded before, during and after the construction.
- An intensive property is independent of the amount of matter present.

In thermodynamic parlance, work is motion against an opposing force. In construction, work is motion against the opposing forces of gravity (physical), and information gaps. The work metaphor leads us to an engine that in construction lies between capital and/or information and waste (Figure 7). In this figure, capital and information are the equivalent energy sources that, along with material and work, produce a product, but generate waste, some of which is recoverable (recycled) and the rest of which is transferred to other systems (such as the legal system).

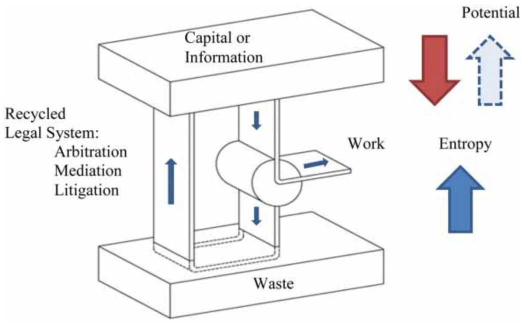


Figure 7. The thermodynamic metaphor of work in construction.



Work constitutes the vectorial transformation of information (direction) and capital (magnitude) through labor, materials, parts and systems in a production environment (origin – space/time) against the forces asymmetric or information degradation and entropic tendencies (chaos) resulting in a product, the building which then embodies a higher entropy potential.

In this metaphorical construct, we have two engines in construction: information and capital (Symeon, Georgios, & Anastasis, 2010).

Information (data + meaning or as Popper (1979) states: symbol + meaning) has three aspects: *as* reality (e.g. physical reality in tree rings, steel) *for* reality (e.g. instructions, commands, algorithms, recipes, contracts) and *about* reality (e.g. semantics, drawings, specifications, models). The use of information has two ends: attributive (information about something) and predicative (information of a phenomenon itself).

Capital is the currency of the general economy that acts as the fuel for the system and its working mechanism, but is beyond the scope of this paper.

Of interest to construction is information as a dynamic procedural structure (DPS) where adaptive agents of change (subcontractors) control and guide the production development process. DPSs are a special type of information entities that are themselves instructions, programs or imperatives. Subcontractors achieve what they achieve because they interpret information as DPSs that require their collaboration as independent agents to successfully carry out the design intent. The relationship between DPS instructions and the outcome is functional, causal and based on established procedures. In the predicative sense of the word, subcontractor agents use information as DPSs *for* reality (building the project) not *about* reality. Work then has three informational aspects: (1) information creation (*for* reality or attributive), (2) transfer (*about* reality or attributive) and (3) physical (*as* reality or predicative). Physical work is labor against gravity such as when we raise a weight (object, material, part, system) and assemble it in space/time. Work is directed by information; thus, there is a correlation between the quality of the information where value/waste is potentially generated and the final product, the building that embeds all the value/waste of the production process.

Production in construction has two results: (1) an in-place product with lower entropy (temporarily, as it is transferred to higher potential entropy manifested at the final decay, destruction); and (2) waste (higher entropy) results from synergistic information gaps and discrete physical construction waste (Fernandez-Solis et al., 2012).

Information embodied in promises to perform (PPC) makes visible, at a meta-project level, the most probable distribution of information entropy over the available states of the on-site construction dynamic system. Information entropy is there, whether measured or not, understood or not, it is there. Entropy existed in engine and nature before it was discovered and measured. DPR

Construction (2012) states that the maximum value of a construction project's PPC when taken at the general contractor level (the average of the subcontractors at work during a particular period of time) falls between 80% and 85%. In thermodynamics, the maximum work that can be extracted from a system happens to fall within the same window (80–85%)! Is this a coincidence or an elegant correlation? Veneziano (Gasperini & Maharana, 2008) states that: "identifying elegant, if empirical mathematical, connections between data is usually an important first step to a subsequent revelation".

PPC is therefore a broad-based index that visualizes the relative population of entropy in a construction production system at a meta-project level. In Figure 8, the rate of variability (RoV) is associated with the Lyapunov ratio. The higher the RoV, the lower the rate of promises that are completed correct, complete, on time and unambiguously (lower PPC). This graph illustrates that a project whose overall PPC is high, even though there are ups and downs, reflects a more predictable project flow. On the other hand, a project flowing at a lower PPC has higher variability and even though the ups and down are not as pronounced, the project is less predictable.

More work, such as filling in gaps in theories and identified future work (e.g. comparative analysis of construction management versus construction science theories) needs to be done to determine if this postulate holds with larger data samples, using the metonymic mapping of thermodynamic understanding of efficiency and the relative population of a system's data. In this paper, we treat reliability as the mentonymic equivalent measure to efficiency in thermodynamics. Reliability is that of the actual versus the promised as in the PPC and therefore it is a ratio just like efficiency.

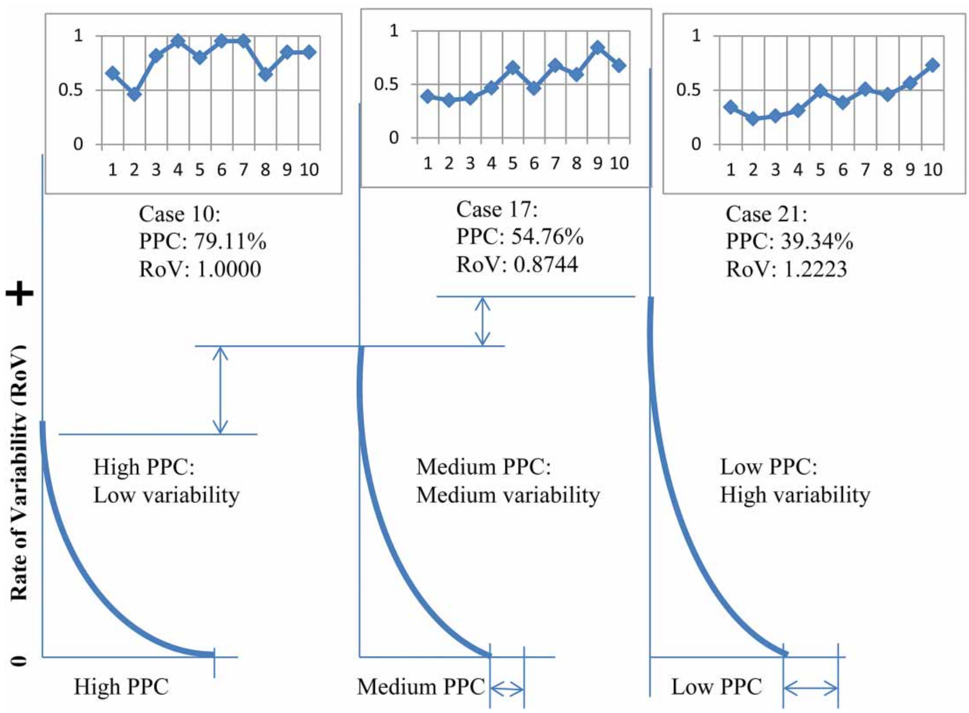


Figure 8. PPC relative population of a system's efficiency. Horizontal is PPC; vertical RoV.

The following definitions of discrete, synergistic and systemic waste and value have been previously elaborated in Fernandez-Solis et al. (2012): Discrete refers to mostly material or time waste by a trade, occurs mostly at the tactical level and is additive. Synergistic is associated or linked to the concept that a system creates a value or waste that is higher than its parts. In construction, the higher value is achieved through the synergy of trades and disciplines, occurs at the tactical and logistic levels, and is multiplicative. Systemic is defined as that caused by the decision made at the strategic level with repercussions at the logistic and tactical levels. For example, the decision by an owner to use a construction sealed proposal, in which lower cost is selected, may end up with general contractors and or sub-contractors that default because the cost of the work is greater than the price given at the bid. The project moves into arbitration, mediation or litigation according to the contract documents and the value is transferred to the legal system.

For example, starting from the left in Figure 9: If the system is such that minimizes the possibility of waste (as in the Toyota Motors Manufacturing Company, TTMC), then the only possible waste is discrete, a bolt here, a washer there … there is no room for synergistic waste. From the right, if the system maximizes waste, such as when a bid project ends in the legal system and cannot be used for its intended purpose, there is only a discrete value for the judicial industry. In the middle is the world where most companies find themselves, with the strategy of survival and growth, playing the game, holding asymmetric information, minimizing chaos and risk and in the end, satisfying the client to the best of their collective abilities. PPC values are the inverse to variability; a high PPC is indicative of reliability, a reduction in variability (Figure 9).

From thermodynamics, we borrow the term stochastic cooling to refer to a smoother flow, one with less variability. For example, Toyota sets a takt time, defined as the work time between two consecutive units, of 63 seconds and it is the same for each station. In construction, we cannot control the time between consecutive units, but we borrow the concept and interpret that less variability in the productivity as promised yields a more reliable flow, hence achieving stochastic cooling. Stochastic cooling produces a reduction in variability at the subcontractor level when promises made are kept. In order for stochastic cooling to happen, the quality of the information must be high; that is, the information must be correct, complete, timely and unambiguous as reflected in a mostly linear PPC. The effects of stochastic cooling are a reduction of the Lyapunov rate below the threshold of 1, that is, below the rate of what is considered to be chaotic performance. In other words, the ups and downs in the individual subcontractor reports represent a form of variability, which is stochastic.

Since the word stochastic simply means random, stochastic cooling is then the amelioration, diminution of random motions, of a system, a process as reflected in its measurements, which in our case is the PPC reported by the subcontractors and general field personnel. If the PPC is vectorial in nature as noted above, we then surmise that vectors that align in direction and magnitude are less random than vectors with opposite directions as well as magnitude.

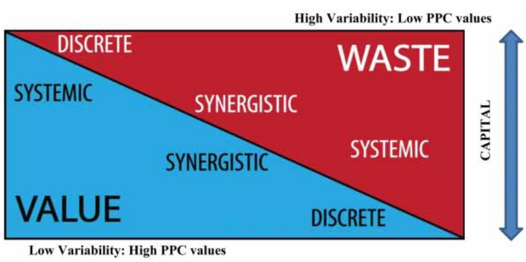


Figure 9. Waste and value relationship and PPC stochastic cooling.

## Chaotic systems

Chaotic systems are characterized by an extreme sensitivity to initial conditions or perturbations. The famous classical example generates chaotic data (May, 1975, 1976).

$$y(n+1) = r\,y(n)(1 - y(n)).$$

When $r$ is bigger than 3, the data show chaotic behavior. Initially, it is an oscillation and then splits occur. After certain $r$, they "settle down" to a kind of fixed oscillation, the chaotic attractor, this is one of the most fundamental concepts in chaos analysis.

In practice, however, it is generally too difficult to directly analyze attractors for chaotic data. Fortunately, a method based on phase space reconstruction is widely used to indirectly detect attractors in real-world dynamical systems using time series data (Takens, 1981).

For a dynamic system, proved the system can be faithfully reconstructed from time series so that a one-to-one mapping can be established between the reconstructed phase space and the dynamic system. Based on phase space, quantities of chaotic indicators for uncovering and understanding the system can be investigated, one of which is the Lyapunov exponent.

## Lyapunov exponent

The Lyapunov exponent is a measure of the rate at which trajectories in phase space diverge and the sensitivity to initial conditions in a nonlinear system. Briefly, if $x(t)$ is time series and $y(t)$ its correspondent $d$ dimensional reconstructed phase space, then there are $d$ Lyapunov exponents. The largest Lyapunov exponent reflects the chaotic degree of $x(t)$. Wolf algorithm (Figure 10) is often used to compute Lyapunov exponent (Wolf, Swift, Swinney, & Vastano, 1985) and involves keeping track of perturbations away from the trajectories in the phase space:

$$\text{LLE} = \frac{1}{t_M - t_0}\sum_{i=0}^{M} \ln \frac{L'(t_i)}{L(t_{i-1})}, \quad (1)$$

where $M$ is the number of steps, and $t_M{-}t_0$ is the time length. Take an initial $y(t_0)$. Its distance to the nearest point $y_0(t_0)$ is $L_0$. Then these two points will be traced until time $t_1$ with their distance is greater than:$\varepsilon$: $L'(t_0) = |y(t_1) - y_0(t_1)| > \varepsilon$. For $y(t_1)$, we repeat the procedure. $\varepsilon$ is defined as a small infinitesimal positive quantity. A positive LLE indicates chaos: the nearby trajectories separate exponentially. Otherwise, the nearby trajectories stay close to each other.

In other words, the PPC downward trajectories are decelerations and the upward ones are accelerations; their prevalent occurrence is indicative of chaos.

The inverse of the Lyapunov ratio is efficiency, with the following formula to set the boundary between 0% and 100%:

$$\text{EFF} = (2 - L)*50. \quad (2)$$

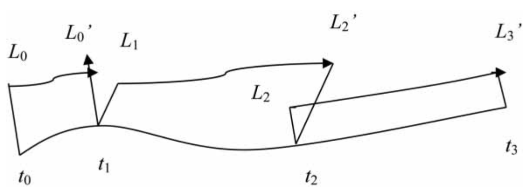


Figure 10. An illustration of Wolf algorithm for computing Lyapunov exponent.

**Defining PPC as a gage of meta-project entropy**

The connection between PPC and on-site construction realities is partial, uncertain, changeable and irrational. In other words, it is loose versus tightly coupled. There are connections; on one hand there is the type of loose connection which is not a hindrance to analysis according to chaos theories. On the other hand, this type of connection is a clear and reliable indicator of the possibility of chaos in a system. The PPC is a rate of the promises performed multiple indexes of indicators (loose, subjective, broad scope mutual fund type of index as given by field personnel. The Lyapunov ratio is an interpretation of that rate in mathematical formulas used on similar rates in mechanical engineering and other disciplines to find a visual metaphor of chaos.

A general contractor's meta-project PPC is the aggregate of the subcontractors' PPCs plus its own. Figure 11 for Company B shows four subcontractors' PPCs plus the general contractor's own PPC in a project during a 12-week period. The superimposed PPCs are indicative of the project reliability and effectiveness through the promises made to deliver on that week and actual delivery of the promises on time, correct, complete and unambiguously. The last item translates into a binary system where a zero (0) is indicative of any value between 0% and 99.999 … % (ad infinitum) and the value of one (1) is unity and contains only one value.

Although the PPC ratio never exceeds 100%, the Lyapunov exponent rate may be above 1; in thermodynamics parlance, that is indicative of chaos. The measure of whether or not a task is done is best interpreted in a binary system of 0 and 1 as explained below. Both under and over performance negatively affect the flow. In the previously mentioned example, the TMMC Texas (TX) plant sets a takt time for all stations at the plant for the next six months based on projected demand from the dealers. For example, at 63 seconds takt time, a group of tasks in any particular station completed in less than 63 seconds, is indicative of under-utilization waste and not of over performance. Takt time greater than 63 seconds disturbs the entire production line, which is immediately stopped. In construction, an accelerated schedule almost always and universally engenders a deceleration upstream because of the poorly coupled supply chain. Most subcontractors keep their crews busy until needed by plan and when the plan accelerates; they may not have the manpower available to respond quickly to the new acceleration.

The Lyapunov exponent ratios, when less than one, manifest stochastic cooling in the rate of change, the deviations. In the above example, TMMC takt time that varies from station to station

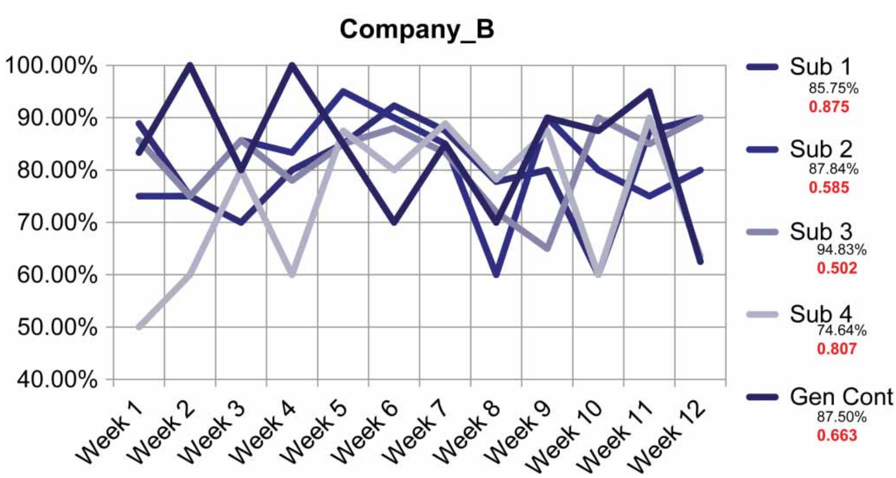


Figure 11. Project PPC 80.41% and calculated RoV of 1.624.

of less than one second is ideal. In construction, a subcontractor that is reliable at 70% PPC can be coupled with a following or concurrent subcontractor that operates at 80% PPC. As long as the rate of reliability in promise delivery is constant or maintained, and the subcontractor's crews are reliable, the flow can be maintained with a higher level of certitude.

## Binary data

Capturing the PPC from field personnel, trades groups, subcontractors and contractors must be unambiguous, is it done (as in complete, correct, and on time yes or no, with no room for in between. Data that are encoded with only two symbols is binary, also called bits (binary digits). Bits can be:

| | |
|---|---|
| • Semantic (meaning) | True/False |
| • Logico-Mathematical | 1/0 |
| • Physical (transistor) | On/Off |
| • Switch | Open/Closed |
| • Electric (circuit) | High/Low |
| • Disc or tape | Magnetized/Un-magnetized |
| • CD (pits) | Presence/Absence |
| • Boolean | All/None |

Bits are like the Rosetta Stone where semantics, mathematical logic (Rodder, 2000), the physics and engineering of circuits and information theory can find common ground and converge. Bits are discrete variations – no confusion, no ambiguity.

Data comes in several types:

- Primary (1/0)
- Secondary (absences of data)
- Meta-data: indicators about the nature of some other (usually primary) data. Meta-information is information about the nature of information. The meta-level is of greatest interest in this paper as it directly relates to the concept of meta-project.
- Operational data: regards the operation of the whole data system and system performance (information about the dynamics of an information system, also of interest to the meta-project concept).
- Derivative data: data that can be extracted from patterns, clues or inferential evidence (e.g. credit cards lead to information of whereabouts at a given time, also of interest to our meta-project concept).

Well-formed meaningful data result in data with semantic content, which can be instructional or factual. Semantic instructional information is about a situation, fact or a state of affairs *w* and does not model, or describe, or represent *w*. Rather, it is meant to (contribute to) bring about *w*. At first glance, we may think that construction information brings about the project but this is a fallacy (plans are identical to execution and are identical to results or push planning as in: just do-it-as-I-say!) a real disconnect between strategic and logistic planning and the tactical field operations.

Information displays characteristics of entropy. It makes sense to talk of information as quantified entropy only if one can specify the probability distribution. The Mathematical Theory of Communication (MTC), also known as information theory (Shannon & Waver, 1949), treats information like a physical quantity, such as mass or energy. The informational and thermodynamic concepts of entropy are related though the concepts of probability and randomness, a better word choice than "disorder". Entropy is a measure of the amount of "mixed-up-ness" in processes and systems bearing energy or information. It can also be seen as an indicator of reversibility. If there is no change of entropy, then the process is reversible. Construction processes lead to a structural re-ordering of materials and in some areas entropy will decrease while in other areas it will increase. *Construction processes are not reversible (because they are time dependent and time is irreversible) and therefore indicative that a change (increase) in entropy in time (real or potential) is a safe assumption.* A highly structured, perfectly organized message contains a lower degree of entropy or randomness. On the other hand, in thermodynamics, the greater the entropy, the less available is the energy. High entropy corresponds to high energy deficit; in MTC, higher values of entropy correspond to higher quantities of data deficit. Not only is data deficit an indicator of entropy, but also the inflection point, the angle of each PPC vector which requires energy as the vector (surrogate of information and gaps) goes from acceleration to deceleration to acceleration from period to period.

The line component on each PPC is actually a vector with origin, direction and magnitude. Figure 11 shows that the vectorial component of the composite PPC between weeks 7 and 9 has an abrupt change of direction as well as magnitude. This can be interpreted as an inflection point of performance predictability or conversely variability.

The sum of all the contributing PPCs from the subcontractors and the general contractor in the field results in Figure 12, which is the average of the weekly PPC reports. Notice that even with the possible smoothing out of PPCs with different values (some high and some low) through the average of numbers, the resultant PPC at the meta-project level has a Lyapunov ratio of 1.624 where anything above 1.0 is indicative of chaos. Furthermore, we can interpret the area above the lines in the meta-project PPC as the sum of the areas above the lines of each contributor. That area corresponds to items that were done in the same week, but not on the appointed day. This is a minor or major (undetermined with the type of data available) adjustment to the schedule as well as items that had to be deferred to the following week(s). In the end these sum up as deficiencies in the project performance; ergo, the 100% – 80.41% = 19.59% of loss opportunity for a better job (however, within the level of a high reliability job, as noted above). What is clear is that broken promises lead to underperformance, which requires additional energy (more labor, longer hours, more days of work) to make up for the underperformance or affect the performance of the next trade.

The PPC of each subcontractor has a different weight in relation to the amount of the contract of each (see Table 1 and Figure 12). In addition, each subcontractor's work has a different risk factor (Tang, Leung, & Wong, 2010) in relation to its direct and immediate impact on the

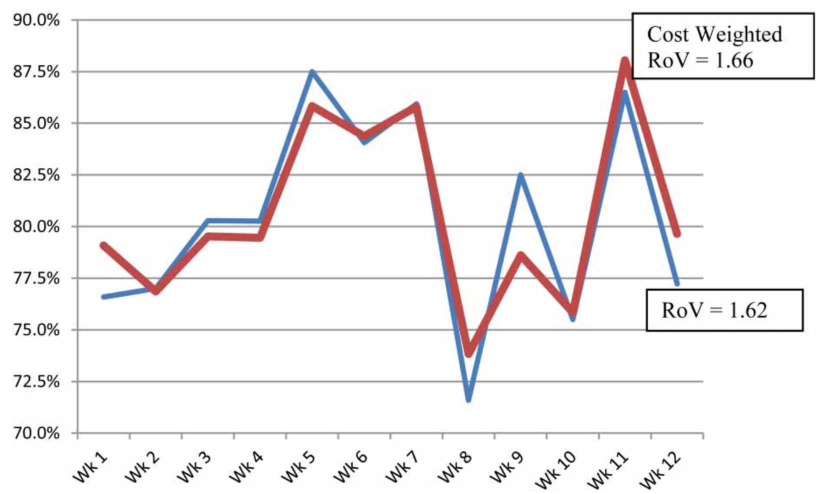


Figure 12. Comparing RoV (efficiency ratio) with cost weighted RoV.

Table 1. Building system typical percentage of the project total direct cost.

| | |
|---|---|
| Site work | 8 |
| Foundations | 5 |
| Structural frame | 18 |
| Exterior wall (A-Sub 1) | 15 |
| Interior finishes (B-Sub 2) | 14 |
| Vertical transportation (C-Sub 3) | 2 |
| Mechanical systems (D-Sub 4) | 18 |
| Electrical systems | 10 |
| Total direct | 90% |
| Total indirect (E – GC 5) | 10% |
| **Total construction** | **100%** |

Note: Turner Construction (2012) estimate based on historical data.



other subcontractors working at the same time, as well as an indirect and relative longer term impact on the total work, noted for future work.

Predictable subcontractors that are reliable most of the time have less variability, expend less energy in chasing broken promises and have a better system for ascertaining the quality of the information at hand before proceeding with the work. Subcontractors that are unpredictable, sometimes reliable, or sometimes less reliable generate accelerations and decelerations in the project that translate into less monthly billable or work performed versus worked planned; more energy spent chasing work not performed and a less efficient system to ascertain information quality.

## Interpreting the PPC in stochastic cooling, decoherence and flow friction terminology

PPC is in essence a measurement of variability from the promise which is derived from the planned activities. This variability, spontaneity, can be further considered a form of randomness, of disorder versus the orderly work in place that the percentage indicates. A disordered amount is considered in thermodynamics and physics to be entropy. Entropy is a somewhat abstract quantity that we tend to interpret as the amount of disorder in a system (Baggott, 2011).

The second law of thermodynamics argues to be unquestionably irreversible (Landauer, 1961; Prigogine, 1967; Tescari, Mazet, & Neveu, 2011) and a matter of natural law that in a closed system, entropy always increases spontaneously and inexorably. Construction is an open system, where work conspires against spontaneity and variability, through careful and detailed logistics and strategic planning as noted before. However, the subcontractors' reported PPC numbers, along with the general contractor's own field personnel PPC numbers indicate that at the tactical, execution level, gaps in performance – completing promises as noted and made to the team and the project – are real. These real gaps cause variability, require spontaneous solutions – putting out fires as they occur – and create disorder in the process that can escalate as other trades become affected. The reverse of a synergistic value creation, a synergistic and feedback loop of waste creation, can easily occur.

## Development of a fundamental dynamical equation in construction project production system using a binary system

The following development is based on initial case studies. Additional work is needed to be able to generalize these propositions.

Since we have the PPC of several sub-contractors that are now weighted by share of the direct cost, as well as risk, we posit that the PPC should be treated as matrices rather than being additive and averaged. In this case, we can apply Born's rule for manipulating matrices. Baggott (2011) reminds us that a matrix (Robinson, Cattaneo, & El-Said, 2001) is a square or rectangular array of numbers (in our case vectors) organized in columns and rows. Like ordinary numbers (vectors), matrices can be added, subtracted, multiplied and divided. Specific rules are necessary to guide matrix multiplications showing how each element (vector) in each matrix must be combined to give the corresponding elements in the final product matrix. Unlike ordinary numbers, it is possible to find matrices (for example $x$, $y$) that do not commute; that is, the product of $x$ multiplied by $y$ is not equal to $y$ multiplied by $x$. In a vector matrix, position and momentum do not commute. This brings us to the fact that in classical dynamics, the knowledge of the state of a closed system (the position and velocity of all its particles) at any instant determines unambiguously the future motion of the system … the occurrence of probabilities is justified by the fact that the ideal initial state can never be exactly known.

### *Fundamental dynamical equation*

The PPC data considered are developed by the crews and rolled into the subcontractors' PPC weekly report. These subcontractors' reports, along with the general contractor's field office PPC, become the project's PPC (Figure 13). The PPC responds to a very basic question: Has the work taken place as you promised? The answer, yes or no, is verified by the general contractor field personnel. The basis for a yes is that the work was correct, complete and finished on time (the day), as stipulated by the crew or subcontractor. This gage of work accomplished depends on the information provided by the promise to execute as well as the information needed to execute the promise. In this sense, the binary response captured in the PPC is reflective of the quality of information at several levels.

The PPC is vectorial in nature and representative of the information characteristics previously mentioned. It is vectorial because each week the PPC has a start, a magnitude and a direction that to some extent are predicated on the previous week's measures (the preceding end point is the successive starting point), but each week's performance is independent (however, this postulate needs to be tested). In other words, the PPC captures information entropy as promises that are not delivered and analyzes it using the Lyapunov method of calculations yielding its RoV.

### *Case studies*

This paper has three sets of case studies. Set (A) contains 20 PPC reported projects from conference papers published in proceedings of the IGLC from 2001 to 2009; set (B) includes 12 reported PPC projects from conference papers published in proceedings and from website case studies of the LCI from 2001 to 2010; set (C) consists of three completed projects by an anonymous company.

## PPC analysis

Set (A) PPC projects (see Table 2) are from the IGLC, and set (C) (see Table 2) are from the LCI's published information. In both of these sets, 93% of the cases explicitly report that LPS was implemented. These two sets have different duration periods. There was no control over the type and quality of PPC data submitted; therefore, the values recorded are taken at face value. Set (A) is of 20 cases with 10% showing chaotic tendencies. Set (B) is of 12 PPC cases with

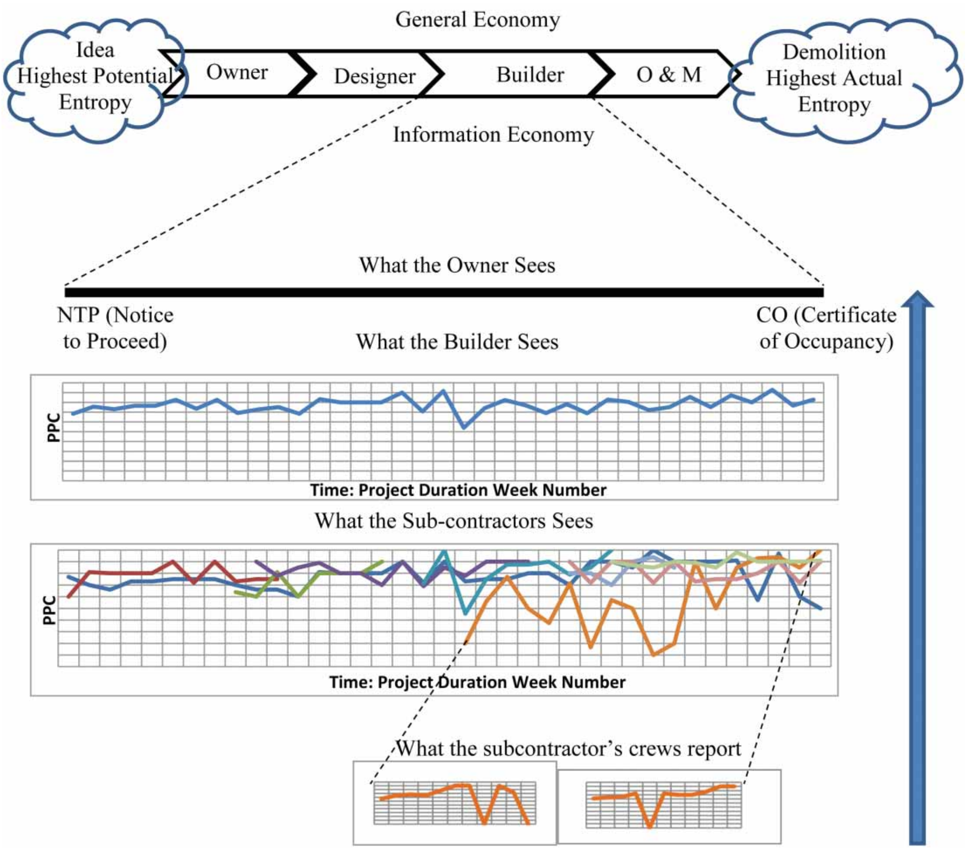


Figure 13. Information taxonomy: PPC data flow (arrow) to stakeholders.

Table 2. Set B: LCI PPC data and Lyapunov exponent (RoV).

| LCI 2001–2008 | | | | | |
|---|---|---|---|---|---|
| No. | GC/sub | No. of weeks | Effectiveness PPC average (%) | Lyapunov chaos ratio (RoV) | Reliability (%) |
| 1 | X2001A | 19 | 63.95 | **<u>1.0740</u>** | 46 |
| 2 | X2002A | 8 | 39.29 | **<u>1.0000</u>** | 50 |
| 3 | X2003A | 20 | 70.85 | 0.6781 | 66 |
| 4 | X2004A | 14 | 67 | 0.7776 | 61 |
| 5 | X2004B | 13 | 75 | 0.9434 | 53 |
| 6 | X2005A | 19 | 63.32 | 0.8814 | 56 |
| 7 | X2006A | 24 | 85.67 | 0.8074 | 60 |
| 8 | X2006B | 17 | 71.41 | 0.5564 | 72 |
| 9 | X2006C | 22 | 85.41 | 0.5406 | 73 |
| 10 | X2006D | 16 | 64.88 | 0.4594 | 77 |
| 11 | X2008A | 15 | 82.93 | 0.5525 | 72 |
| 12 | X2008B | 12 | 80.92 | **<u>1.1155</u>** | 44 |
| | **Average** | **16.58** | **70.89** | **<u>0.7822</u>** | **61** |

Note: In bold and underscored are cases with RoV = or > 1; therefore, 25.9% have a chaotic tendency.

Table 3. Set A: IGLC PPC data and Lyapunov exponent (RoV).

| IGLC 2001–2009 | | | | | |
|---|---|---|---|---|---|
| No. | GC/sub | No. of weeks | Effectiveness PPC average (%) | Lyapunov chaos ratio | Efficiency (%) |
| 1 | Y2001A | 11 | 94.00 | 0.9329 | 53 |
| 2 | Y2001B | 7 | 50.57 | **1.5146** | 24 |
| 3 | Y2002A | 32 | 65.78 | **1.0875** | 46 |
| 4 | Y2002B | 15 | 74.07 | 0.6167 | 69 |
| 5 | Y2002C | 15 | 44.87 | 0.6781 | 66 |
| 6 | Y2002D | 24 | 49.29 | 0.7004 | 65 |
| 7 | Y2003A | 20 | 70.85 | 0.7225 | 64 |
| 8 | Y2004A | 26 | 36.35 | 0.8231 | 59 |
| 9 | Y2004B | 26 | 36.54 | 0.9720 | 51 |
| 10 | Y2004C | 26 | 42.92 | 0.7914 | 60 |
| 11 | Y2005A | 12 | 75.25 | 0.6630 | 67 |
| 12 | Y2005B | 12 | 72.08 | 0.8745 | 56 |
| 13 | Y2006A | 24 | 63.17 | 0.5025 | 75 |
| 14 | Y2006B | 10 | 67.00 | 0.5850 | 71 |
| 15 | Y2007A | 13 | 50.92 | 0.6215 | 69 |
| 16 | Y2007B | 24 | 72.67 | 0.4594 | 77 |
| 17 | Y2009A | 18 | 79.56 | 0.1520 | 92 |
| 18 | Y2009B | 17 | 74.00 | 0.2345 | 88 |
| 19 | Y2009C | 38 | 49.68 | 0.8182 | 59 |
| 20 | Y2009D | 37 | 66.14 | 0.5719 | 71 |
| | **Average** | **20.35** | **61.79** | **0.7161** | **64** |

Note: In bold and underscored are cases with RP = or > 1 and therefore 10% with chaotic tendency.

Table 4. Set C: Three company project PPC data and Lyapunov exponent (RoV) and all published 2001–2009.

| Three company projects 2012 | | | | |
|---|---|---|---|---|
| GC/sub | No. of weeks | Effectiveness PPC average | Lyapunov chaos ratio (RoV) | Efficiency |
| XXXX C12 | 37 | 76.28% | 1.0573 | 47% |
| YYYY C12 | 26 | 72.68% | 0.9143 | 54% |
| ZZZZ C12 | 55 | 71.05% | 0.8186 | 59% |
| **Averages** | **39** | **73.34%** | **0.9301** | **53%** |
| Published (IGLC + LCI) 2001–2009 | No. of publications | PPC average | Lyapunov chaos ratio (RoV) | Efficiency |
| **Averages** | **32** | **66.34%** | **0.7492** | **62.5%** |

3/12 or 25% showing chaotic tendencies. The total sample set of all three batches show14 out of 56 total project cases (or 25% or ¼) with PPC in the chaos range.

The reported PPC should, hypothetically, be significantly affected by the relative weight of each subcontractor's portion of the work, as noted by the project budget in the application for payment. However, Company B's $PPC_u$ was weighted by the ratio of each corresponding subcontractor budgeted amount (Table 3), as shown in Figure 12 ($PPC_w$). A comparative analysis found that the RoV did not change significantly ($PPC_u$ $RoV_u = 1624$ whereas $PPC_w$ $RoV_w = 1.663$).

Future work will focus on identifying the risk factors of each subcontractor and pose the hypothesis that the risk factors should significantly affect the PPC. This will require that risk factors can be attributed to each trade based on historical performance, and represents a challenge.

Table 5. Comparative analysis of three company PPC project data and Lyapunov chaos ratios (RoV).

| | | XXXX C12 company project $25M 37 weeks | | | | | YYYY C12 company project $15M 26 weeks | | | | | ZZZZ C12 company project $48M 55 weeks | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Stakeholder | Typical % of bldgcost (%) | No. of crews | No. of people per crew | Total no. of folks per sub | Stakeholder average PPC (%) | Lyapunov (RoV) | No. of crews | No. of people per crew | Total no. of folks per sub | Stakeholder average PPC (%) | Lyapunov (RoV) | No. of crews | No. of people per crew | Total no. of folks per sub | Stakeholder average PPC (%) | Lyapunov (RoV) |
| GC field | 10 | 3 | 5 | 15 | 77.4 | 0.92 | 3 | 4 | 12 | 73.8 | **1.08** | 2 | 5 | 10 | 73.3 | **1.03** |
| Site work | 8 | 5 | 6 | 30 | 77.8 | 0.93 | 4 | 5 | 20 | 52.6 | **1.17** | 5 | 6 | 30 | 59.0 | 0.38 |
| Foundations | 5 | 3 | 8 | 24 | 74.4 | **1.17** | 3 | 6 | 18 | 77.5 | **1.00** | 5 | 8 | 40 | 72.7 | **1.36** |
| Structural frame | 18 | 6 | 8 | 48 | 83.1 | 0.95 | 4 | 6 | 24 | 80.8 | **1.00** | 8 | 8 | 64 | 62.3 | **1.14** |
| Exterior wall | 15 | 4 | 8 | 32 | 82.1 | **1.38** | 4 | 6 | 24 | 83.1 | 0.65 | 4 | 8 | 32 | 65.6 | **1.56** |
| Interior finishes | 14 | 8 | 6 | 48 | 59.1 | **1.76** | 6 | 4 | 24 | 82.2 | **1.06** | 8 | 8 | 64 | 69.2 | **1.32** |
| Vertical transportation | 2 | 4 | 2 | 8 | 83.2 | 0.88 | 2 | 2 | 4 | 50.5 | **1.46** | 2 | 4 | 8 | 70.8 | **1.12** |
| Mechanical systems | 18 | 5 | 6 | 30 | 81.5 | 0.89 | 4 | 4 | 16 | 80.7 | 0.85 | 5 | 6 | 30 | 87.1 | **1.20** |
| Electrical systems | 10 | 3 | 8 | 24 | 89.6 | 0.63 | 3 | 6 | 18 | 68.5 | **1.44** | 3 | 8 | 24 | 75.5 | **1.94** |
| **Sum/average** | **100** | **41** | **6** | **259** | **76.3** | **1.06** | **33** | **5** | **160** | **72.7** | **0.91** | **42** | **7** | **302** | **71.1** | **0.82** |

Note: The bold values are indicative of chaos. Chaos is indicated by Lyapunov RoV values that are above 1.0.

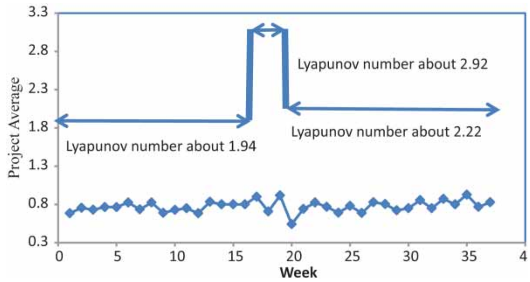


Figure 14. Lyapunov number of XXXX project.

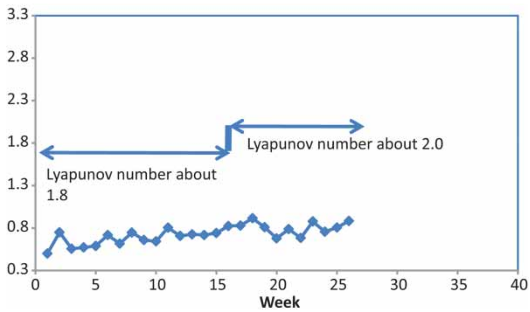


Figure 15. Lyapunov number of YYYY project.

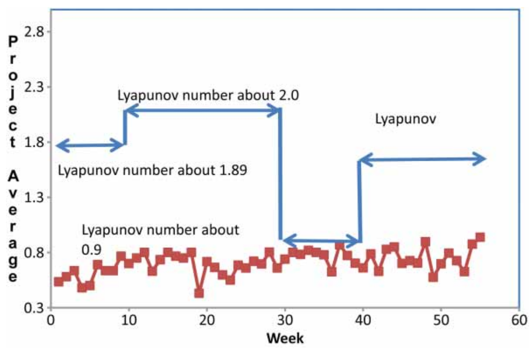


Figure 16. Lyapunov number of ZZZZ project.

Table 4 compares 2012 data from the three companies (XXXX, YYYY, ZZZZ, Table 5 and Figures 14–17) and that of IGLC and ILC– a total of 32 published PPC cases. The average PPC of both of these sets is approximately 72%, which is relatively much higher than an earlier industry wide reported PPC average of approximately 55%. We do not know with certainty the underlying reasons for the higher effective performance of subcontractors and general contractors in 2012 when compared to the earlier industry report.

Table 6 ranks the average PPC and Lyapunov ratings and compares the rankings, which are then grouped into items. Item 1 is of interest in that, although it has the worst PPC, it has the best Lyapunov rating, meaning it was consistent in low effectiveness. Item 2 has the next largest

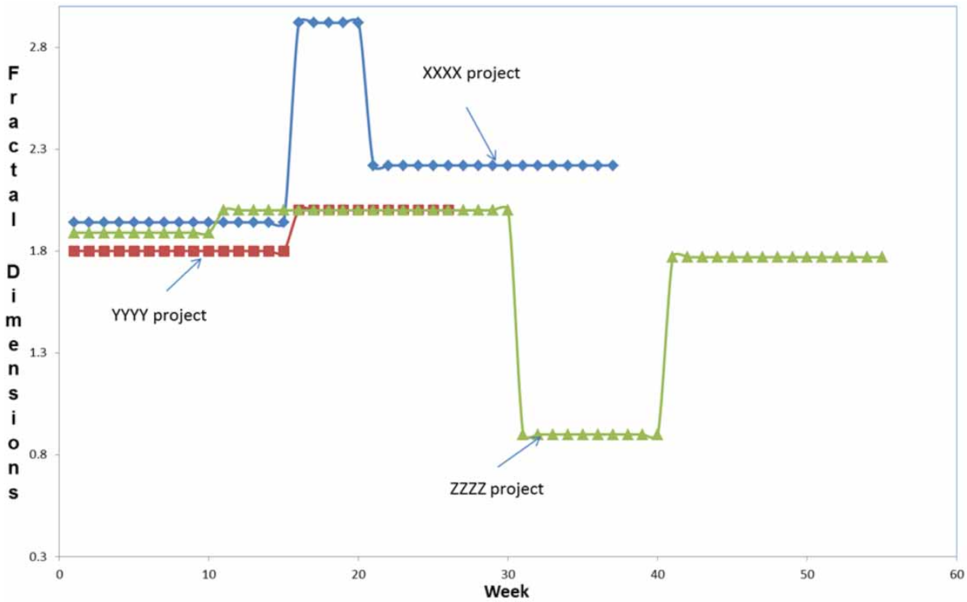


Figure 17. Graphic comparison of Lyapunov number of XXXX–ZZZZ projects.

Table 6. Comparative analysis of three company's PPC project and Lyapunov chaos rankings.

| Stakeholder | XXXX | YYYY | ZZZZ | Average PPC per stakeholder | Rank 1 = best |
|---|---|---|---|---|---|
| GC field | 77.35% | 73.83% | 73.28% | 74.82% | 6 |
| Site work | 77.82% | 52.56% | 59.00% | 63.12% | 9 |
| Foundations | 74.38% | 77.47% | 72.74% | 74.86% | 5 |
| Structural frame | 83.14% | 80.80% | 62.30% | 75.42% | 4 |
| Exterior wall | 82.09% | 83.13% | 65.62% | 76.95% | 3 |
| Interior finishes | 59.04% | 82.16% | 69.19% | 70.13% | 7 |
| Vertical transportation | 83.17% | 50.47% | 70.83% | 68.16% | 8 |
| Mechanical systems | 81.46% | 80.73% | 87.06% | 83.08% | 1 |
| Electrical systems | 89.55% | 68.47% | 75.52% | 77.85% | 2 |
| Stakeholder | XXXX | YYYY | ZZZZ | Average Lyapunov per stakeholder | Rank 1 = best |
| GC field | 0.9198 | 1.0793 | 1.0260 | 1.0084 | 3 |
| Site work | 0.9329 | 1.1699 | 0.3785 | 0.8271 | 1 |
| Foundations | 1.1699 | 1.0000 | 1.3626 | 1.1775 | 7 |
| Structural frame | 0.9475 | 1.0000 | 1.1375 | 1.0283 | 4 |
| Exterior wall | 1.3785 | 0.6521 | 1.5564 | 1.1957 | 8 |
| Interior finishes | 1.7608 | 1.0641 | 1.3219 | 1.3823 | 9 |
| Vertical transportation | 0.8745 | 1.4594 | 1.1155 | 1.1498 | 6 |
| Mechanical systems | 0.8845 | 0.8480 | 1.1979 | 0.9768 | 2 |
| Electrical systems | 0.6280 | 1.4406 | 1.9434 | 1.3373 | 5 |

discrepancy. Items labeled 3 line-up effectiveness and reliability. More work is needed for analyzing and interpreting this data.

The Lyapunov number of the weekly RoV in a project in Table 3 with 10 phases was calculated, as shown in Figure 14. Among the 10 phases, 5 chaotic events were found based on the Lyapunov numbers.

These transitions between phases, along with their Lyapunov numbers (Figures 14–16), are called "critical phases" in thermodynamics because they undergo phase separations driven by non-ideal entropy based on energy increases and decreases due to a multitude of reasons. These systems, thermodynamic in nature, are critical and chaotic precisely because of the self-adaptation required by asymmetries and gaps in information. The self-adapting system, in terms of thermodynamic parlance, must be driven "slowly" through a succession of metastable states showing jumps from one metastable state to another (Paczuski, Maslov, & Bak, 1996).

This analysis, unlike previous investigations, allows us to study temporal properties of the PPC project and the dynamics of project fluctuations. The results exhibit specific properties illustrated in Figure 16. Relatively stable time periods, before week 15 and after week 20, comprise one fundamental property. For the investigated period, the Lyapunov numbers in three companies stay nearly constant at the beginning. The Lyapunov number, starting at week 15, increases for both XXXX and YYYY. Then, the Lyapunov numbers decrease after week 20 for XXXX and week 30 for YYYY. The fractal numbers increase only slightly for ZZZZ at week 10 but exhibit an overall decreasing trend. A related property is demonstrated in Table 6 by the Lyapunov chaos ratios for these companies.

Unfortunately the data were recorded at by others and published without sufficient granularity as to the specific events that made the jump. However, this research indicates that we need data not only at the general contractor level which smooth out variability but at the subcontractor and even further down at the crews of the subcontractors along with a log of weekly events at the crew level.

These results present phase directions which are said to be predictable when the direction, during one time period, has a higher probability of being the same as in the previous period (before week 15). Similarly, phase directions are called unpredictable when the following period's direction is likely to be opposite that of the previous one (weeks 15–20). The beginning of the 15 weeks can be thought of as information gathering and weeks 15–20 as decision making. As time passes, the tendency of the phase change to go in the same direction increases in general, as illustrated in Figure 17 for week 20 and after. These temporal properties mostly reflect the interaction between environment and central project processes inducing the phase changes and the coping mechanisms that companies develop to best cope with environmental conditions. Obviously, we are more interested in when and what have brought about unpredictable phase changes. These analyses demonstrate that temporal analysis using Fractal theory may be used as an indicator for predicting, studying and even documenting the properties of PM.

### *Summary*

Information drives the act of construction. Information theory and GT show how information is prone to entropy, a law of thermodynamics that has been found to be applicable across different domains through metonymic mapping. Metonymic mapping is used to translate and transfer thermodynamic theories, laws and concepts into the construction domain in the areas of information, work and entropy. Stakeholders in construction are engaged at the strategic, logistic and tactical levels, where all except the tactical are exclusively engaged in information creation and transfer. At the tactical level, the information is used in the act of construction. Information creation is analyzed and defined using force-dynamic schemas. These schemas reveal that the owner, architect (or designer) and general contractor, each with its particular set of consultants, manages a *project of projects* rather than a single project. This novel paradigm has critical consequences, as the typical management tools used at the boundary between work and production do not apply to the strategic/logistic and tactical information transfer and control. All stakeholders in construction work in an open system where asymmetrical information is pervasive. Information gaps exist within the stakeholders groups, and among stakeholders across phases; asymmetrical information conspires to create, in this open meta-project, entropy that is not captured in traditional production control systems. For meta-projects, flow, reliability and predictability/variability are better gages of production loops (request, promise, execution and acceptance) than cost, schedule and quality controls. Most thermodynamic systems have an upper reliability ceiling of 80–85% and industry leaders report the same ceiling in construction, which leads to an "elegant correlation" à la Veneziano and encourages a continuation of this work. The case studies indicate that projects without LPS have approximately the same PPC as those with LPS, but with significantly higher Lyapunov RoV (i.e. a tendency to chaos), due to the higher rate of changes in the flow as measured by the reported PPC. If this is the case, then we can surmise that LPS acts as an agent of stochastic cooling (reducing variability, vectorial energy, smoothing out inflection points), in the information that is needed for smooth flow in construction.

Construction work is a constant struggle against entropy, using information as its main tool aimed at operations (e.g. work, labor, parts, materials, methods, assembly and systems) to create order. This results in a product that becomes an asset capable of capital creation through its use.

The economic value of information is the expected utility that results in a willingness to pay a corresponding price for the services that produce it. This is basically how much benefit (or lack of) the agent holding the information would enjoy. Information, therefore, must offer some add value and value preserving features, such as relevance, usefulness, courses of action, options considerations, errors avoidance, choice making, securing permitting and securing zoning approvals, that would normally yield results with higher payoffs (expected utility) than the agent would obtain in the absence of such information.

PPC is not simply one control parameter. At the meta-project level, it is a mutual fund of parameters that monitors the promises made. In turn, the promises of the subcontractors, the boots on the ground, address the cost, time and quality which are the purview of their contract. HERE lies the essential difference between the meta-project approach to PM and the rest! Through PPC we can measure project flow through the promises, and this measure is capable of making graphically visible the presence or absence of chaotic tendencies and practices, as well as the level of information entropy and the asymmetric information that is found in construction gaming.

## Further work

This research should be followed by a longitudinal study in 5 and then 10 years to verify the findings and confirm expected trends. Currently, further studies into topics such as: Topic A: resiliency and construction, dualism at the core (project – synergistic; meta-project – entropic), Topic B: Information entropy and construction and Topic C: GT and construction are planned by members of the research team.

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