Is building construction, as a social project organization and production system, complicated or complex?

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Abstract

A recent study of chaos in construction as a project production process and system has raised a valid question: Is construction production really complex or just complicated? More importantly, how do we know which one is the best characterization of construction? The answer to these questions is developed through a systematic story of the following topic headings: Comprehensive literature search of complicated and complex key words; development of complexity theory and complexity science – similarities and differences; behavior of complex systems – as opposite to ordered (complicated) systems; construction as a system – product (object), organization and process (social systems); implication on the project execution; new approaches to project management.

Understanding complexity in construction management is important for two reasons: (1) to visualize how both complicated and complex traits exist in a construction project (an object as well as a social systems), and (2) to identify for stakeholders new types of managerial competencies and tools that reflect the understanding of complexity in construction.

Key Words: Construction, complicated, complex, production, systems

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1. Introduction

Since the 1980's, those engaged in teaching and practicing construction have used the term Project Delivery System (PDS) to refer to the contractual aspects of agreements to procure and deliver a construction project. In a narrow sense, PDS can be construed as a type of contractual arrangement between stakeholders to build a project. In a broader sense, PDS is more than the contract and includes the actual delivery of the project with all the ramifications from cradle to grave, along with everyone involved directly and indirectly (social system) in the enterprise of building the project (object). The project gets built under unique circumstances in comparison to manufacturing processes: The project is a prototype, built one time only not to be exactly repeated, the project social team is temporary – comes together for this project only and trades come in and out of the project as autonomous agents, the project is built on a site open to the weather and its interference on the schedule, the project production team of mostly subcontractors is affected directly and indirectly by what is happening on other projects that the sub is involved, among many other observed peculiarities. In the broadest sense, it involves interacting static and dynamic systems, energy, entropy, chaos and the socio-economic activities required to produce a project for its intended purpose in the general economy.

If building construction's project delivery can be loosely categorized as a production system, (1) what kind of system is it? (2) What do the best minds of researchers, philosophers, scientists, academicians and practitioners say about a building project production as a system? (3) How does thinking of a project one way or another affect the way we understand the system of construction? (4) Moreover, does a particular understanding of construction, as a particular type of system, have any practical implications?

Our interest in the topic arose out of papers that identified and showed the presence of chaos in the social and organizational production of construction projects as measured through the variability of promises to deliver a particular piece of work that is correct, complete, timely and unambiguous. Fernández-Solís [1] described the systemic nature of construction operations as deterministic dynamic, non-linear flow, which involves owners, consultants, designers, contractors, sub-contractors and suppliers. Construction processes also exhibit tendencies of a complex system that will be elaborated in this paper [1], [2], [3]. Reviewers have challenged this characterization and posed the valid question: Is construction as a system complex or merely complicated? This paper answers this question.

1.1 Comprehensive literature search of complex and complicated key words

Dimensions of complex systems

An exploration of the literature reveals a wide range of factors that may contribute to project complexity. These contributing factors are defined by Remington et al. [23] in terms of dimensions; see Table 1.

Table 1 Dimensions of Project Complexity, adapted from Yugue and Maximiano [35] and Remington et al. [23]

DIMENSION OF COMPLEXITY	AUTHORS
Uncertainty about the product of the project	Turner and Cochrane [10]; Williams [36]; Remington et al. [23]
Uncertainty about the scope of the project	Turner and Cochrane [10]; Baccarini [11]; Tatikonda and Rosenthal[38];
Novelty of technology	Baccarini [11]; Williams[36]; Geraldi[40]; Fitsilis[37]; Remington et al. [23]; Tatikonda and Rosenthal [38]
Highly multidisciplinary	Baccarini [11]; Geraldi[40]; Geraldi and Adlbrecht[39]; Fitsilis [37]
Large number of stakeholders with influence on the project	Williams[36]; Fitsilis[37]; Remington et al. [23]
High difficulty to achieve performance goals	Remington et al [23]
Significant change in the scope of the project during its implementation	Turner and Cochrane [10]; Williams[36]; Geraldi[40]; Geraldi and Adlbrecht[39]; Fitsilis[37]; Remington et al. [23];
High interdependence between the technologies	Baccarini [11]; Williams[36]; Geraldi[40]; Fitsilis[37]; Remington et al. [23]; Tatikonda and Rosenthal [38]
High interdependence between firms involved in the project	Baccarini [11]; Williams[36]; Geraldi[40]; Remington et al. [23]

Types of complex systems

"System" commonly means a group of interacting, interrelated, or interdependent elements forming a holistic functional whole [30]. However, the "complex" nature of systems elicits multiple definitions.

The first definition is that complex systems integrate multiple thematic domains. None of the agents or subsystems could be fully understood when considered in isolation. A second and narrower understanding of complex systems lies in the paradox of complexity arising from simplicity. This point of view sees complexity as emerging from nonlinearities due to the large number of interactions involving feedbacks occurring at one or more lower levels within the system [31]. Manson [32] refers to this idea as "aggregate complexity." One more concept of complex system extends the notion of complexity emerging from simplicity by creating more refined representations of micro-level heterogeneity and interactive processes and factoring in top-down (perhaps emergent) structures that feed back to influence bottom-up phenomena [32].

There is no consensus with respect to a definition for complex system, as well as for the definition of complexity [5]. As Sinha et al. [34] assert, "There is no single concept of complexity that can adequately capture our intuitive notion of what

the word ought to mean." Complexity can be understood from *different points of view*. It even has different connotations within the same field; see

Fig. 1.

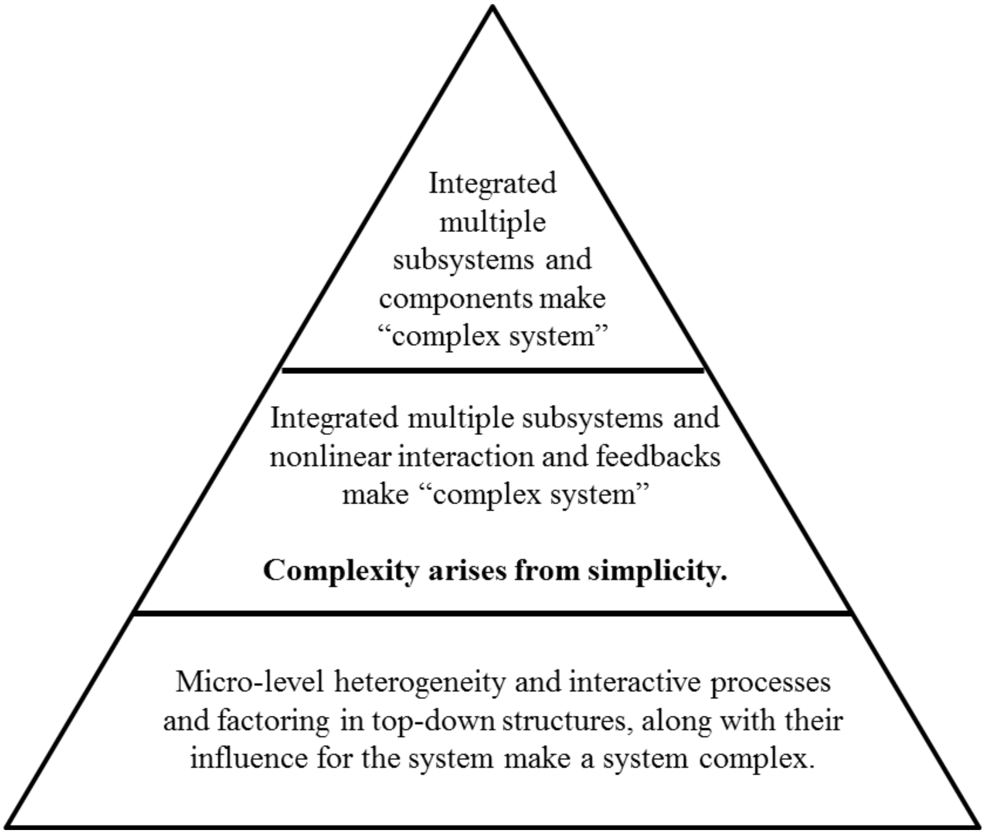

Fig. 1. Three different understandings of complex systems

Concepts about project complexity vary according to different theories and perceptions, summarized in

Table 1; each definition has its own focus.

Table 1 Types of project complexity, adapted from Yugue & Maximiano [35]

COMPLEXITY OF PROJECTS	AUTHORS
Two types of complexity: organizational and technological complexity, operationalized in terms of differentiation and interdependence.	Baccarini [11] Williams [36] Fitsilis [37]
Project complexity is related to the novelty of products, of its manufacture; and of its technological interdependence and difficulty.	Tatikonda and Rosenthal [38]
Main types of project complexity: Complexity of Faith (related to uncertainty), Complexity of Fact (referring to the amount of interdependent and concurrent information), and Complexity of Interaction (with respect to the interfaces between systems, people and places).	Geraldi and Adlbrecht [39] Geraldi [40]
Two levels of project complexity: dimension of complexity (characterize the nature or origin of complexity) and factor of severity (to what extent it is a problem).	Remington et al. [23]
Subjective connotation is the main reason for the difficulty in understanding and dealing with a project's complexity.	Geraldi and Adlbrecht [39], Geraldi [40], Fitsilis [37], Remington et al. [23]

1.2 Development of complexity theory and complexity science – similarities and differences

Projects as systems

According to systems analysis [4], [5], a system could be defined as follows:

> *"A system is an object, which, in a given environment, aims at reaching some objectives (teleological aspect) by doing an activity (functional aspect) while its internal structure (ontological aspect) evolves through time (genetic aspect) without losing its own identity."*

Vidal and Marle [6] state that: a project is a temporary and unique endeavor undertaken to deliver a result. Each project is unique because among targets, resources and environment, at least one of these parameters changes. Merging the two definitions, we have: A system is an object (project), in a given environment (site conditions), aimed at reaching some objective (final building) by doing an activity (building construction) while its internal structure evolves through time (project delivery) without losing its own identity (stakeholder contracts).

Based on these two definitions of projects and systems, construction projects can thus be considered as systems. However, there are different types of systems: complicated and complex.

Complicated systems

According to Dekker et al. [7], complex is not the same as complicated, and conflating these two notions can lead to confusion.

The term "complicated" was first used in 1656, mainly referring to an object that is difficult to analyze, understand, or explain. When it refers to a system, a complicated system consists of parts intricately combined. From a structural and visual point of view, it consists of interactional sub-systems. It is built from a large number of elements but with a function well defined, and governed by well-defined and understandable laws similar to simple systems [8]. Its maximal characteristic is in its multiplex nature, which controls behavior of multiple sub-systems with different attributes [8]. A Boeing 747 is frequently cited as an example of a complicated system.

Most authors, like Turner and Cochrane [10], Baccarini [11] and Williams [12], have tended to focus on uncertainty and difficulty of the technical or management challenges, or on organizational complicacy when referring to complicated systems.

According to the above authors, complicated systems can be fully studied. They afford a complete, exhaustive description. Because of this, complicated systems are controllable and there is one best plan to operate them. Order and stability are achieved by compliance with the identified best operating plan. Besides this, there is a clear boundary where the system ends and the outside environment begins.

Complex systems

Both complicated and complex systems consist of a large number of interacting components, but that is where their commonality ends [13], [14].

Unlike complicated systems, complex systems are never fully knowable [15]. A complete, exhaustive description is impossible to attain, and they are mathematically intractable. No set of rules or formulas can capture their nature or full workings [16].

Even it is not a rule, complex systems usually are built of many identical elements cooperating together according to rules, which are not well defined and can change with time [17]. Furthermore, they are open systems, which mean they keep changing by interaction with their environment; their boundaries are difficult to determine. Complexity emerges from a deep and extended network of interactions and interconnections. As a result of this, any component's action controls very little, but influences almost everything. Order in complex systems cannot be imposed, it "emerges" from the multitude of interactions between components. This emergent property is a characteristic of a complex system, which cannot be deduced by examining the components of the system in isolation. One part cannot explain all. Success in a complex system comes not from following one best method—but from a diversity of responses that allow it to cope with a changing environment [18], [19]. Additionally, the understanding of a complex system is based on created models of the system [20].

1.3 Behavior of complex systems – as opposite to ordered (complicated) systems

1.4 Construction as a system – product (object), organization and process (social systems)

Comparative analysis of complicated and complex instances in building construction

Building construction has a great number of components as well as participants (stakeholders) in a temporary arrangement of unique inter-professional relations. This does not clarify whether building construction's project delivery system is complicated or complex. The evidence may be glimpsed in the following comparative analysis table (**Table** 3), which summarizes the definitions and characteristics of these two systems.

Table 3 Comparison between a complicated system and complex system (adapted from several sources)

COMPLICATED SYSTEM	COMPLEX SYSTEM
Consisting of a large number of interacting components	
▪ Specialized structures, deterministic	▪ Structures for general use, non-deterministic
▪ Algorithmic processing	▪ Interactive processing
▪ Fully understandable	▪ No rules or formulas can capture the whole system
▪ Static planning of performance, Mean Value Analysis	▪ Dynamic planning of performance at the edge of chaos
▪ Bounded resources	▪ An open system with unbounded resources
▪ Lack of memory (independence of processes)	▪ Existence of memory (dependence of processes)
▪ Simple feedback	▪ Self-organization
▪ Having best method to operate the system	▪ No best plan due to a changing environment

The building (final product, noun):

- Consists of a large (bounded) number of interacting components
- Is a specialized structure
- Has an operation that can be mapped and put in algorithms
- Is fully understandable
- Has static performance, and mean value analysis of its functions can be readily made
- Uses bounded resources, except for operation and maintenance; those can be considered un-bounded
- Provides simple feedback loops
- Contains a best method to operate the facility composed of all its systems

To build, as in the physical work of construction which encompasses materials, equipment and labor, a verb that mobilizes labor and equipment to erect and assemble materials, is characterized by the following statements:

- Consists of an extremely large number of contributing components (mineral extraction, fabrication, transportation, general economy, assembly, erection, finishing, code compliance; the list is as big as the amount of granularity we seek to inform).
- Non-deterministic switching is due to the fact that the players are autonomous agents. Autonomous agents have particular strategic, logistic and tactical interests and therefore may withhold asymmetric information from other players. This non-deterministic switching property of complex systems, as shown in Table 1, is relative to deterministic switching. (Deterministic switching could be evaluated using specific algorithms, which means it is foreseeable. However, in a construction system, the autonomy of each participant, along with its own strategies that induce a variety of actions, lead to behavior ranging from almost deterministic actions to chaos-like dynamics, which makes the switching non-determinable).
- Processing is interactive, due to the amount, quality and type of information that all the stakeholders must contribute, check, verify and approve to achieve the intended results.
- No rules or formulas can capture the whole production system because each production is unique, one of a kind, different and distinct in multiple aspects, starting with the fact that the team of stakeholders is temporary and it intervenes as needed.
- Dynamic planning of performance at the edge of chaos is due to the fact that the autonomous players' interventions are predicated by activities in other projects and are determined by the strategic plan of each stakeholder.
- If the process takes into consideration all the materials and players necessary to make the final product, a large portion of national or world economies would be included, as the process is energy and material intensive as well as labor intensive and information super intensive.
- Existence of memory is required so that each process does not require reinvention each time it is needed.
- Self-organization is essential for the production system, as it has no central control.
- Having no best plan, due to a changing environment, is apparent from the above mentioned characteristics of the construction process or project delivery system.

According to Fernández-Solís' [1] summary of the systemic nature of construction, construction operation and organization is a deterministic dynamic, non-linear flow, in which an extremely large number of stakeholders are involved. The outputs of construction are not proportional to the inputs and the whole is different from the sum of its parts, where the sum of its parts is much larger than the final product. The building construction system must consider an open social system and also the inter-operability of each participant (working inside the company) as well as extra-operability of the participants (working with other companies). It is nested in a social system with a varying team where communications and cooperation are emergent phenomena in each project; this emergent nature also helps the system learn from itself and achieve its self-organized goals toward the completion of the design intent. All of these natures of building construction's project delivery system favor considering it as a complex system.

In spite of the fact that there are numerous views on explaining the differences between complicated and complex systems, most scholars mentioned in this paper would agree with the differences summarized in Table 1; the only characteristic common to complicated and complex systems is that both contain a great number of components. In this study, the definitions, descriptions and distinctions between complicated and complex are used to shed light on the concepts of building and building construction system. While a building (noun, i.e. final product) is a complicated system, constructing a building (verb, i.e. to produce and erect the design intent) is a complex social system, which emerges from a deep and extended network of interactions and interconnection. It requires further detailed analysis.

Building construction as a complex system

Scientists have attempted to understand construction systems using a reductionist approach in which the behavior of a system is represented as being an equilibrium mechanical interaction of its components. This equilibrium assumption views spatial distribution as optimal and stationary [21]. That is to say, rigid traditional construction management focuses on order, structure and planning. That is, an strategic or logistic plan command is considered to be carried out in time, just as ordered; command is identical to action. However, the unknowns in construction systems are better handled by a flexible process that promotes openness, coincidence and serendipity [21]. For this reason, the behavior of complex systems offers an appropriate set of concepts with which to begin a new reflection on human systems, especially construction systems [21]. Unlike the mechanical systems of a bygone era, overall system behaviors are no longer exclusively deterministic. In this new point of view, in construction systems, non-equilibrium phenomena are much more critical and offer a new way of understanding structural emergence and organization in systems with many interacting individual elements. In this complex system, all powers are connected. This new attitude toward construction systems puts forth a number of characteristics to predict project outcomes, in order to control or manage the construction procedure [23]. Homer-Dixon's work [24] summarizes the characteristics of complex systems and we apply them to construction performance:

1) Multiplicity: the number of ways that could produce a certain state. Construction's stakeholders consist of owner, architects, engineers, and consultants, and especially, construction teams like general contractors, sub-contractors, vendors and suppliers. Each organization has an identical structure of strategic, logistic and tactical personnel.

2) Causal connections: numbers of links between components (to the extreme, there is causal feedback where a change in one component loops back to affect the originals). This is common in construction practices. One of the most common examples is the misunderstanding of a client's requirements by the design team, which causes project schedule delays or over-budget performance.

3) Interdependence: the larger the module that can be removed from the complex system without affecting the overall system's behavior, the more resilient and less complex the system. However, in the construction system, none of the tasks, parts or units involved in the process can be easily removed or replaced, which makes construction a highly complex industry [25]. Supply Chain and contractors' networks are good examples to illustrate interdependence of autonomous agents in construction systems.

4) Openness: to outside environment, not self-contained, difficult to locate boundary. Construction systems are nested in a social environment. Policies, economic situations and advanced technologies regularly affect construction systems.

5) Emergence: the degree to which the entire system is more than the sum of its parts, because a system may transcend its components. This is also the philosophical core of complexity theory [26]. According to the recently specified “value” theory in construction [27], a constructed project has no value until it is turned over to the owner and used for its intended purpose; the value of the whole building is greater than the sum of parts.
6) Nonlinear behavior: the effect on the system in not proportional to the size of the change on a component. The nonlinearity of the construction project carries through the nonlinearity of the subsectors, and the nonlinearity of the industry and the general economy. In construction projects, most mathematical equations are complex and nonlinear, and generating these equations can be a remarkable challenge [28]. For instance, the total cost is not only related to the building mass; it is also affected by construction location, delivery method and so on.
7) Adaptiveness: Organizations are adaptive in that they do not simply respond to events, but evolve or learn. Each component, or we can say agent, in the construction system is guided by its own schema or rules of behavior and also by a schema shared with others in the system [29]. Curlee and Gordon [21] agree that transformation or adaptive-ness is the nature of construction projects. One of the most famous theories of this is the transformational leadership idea in lean construction.

2.3 Graphic Metaphor of Complexity

Overall, the complexity of construction systems and its characteristics stems from potential non-linear, emergent behavior which can occur from interactions between many interconnected tasks [23]. Actually, chaos is where complexity arises through the non-linear interaction of small numbers of simple components and parts, people, equipment, materials and so on [2][3][21]. Project complexity is interested in the two zones to which a disturbed system may return: stable or unstable zones. Under appropriate conditions, systems may operate at the boundary between these zones, sometimes called a phase transition, or the “edge of chaos” [41]. Thompson and Gray [42] provide the elements for a graphic metaphor on the range from order to disorder with its transitions.

Based on their ideas, we summarized the different status of a system in a more vivid graphic metaphor, as shown in Fig. 2. This figure illustrates a typical project flow: a project starts with a design and plan for execution that is orderly until the project receives a notice to proceed when external and internal circumstances create complications reaching a level of complexity; the increased number of agents and the random accelerated and decelerated performance of each that affects the others increases the probability of chaotic behavior; toward the end of the project, apparent disorder reigns on the mash dash to finish on time, on budget with the quality assured. Fortunately, like in chaos, the end is one of order.

"Complexity is the 'edge of chaos', the transition from order to disorder."

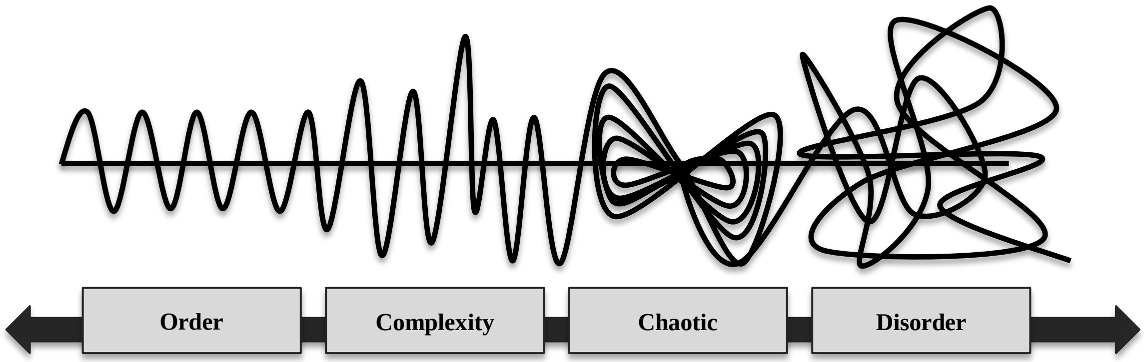

Fig. 2. Graphic metaphor of order, complexity, chaos and disorder

Fernández-Solís et al.'s [2] case study of chaos arrived at a graphic image of PPC time series data (Fig. 3**)**. PPC data in the case fluctuates in chronological order. In order to analyze this non-linearity, PPC data is reconstructed by constructing an attractor diffeomorphic to the original dynamic system in a phase space of sufficiently high dimension.

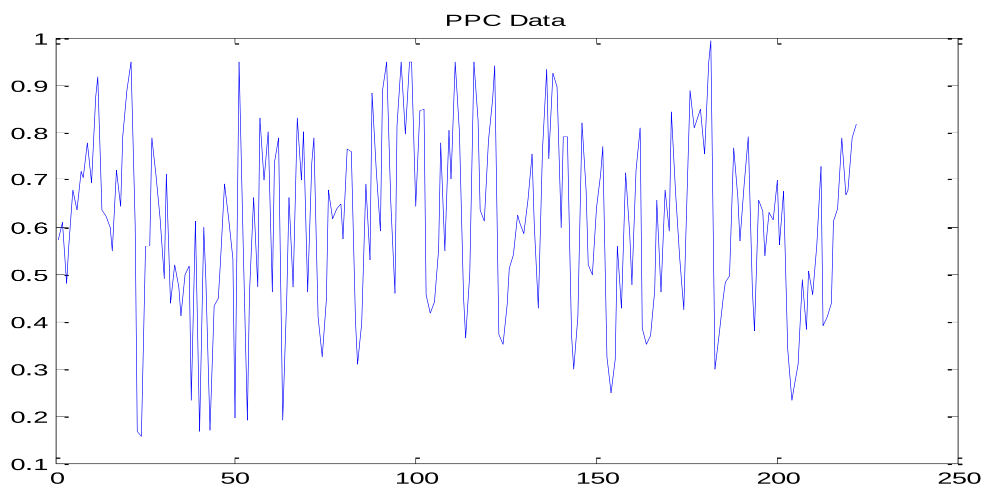

Fig. 3. PPC time series data compiled to reconstruct its attractor [2]

This graphic visualization of the Percent Plan Complete (PPC) attractor from the case study, which was also found in other PPC studies, is indicative of the presence of complexity in the social process of building construction.

The power spectral density of the same case study is also characteristic of subsequent PPC case studies with the following graphic representation. In Fig. 4, the periodogram of PPC data shows a zigzag aperiodic characteristic of the PPC data.

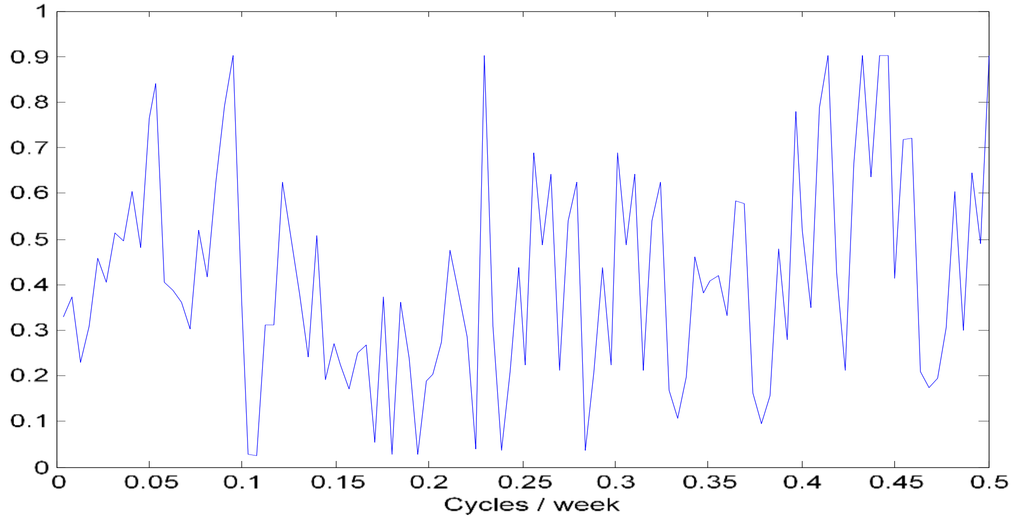

Fig. 4. Periodogram of PPC data revealing the power spectral density (PSD) - Fernández-Solís et al. [2].

Furthermore, the Autocorrelation Function (ACF) of PPC data points to a non-linear structure as found in the following graphic representation. Fig. 5 reveals the results of the ACF of the PPC data. In this case, the ACF appears to be decaying quickly, pointing to a non-linear structure.

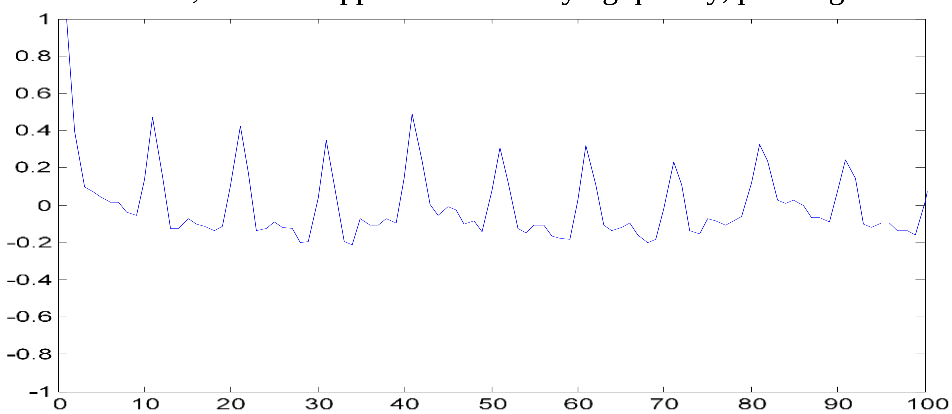

Fig. 5. Autocorrelation Function of PPC data pointing to a non-linear structure [2].

Lastly, the phase reconstruction with embedding dimension d=6 and delay time τ= 5 shows chaotic behavior in the lines of disorder per the following graphic from the same study. Fig. 6 shows the map that the compiled data create: a disorderly state.

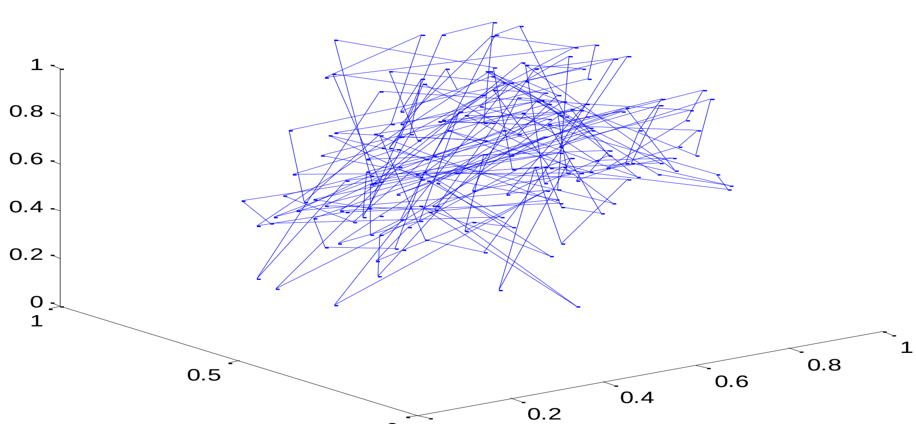

Fig. 6. PPC phase space reconstruction with embedding dimension d = 6 and delay time τ= 5 showing its disorderly behavior [2]. This is a correction from the published analyses of previously cited papers.

From the graphics above, we observed that in building construction, the organization for a production process, can expect an orderly start that flows through and into transitions to complexity and then experiences chaotic or near chaotic episodes in an ambience prone to disorder; that it is always at the edge between stable and unstable process. This conclusion fits well with the observation that a construction effort is a constant focused effort at applying information and knowledge against an ever present tendency toward entropy, the increase of disorder which is conquered through labor but nevertheless takes place in the arena, the edge between stable and unstable process.

3. A deeper understanding of building construction complexity

Complexity sciences are a relatively eclectic collection of academic efforts crossing a wide variety of disciplines [29]. From Thomas and Mengel's statement, we categorize two different types of complex systems: complexity theory and complexity science.

3.1 Complexity Theory

Complexity theory states, in general, that the whole is greater than the sum of its parts in complex systems [43]. In building construction, for example, the building has no value until it is completed, receives a certificate of occupancy, is accepted by the owner and put to use for its intended purpose. At this point, the building value is greater than the sum of its parts.

Complexity theory is concerned with the behavior over time of certain kinds of complex systems.

Complexity theory is a relatively new way of thinking about systems of interacting components, such as firms and projects. Unlike classical mechanistic theories, which assume a centrally controlled governing structure, complexity theory rests on the idea that order emerges through the interactions of components [44]. "Agent" is a general term used to designate semi-autonomous entities, such as atoms, molecules, biomolecules, processes, people, groups, firms, industries, and participants, or general contractor and subcontractors in a construction project [45]. As modern complexity theory suggests, some systems with many interactions among highly differentiated agents can produce surprisingly simple, predictable behavior, while others generate behavior that is impossible to forecast, though they feature simple laws and few agents [46]. Complexity theory does not invoke inertia to explain punctuated equilibrium. Rather, it suggests that a pattern over time of large and small changes is what one would expect from a system of coevolving agents subjected to selection pressures [47]. Complexity theory suggests that attempts to rigidly control a complex system can increase problems and unintended consequences as individuals in the system "work around" these controls [48]. It also suggests that, in order to affect change in a complex system, we must understand the recurring patterns in the system, including the patterns of relationships.

Cohen and Stewart [49] sum up the basic ideas underlying complexity theory: Complexity theory describes how complex causes can produce simple effects, while established science shows how complex effects can be understood from simple laws; chaos theory demonstrates that simple laws can have complicated, unpredictable consequences.

Building construction exhibits, at the observational level, all the characteristics above mentioned, of complex theories.

3.2 Complexity Science

Complexity science thinking, within the natural sciences, began in the 19^{th} century with roots stretching back to early work on cellular automata, cybernetics, and general systems theory [30][50]. It continued into the 20^{th} and 21^{st} centuries, with scholars from politics, social policy, social network, geography and healthcare applying complexity science within their disciplines. As Linstone [51] stated, complexity science was the most exciting development in the systems area in recent years.

A science of complexity is the systematic and deliberate descriptive reduction of complex systems into a transmittable and understandable form. In other words, the science of complexity is principally a deliberate program of simplification in which the vague complexes of sense-experience are systematically compressed and converted into a conventionally recognizable and accepted form of discourse [52]. The science of complexity also demonstrates that for a system to be innovative, creative, and changeable, it must be driven far from equilibrium where it can make use of disorder, irregularity, and difference as essential elements in the process of change [53]. Rather than merely confirm the inherent limits to forecasting, complexity science should be seen as opening up new paths to reveal important insights to assist decision making [51].

In the last 30 years, in particular, there has been a re-evaluation of the nature of complexity, and more fundamentally, of the relationship between order and disorder [54]. Both systems theory and complexity science focus on the relationships between these elements rather than on each element alone within the system. The best way to understand complexity science is to contrast it with established science, since most individuals have an understanding of the latter field of knowledge (see

Table 2).

Table 2 Complexity science compared with established science, adapted from Begun et al. [55]

COMPLEXITY SCIENCE	**ESTABLISHED SCIENCE**
Holism	Reductionism
Indeterminism	Determinism
Relationship among entities	Discrete entities
Nonlinear relationship	Linear relationship
Critical mass thresholds	Marginal increase
Quantum Physics	Newtonian Physics
Influence through iterative nonlinear feedback	Influence as direct result of force from one object to another
Expect novel and probabilistic world	Expect predictable world
Understanding; sensitivity analysis	Prediction
Focus on variation	Focus on averages
Behavior emerges from bottom up	Behavior specified from top down
Metaphor of morphogenesis	Metaphor of assembly

However, it is not easy to give complexity science a common definition, given its long gestation and continuing growth and maturation [56]. As a result, definitions of complex science still vary according to the field of application, such as physical sciences, ecology, civil systems and social sciences. Manson [32] reviewed a diverse literature of complexity and summarized three categories of research where the term is used: algorithmic complexity, deterministic complexity and aggregate complexity:

Algorithmic Complexity: refers to measurement of the difficulty of computational problems [56]. The most widely known definition of algorithmic complexity is the Kolmogorov–Chaitin measure, which is often referred to simply as the Kolmogorov complexity. The Kolmogorov complexity of an object, such as a piece of text, is broadly defined as the length in bits of the shortest description for that object. Alternatively, it is the length of the shortest program required to obtain the output [57].

Deterministic Complexity: refers to the unpredictable dynamic behavior of relatively simple deterministic systems [32]. According to this definition, unpredictability is framed as sensitive dependence of outcomes on initial conditions.

Aggregate Complexity: the study of phenomena characterized by interactions among many distinct components [32]. This is the most comprehensive definition with encouraging characteristics for the analysis of building construction systems.

The notion of complexity has been widely studied in fields such as astronomy, chemistry, evolutionary biology, geology and meteorology [58]. However, its translation into the project management field started in the 1990s. In the project management field, the science of complexity seeks systematic and deliberate reduction in order to harness chaos in a manner that allows the project manager to increase his/her team's effectiveness by allowing a certain degree of individuality to move a project forward [21].

3.3 Complexity science in building construction

The dynamic complexity of a construction project intuitively results from the stochastic spatial and temporal interactions between multiple components such as on-site equipment resources, labor productivity, unexpected external events, and human decisions regarding resource allocation and activity rescheduling [59]. However, this is not the real complexity for long-term research. Curlee and Gordon [21] indicate that complexity does not necessarily reflect complicated or large projects; nor does it imply technical difficulty. In fact, complexity science is a relatively new science with roots in math and science. It is concerned with the behavior over time of certain complex systems, while complex systems combine elements of both ordered and random behaviors in an elusive but striking manner [60]. Complexity science describes how systems actually behave rather than how they should behave.

From the science perspective, a great number of complexity studies focused on the project management discipline have produced a number of approaches:

- Turner and Cochrane [10] first connected project complexity with lack of clarity on project goals.
- The first established dichotomy about complexity is from Baccarini [11]. He proposed the complexity of a project could be interpreted and measured in terms of differentiation and interdependencies for both organizational complexity and technological complexity, in which the differentiation holds two dimensions: vertical differentiation and horizontal differentiation.
- Based on previous studies, Remington and Pollack [61] categorized complexity into four dimensions, factors that characterize the nature of the complexity or a mixture of the two, based on the source of complexity: structural, technical, directional and temporal.
- Vidal and Marle [6] summarized the historical research of project complexity into two main scientific approaches. The first one, usually known as the field of descriptive complexity, considers complexity as an intrinsic property of a system. An example of this vision is the work of Baccarini [11], which incited researchers to find methods and tools to quantify or measure complexity. The other one, usually known as the field of perceived complexity, treats complexity as subjective, seeing the complexity of a system as improperly understood through the perception of an observer. On the basis of this, a project manager deals with perceived complexity as he/she cannot understand and deal with the whole reality and complexity of a project.

All of the above research emphasized that a clear understanding of complexity helps in selecting appropriate tools and approaches to manage a project successfully.

4. Conclusion

This paper reviews and summarizes three different concepts of complexity-- complex system, complexity theory and complexity science--and connects them with construction management theories. We found that: If building construction's project delivery can be loosely categorized as a production system, (1) what kind of system is it? (2) What do the best minds of researchers, philosophers, scientists, academicians and practitioners say about a building project production as a system? (3) How does thinking of a project one way or another affect the way we understand the system of construction? (4) Moreover, does a particular understanding of construction, as a particular type of system, have any practical implications?

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