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CONSTRUCTION AS A COMPLEX SYSTEM

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ABSTRACT

Complexity and complex systems' theory are issues coming more and more into focus as it seems that most systems in our lives must be understood in this perspective. This new way of understanding, explains features otherwise ignored or considered noise in an ordered perspective.

The paper argues that construction should also be understood as a complex, dynamic phenomenon. It analyzes the construction process, the production system and the industry, as well as the social systems formed by humans involved in the project execution from a complexity perspective using a number of general characteristics of complex systems. It finds all of these characteristics present in the construction system.

The paper concludes that the complexity view should thus be more in focus when discussing new project management paradigms.

KEY WORDS

Construction; complex dynamic systems; project management; chaos

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INTRODUCTION

It has been argued that projects in general and construction particularly should be understood as a complex, dynamic system. This understanding may better explain project characteristics such as wicked problems as well as the working of useful management tools such as Last Planner as proposed by Ballard (2000). (Thomassen et al 2003, Bertelsen 2002a) But what is a complex, dynamic system?

The paper reviews briefly complexity as a new way of understanding systems of different kinds and outlines a number of characteristics found when looking at the systems in this way. It then proceeds by demonstrating that these characteristics can all be found in construction. In doing so, the paper expands the term construction to encompass not only the construction project and the associated process but the construction arrangement – the production system – and the social system established in relation to the project realization as well.

COMPLEXITY – A NEW SCIENCE

Even though complexity is an emerging new science from which there has been a steady growing output of literature in recent years, a common definition of complexity is still missing (Bertelsen 2002b). Quite often a general quote from the dictionary is used. Williams (1999) states: *While many project managers use the term complex project, there is no clear definition about what is meant – beyond the general acceptance that it is something more than simply a 'big' project.* Baccarini (1996) proposes complexity be operationalized in terms of *differentiation and interdependency* and applied to dimensions relevant to the project management process, such as *organization, technology, environment, information, decision making and systems.*

However, most frequently cited contributors seem to deal more with what complex systems are not, than with what they are. And often these authors give some examples of complex systems' characteristic behavior such as emergence or strange attractors, but these phenomena are stated more as symptoms than as deciding factors (Waldrop 1992; Lorenz, 1993; Kauffman, 1995). Indeed, Stuart Kauffman – one of the leading figures in this new science – has stated: *The efforts are still so new that there is not yet even a generally accepted, comprehensive definition of complexity.*[2]

The reason for this seemingly odd situation may be that almost any system can be seen as being complex. Thus, complex systems are not a special class of systems but a way of looking upon any system as opposite to the ordered viewpoint, which has dominated the Western science's reductionistic approach since the Renaissance. In this interpretation complexity studies mean studying the system as a whole without simplifications, and observing the interaction between the elements just as much as the elements themselves. As most – at least living – systems are characteristized by their non-linearity and richness in feed back loops, a formal analytic approach is no longer possible – the equations can not be solved but

[2] Stuart *A. Kauffman:* Antichaos and Adaption, *Scientific American, June 1995. (*Horgan, 1995).

most be simulated. Neither can a pure statistical approach as used in quantum mechanics be used. (Kauffman, 1995)

Looking upon the system as a whole opens one's eyes for new features and behaviors not found through the traditional approaches, and this view contributes greatly to one's understanding of the system in question. This has been shown within a number of domains as different in nature as meteorology (Lorenz, 1993), Biology (Kauffman, 1983, 1985, 2000), traffic (Resnick 1997) and economy (Kochugovindan and Vriend 1998). Also management in general has been fruitfully studied and understood in this new perspective (Thiétart and Forgues 1995). This strongly argues for looking at and interpreting construction from a complexity perspective as well, when establishing and operating new project management paradigms, as opposed to the ordered and top-down approach traditionally used in organizing and operating projects. (Tavistock 1966, Koskela and Howell 2002)

COMPLEX SYSTEMS' CHARACTERISTICS

Several authors have dealt with complex systems' characteristics in general. Often quoted are (Waldrop 1992 and Kauffman 1995) but also Lewin (1993) and Johnson 2001 should be mentioned.

Lucas (2000) presents in his brief introductions to the world of complexity in the paper: The Philosophy of Complexity a comprehensive list of 18 characteristics of complex systems such as self-organization, emergence, attractors and phase changes. An examination of other studies of complexity shows that Lucas' overview is fairly exhaustive. Thus, his list is used as a basis for the analyses of construction presented in this paper.

A closer examination of the list also shows that a few of these characteristics are general but that most may be divided into three groups. These groups are: Autonomous agents, Undefined values, and Non-linearity. One can say that we have a number of autonomous agents with undefined values (at the outset)[3], which each acts in a non-linear fashion. Such systems show a number of characteristics. This paper reviews these characteristics and relates each of them to one of the three aspects of construction as proposed by Koskela (2000)

Even though Koskela's TFV-process model is very useful in understanding construction and construction project management (Koskela and Howell 2002, Bertelsen and Koskela 2002), the construction process is not the only way of looking at construction. It can also be seen as an industry which provides autonomous agents to undertake the project in question (Bertelsen 2002a), just as it can be seen as a social system – a cooperation between individuals and groups brought together for the project (Tavistock 1966). This paper thus introduces these two new perspectives and uses them along with the process view in analyzing construction as a complex system.

[3] This is a quote from Lucas (2000) on complex systems in general. In construction one may state that the values f.i. in the sense of the agents in the production and the social systems exist at the outset but change as the cooperation evolves.

COMPLEX SYSTEMS' CHARACTERISTICS [4]

Fourteen of the eighteen characteristics identified by Lucas are placed in three groups, which are set up with an aim to understand construction from a complexity point of view. These groups are then in the following sections used as the tools for analyzing construction from a complex perspective. The grouping of the characteristics from Lucas (2000) is shown in table 1.

The characteristics not put into the groups characterize complex systems in general as being unstable and out of equilibrium where they show fuzzy behavior and mutability.

Table 1: Complex Systems' Characteristics

Autonomous agents	**Undefined values**	**Non linearity**
Autonomous agents	Undefined values	Nonlinear
Non-standard	Fitness	Emergence
Co-evolution	Non-Uniform	Attractors
Self-modification		Phase changes
Downward causation		Unpredictability
Self reproduction		

AUTONOMOUS AGENTS

Complex systems are generally composed of independent or *autonomous agents*, which are not identical. All of these agents are equally valuable in the operation of the system and no executive or directing node exists by design in the system. Therefore any control structure or leadership – a power asymmetry – must emerge by self-organisation.

As the parts are *non-uniform*, each can obey different rules or local laws – rather than all behaving under the same global laws. Each part evolves separately, giving diversity in rule or task space. But the parts *co-evolve* as well in order to fit into a wider system environment, thus fitness must be measured in contextual terms as a dynamic fitness for the current niche, and the structure will correlate to the external environment. The parts can also *modify* their associations – either randomly or by evolved learning procedures. Thus the system can be regarded as redesigning itself over time, as far as proves necessary to maintain or change its function within the operating context.

Along with the traditional form of upward causation – the parts creating the whole – we have in complex systems a *downward causation* too. This means that the existence and properties of the parts themselves are affected by the emergent properties – or higher level

[4] This section draws to a great extent on the general overview presented in Lucas (2000)

systemic features – of the whole, which form constraints or boundary conditions on the freedom of the constituents.

Usually complex systems have an ability of *self-reproduction;* they can clone identical or edited copies. Social systems can thus replicate to create additional systems (e.g. organizations). Copying errors – including mutations – permit new system structures to become available, allowing open-ended evolution. Errors are thus highly valuable for the system!

UNDEFINED VALUES

The purpose of the system's interface with the environment is not initially specified but must evolve. This requires that a communication is created dynamically by the system as a result of environmental interaction.

The distribution of local optima around the state-space can be modelled by the concept of a *fitness landscape*. Here the height of the hills relates to how good the option is. The gradual evolution makes it possible for the system to be stranded on a local peak, thus giving a situation where a copying error or mutation is the only possible way out.

Complex systems are *non-standard* as well. They contain structures in space and time. Their part freedoms will allow varying associations or movement, permitting clumping and changes over time. Thus initially homogenous systems will develop self-organizing structures dynamically; order – and thereby value – increases over time rather than decreasing as expected in conventional thought.

NON-LINEAR

Complex systems are *non-linear* – their outputs are not proportional to their inputs. This means that reductionist superposition – the idea that $F(x+y) = F(x) + F(y)$ and that $F(ax) = aF(x)$ – does not hold for these systems. Thus, taking the properties of each part and adding them will not give a valid solution to overall fitness – the whole is different from the sum of the parts.

Mutual interference between the parts requires that we analyse the system in a holistic way, as it usually shows *emergent* or higher level functions. These functions or properties will not even be describable using the language applicable to the parts only. They comprise forms of synergy or co-operation that go beyond the simple ideas of aggregation used in reductionist science and disprove the Laplacean deterministic fallacy that claimed that all system behaviour is predictable from total part data.[5]

The emergence and self-organization relates to the presence in the system of *dynamical attractors*. Each attractor will occupy a relatively small area of overall state space. The system will thus be expected to contain multiple alternative attractors, giving several different possible behaviours for the same system. Which actually occurs will depend upon both the initial configuration and the subsequent perturbations and transients – the system history.

Feedback processes lead to *phase changes*, sudden jumps in system properties. These 'edge of chaos' states are critical points in connectivity terms and the system is maintained

[5] Emergent properties may be seen as blessings but are not always so as shown in the section on construction as a social system.

at the phase boundary by its self-organising dynamics – very different than the either/or phases of conventional systems. In such states a *chaotic sensitivity* to initial conditions can occur – the butterfly effect.

THE CONSTRUCTION PROCESS IN A COMPLEXITY PERSPECTIVE

Koskela (2000), which again is based on Shingo (1988) demonstrates that the construction process should be understood from three different perspectives: Transformation – which Shingo names *operations*, Flow – by Shingo *process*, and Value generation. As shown below, these three perspectives may be directly related to the three groups of characteristics as 'autonomous agents' relate to transformation in Koskela's terminology (and to operations in Shingo's), 'undefined values' relate to the value generation, and 'non-linearity' relates to the flow (process by Shingo).

GENERAL CHARACTERISTIC

The construction process is an assembly-like process, which is complicated, parallel and dynamic, and thus more complex and dynamic than project management often envisages. The mistake is the ordered view of systems, which is reflected in the underlying management-as-planning and dispatch theories as found by Koskela and Howell (2002). All supplies are believed to be made in accordance with the project's – unreliable – schedule, and all resources such as equipment and crew are supposed to stand by, ready for the project's beck and call. And changes will not occur. However, this is not the way the world operates and project management should reflect this situation. Koskela (2000) points out, that even small uncertainties in the prerequisites adds up to a significant uncertainty on the project's workflow as a whole, a phenomenon analyzed in detail by Hopp and Spearman (2000) but not reflected in current construction management practice.[6]

AUTONOMOUS AGENTS

From a process perspective the project's 'agents' can be perceived as the design solutions – the systems and modules of the building – and their associated transformations or operations. At the outset no features are decided and all of these solutions are equally valuable in the system. But as the design progresses, features evolve and act as an emergent control structure for the rest.

Construction also has a co-evolution of the product and production processes, just as the design is unique for the problem and thus for the external environment. The development of new project designs, new types of structures and systems etc, just as the introduction of new materials, equipment and methods can be seen as a self modification of the process. Also design as an art and as a skill is constantly evolving.

The design and the associated construction process as a whole defines the details of the components and solutions – a downward causation – just as it establishes and changes the operations – new or old – of the production system.

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[6] Indeed, this phenomenon was exactly the one found by Edward Lorenz in 1961 and which gave rise to the 'chaos movement' later turned into the science of complexity.

An important part of this evolvement is learning, which takes place by getting inspiration from other projects – as often seen in architecture. But also learning from mistakes and errors, and the following development of new solutions and methods happens all the time.

UNDEFINED VALUES

The project establishes its own values during the initial design stages, and it develops these values further through the project life cycle. Every project is a new undertaking with an exchange of resources and ideas with the environment; designs reflect their environment and cause impact on the surroundings.

It is in the nature of the project that it exists in its own fitness landscape for the design as well as the production process. The notion of fitness landscapes suggests that the system exists in a situation with a number of local optima. If the system develops gradually it may get stranded on a local peak which may be much lower than the global optimum. However, more important is that the form of the landscape is dependent of the system itself and its complexity and that the landscape thus may change as the system develops. There does not exist an absolute optimum at all, but the best solution is dependent of the system's actual status. This is exactly what characterizes wicked problems. They are problems without an optimal solution as their preconditions change as the solutions evolve.[7] The construction richness in such problems not least in the design phase is an argument for the existence of a fitness landscape in the construction process.

The project modules and their construction processes can be seen as independent parts, each with their own design and production characteristics. No two projects are equivalent and their parts are often non-standard. The project thus represents a structure in time and space, where an increasing order is emerging, generating value for the client.

NON LINEARITY

The process outcome is obviously characterized by the whole being more than the sum of the parts. The value of a house is critically dependent of fi. the roof. Without a roof: low value, with one: much higher. However, the dependence is not expressed as an AND function neither. Some parts may be needed – or almost always needed, whereas other may only be nice to have. The relation between the parts must be expressed in a sort of fuzzy arithmetic.

Emergence is found in the nature of the production process according to Shingo: Operations – the parts – and the process are two different phenomena. Even the most careful study of the operations as independent parts will not tell much about the process as a whole and its outcome in form of the product. This can only be seen through the process dimension.

The building understood as an assembly of systems gives rise to a number of attractors. The wicked nature of the design process makes it possible that even small differences between two groups of stakeholders may lead to different solutions or to different process designs, which can be seen as the project's attractors.

The construction process is indeed rich in unforeseen events, deviations from plans and changes. Also, a chaotic sensitivity to initial conditions can be found. The temporary nature

[7] An introduction to wicked problems in projects can be found at: http://www.poppendieck.com/wicked.htm

of the project and its one-of-a-kindness may make it unstable as well. Projects are known going totally askew – and when things go wrong in construction, they really go wrong. Thus, considering the construction process ordered and frozen is indeed a great mistake!

THE PRODUCTION SYSTEM IN A COMPLEXITY PERSPECTIVE

GENERAL CHARACTERISTIC

The construction industry is highly fragmented and its firms cooperate in ever changing patterns. Almost all construction projects are divided into parts that are subcontracted to individual enterprises chosen mainly by lowest bid. As every firm at the same time participates in more than one project, utilizing the same production capacity, the industry as a whole is thereby also highly interwoven.

As almost all contracts are made to the lowest price there exists a strong incentive for each contractor to optimize the utilization of his own resources, which inevitably gives rise to growing buffers and prolonged cycle time (Hopp and Spearman, 2000). This causes waiting by the other contractors, which again enforces them to take preventive actions. Thus we often have a positive feed back loop, where only the contractual penalties seem to have a reducing influence on the duration. (Williams et al 1995)

In other words, we have a production system, which ties the project in question firmly – but secretly – more or less to all other projects that are being executed in the region, the State or maybe in the whole country. As the system consists of individual operators, nobody has any idea of where the ties are so tight that we get strong and unplanned influence from unforeseen events in other projects. The construction sector – due to its contracting practice – forms an interwoven network of high complexity and great dynamic.

AUTONOMOUS AGENTS

From a production system point of view the agents are the participating consultants and trade contractors. They are independent to the extent that they are not solely members of the production system for the project in question, but participate in other systems at the same time and with a similar engagement. Partnering arrangements are often mentioned as a means to bring these autonomous agents together, but such initiatives can also be seen as indicators of the existence of the autonomous agents in construction. When it comes to the control structure, the sole purpose of the project management is to establish an executive node without waiting for its emergence. However, Danish experiments with self-managing construction teams show that control structure and leadership do emerge in practice if not established through design. (Dam and Elsborg 2003) Also Tavistock (1966) points at the importance of the informal control structures in construction.

Project and process system design is parallel activities establishing a co-evolution. The temporary production system is developed for the project and each project's production system has its own characteristics as a result of the co-evolution between the parties. Also the development of the industry such as new forms of cooperation – where the project management tradition only seems to be a hindrance – may be seen as a co-evolution and self-modification.

Firms in the industry are created in accordance with the tasks requested by the market as a downward causation; just as the firms adjust to the market and motivate their staff to a company behavior – another downward causation.

Emergence and disappearance of enterprises is a kind of self-reproduction, which can be compared to birth and death in living systems. New firms within a trade tend to look like the ones already there, but new types may turn up from time to time, and we have thus an open-ended evolution.

UNDEFINED VALUES

The construction sector as a system has no initial values in itself before the outset of the project. Only the interaction with the project's solutions attaches value to the system. The project's production system can also be seen as a new activity in the regional industry and thus the production system interacts with its environment in creating value.

The temporary nature of the production system establishes a fitness landscape unique for the project. The optimal solution – or the local optima – must be found each time. But also the industry in general acts in a fitness landscape where the ongoing competition and the development of new methods for organizing, managing and executing the work change the landscape.

The production system's different participants are the agents. They are all different, just as different forms of contracts, which allow varying associations and changes over time, establish the production system. The production system is also formed for the job, making it very non-standard indeed. The production system thus represents a self-organized structure in time and space, where an increasing order is emerging.

NON LINEARITY

The production system is non-linear as well. Usefulness can not be added up. The system looses value in a very steep way if one or a few participants are not available. This characteristic can also be found by the fact that the project production can not be envisaged by looking at the trade contractors as individuals or on the construction industry as a whole. Only as a group emerges the production system providing the process in accordance with Shingo (1988).

The project can be seen as an attractor for the participating firms, and the whole sector has thus a dynamically changing number of attractors stabilizing the pattern for a short while, but then changing it again. The temporary production system can also be seen as a living system, where the trades come and go, but as the system stabilizes itself in a new pattern, it has again found an attractor.

The project life cycle is a series of phases and phase boundaries; the nature of the wicked problems found in all scales and the frequent project alterations keep the project on the edge of these boundaries until completed. Change in participant firms or staff expresses phase changes in the production system as well.

The choice of project participants by lowest cost and staff selected for the job in question causes unpredictability in the production system. The system may also suffer from instability if one or more of the parties is heavily occupied on another project or go out of business, and the system is in general very transient. New trades, new kinds of equipment give rise to new players in the production system.

The production system – not least the industry as a whole – is indeed very complex and dynamic. And it is it in a way almost impossible to study in detail. Thus, project management must often work without knowledge of the project integration, and management routines should reflect this complexity!

THE SOCIAL SYSTEM IN A COMPLEXITY PERSPECTIVE

GENERAL CHARACTERISTIC

Construction is a temporary undertaking for which a new organization is established for every project. However, this organization is clarified down to a certain level only and the whole setting is thus not described. Indeed, the Tavistock report (1966) identifies several layers of social relations supplementing the formal management without being recognized by the project management but being of paramount importance in getting the work done.

Also the construction site is a working place for humans and thus a place for cooperation and social interaction, albeit – because of the temporary character – a highly transient social system. However, this social aspect is often hidden by the fact that the staff at the production facility – the construction site – is not hired and reimbursed by the place where they work – i.e. the project. Their loyalty is thus divided between their own firm and the job at hand, often with the firm as the one with the highest priority as their measurement of success lies within that system. Smith (2002) points at the importance of the measurement system for the measured system's behavior. [8]

Traditional project management often overlooks these aspects and does not perceive the crews on the site as their own employees in a virtual firm, the criteria for success of which is the expedient execution of the project.

AUTONOMOUS AGENTS

Looking at construction as a social system, the groups and individuals brought together for the purpose of executing the project can not be considered completely autonomous, but they are to a great extent equal individuals as they formally belong to other organizations than the one established for the project execution. As the project progresses an informal project organization emerges along with the formal organization established by the project management.

Job description and work conditions are functions of the product and process design. This causes a co-evolution of the social system along with the design and the establishing of the production system. The social system should also be seen as a temporary system to be designed for the parties to co-evolve. The Danish BygLOK project (Dam and Elsborg 2003) has tried this approach with great success, introducing continuos adjustments to the situa-

[8] The statement is supported by author's own experiences as project manager as well as his observations as a process consultant during the recent years on (not formally reported) projects, where an effort has been made to change the priorities of loyalty.

tion in the human system. Multi-skilled gangs, emergence of teamwork and the effects of action learning can be seen as signs of self-modification in the social system.

The organizational and social systems are also rich in traditions which act as carriers of behavior from one agent to other agents entering the group as a form of downward causation. Crew teams also influence their members' attitudes in the same way.

UNDEFINED VALUES

The temporary hiring of firms and crewmembers and bringing these crews together on the site establishes a system with undefined common values at the outset. During the project execution social values – good or bad – emerge and cause an impact on the trade as a whole, just as the project's social system gets impact from outside agents such as trade unions etc.

The development of the social system establishes a fitness landscape unique for the project, where the optimal solution – or local optima – must be found each time.

The social system's different trades are not uniform as they have different traditions, different rates and different forms of reimbursement. These differences in the system may give mutual inspiration to new ways of behavior: cooperation or fight.

Also the organizational and social systems on a construction site can be seen as non-standard structures in time and space, where an increasing order is emerging. This system is characterized by its dynamic nature and its informal cooperation, or – more often – fighting.

NON LINEARITY

The social system is characteristic by the group always being either more or less than the sum of the participants. The general accepted idea that the whole is more than the sum of the parts may thus be interpreted that the whole is different from the sum of the parts, because the social system is nonlinear. The group working on the project consists of the individuals, and the team spirit and cooperation are emergent phenomena. However, practice in construction unfortunately often shows that the lack of cooperation makes the whole very inefficient compared to the sum of the participants, and cooperation has a hard time to emerge. Instead we see sub-optimization and self-interest grow as another kind of emergent phenomena.

The project can be seen as an attractor for the participating individuals and thus for the whole crew on the site or at the design office at any given time. However, another and more important attractor is the common behavior, which stabilizes the project's cooperation in either a good or bad way. The force of such attractors makes it very hard to move a project once stabilized to another basin of attraction.

The exchange of staff and of crews and their adjustment to project dynamics are signs of a non-equilibrium state in the human system. Changes in the group participants and thus in the group's nature and attitudes – the 'project culture' – often keep these attitudes close to the former ones, but not always. The working climate in the social system – cooperation or fighting – indicates a degree of unpredictability, even if the social system tends to stabilize itself – it finds its own form for the job in question. But new participants entering the system may disturb this stability in a completely unforeseen way. 'One bad apple…' and the system may turn chaotic.

The social system in the construction project is indeed very complex. And worse: This is an often overlooked part of the project setting!

CONCLUSIONS

The above analysis demonstrates that construction should indeed be seen as a complex dynamic system. Most of the complex system's characteristics can be found, and they can be found for all three perspectives examined. It is the author's firm belief, that further analysis will increase the number of examples in all nine areas looked at, and thus confirm the result.

For use in future work the complexity analysis should be further refined. Not with an aim to just demonstrating that construction is not ordered and linear, but as a way of getting a deeper understanding of the projects' and process' true nature.

Even though analyses of the construction process' complexity may be an interesting exercise in its own right, the important conclusion is that the complexity of construction can no longer be ignored and that the basis for our project management paradigms should thus be redefined. Our managing projects in practice must then be changed accordingly.

This is the real challenge!

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