ENGINEERING STRATEGY: A HOLISTIC VIEW ON THE DESIGN OF COMPLEX SYSTEMS

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Abstract

Adaptation can be seen as an evolutionary process. Biological studies show that variation; retention and selection are enough ingredients for a system to drift in an amoral and unintentional way. The same mechanism works with organizations and complex systems. Human behavior shows variations from the best practice, unprofitable variations are wiped out, and the most profitable variations are retained in the new best practices. The variations that have the largest probability to be retained in best practices determine the adaptation or drift of the system.

Management to prevent systemic accidents often tries to control variation. People are pushed toward compliance with best practices. However, controlling variation without controlling drift will only postpone systemic accidents. Moreover, drift is also necessary to adapt to a changing environment. The most promising approach seems to get better grip on the mechanism of selecting variations for best practices.

The paper addresses the mechanism behind design and adaptation of complex dynamic systems. It elaborates on the conflict between diminishing variation in order to prevent accidents and the necessity of variation in order to adapt to changing environments. A possible way is shown to enhance the ability to adapt without jeopardizing safety.

1 INTRODUCTION

Ashby (1957) formally defined the dynamics of systems. He described a system by its state. In deterministic systems, the current state determines the state after one transformation. The consequence is, that all future states are determined from the first state, or starting condition. Ashby called the set of future states belonging to one starting condition a trajectory. He observed that the state space could be divided in several subspaces, whose boundaries where not crossed by any trajectory. He called these subspaces basins. In each basin the system tends to an equilibrium state, what he called an attractor. Attractors can be stable states, in which the system is stationary, and periodical states, that consist of a number of states that follow each other periodically. Later research (Lorentz, 1963; Ruelle & Takens, 1971) showed that even a third kind of attractor is possible, a so called 'strange attractor', that consists of a seemingly random sequence of states within a basin. It is impossible for a deterministic system to leave a basin as long as the environment of the system remains unchanged.

Changes in the system's environment shift the boundaries of the basins. In fact, it is even possible, that new basins are formed or old ones disappear (De Souza & Rodrigues, 2002). During such an environmental change, the system can get into a different basin, if the change in the environment happens so quickly that the system can not adapt. If a bowl with a ball resting at the bottom is moved slowly, the ball will remain near the lowest point of the bowl. If the bowl is moved suddenly, the ball doesn't have the time to adapt and can jump out of the bowl.

2 COMPLEXITY

If the number of components increase, the complexity increases. Weaver (1948) called this kind of complexity unorganized complexity. Modern literature commonly refers to this kind of systems as complicated (Hertogh & Westerveld, 2010).

Some systems possess such complexity that humans can not model them as a deterministic system. Then it is perfectly adaquate to describe them stochastically on a higher level of abstraction. In stochastical systems, the next state is only partly determined by the last one, because a stochastical variation is added to it. This variation is independent from the history of the system. The boundaries between basins are no longer crisp; the system now has a probability to cross the boundary. Stochastical systems that are in their operational basin, have a probability of leaving that basin. Reliability is a measure for the probability that a system leaves its operational basin. Reliability belongs to the realm of stochastic models.

One characteristic of complex systems is, that they possess more than one, and sometimes a large numbers of basins. Also, in complex systems, relations tend to be non-linear. This means, that if the a change in the systems environment is made twice as big, the resulting change in the system state will no longer be twice as big as well. Lorentz (1963) showed that in non-linear systems small differences in starting conditions can have enormous consequences. These two factors make those systems very intangible for humans observing them. Intangibility and human incapacity of understanding, however, is not the main characteristic of complexity. It is merely a result of the large number of basins and the non-linear behavior.

3 ADAPTATION IN BIOLOGY

The properties of the system may change over time. Examples of this are wear and tear of mechanical components, but also the adaptation and learning of human components. Adaptation takes place due to some internal incentives of components and their exposure to environmental conditions.

Socio-technological systems are not only dependent on external factors to get moving. Humans differ from technology in having emotions. Internal drives for adaptation are pride, greed, lazyness, and fear. Instead of these pejorative words, literature uses wordings like cost minimization, profit optimization (greed), finding easier ways to do things, optimal use of technology, tight plannings (lazyness), risk avoidance (fear). This changing in the system originating in internal factors can be seen as adaptation. Essentially, these factors are the same as identified by Rasmussen (1997). Several components of the system can adapt independent of each other. The overall system can change its properties thereby drifting into failure (Woods, 2003; Dekker, 2011).

Comparing adaptation in socio-technical systems, whether engineered or emerged, to biological evolution can give some additional insights to the phenomenon of adaptation. Let us first have a look into the evolutionary process in biology. Wallace (1870) and Darwin (1876) formulated this concept. Simply said, it means that individuals within one species show some genetic variation. Darwin and Wallace were the first ones to note that the variety in species could be explained from small variations in individuals that cumulated over time. Some individuals have larger chances of reproducing than others. The children of the reproducing individuals inherit the genetic variations from their parents. The variations that have the largest probability to be carried over to the next generation will prevail and become the starting point for the variations in the next generation. The logical consequence of this mechanism is that the set of variations withing the species changes in a way that variations with a greater chance of reproduction are more abundant in within the species. The resulting evolution process, although amoral and unintentional, produces species that are fittest for the environment they live in.

Therefore, in order to have evolution, three elements have to exist in the system: variation, retention and selection. Without variation, we have no alternatives for the selection to work on. Without retention, the variations cannot accumulate. The selection mechanism is simply a mechanism that makes the probability of being copied in the next generation of variations dependent on the emergent properties of the previous generation. It can be intentional, as is the case in dog breeding programs, or unintentional, as is the case in natural selection. Evolution does not require a goal for evolution, in fact evolution as we find it in nature can be understood without an hypothesis about a goal.

4 ADAPTATION IN SOCIO-TECHNICAL SYSTEMS

Every function in a complex system is executed with a certain variation (Hollnagel, 2012). This variation may be very small, as it is in automated processes, or large as it is in human actions. There is a striking resemblance between the way these variations can lead to adaptation and the way evolution results from genetic variation in biology. All three elements can be found in socio-technical systems. Variation is abundant in human performance, retention is found in experience, best practices and procedures. The selection mechanism consists of the copying of variations. Variations in performance that are percieved as more successful are copied or retained in best practices. Variations that are percieved as less successful are not copied. We do have some clues as how this selection works. People tend to keep variations that earn more money, cost less, take less time, are easier, or are safer. Essentially we have the incentives as identified by Rassmussen. As all three necessary elements of evolution are present, we may expect evolutionary processes.

The best practices in a system tend to differ more and more from the original. Around this best practice many variations occur. One of these variations may prove to be fatal, a systemic accident occurs (Dekker, 2011). It is impossible to determine whether the variation or the best practice is to blame for the accident. There is simply no way to determine whether the deviation of the best practice was too big or that the best practice was too dangerous because it didn’t allow for variations that occur.

Systems will adapt until the combination of adaptation and variation will result in accidents. Accidents are a collateral damage of evolution. In nature, many individuals die while the species adapt, and many species become extinct during evolution. Evolution in nature has no ethical considerations. The evolutionary process is amoral and unintentional. It chooses the adaptations that enlarge the probability of reproduction without ethical considerations.

In fact, the same selection process takes place at the level of organizations. Few systems are complete monopolists. Most systems compete with other systems for scarce resources. A system that does not adapt will be wiped out by competition. This is why systems that do not allow variation will not survive in the long term. In our analogy with biology, the organization can be seen as the species, while existing variation between individual occurrences of actions can be seen as the individuals. In biology, we find species with little genetic variation and species with large genetic variation. Species with little genetic variation are very sensible to environmental changes because they cannot adapt quickly enough. Genetic variation is considered a value because it makes the species resilient to enviromental changes.

Systems that have too much variation will finish because some fatal combination of variations occurs that is not compatible with the existance of the system. Systems with are successful in regulating the amount of variation, in such a way that they remain compatible with their existance and they will remain competitive at the same time, will ultimately survive. This is the sustained adaptability of Woods.

The organizations that exist today are the product of the selection in the past. We may assume that the existing organizations have been pretty successful in adapting to the environmental changes in the past, as is proved by their mere existance today. The question remains whether we as humans can outperform the natural selection that is already taking place. We have an ethical obligation to ensure that the variations will not jeopardize human safety.

We humans have a marking difference with nature in that we can reflect on our own adaptation. We are, however, still subject to the laws of natural selection. In the same way, humans in socio-technical systems are subject to the adaptation laws, but they can reflect on the way they select variations as successful. We have the possibility to determine the incentives in the organization that will determine how best practices are selected. Only trying to diminish variation will not contribute to sustained adaptation, but will lead to extinction.

As we humans have ethical objections against accidents. Two approaches exists to avoid accidents. One is to control variation and the other to control drift. Many organizations tend to control variation. In fact, the whole concept of 'human error' is based on the idea that humans should not variate from best practice. Variation, however, is an essential ingredient for adaptation. At the same time, controlling variation without controlling adaptation will prove ineffective. The adaptation is simply allowed to proceed a little further until an accident happens.

The other, and more promising approach is to control drift. The system should not be allowed to adapt that much, that accidents will start to occur. We can try to continuously monitor the safety of the system and to intervene as soon as safety is jeopardized. But the most promising approach seems to be to have a closer look at the mechanism of selection. Which varieties are perceived as successful and allowed to be copied into best practices. Are the variations only selected by cost and time? Are variations selected on benefit for one department or also on benefit of the whole organization? Our research efforts should be aimed at this selection mechanism.

These internal adaptations of the system are to be well distinguished from the stochastical variations mentioned above. While stochastical variations are independent from each other in time, adaptations are systematic in character. Technological aging changes the parameters of the system as a function of time. Human adaptations are dependent on incentives and exposure. The system has a memory for things that happened in the past, the system 'learns'.

5 RESILIENCE

Resilience can be better understood if looked upon from a evolutionary point of view. When looking at systems of systems, these systems can be in competition for a common resource. Darwin (1876) called the changes that occur in those situations evolution. A selection mechanism is needed to wipe out some systems from the world. As Slobodkin (1964) says: 'Evolution is like a game, but a distinctive one in which the only pay off is to stay in the game.'

Resilience is about 'staying in the game', about survival of the system. Systems can cease to exist because their essential variables (Ashby, 1957) are sub standard as in the case of a human who is left without oxigen, or a company that goes bankrupt. But systems can also cease to exist because they loose the competition and are wiped out by selection. When talking about resilience, it is necessary to denote the evolutionary context of the system.

Systems whose essential variables are not compatible with survival, can simply be wiped out, like the human without oxygen. They can also get a sufficiently large disadvantage to loose competition with other systems.

In the latter case, the non resilient system is replaced by a completely new system, that was more able to survive than the old one. We could call such a complete replacement of one system with another a transition. In technology we often see that two completely different concepts are competing and that a disturbance in the old system gives the new one a great advantage in an evolutionary sense, thereby causing a transition to a new technology. Resilience of a system can thus be understood as the ability to maintain its competitive power in case of a disturbance. It is difficult to see what resilience means if no alternative is present; a monopolist will remain in power anyway. A strong competition puts the systems under pressure of losing their resilience.

As evolution knows the variation of individual behavior, the adaptation of species and the extinction and replacement by newer species, so does technology know variation within a mission, adaptation within a system and transitions where systems are replaced by new ones. Transitions are in the realm of evolution.

As stability relates to different basins, so does resilience relate to transitions between different systems. Lack of stability makes a system to transit to another basin, lack of resilience induces a transition to new system.

In the operational basin, the operator’s behavior will be aimed at performance of the system. Near the edges of operational basin, safety will be the dominant factor. Once in a non-operational basin, operation’s actions will be aimed at survival. Safety and resilience are not contradictory notions. They are indeed properties that have to be used together (van Kleef & Stoop, 2014).

6 CONTROLLING THE DESIGN OF COMPLEX SYSTEMS

Design processes are itself adaptable systems. They exist of a draft design and the designers, adapting themselves to the requirements under an incentive, most of the time some form of cost optimization.

If two designers have to self coordinate, they have to make sacrifices. Making sacrifices is only profitable, if making the sacrifice and thereby reaching a solution contributes more to the aim of the designer than reaching a deadlock. But if a deadlock is reached, the only way to get the flow back again is to make it more profitable to make sacrifices.

Ashby (1957) concentrates on systems that are controlled from outside. One of his observations was the law of requisite variety, stating that the variety in the dominant, controlling system has to exceed the possible variety of the controlled system. The consequence of this law is that controlling a complex system is practically impossible, because we need a very complex controller for this. An illustration from this idea can be found in the military. As armies bevcame more and more complex, the command and control structure grew. The last modern armies that were controlled, were the Brittish army in WO I, and the American army in Vietnam. Both armies proved not very successful (van Creveld, 1985).

This makes the decision not trying to control the development of new large complex infrastructure systems plausible. In fact, it would be impossible to control this design in every possible way from a central organization.

In the eightteenth and nineteenth century it was quit normal to look upon humans as variable in their acts. Emphasis in safety was put on values as ‘good seamanship’. Scientific reductionism tried to explain everything from the properties of parts. Taylorism at the dawn of the twentieth century brought the legacy of reducing humans even further and depriving them of the essence of humanity, their spirit.

Complex systems have properties that can not be reduced to the properties of their composing elements. A reductionistic view on these systems will not be enough to describe them. The commissioner is interested in the properties of the system as a whole and not in the properties of the components. The emergent properties are too important to be left emerging. The different systems all have their own incentives. They can adapt in different directions. During this adaptation they influence each other in a highly complex way. There is no guarantee that these adapted systems still have the right properties together.

The growing complexity of the systems we build, makes this paradigm more difficult to maintain. In a lot of disciplines, scientific reductionism still hampers new paradigms about safety and resilience. We need a return to holism as an additional paradigm (van Kleef & Stoop, 2014). We have reached a point in history where we are no longer designing systems, but systems of systems, that are closely coupled. These systems of systems have such a large complexity that it is no longer feasable to control them completely. The commissioner has, however, still an aim to get a system that has some preset properties. It is therefor not enough to manage the process and just to wait and see what will happen, and only looking upon the process.

In the design of infrastructural systems, a stratification in control can be seen. The top level decisions are political ones. Westerheijden (1988) showed, that these decisions are made almost without techological knowledge. The next centralized level, what could be called a engineering-strategic level, seems however to be missing. Different actors, each designing one system in a system of systems, can not be relied upon to self-coordinate their designs. In one form or another, the functionalities of the sub systems and their interrelations have to be looked upon in a holistic way, in order to control the emergent properties, that are of imminent importance to the commissioner. There seems to be a need of an engineering-strategic level. In former days, chief engineers could fulfil this function. The increased complexity of the systems co-incided with a decrease of high-level technological knowledge in commissioning organizations. Also the tools that are needed at a engineering-strategic level are missing.

Designing with a fear and greed objective under technological constraints as is frequently done now, faces us with the problem that these technological constraints has to be such, that they guarantee technologically sound solutions. If these technological constraints take the form of 'comply with standards', or 'comply with law', we are using legal formulations as a technological specification. The combinations do not guarantee resilient or sometimes even operational solutions. Making technological designs on a strategic level, using functional analysis, enables us to add specific constraints to the standards. It will even enable us, to make strategic decisions about where to use 'greed and fear' optimizations and where to use technological optimizations. Tools for the engineering-strategic level of design are still in the first stege of development. Functional analysis seems to be a promising approach.In this way, functional analysis is in no way replacing old methods, but is complementing them, enabling technology to retake its central position in complex design problems. This approach may be a seen as a first attempt to address the problem of sustained adaptability (Woods, 2014) during the design stage.

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