EVOLUTIONARY DYNAMICS OF DIGITIZED ORGANIZATIONAL ROUTINES

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ABSTRACT

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This dissertation explores the effects of increased digitization on the evolutionary dynamics of organizational routines. Do routines become more flexible, or more rigid, as the mix of digital technologies and human actors changes? What are the mechanisms that govern the evolution of routines? The dissertation theorizes about the effects of increased digitization on path dependence and interdependence mechanisms, and therefore extends current theory on the evolutionary dynamics of organizational routines by taking into account the effects of three basic phenomena: digitization, path dependence and interdependence.

In this dissertation, I use computer-based simulation, grounded with data collected in field interviews, to model the evolution of routines. More specifically, this dissertation models routines as networks of action that are subject to an evolutionary process of random variation and selective retention. To assess the evolution of routine, I introduce the idea of *evolutionary trajectory*, which is defined as the product of the *magnitude* of change and the *direction* of change in the networks of action.

The dissertation also addresses a foundational issue in the literature on organizational routines. Routines are generally believed to remain stable due to *path dependence*. An alternative explanation is that routines may be stable due to *interdependence* among actions, which tends to constrain the sequence in which actions can occur. I have developed a simulation that allows me

to test the relative importance of these factors, a question that has never been addressed. By addressing this fundamental issue, I provide a deeper, theory driven explanation of the effects of digitization.

Dedicated to my fiancée, Chaoyi Ding

Thank you for making our life fun, enjoyable and memorable.

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Chapter 1: Introduction

The goal of my dissertation is to build a better theory of the evolutionary dynamics of digitized organizational routines. Organizational routines are an integral part of organizations. They are important to understanding how organizations accomplish tasks and how organizational capabilities are accumulated and applied (Winter, 2003). Routines are usually seen as the building blocks of capabilities (Winter, 2003; Dosi et al., 2000), which in turn has been identified as one major source for sustainable competitive advantage (Barney, 1991; Teece et al., 1997; Pavlou and El Sawy, 2010). Nowadays organizational routines are becoming more digitized, as technologies for process support and management continue to flourish. Many organizational processes are virtualized (Overby, 2008) and digitized (Yoo et al., 2009). Digital technology like the workflow system literally takes actions (Pentland et al, 2012), more than just enabling and constraining routines (Orlikowski, 1992; Pentland and Feldman, 2005). Organizational capabilities, as routine bundles, also have a significant IT component (e.g., service-oriented architecture, new product development, financial services, marketing, etc.).

However, our theories of the change of digitized organizational routines are incomplete; and how routines contribute to organization change is still untapped (Becker and Lazaric, 2009). Organizational routines show a range of outcomes, from stability to change. On the one hand, it is common to equate the evolution of routine with “lock-in”, a total inflexibility of routine (Sydow et al 2009; Vergne and Durand, 2011). On the other hand, it is also not unusual to discover endogenous change in a routine like invoice processing (Pentland, Haerem and Hillison, 2011) or university housing routines (Feldman, 2000). The reason for these mixed findings may be the lack of good theory on routine change.

This dissertation explores the effects of increased digitization on the evolutionary dynamics of organizational routines. Do routines become more flexible, or more rigid, as the mix of digital technologies and human actors changes? What are the mechanisms that govern the evolution of routines? To answer these questions, this dissertation starts with the definition of organizational routines: "*repetitive*, *recognizable* patterns of *interdependent* actions, carried out by multiple actors" by Feldman and Pentland (2003: 93). This definition implicitly embodies two mechanisms that govern the evolution of organizational routines: (1) *path dependence*, the tendency of past actions to influence future actions within a routine, explains the repetitive and recognizable nature of routines and (2) *interdependence* among actions within routines, the extent to which one action is dependent on other actions within a routine, constrains the way actions can be combined. The dissertation theorizes about the effects of increased digitization on path dependence and interdependence mechanisms, and therefore extends current theory on the evolutionary dynamics of organizational routines by taking into account the effects of three basic phenomena: digitization, path dependence and interdependence.

This dissertation addresses four major research questions, each of which is developed in chapter four: 1) How does digitization influence the evolution of organizational routines? 2) How does interdependence among actions influence the evolution of organizational routines? 3) How does path dependence influence the evolution of organizational routines? 4) How does the complexity of routines influence the evolution of organizational routines? These are important questions in themselves, but also because organizational capabilities are based on organizational routines. Firms have sought digital artifacts to help them become reliable, flexible and responsive to environmental changes and competitions, they need to know how to govern the evolution of digitized organizational routine and manage the change of business process.

In this dissertation, I use computer-based simulation, grounded with data collected in field interviews, to model the evolution of routines. This dissertation extends a simulation model that I developed for a paper published in the *Journal of Management Studies* Special Issue on the Micro-foundations of Organizational Routines and Capabilities (Pentland, Feldman, Becker and Liu, 2012). More specifically, this dissertation models routines as networks of action that are subject to an evolutionary process of random variation and selective retention (Bickhard and Campbell, 2003). To assess the evolution of routine, I introduce the idea of *evolutionary trajectory*, which is defined as the product of the *magnitude* of change and the *direction* of change in the networks of action.

The dissertation also addresses a foundational issue in the literature on organizational routines. Routines are generally believed to remain stable due to *path dependence*. An alternative explanation is that routines may be stable due to *interdependence* among actions, which tends to constrain the sequence in which actions can occur. I have developed a simulation that allows me to test the relative importance of these factors, a question that has never been addressed. By addressing this fundamental issue, I provide a deeper, theory driven explanation of the effects of digitization.

After this introduction, chapter two is conceptualization of organizational routines, business processes and capabilities. Chapter three is about theories and phenomena on the evolution of routines. Chapter four develops propositions regarding the research question mentioned above. Chapter five is the overview of research method and simulation model. Details of empirical data collection are in chapter six. Results and analysis are in chapter seven. Finally, Contributions and limitations and conclusion are in the last chapter.

Chapter 2: Conceptualizing organizational routines, processes, and capabilities

This chapter's objective is to define key concepts such as routines, processes and capabilities and clarify the relationship between them. This chapter mentions business process, because business processes and organizational routines have very similar ideas, although they are different labels in IS literature and organization literature respectively. This chapter also reviews dynamic capability. I am choosing dynamic capability perspective because it fits well with theories of organizational routines (Winter, 2003). The idea of dynamic capability links changes in routines to larger organizational change (Zollo and Winter, 2002).

Section one reviews the definition and characteristics of organizational routines, and introduces the idea of action network, an operationalization of routines. Section two is concerned with organizational capabilities which are conceptualized as routine bundles (Winter, 2003). It concentrates on the distinction between dynamic and operational capabilities which can be conceptualized as the distinction between exploration and exploitation by March (1991). Section three reviews the definition of business processes. It clarifies the usage of “organizational routines” and “business processes”, two different labels used in organization literature and IS literature, respectively. Finally, section three also includes an example (service-oriented architecture) that shows relationship between digital technologies, routines and capabilities.

2.1 Organizational routines

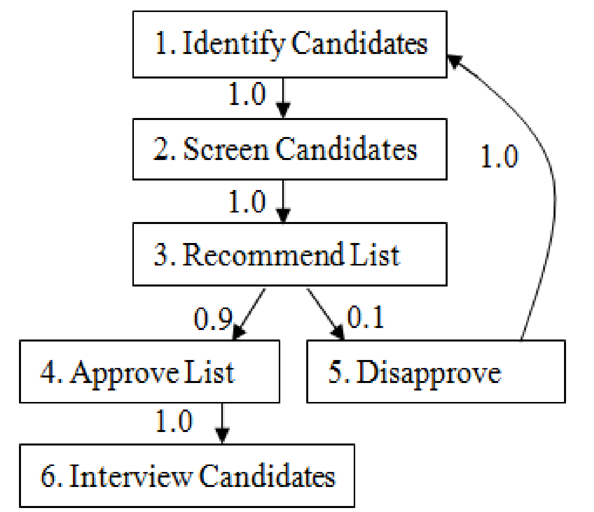
Organizational routines are defined as “repetitive, recognizable patterns of interdependent actions, carried out by multiple actors” by Feldman and Pentland (2003: 93). This definition has been widely adopted. (e.g. Goh et al., 2011; Dionysiou and Tsoukas, 2013). Organizational routine can be conceptualized as having two levels that are recursively related: a concrete level and an abstract level (Feldman and Pentland, 2003). The concrete level is specific performances or patterns of actions, evoked from the abstract level. One specific performance includes realized instances of action, actors, time and place (Pentland et al, 2011). The abstract level shapes these specific concrete performances (Becker, 2004, 2005; D'Adderio, 2008; Feldman and Pentland, 2003; Pentland and Feldman, 2008; Howard-Grenville, 2005; Hodgson, 2008).

Organizational routines can be operationalized as action networks (Pentland et al., 2010, 2011), as patterns of actions are an essential feature and the most observable aspect of organization routine (Pentland, 1999; Pentland et al., 2011). In an action network, nodes are abstract actions, and ties represent sequential relationships between actions. Action refers to a step in a routine to accomplish an organizational task; and tie shows the order among actions. Actions and the sequence of actions constitute the action network that represents a routine (Pentland et al, 2011). When a network of action is represented as a matrix, the elements in the matrix, a_{ij}, express conditional probabilities that one action a_j will occur, given that another action a_i has occurred. Pentland et al. (2012) refer to this as the "history" matrix or transition matrix (More details of transition matrix is in chapter 5.1). Unlike a social network, nodes in a network of actions can be self-connected ($a_{ii} \neq 0$ means that an action can occur twice in a row).

To illustrate this concept, consider the routine for developing and approving a pool of candidates for a faculty position.[1] We can represent this portion of the routine using a network of action, as shown in Figure 1. On the left, the network of action is represented as a directed graph (like a flow chart). This portion of the routine begins with "identify candidates", which is always followed by "screen candidates". The result of this is a list of candidates, which is

[1] In the full hiring process, there would be many actions upstream and downstream.

submitted to the Provost's office for approval. At this point there is a branch in the network: the list can be approved or disapproved. If approved (which occurs 90% of the time, according to the probability in the matrix on the right), then the candidates are interviewed. If disapproved (which occurs 10% of the time), the department must go back and identify additional candidates. On the right, the action network is summarized as a matrix. The accumulated history of past sequences, in this case, is modeled as a 6 x 6 transition matrix.



	1	2	3	4	5	6
1	0	1	0	0	0	0
2	0	0	1	0	0	0
3	0	0	0	.9	.1	0
4	0	0	0	0	0	1
5	1	0	0	0	0	0
6	0	0	0	0	0	0

Figure 1: An action network for part of the academic hiring routine

A network of action is a convenient way to represent what Cohen (2007:781) calls "pattern-in-variety." A network of action can display many different performances depending on specific path through which a performance goes. The matrix can be used to generate sequences by simply tracing through the entries implied by the conditional probabilities. In this way, a network of action represents both the actual and potential patterns of action that could occur within a routine.

Different networks of action have different structure. By *structure*, this dissertation means the number of branches and loops in the network of action that describes the routine. *Branches* mean there is more than one choice of action to go forward. *Loops* mean the process can go back to a previously occurring action. Intuitively, the total number of branches and loops, which equals to the total number of non-zero entries in the matrix, provides an index of the *complexity* of routine. If a routine has few branches and/or loops, it is simple. If a routine has many branches and/or loops, it is complex. The complexity of a routine can be indexed by the density of the network of actions (Pentland, 1999).

The transition matrix has a simple practical interpretation. Entries in the upper right triangle (above the diagonal) represent branches if they are not equal to zero or one. For example, within a given row, if there are two non-zero numbers (0, 0, 0.8, 0, 0.2), then there is an 80% chance of action #3, a 20% chance of action #5, and no chance of the other actions. Likewise, any non-zero entry in the lower left half (including the diagonal) represents a loop, where the process can loop back to a previously occurring action.

2.2 Organizational capabilities

Since organizational capabilities are viewed as routine bundles, this section reviews organizational capabilities. Prior research has defined different kinds of capabilities. An organizational capability, whether operational or dynamic, is the ability to perform a particular task or activity (Helfat et al., 2007). The distinction between operational and dynamic capabilities parallels the distinction between routine in steady state and routine contributing to change (Helfat et al., 2007). Operational capabilities enable an organization to earn a living in the present (Winter, 2003). In contrast, dynamic capabilities concern change.

Operational capabilities are conceptualized as a collection of routines (Nelson and Winter, 1982; Collis, 1994; Barney, 1992; Teece et al., 1997; Dosi et al., 2000; Winter 2003). Routines are also the basis for dynamic capabilities (Teece et al, 1997; Winter, 2003). A collection of operating routines constitutes operational capabilities. The development and adaptation of operating routines are directed by higher level routines (meta-routines) usually referred to as dynamic capabilities (Zollo and Winter, 2002; Winter, 2003). One common thing about operational and dynamic capabilities is that the set of actions need to be planned, collective, patterned, and purposeful (Winter, 2003).

However, operational capabilities and dynamic capabilities are fundamentally at odds (Schreyögg and Kliesch-Eberl, 2007). The distinction between operational and dynamic capabilities can also be understood in terms of March's (1991) distinction between exploration and exploitation. Operational capabilities contribute to exploitation, because operation capabilities emphasize the implementation and refinement of existing competences, technologies, and paradigms; whereas dynamic capabilities contribute to exploration, because dynamic capabilities concentrate on the discovery and experimentation of new alternatives. Exploitation's returns are more predictable and greater than exploration's returns in the short run, which lead to a tendency to substitute exploitation for exploration (March, 1991). Therefore, it is not easy to be "ambidextrous" (O'Reilly and Tushman, 2004) and pursue exploration and exploitation simultaneously.

Operational capabilities usually refer to habitual action patterns (Schreyögg and Kliesch-Eberl, 2007). Operational capabilities need to be stable, reliable, and reproducible. Due to path dependence, structural inertia and commitment, operational capabilities may have narrowing scope of strategic paths and may lose flexibility and develop rigidity (Schreyögg and Kliesch-Eberl, 2007). Sometimes, operational capabilities might be locked in at a few paths.

Dynamic capabilities refer to capabilities to update capabilities (Teece et al., 1997). As Zollo and Winter (2002) defines, dynamic capabilities is “a learned and stable pattern of collective activity through which the organization systematically generates and modifies its operating routines in pursuit of improved effectiveness.” Dynamic capabilities, which associate with change (Winter, 2003), can adapt, integrate, and reconfigure clusters of resources and operational capabilities to match requirements of a changing environment (Teece, 1997). To cope with environment changes, strategic paths a firm takes could be different from the past. Due to the path-making strategic logic (Eisenhardt and Martin, 2000), dynamic capabilities can broaden scope of strategic paths and break rigidity of operational capabilities.

Operational capability and dynamic capability also have different reactions to environmental dynamism and the degree of capability heterogeneity. Environmental dynamism negatively affects the contribution of operational capabilities and positively affects the contribution of dynamic capabilities to firm performance (Drnevich, and Kriauciunas, 2011). Capability heterogeneity strengthens the contribution of dynamic capabilities to firm performance, but is less important for operational capabilities.

Dynamic capabilities serve two main functions: search and selection; and deployment (Helfat et al., 2007). An example of dynamic capability (meta-routine) is variation and selective retention mechanism which has been applied to many organizational phenomena (Pentland, et al., 2011; Zollo and Winter, 2000). Evolutionary theories have been proposed where organizations evolve by variation and selective retention of whole routines. More detailed review on variation and selective retention is in chapter three. Another example is BPM. Business process management (BPM) is supported by BPM software that makes it possible to model, assemble, deploy and monitor a wide array of business processes across the enterprise (Papazoglou and van den Heuvel, 2007). Other examples also include new product development (NPD), new process development, which are all technology driven (Winter, 2003, Pavlou and El Sawy, 2006, 2010; McAfee and Brynjolfsson, 2008).

2.3 Business processes

Organizational routines and business processes are key terms in organization literature and IS literature respectively. Though they have different labels, the ideas are very similar. In this dissertation, organizational routines and business processes are interchangeable, but the term of organizational routine is used most of the time. This section of dissertation reviews definitions, conceptualization and features of business process.

A business process is defined as “the specific ordering of work activities across time and place, with a beginning, an end, and clearly identified input and output” (Davenport, 1993: 5). A business process is a set of logically related tasks performed to achieve a defined business outcome (Hammer, 1990). The tasks used to realize a process under a particular set of conditions is defined as a workflow (Basu and Blanning, 2000).

A process may include several alternative workflows (Basu and Blanning, 2003). So business processes can be conceptualized as generative structures that can produce a wide variety of different patterns or sequences of actions (Fararo and Skvoretz, 1984, Pentland, 2003). For any particular process, there may be several ways of accomplishing it, depending on variations in inputs (Malone et al. 1999). This distinction between a business process and a workflow parallels the distinction between the abstract level and the concrete level of organizational routine.

	Exploitation	Exploration
Capability	Operational Capability (routine bundles)	Dynamic Capability
Routine	Operating Routine	Meta-routine
Process	Business Process	Business Process Management

Table 1: Business process, organizational routines and capabilities

The relationship between organizational routines, processes and capabilities is summarized in Table 1. Operational capability is routine/process bundles; meta-routine and business process management are two types of dynamic capability. Service-oriented architecture (SOA) is an example that shows the relationship. SOA (Papazoglou and Georgakopoulos, 2003) has made it possible to transform a firm from a collection of proprietary software where activities could not be easily shared across processes or business into a collection of "plug-and-play" activities where function can be shared over the internet as web services. These technologies are already in wide use (e.g., every time people use their laptop to track the delivery status of their letters or goods). In the technological literature and in practice, the business service or web service is a fine-grained business process such as updating inventory and check availability, and so on.

SOA's greatest value lies in the opportunity to create much more focused, efficient, and flexible organizational structures, because It is becoming possible to design many business activities as Lego-like software components that can be easily recombined and taken apart (Merrifield et al., 2008). More specifically, the technology first makes it possible to encode identifiable, repetitive work processes into modular, re-usable "services" or web-services (Pentland et al., 2012). Each service that makes up an SOA application is very independent and well-defined. Firms can reuse those services from a variety of sources in new ways, and recombine them into flexible, dynamically reconfigurable organizational capabilities. Finally, their underlying software or electronic user interface allows the activity to be turned into a web service (Merrifield et al, 2008).

For example, Delta Airlines is using SOA to reduce the cost of running many computer systems and applications and achieve flexibility. Delta used to have separate databases and different software across a range of systems such as ticketing kiosks, ticketing counters and gate systems (McKendrick, 2008). After more than a decade's effort on SOA, Delta nowadays uses standards such as SOAP over HTTP to reuse the same customer data from all the different systems (McKendrick, 2008). Delta also offers many services to its vendors and partners.

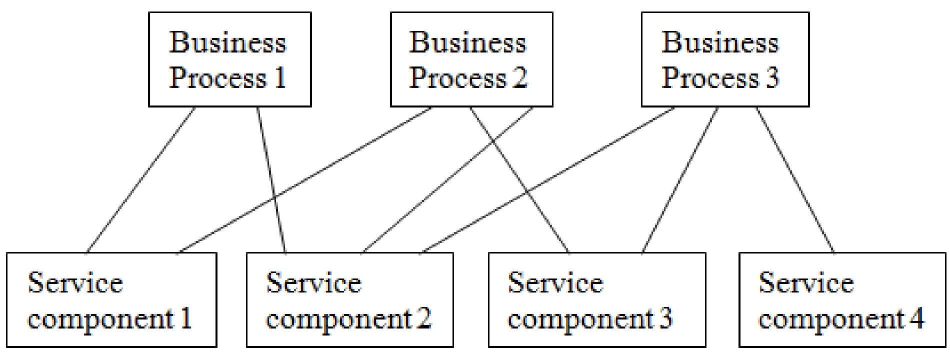


Figure 2: An example of SOA

As shown in Figure 2, SOA allows recombination of different service component to provide different services. Service component could include create invoice, check credit history, check flight status, and so on, and business process could be ordering processing, account management and so on.

This chapter introduces action network, history matrix, and branches and loops (complexity of routine), as a way to describe organizational routines. In the next chapter, I use these concepts and introduce variation and selective retention process and different types of trajectory model.

Chapter 3: Trajectories of routine evolution

This chapter introduces the evolutionary process of random variation and selective retention (VSR), and proposes a new measure, evolutionary trajectory, to access the evolution of organizational routines. Section one introduces the evolutionary process of random variation and selective retention, which is one way to model dynamic capabilities (Teece and Pisano, 1994; Zollo and Winter, 2002). VSR incorporates both path dependence and interdependence mechanism. More detailed discussion on path dependence and interdependence is in chapter four. Section two explains evolutionary trajectory and discusses four different kinds of trajectory.

3.1 Evolutionary process of random variation and selective retention

VSR has been widely used in social and biological science (Bickhard and Campbell, 2003; Weick, 1979). Zollo and Winter (2002) used VSR as a theoretical model to explain changes in organizational capabilities and routines. Their model relied on the variation, selection and retention of knowledge. Here, I provide a more precise model of variation and retention of action patterns within routines, as hypothesized by Feldman and Pentland (2003). This allows me to simulate and theorize about the evolution of routines.

Networks of action can be used to model the dynamics of a routine by adding a process of variation and selective retention (Pentland et al., 2012). This dissertation models the evolution of routine as a process of variation and selective retention. It is illuminating to try to understand routine change over time as being driven by a process involving variation, selection, and retention (Nelson, 2009).

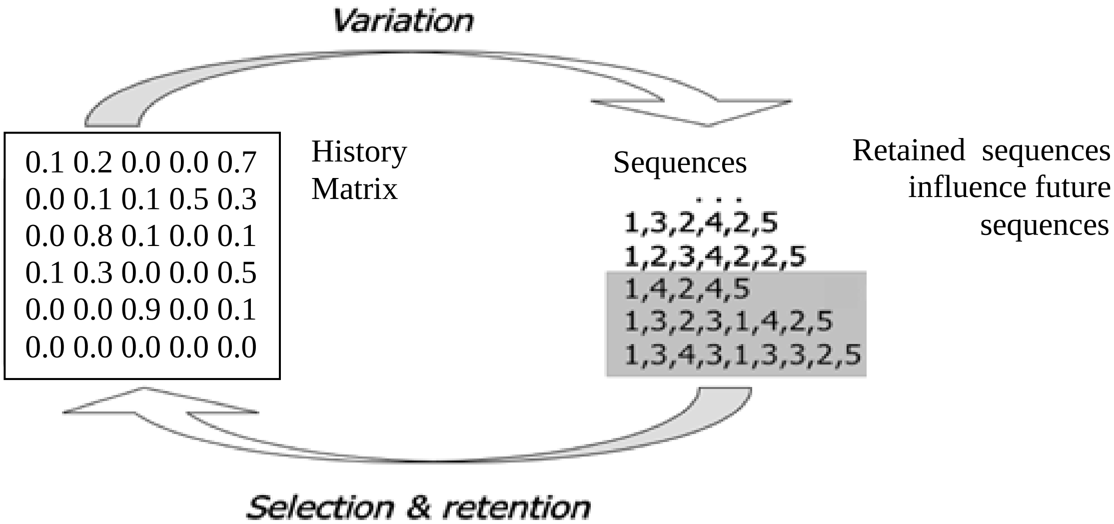


Figure 3: Variation, Selection and Retention of Action Patterns

Sequences of action can be summarized into a matrix, as shown in Figure 3. Pentland et al. (2012) refer to this as the "history" matrix or transition matrix. The matrix can be used to generate sequences by simply tracing through the branches and loops implied by the conditional probabilities.

More specifically, the variation and selective retention of action patterns are captured in an action network. Each new performance depends, to some extent, on the history of prior performances (shaded area in Figure 3). These performances might include some level of random or deliberate variation. After they are carried out, some sequences may be selectively retained and reproduced via the action network. As hypothesized by Feldman and Pentland (2003), the performances of a routine may be subject to random variation and selective retention:

> "the relationship between ostensive and performative aspects of routines creates an on-going opportunity for variation, selection, and retention of new practices and patterns of action within routines and allows routines to generate a wide range of outcomes, from apparent stability to considerable change."

Variation can be seen as a core mechanism for search. Natural evolutionary processes rely on random variation, but business organizations usually try to plan variations, and variations sometimes are in human minds and is explored through analysis, discussion and argument (Nelson, 2009). Variations can occur because of error, improvisation, innovation, exceptions, learning, or some recombination (Salvato, 2009). However, if there is no variation, and retention is the only mechanism operating, an organizational routine will eventually lock into a fixed pattern (Pentland et al., 2012; Sydow et al., 2009).

This dissertation extends the work by Pentland et al. (2012) by adding recombination or improvisation as one of the key variation mechanism[2]. By breaking processes down into reusable pieces (actions), there exists a repertoire of actions to assemble (like Lego blocks). As in the example mentioned in previous chapter, rather than rewriting all the programming codes, Delta can reuse or recombine these basic services in many different ways to adapt an old service or create a new service quickly to changing needs. More specifically, a process component (actions) can be added, deleted or replaced with other components. It could impact all the performance that has these components. By definition, recombination involves the repertoire of actions, so it exemplifies a kind of global search.

3.2 Evolutionary trajectory of organizational routines

It has been hypothesized that organizational routines go through a simple life cycle that consists of three stages, such as preformation, formation and lock-in (Sydow et al., 2009), as shown on the left side of Figure 4. Due to path dependence of actions within the routine, these patterns will tend to be self-reinforcing (Vergne and Durand, 2010), as frequent patterns become

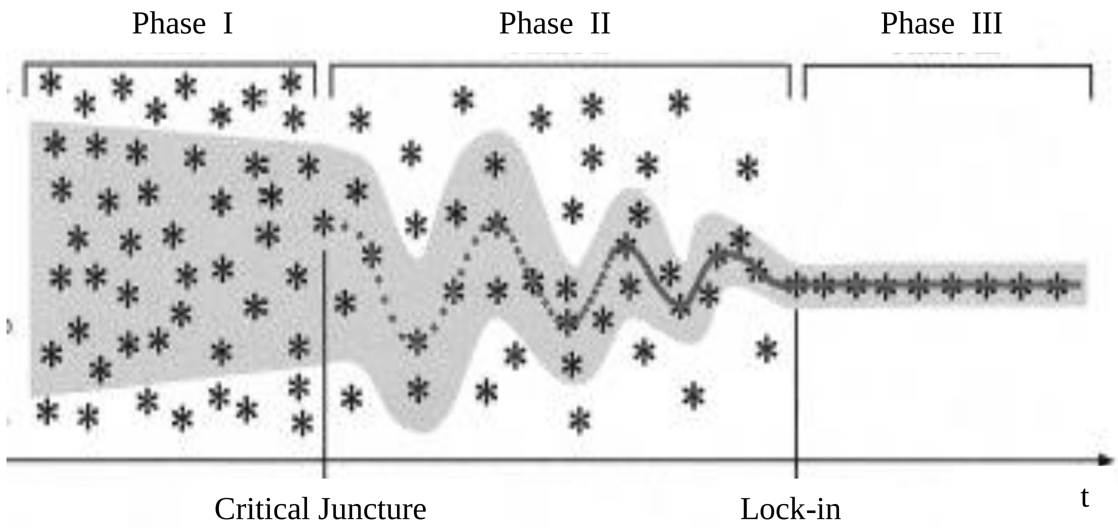
[2] Improvisation is the first-time recombination, and it may or may not involve new actions; however recombination usually only needs existing actions.

more strongly engrained in memory (Schulz, 2008). In this view, the direction of change is expected to progress from relatively complex to relatively simple (from non-routine to routine). Following this line of reasoning to its logical conclusion has led some observers to equate routinization with "lock-in" (Sydow et al., 2009). To the extent that routines are truly locked-in to fixed patterns of action, it might make sense to treat them as unchanging objects, like atoms or genes (Nelson and Winter, 1982; Baum and Singh, 1994; Aldrich, 1999).

However, observational fieldwork on routines tells a somewhat different story. While some routines clearly express stable patterns, others create patterns with a lot of variety (Pentland and Reuter, 1994; Egidi and Narduzzo, 1997; Rerup and Feldman, 2011). Routines have been observed to exhibit changing patterns of action, even in settings where the context is quite stable. For example, Feldman (2000) observed this in university housing routines; Pentland et al. (2011) observed endogenous change over a five month period in invoice processing routines used by four Norwegian companies.

Thus, an alternative hypothesis is that variations within a routine can lead to new patterns of action if those variations are retained (Garud et al., 2010; Rerup and Feldman, 2011). Variations can occur for many reasons; they can be deliberate or accidental. This hypothesis is consistent with the notion of path dependence, but it allows for the offsetting effects of variation and retention to determine the trajectory of the routine. I refer to this as the trajectory model. Rather than having a life-cycle that consists of a one-way transition from disorder to lock-in, the trajectory model suggests that routines may increase or decrease in complexity over time, as shown on the right side of Figure 4. The tendency for routines to increase in complexity can be seen whenever a new procedure or control is added to account for a new perceived risk (e.g., credit card payment systems or airport security procedures).

Life cycle view: Retention leads to lock-in



Adapted from (Sydow et al., 2009)

Trajectory view: On-going process evolution

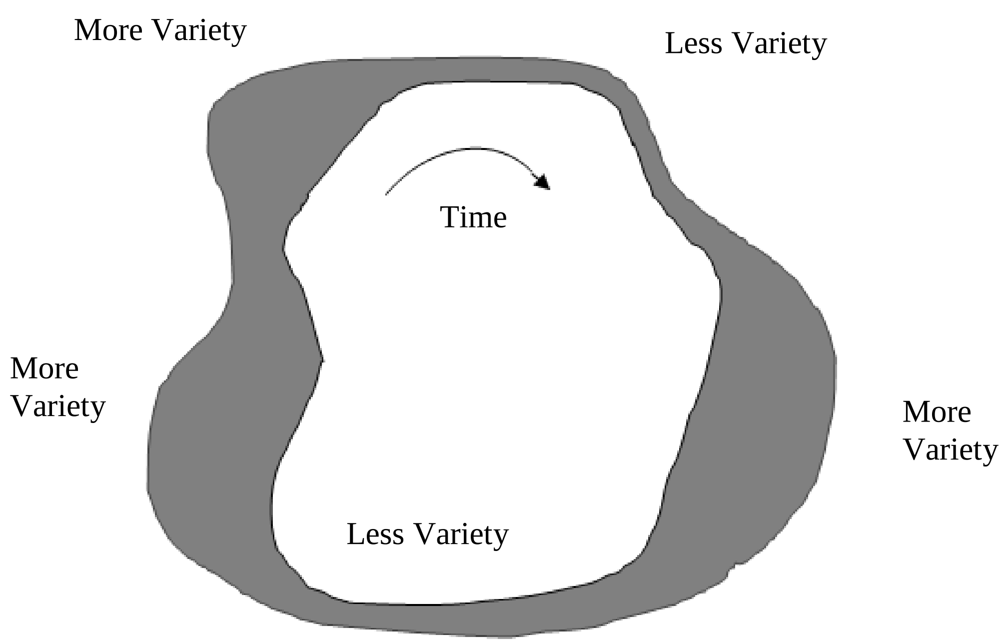


Figure 4: Life cycle view vs. trajectory view

While there is a great deal of interest in the dynamics of organizational routines, we currently have no precise way to describe (much less predict or explain) their change over time. If we look in other disciplines, there are many measures and methods. For example, in biology, DNA-fingerprint similarity, the average percentage of shared restriction fragments in the fingerprint profile, is being used to make inferences about levels of genetic variation within and between natural populations (Lynch, 1990). Longitudinal analysis techniques such as latent growth curve modeling (Singer and Willett, 2003) are being used to study growth or change over a period of time. However, these measures or methods don't directly apply to the matrix based representation of an action network. The change of routine is not just change over time of a single scalar variable, which would be the easiest case. Here, we use a matrix to represent the process at one point in time. Different representations of the phenomena need different measures. See table 2 for example of change measures.

Phenomenon Discipline	Representation	Metrics of change
Biology	DNA-fingerprint similarity	Percentage
Economics	GDP	Percentage
Education	Student performance	Slope
Business	Organizational routine	Distance (matrix)

Table 2: Examples of change measures

To assess the *evolutionary trajectory* of a routine, we can measure the magnitude and direction of change, as trajectory is defined as the product of the magnitude of change and the direction of change. The network of action (defined in next section) provides a convenient way to represent the *magnitude and direction of change*.

- The *magnitude of change* can be computed by comparing the network of action at two points in time. Any method for computing the distance between two matrices is potentially feasible. There are several metrics available for this comparison, including Euclidean distance, Hamming distance (Hamming 1950, 1986) and matrix correlation using Quadratic Assignment Procedure (Hubert and Schultz, 1976).

- The *direction of change* indicates whether the routine is moving towards lock-in (complexity is decreasing) or away from lock-in (complexity is increasing) or not changing in complexity (complexity-neutral frontier). In the above three scenarios, the direction of change is negative one, positive one or zero, respectively.

Table 3 identifies four idealized cases that can occur within the trajectory model. The first dimension of Table 3 is the main driver of evolution: variation or retention. The second dimension is the structure of routine: simple or complex. Each of these idealized trajectories can be characterized in terms of the magnitude of change and direction of change.

On one diagonal of Table 3, we find the extreme cases where the trajectory is either “fully locked-in” or “non-routine.” When a routine is fully locked in, the trajectory is characterized by a lack of change. This is most likely when the current structure is relatively simple and retention is dominant. There might be variations, but they do not influence future actions. At the other extreme, the current structure of the routine is complex and variation is dominant. Trajectories in this quadrant might fail to meet the definition of a routine because the patterns of action might not be recognizable as instances of the same routine. Here, the magnitude of change is small and direction of change is neutral.

<table>
<tr><td colspan="2"></td><td>Simple Routine Structure</td><td>Complex Routine Structure</td></tr>
<tr><td rowspan="2">Main Driver of Evolution</td><td>Variation</td><td>Complexity-increasing

Magnitude =small/ large
Direction = increasing</td><td>Non-routine

Magnitude = small
Direction = neutral</td></tr>
<tr><td>Selective Retention</td><td>Fully Locked-in

Magnitude = none
Direction = neutral</td><td>Complexity-decreasing

Magnitude = small/large
Direction = decreasing</td></tr>
</table>

Table 3: Four kinds of trajectories

On the other diagonal of Table 3, we have trajectories where complexity is either increasing or decreasing. The complexity of a routine will tend to increase when the current structure of the routine is simple, and variation is dominant. The complexity of a routine will tend to decrease when the current structure of the routine is complex, and retention is dominant. Here, the magnitude of change could be large or small, depending on the effects of variation and retention.

To develop a more general theory, I would like to predict the conditions under which each trajectory is likely to occur. I can predict the magnitude and direction of change independently or the evolutionary trajectory in general, based on the current complexity, variation and retention.

Causal variable	Magnitude of change	Direction of change
Complexity	--	--
Variation	+	+
Retention	--	--

Table 4: Predicted first order effects of complexity, variation and retention

The predicted first order effects of complexity, variation and retention are summarized in Table 4. Complexity of routine has a negative effect on the evolutionary trajectory, as it is hard (costly) to maintain a complex routine. A routine tends to become simpler and lose variety over time unless there is control mechanism or the routine is already fully “locked in” or automated. Realistically, routines contain a few branches and a few loops. From the empirical data I collected (see chapter 6 for more details), a typical organizational routine has 6 branches and 2 loops. As discussed early in this chapter, variation and retention have offsetting effects on the evolutionary trajectory. Variation contributes to change or “path breaking”, while retention can explain stability or “path dependence”.

In a real routine, the effects of these factors can interact with each other. In the next chapter, I will offer propositions about their interactions. On the basis of the general conceptual model introduced in this chapter, I can begin to examine the research questions of this dissertation. I will also offer several propositions regarding the four factors that are important to the evolution process: digitization, organizational path dependence, interdependence among actions, and the complexity of routines.

Chapter 4: Evolutionary dynamics of organizational routines

This chapter introduces four fundamental factors that might contribute to the evolutionary dynamics of organizational routines: digitization, organizational path dependence, interdependence among actions, and the complexity of routines. Routines are generally believed to remain stable due to path dependence. Path dependence is a fundamental factor that governs the routinization process and leads to routines stability (Schulz, 2008). However, interdependence has been neglected in literature on routine, although interdependence is part of the definition of routine by Feldman and Pentland (2003). So an alternative explanation for routine stability is that routines may be stable due to *interdependence* among actions. As biological complexity is important in biological evolution (Adami et al., 2000), routine complexity is expected to play a role in routine evolution. Finally, digitization is the focus here, because it affects the other three factors.

Although this dissertation consider all above four factors, it is still an abstract and general model. It deliberately chooses to exclude situational specific features, such as human resources or environmental shocks that could be relevant in real routines. In this chapter, each section reviews theory around one research question and develops some specific propositions. The four research questions are:

- How does digitization influence the evolution of organizational routines?
- How does organizational path dependence influence the evolution of routines?
- How does interdependence among actions influence the evolution of routines?
- How does the complexity of routines influence the evolution of routines?

Section 4.1 theorizes about the effects of digitization on routines. Digitization influences path dependence and interdependence mechanisms which govern the evolution of routines. Section 4.2 introduces key elements of organizational path dependence, understood as a process of variation and retention in the VSR framework by Bickhard and Campbell (2003). The changes of organizational routine are often cited as a path dependent phenomenon (Schulz, 2008; Vergne and Durand, 2010; Driel and Dolfsma, 2009; Sterman and Wittenberg, 1999). In my dissertation, path dependence means the tendency of past actions to influence future actions within a routine.

Apart from path dependence, there is another mechanism: interdependence, understood as a type of selection in VSR. Interdependence among actions enables and constrains the actions and patterns of actions and shows the constructive nature of routine. For example, some actions depend on the occurrence of other action just like people need to cook before they eat. Section 4.3 concentrates on two kinds of interdependence: structural and functional. Finally, the last section concerns with the complexity of organizational routines. Different routines have different complexity, some are simple some are complex.

4.1 Digitization and digital intensity

Real routines are usually carried out by a mix of human and non-human actants, such as digital artifacts. Digital artifacts can be defined generally as software-based information technology (Bailey et al., 2010). Leonardi (2010) has noted, routines and technologies are usually so closely imbricated that you cannot observe one without observing the other. Digitization usually means a process of applying digital artifacts (Tilson et al., 2010). To make it compatible with the routine context, *digitization* in this dissertation simply refers to the fact that some of the actions within a routine are carried out by digital artifacts or people using digital artifacts. The degree of digitization is *digital intensity*, the percentage of actions within a routine supported by digital technologies (or people using digital technologies). Originally, digital intensity means the proportion of digital tools used in the routine to total tools used in the routine (Gaskin et al., 2012). In my dissertation, since I use action network, digital intensity measures actions, namely what people do or what technologies do or what people use technologies to do, rather than actors like people or technologies.

Digitization can have different meanings. If the actions are purely carried out by digital technology: "email server sends out and receives emails" or "system updates itself", digitization simply means automation. When people are involved, this dissertation categorizes three ways how people can interact with digital technologies: parallel, technology-first and people-first. Parallel type means people use digital technology as a tool, and the action neither consumes nor produces any digital resources. For example, people review digital documents. The review action doesn't change the digital documents; no new digital content is consumed or generated.

The second type is technology-first which means people consume digital content/information generated by digital tools. For example, Outlook can generate meeting or events reminders, and some newly built cars can generate a warning sign when the gas level is low. In these cases, people consume or are informed by the digital content/information from digital technology. The third type is people-first type meaning people generate/produce more digital content. For example, people can update database, and enter new data into a spreadsheet. The three types of people-digital technology relationship are not mutually exclusive. One action can have one type or more types, and the more types an action has, the higher digital level the action is.

There are many ways that digitization influence action patterns of a routine. Intuitively, digitization influences the size of the choice set of a routine[3]. Some digital technologies can create new actions, and therefore could increase the size of the choice set (e.g., online search for information, video conference). Some other digital technologies can remove old actions and therefore decrease the size of choice set (e.g., distributing documents to offices). If the choice set is changed by digitization, the patterns of actions generated by the choice set are also influenced by digitization. Therefore, digitization changes the patterns of action of a routine through changing the choice set of the routine. When the choice set is getting larger, there are more possible ways to combine the actions into a performance. Therefore the performances tend to have more actions and more variations in the patterns of actions. Conversely, smaller choice set will generate fewer actions and fewer variations. These kinds of change are very important, however, they are beyond the scope of this dissertation. I concentrate on the effects of digitization assuming the choice set is constant.

Automation is also a type of digitization. When digital technologies are used to fully automate a routine, they can greatly reduce variations in performances (Pentland and Feldman, 2008). An automated process is highly stable reliable, predictable and efficient, which is a perfect example of a "locked-in" routine. This dissertation doesn't investigate the effect of total automation, rather it examines routines that are carried out by a mix of human and digital artifacts.

This dissertation is also interested in the concept of restrictiveness to understand the relationship between digital intensity and the evolution of routine. Restrictiveness refers to the degree to which and the manner in which digital technologies limit its user's processes to a

[3] Choice set means the number of actions available in a routine. It is further defined and operationalized in Chapter 5.1.

subset of all possible processes (Silver, 1988, 1990). A technology is highly restrictive if the number of technology-supported processes is small relative to the number of possible processes. This view holds that the degree of restrictiveness is innate to the technology. The restrictiveness effect offsets the effect of variations in actions. When the variation level is very low due to restrictiveness of digital technologies, the routine will quickly move towards lock-in and then stay on track.

Digital technologies can not only influence the variation level of a routine, but also the retention level. In people private lives as well as professional roles, digital technologies can help people track the history of events. For example, order taking systems in restaurants can remember the past transactions; Outlook can remember the email we received and sent. So the digitization increases the level of retention by supporting individual and organizational memory. When retention level is high, the variations in the action patterns can be retained and maintained. Therefore, digital technologies influence routines because of their effect on *path dependence* mechanism of routine (more detailed review on path dependence mechanism is in section 4.2). The higher the percentage of actions that are carried out by digital technologies, the higher the restrictiveness effect, the more rigid the routine is.

Proposition 1: *The higher the level of digital intensity, the smaller the magnitude of change from one period to the next*.

Recently, researchers have sought to bring materiality and artifacts into the study of organizations in general (Orlikowski, 2007; Orlikowski and Scott, 2008; Leonardi, et al., 2013) and routines in particular (D'Adderio, 2010; Robey et al., 2013). Artifacts in routines include written rules, standard operating procedures, and digital technologies (Lazaric and Denis, 2001; Pentland and Feldman, 2008). Artifactual representations of routines are important constituents of routines (D'Adderio, 2010), as some routines cannot be performed without the artifact's presence (Robey et al., 2013). Digital technologies can be embedded through an organizational work processes, and they are used to coordinate interdependent actions (Robey et al., 2013).

The connection between digital technologies and action is often conceptualized in terms of affordance, enablement or constraint (Norman, 1988; Robey et al., 2013). This concept applies most readily to particular actions or steps in a routine. For example, a hammer enables the driving of nails, a saw enables cutting of wood, and a tape measure enables accurate measurement. However, the presence of these tools (hammer, saw, tape measure) does not necessarily enable a well-coordinated construction project.

Robey et al (2013) argue that affordance is an inherently a relational concept: the affordance (or enablement or constraint) exists in the relationship between the artifact and a particular action or type of action in a particular context. Interdependence is also an inherently relational concept, but it exists in the relationship between two or more activities (Malone and Crowston, 1994). While it is useful to understand the relationship between artifacts and particular actions, I am interested in the relationship between artifacts and patterns of actions.

Towards that end, I hypothesize that digital technologies influence routines because of their effect on interdependence between the actions. This can occur via two distinct mechanisms. First, digital technologies can influence which patterns of action are possible. Second, they can influence which patterns of action are preferable. I discuss these mechanisms in the following sections. More detailed review on interdependence dependence mechanism is in section 4.3.

4.2 Organizational path dependence

Since digitization can affect organizational path dependence, this section concentrates on path dependence mechanism. There are two types of path dependence in organizational routine:

Path dependence between performances and path dependence within a performance (Schulz, 2008; Pentland et al., 2012). Path dependence within a performance can be modeled using a transition matrix comprised of conditional probabilities. As mentioned in chapter two, the conditional probabilities capture the tendencies of one action to be followed by another specific action. Each conditional probability also expresses the actual and potential performances that could be generated by the routine (Pentland and Feldman, 2007). When there is no history, all actions are equally likely. "The transition matrix can be thought of as a summary of the directly observable sequences of action generated by a routine. It is a record of the history." (Pentland et al., 2012)

In the path dependence between performances, each new performance or pattern of actions depends, to some extent, on the history of prior performances. Path dependence mechanism is represented by variation and retention in the VSR framework. For example, in preformation stage in the life-cycle view, variation is dominant force of evolution; in formation stage and "lock-in" stage, selective retention is playing the major role. Variation and retention have opposing first order effects. Variation has positive effect on the magnitude of change, while retention has negative effect on the magnitude of change. More variation leads to complexity increase, more retention leads to complexity decrease. If variation is like the accelerator, retention is like the brakes. When retention is high, it slows the rate of change because larger numbers of performances are averaged together; any particular performance has less influence. At the opposite extreme, we expect that very low values for retention (R=1) will quickly lead to low complexity. This is because the history matrix will encode only the single most recent performance. Low retention is like low inertia; when a variation occurs, it has greater influence, so the potential magnitude of change is larger.

Of course, in real world, these factors interact to influence the trajectory of the routine. The interaction between variation (accelerator) and retention (brake) can influence the magnitude and direction of change. If we only consider variation, magnitude of change is large and direction of change is complexity increasing when variation is large. When we introduce greater retention, a stronger "braking effect" should lead to a smaller the magnitude of change, making is less likely that complexity will increase.

Proposition 2: *The effect of variation on the evolutionary trajectory is moderated by retention, such that the effect is stronger for higher retention levels.*

The trajectory of a routine is determined by the offsetting effects of retention and variation. In other words, a routine may be continuously evolving, but its trajectory may not reveal any increase or decrease in complexity, which is referred to as complexity-neutral frontier.

Proposition 3: *Balanced effects of variation and retention can lead to no change in direction (complexity-neutral frontier).*

4.3 Interdependence among actions

Since digitization can affect interdependence, this section concentrates on the interdependence phenomenon, which is very common in organizations. In their paper, Malone et al. (1999) identified three basic types of dependencies among activities: flow, fit and sharing. Flow dependencies mean one activity produce a resource that is used by another activity (Malone et al., 1999). Flow dependencies reflect the *order or sequence* of actions. Fit dependencies arise when multiple activities collectively produce a single resource (Malone et al., 1999). Two actions in fit dependencies could happen simultaneously or not, but new action follows when these two actions finish. Sharing dependencies happen when multiple activities all use the same resource (Malone et al., 1999). Sharing dependencies are like the inverse twin of fit dependencies. Any other dependencies can be analyzed as specializations or combinations of those three types. These dependencies are used to classify organizational processes.

In organizational theory, Thompson identified three kinds of interdependence between two actors or organizational units: sequential, pooled, and reciprocal (Thompson, 1967). In sequential interdependence, one department must act properly before another department can act (Thompson, 1967). Sequential interdependence reflects order or sequence of actors when performing organizational tasks. In pooled interdependence, unless each of two departments performs adequately, the total organization is influenced (Thompson, 1967). Reciprocal interdependence refers to the situation in which the outputs of each department are the inputs for the other department (Thompson, 1967).

Interdependence between actions introduces a kind of selection in the VSR framework, which involves evaluating the outcomes of a particular iteration or variation. Therefore, interdependence provides the selection criteria that guide the evolutionary process. In real routines, selection can come from individual actors performing actions within routine (Pentland et al., 2012) and from managers monitoring the routine (Vergne and Durand, 2011). There are two types of interdependence in this dissertation. Structural interdependence means some actions depend on the occurrence of other action, and functional interdependence means some action's benefits to organization depend on some other actions.

Structural interdependence captures the fact that some actions must occur before others, physically or logically. It shows the structural feature of organization routines. Structural interdependence has similar meaning to Thompson's (1967) concept of sequential interdependence, however sequential interdependence concentrates on actors (organizational units). Here, structural interdependence applies to the actions that occur within routines.

Structural interdependence means some actions must happen before some other actions. It defines what sequences of action are *possible*. For example, when using an online bank, customers must put in the account name and correct password before making payment or transfer money online.

Structural interdependence is especially important when it works with recombination. If action one must happen before action three, so action three cannot be recombined before action one. The structural interdependence between actions in a routine is important, as it enables and constrains the actions and patterns of actions and so it influences the evolution of routine. Similarly, organizational structural influence the evolution of organization. For example, Bavelas (1955) shows in his experiment that recognized leader will most probably emerge at the position of highest centrality. In patterns with a high, localized centrality, organization evolves more quickly and is more stable, and errors in performance are less (Bavelas, 1955).

Functional interdependence captures the fact that the fitness or benefit from each action in the performance of a routine is dependent on other actions. It indicates which sequences and combinations of actions are *preferable* within a routine. For example, the inputs of one technology depend on the outputs of another technology, when a routine has multiple technologies (Bailey et al., 2010). When the steps are interdependent; the quality and/or cost of the overall performance depends on the combination of steps.

In this dissertation, functional interdependence between actions within a routine is modeled as an NK fitness landscape (Kauffman, 1993; Siggelkow, 2001). The NK model has been extensively applied to management research (Levinthal, 1997). In this framework, n refers to the number of interdependent actions, and k refers to the level of interdependence. As the level of interdependence increases, the fitness landscape becomes more "rugged" and it is difficult to predict how changing one action might affect the overall performance of the routine. As shown in Figure 5, two adjacent sequences could have quite different fitness values.

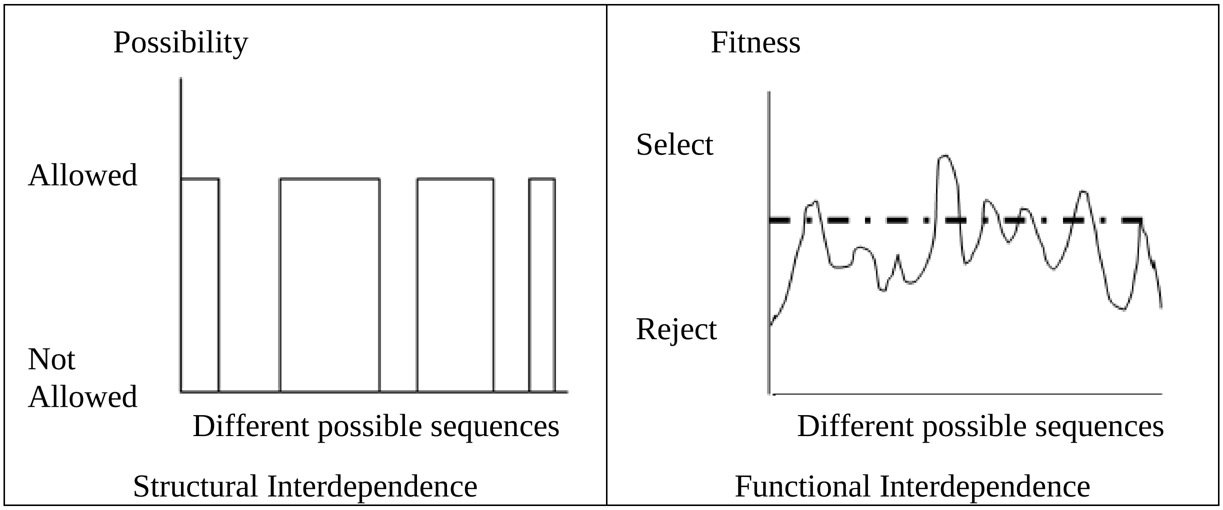


Figure 5: Two types of Interdependence

The NK fitness landscapes model originally developed by Kauffman (1993), provides a powerful framework to study organizational problem solving from the perspective of adaptive search. This model has been extensively applied to management research to study such topics as organizational adaptation.

In the NK fitness landscapes model, a complex adaptive system (e.g., an organization routine) is conceptualized as operating in an environment involving N decision variables and K interactions among these decision variables (Levinthal,1997). Each configuration of the set of decision variables is associated with a fitness value (Levinthal, 1997). The system uses search strategies to navigate within the fitness landscape to find positions of greatest fitness (i.e., best performance). When there is little interaction among decision variables (K is small) the resulting fitness landscape is "smooth". When the decision variables become highly interdependent, which means K is getting bigger; the resulting fitness landscape (e.g. Figure 5) is "rugged" and multi-peaked.

If we only selectively retain sequences that offer improvement, then a little bit of interdependence should lead to lock-in pretty quickly. When a routine engages in learning or changing, only sequences which meet the structural or functional criterion will be selected and retained. Figure 5 shows some sequences are allowed and some others are not. In short, structural interdependence constrains the sequence and combination of actions that are possible within a routine. Functional interdependence constrains the sequence and combination of actions that are preferable within a routine.

Structural interdependence offsets the effect of variation, because only action patterns which meet the structural interdependence criterion will be selected and retained. Structural interdependence acts like another brake on the evolutionary process. The higher the degree of structural interdependence, fewer actions patterns are feasible, so and the fewer action patterns will be selected and potentially retained. This will reduce the potential magnitude of change and introduce a bias toward lower complexity:

Proposition 4a: *The level of structural interdependence is negatively related to the magnitude of change from one period to the next.*

Functional interdependence has a somewhat different effect than structural interdependence because it influences which patterns are preferable, rather than which patterns are possible. When selective pressure is based on functional interdependence, the fitness of the sequences is used for selection. Only sequences with higher functional fitness will be selected and retained, and the direction of change is most likely to be a decrease in complexity.

Functional interdependence also influences the magnitude of change. The higher the degree of functional interdependence, the more rugged the fitness landscape (Levinthal, 1997). Therefore, when the functional interdependence is high, incremental changes are not likely to result in finding an improved fitness, much less the global optimum. In this situation, the routine can be locked-in with a complex structure. Therefore, functional interdependence tends to promote lock-in, but not necessarily simplification.

Proposition 4b: *The level of functional interdependence is negatively related to the magnitude of change from one period to the next.*

4.4 Complexity of routine

There are many ways to measure complexity. For example, task complexity is a complexity measure for organizational task. Wood (1986) argues that task complexity consists of three factors: component complexity, coordinative complexity and dynamic complexity. Component complexity concentrate on the number of steps required to complete a task; coordinative complexity measures the interdependence between steps; dynamic complexity consider time as an important factor in complexity measure (Wood, 1986).

Information complexity, generally speaking, means the length of the shortest message conveying some information (Gell-Mann, 1995). One characteristic of this complexity measure is that it doesn't correspond to what is usually meant by complexity in ordinary conversation (Gell-Mann, 1995). For example, a novel has a lower complexity than random letters of the same length. This measure is easy to compute.

Algorithmic complexity is concerned with the size of the minimal program yields some output (Zurek, 1989). For example, Kolgomorov complexity is a type of algorithmic complexity; it provides an index of the shortest program needed to reproduce a given sequence or set of sequences (Kolgomorov, 1965). However, it is non-computable (Kolgomorov, 1965); you cannot be sure if you have the shortest program. Later on, Lempel and Ziv's complexity measure is a computable index of the Kolgomorov complexity (Lempel and Ziv, 1976).

Regularity complexity corresponds to the length of a concise description of a set of the phenomenon's regularities (Gell-Mann, 1995). It measures the features or regularities of the phenomenon. For example, a random string would have near zero complexity, because it is totally random with no regularities. A bit string consisting entirely of zeroes would be completely regular (Gell-Mann, 1995).

The total number of branches and loops in action network are examples of regularities, and they are meaningful, stable parts of the structure of organizational routines. As mentioned in the chapter two, they provide an index of the complexity of routine. More specifically, if a routine has many branches and/or loops, it is complex. If a routine has few branches and/or loops, it is very simple. The total number of branches and loops are positively related to the number of the network paths.

The effect of complexity in terms of the number of branches and loops results, in part, from ceiling and floor effects within the model. When the model is contains no branches or loops, and a fixed number of steps, it can only get more complex. At the opposite extreme, it can only get simpler. Realistically, most real-world processes are probably much closer to the floor (low or moderate complexity) than the ceiling; they contain a few branches and a few loops, far fewer than the maximum.

Variation also interacts with the current complexity of the routine. Variation can lead to increased complexity and rapid change, but as a routine gets increasingly complex, the effect of variation gradually disappears. The magnitude of change gets smaller and the direction may become neutral from complexity increase (neither increasing or decreasing, because it is near the ceiling). So I expect that variation has stronger effects on a simple routine than a complex routine.

Proposition 5a: *The effect of variation on the magnitude of change is moderated by the complexity of routine, such that the effect is stronger for low level of routine complexity.*

Proposition 5b: *The effect of variation on the direction of change is moderated by the complexity of routine, such that complexity increase is more likely to happen for low level of routine complexity.*

This chapter completes theory development. The next chapter will introduce the simulation model and experiments. Then chapter six summaries the results from empirical data I collected. Chapter seven reports simulation results, followed by discussion and limitations in the last chapter.

Chapter 5: Research methods and simulation models

This chapter introduces the simulation methods and how I set up the simulations experiments. The use of computer simulation for theory development is particularly appropriate here. First, it will allow me to theorize about digital routines in general, rather than being limited to a particular situation. Second, in the real world, it is difficult or impossible to measure digitization, path dependence and interdependence over time. For example, Schulz (2008) put a long list of factors under the umbrella of path dependence. While it may be possible to measure a single factor, a universal measure of path dependence doesn't exist yet. Third, to increase the validity of simulation results, it is important to make sure the simulation is based on realistic parameters. I have conducted a series of interviews to estimate the upper and lower bounds on key simulation parameters about action networks such as the size and complexity of the networks. The description and results of empirical data is in the next chapter.

I used a simulation model that was implemented in Matlab 7.2. The core of the model is a first order Markov transition matrix that is continuously updated through a process of variation and selective retention, as shown in Figure 3. This model first is used in the *Journal of Management Studies* Special Issue on the Micro-foundations of Organizational Routines and Capabilities. Moreover, this dissertation extends the model by including a digitization part and two types of interdependence.

5.1 Simulation Model

Choice set: A

Actions are chosen from a set of possible actions, the choice set, A. I represent the choice set as a set of integers, (1, 2, 3, … , A). An important assumption of this model is that the choice set is fixed. I consider the choice set given by the context. I thus assume that the time scale of repetition for a routine is shorter than the time scale of exogenous change pertaining to possible actions. For instance, artifacts such as keyboards provide a choice set (the keys on the keyboard) and limit the degree to which that choice set can change. While the stability of the choice set in real organizational routines is a matter of empirical investigation, our model makes the conservative assumption that the choice set is stable. In the model, A=10. I have tested other values of this parameter (A =5 and A =20) and results are qualitatively similar. Some simulation is based on A=12, which is the average size of routine from empirical data I collected.

History: H

The network of actions is represented in the history matrix, H. Each cell (i,j) in the matrix represents the probability p_{ij} that action ai will be followed by action a_j. If one row in the matrix contains non-zero probability, the sum of the probability in the row is 1. This matrix can be interpreted as a first order Markov transition matrix (Anderson and Goodman, 1957). The history matrix describes the potential action sequences that are likely to emerge. The history matrix is used to generate sequences according to these probabilities. The first history matrix (t=1) in the evolutionary trajectory is initiated randomly by simulation: there are a random number of branches and loops (non-zero entries in the matrix) and their positions in the matrix are also randomly assigned. Next, the first history matrix generates some number of sequences, some of which (shaded sequences in Figure 3) will be retained and summarized into a new matrix, the second history matrix (t=2). These generation and retention processes continue and the history matrix keeps updating (t = 3, 4, 5 … 500).

Using the matrix in Figure 1 as an example of a history matrix, I can explain how sequences are generated from a history matrix. Generation mechanism starts with the first row in a history matrix. First, the simulation program records action 1 as the first step. So far the generated sequence is: 1. Second, because cell (1,2) in the first row is 1, the mechanism then applies to the second row, and the simulation program records action 2 as the second step. The sequence is: 1, 2. Third, because cell (2,3) in the second row is 1, the mechanism then applies to the third row, and the simulation program records action 3 as the third step. The sequence is 1, 2, 3. In the third row, cell (3,4) is 0.9 and cell (3,5) is 0.1, so the mechanism can apply to either the fourth row or the fifth row and the program records either action 4 or action 5 as the fourth step. The sequence can now be either 1, 2, 3, 4 (90% chance) or 1, 2, 3, 5 (10% chance) depending on which cell between cell (3,4) and cell (3,5) the program picks. Consequently, the matrix in Figure 2 can generate sequences such as 1, 2, 3, 4, 6 and 1, 2, 3, 5, 1, 2, 3, 4, 6.

Note that the first row in the matrix must have at least one non-zero entry, as the sequences always start with action 1, and also note that at least one row in the history matrix contains all zero entries; otherwise, the length of performances generated by the matrix might be infinite. Sometimes a performance generated by the matrix continues forever through loops, therefore, in order to prevent the infinite looping, I set the maximum length of the performance. In our model, the length limit is five times of the size of choice set: A.

Variation: V

When a sequence is generated, it may be subject to random variations. The frequency of these variations is governed by the parameter V, which is the probability, $0 <= v <= 0.05$, that any action in a sequence may be subject to *deletion, replacement or insertion*. Any action may be deleted, or replaced or added with another action drawn randomly from the choice set. For example, the sequence (1, 2, 3, 4 …) might become (1, 2, 4, …), (1, 2, 8, 4, …) or (1, 2, 3, 8, 4, …). The variation is applied at the level of the individual actions, so a given sequence can have more than one variation. More elaborate variation strategies are available (e.g., in genetic algorithms), but if we assume that actions are taken by individuals, then limiting variations to single replacements is a good model. This random variation is applied after sequences are generated from a history matrix, but before they are retained into a new history matrix. In this way, the variations may be retained in the history matrix, H.

Retention: R

The parameter R refers to how many past action sequences are incorporated into the history matrix, H. It defines the depth of the record of the past that is retained, and thus, the effect of history. R is defined as a "moving window" of previous sequences – when the most recent action sequence is added to the history matrix, H, the oldest action sequence in the 'window' is dropped. In Figure 3, it is represented as the shaded area. In our simulations, R varies from 1 to 50. When R=0, there is no effect of history and the process is stationary.

Here is how retention works in the simulation. First, the simulation program computes each retained sequence into a matrix. For example, sequence 1, 2, 3, 4, 6 will be computed into the matrix in Figure 1, except, the cell (3,4) is 1 and cell (3,5) and cell (5,1) are 0. Sequence 1, 2, 3, 5, 1, 2, 3, 4, 6 will be computed into the matrix in Figure 2, except, the cell (3,4) and cell (3,5) are 1. Next, the history matrix is computed as a simple average of all the matrices, each of which represents a retained sequence. Thus, in the history matrix, the probability that action j will follow action i is given by H_{ij}, which is simply the number of times that pair of actions occurred in the set of retained sequences divided by the total number of retained sequences. I considered a log-weighted average based on time, so that the most recent sequences would have the greatest influence (Abbott, 1992), but this refinement does not change the substantive results of the model.

Selection: S

This parameter determines whether a particular sequence will be selected for retention and averaged into the history matrix, H. Only sequences that meet certain selection criteria are retained into a new history matrix. This selection is applied after generated sequences are subject to random variation, but before they are retained into a new history matrix. The selection/retention process applies to whole sequences. While many different selection rules are possible, the simulation implements three basic selection rules.

No selection. All performances are retained, up to the limit R.

Structural Interdependence (SID). It specifies which actions must occur before other actions and then filter on that. Only "possible" patterns are allowed. This constraint can be represented by an interdependence matrix where entry $a_{ij} = 1$ means that action i can happen before action j, and $a_{ij} = 0$ means that action i cannot happen before action j. When structural interdependence increases, the number of 0 entry will increase and the number of 1 entry will decrease.

Functional Interdependence (FID). Performances are selected and retained if and only if they are better than the average of the performances that are currently being retained. Only "feasible" patterns are allowed. Action's fitness are randomly signed from NK fitness landscapes, where the value of action a= f(k other actions) and N =A, the size of choice set. Value of one action depends on the others. The control variable is k. If k=0, landscape is smooth. When k increases, the landscape becomes more rugged.

Digitization: D

Digital artifacts can reduce the variations between two actions, actions carried out by them are less varied, and actions carried out by human are subject to full variation level (V). Due to the interdependence of actions, the more digital artifacts in a routine, the less variation an action has. Therefore, I make simple assumption that the variation of the focal action depends on the next neighbors upstream and downstream. If the previous action or next action is carried out by digital artifacts, the focal action is subject to smaller than full variation. If both previous action and the next action are carried out by digital artifacts, the focal action is subject to variation that is smaller than previous scenario. The extreme case is that the focal action is carried out by digital artifacts, it cannot vary. The goal here is to use qualitative assumption to differentiate variation levels, and thus I make four simple rules in Figure 6. Here, I choose 1, 2, and 4 as the denominator of variation. It is possible to pick other numbers like 1, 3 and 6 or 1, 4, and 8. The results are quantitatively similar.

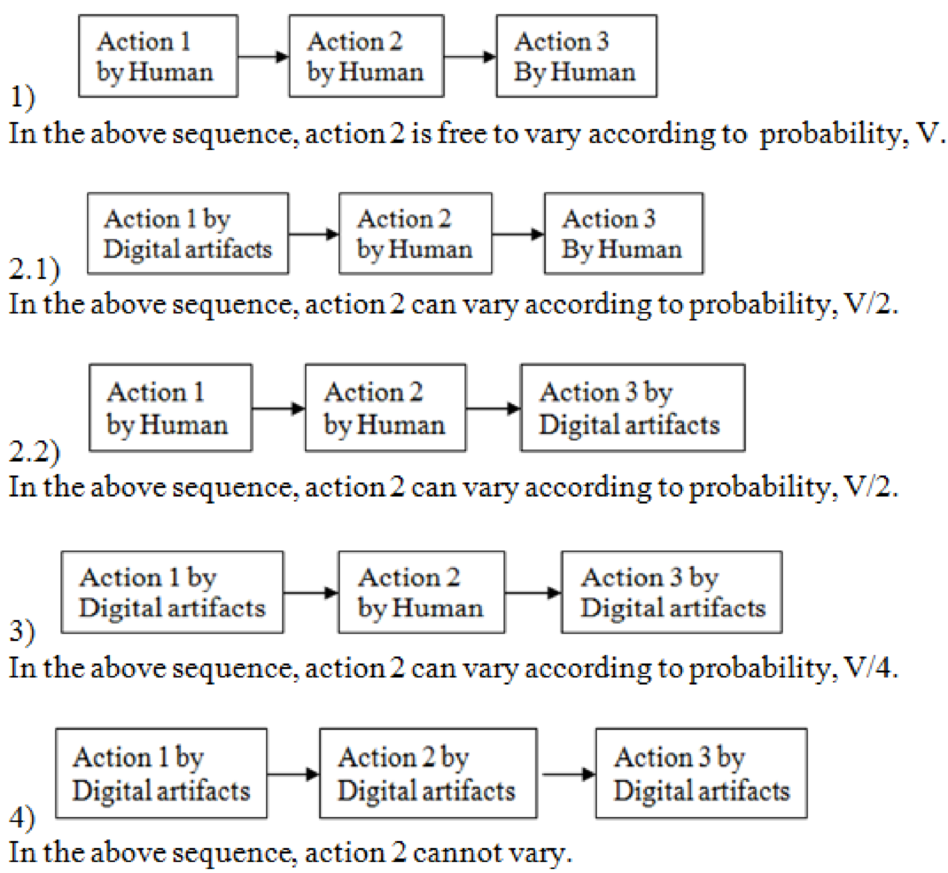


Figure 6: Four rules of variation

5.2 Method and Measures

There are total of five simulation experiments:

1) variation and retention (No Selection);

2) variation, retention, and structural selection;

3) variation, retention, and functional selection;

4) variation, retention, structural selection, and digitization;

5) variation, retention, functional selection, and digitization.

For each experiment, simulation generates 1000 networks of action (sample size =1000), each of which provides a starting point for an evolutionary trajectory. In effect, I am sampling 1000 networks from the space of all possible networks of action - every combination of branches and loops - for the given choice set. The 1000 randomly drawn networks are independent from each other.

Random Matrix and Fixed Matrix. All experiments use 1000 random matrices, where the number of non-zero entries and the position of the entries are random. The last two experiments also use fixed matrices. The fixed matrices are based on empirical data I collected. According to the empirical data, an average organizational routine has 12 steps, 5 branches and 2 loops. So the size of the fixed matrix is 12, and there are 5 total branches, and 2 loops in the matrix, however, the position of branches and loops are still random. Other more extreme cases, such as only 1 branch with no loop or 14 branches and 8 loops, can be found in the 1000 random matrices.

Short term and long term scenarios. I examine the propositions under two scenarios: short run and long run. Short run means a routine is subject to 50 iterations in the simulation, where each iteration involves the generation and retention of one sequence. Long run means a routine is subject to 500 iterations. In real life, 50 or 500 iterations could take minutes, months or years, depending on the frequency that a routine is performed.

Complexity. Given the network of action, complexity is measured by the total number of branches and loops (non-zero entries in the matrix that represents the network).

Variation, Retention and Selection. I vary retention between 1 and 50, and variation is any value between 0 and 0.1 (Note 0.1 is a very big number in a real routine, it means variation will occur in every 10 actions). Proposition 2, 3, and 5 are tested under no selection pressure. Proposition 1 and 4 are tested under different selection pressures.

Structural and functional interdependence. In the NK model, an organization routine is conceptualized as operating in an environment involving n variables (here variables are actions within routine = A) and k interactions among these variables (Levinthal, 1997). The value of structural or functional interdependence (k) is any random integer between 1 and 10, the size of choice set.

Evolutionary trajectory (ET) equals the magnitude of change (M) times the direction of change (D). Mathematically, ET = M x D (D = -1, 0 or 1). Although different measures, such as Hamming distance, Euclidean distance and matrix correlation, all have similar results; Hamming distance is the easiest to compute. Therefore, I use Hamming distance to measure the magnitude of change in the action network (Hamming 1950, 1986). This variable always has a non-negative value. If a matrix entry changes from non-zero to zero between observations (or from zero to non-zero), the hamming distance of this entry is one. If there is no change, the hamming distance is zero. The sum of hamming distance for all matrix entries is the measure for magnitude of change. Other possible measures include Euclidean distance (Pentland et al., 2012) and matrix correlation using Quadratic Assignment Procedure (Hubert and Schultz, 1976). I measure the direction of change by whether complexity (the number of non-zero entries in the matrix) increases or decreases. When complexity is increasing, the direction of change is positive one, and the evolutionary trajectory is the magnitude of change. When complexity is decreasing, the direction of change is negative one, and the evolutionary trajectory is the negative value of the magnitude of change. When complexity is not changing, the direction of change is zero, and the evolutionary trajectory is zero as well. I use multiple regression with standardized coefficients to analyze the simulation data. Regression results are reported in chapter 7.

Chapter 6: Grounding model in empirical data

Validity is crucial to simulation (Kleindorfer et al., 1998). To increase the validity of simulation models, it is important to make sure the simulation is based on realistic parameters. Validation cannot be done by the modeler alone, rather communication with people in the real world plays an important role in building a valid model (Carson, 1989). This dissertation uses interview to validate simulation model. Towards this end, I have conducted a series of 70 phone interviews to estimate the upper and lower bounds on key simulation parameters: the degree of digital intensity, the size of the action network, and branches and loops in the network.

Telephone interviews are used extensively in quantitative research. One claimed drawback of telephone interview is the reduction of visual or social cues. Yet, telephones may allow respondents to feel relaxed and able to disclose sensitive information. Although the data I collect is not sensitive, the relax mode of data collection can help produce high quality data. Researchers generally conclude that telephone interviewing is an acceptable and valuable method of data collection (Rubin and Rubin, 1995). Telephone interview is particularly appropriate for short and structured interviews (Fontana and Frey, 1994) or in very specific situations (Rubin and Rubin, 1995). Therefore, I limit the time of the interview to be 45 minutes to 1 hour and follow very structured interview questions which are listed in the Appendix section.

Interviewees are volunteers from three weekend MBA classes in a comprehensive university in North America. They were given extra credit of 1% of course points. There are totally 130 students, and so the participation rate is 53.8%. Their job titles of the interviewees include quality manager, design engineer, human resource manager, risk managers, software engineer, and office manager and so on. The interviewees are from many different firms from various industries, so the data collected from interview provides a reasonable basis for simulation.

There are total seven simulation parameters, four of which are the measures of action networks representing organizational routines. The *Size* of the network means how many actions in the network. The degree of digital intensity refers to the percentage of actions that are carried out by digital artifacts. *Branches* and *loops* show the structure of the action network. Branches mean there is more than one choice of action to go forward. Loops mean the process can go back to a previously occurring action.

The other three variables serve as mechanisms that govern the evolution of action networks. More specifically, variation and retention represent the path dependence mechanism, and selection represents the interdependence mechanism (structural and functional). Unlike the first four variables, static features of routines, which can be easily grounded by interview, it is difficult to measure the level of variation, selection and retention, dynamic features of routine, using interview. Actually, it is difficult to empirically measure path dependence and interdependence phenomena in the real world. For example, Schulz (2008) put a long list of factors under the umbrella of path dependence. While it may be possible to measure a single factor, a universal measure of path dependence doesn't exist yet. This issue also applies to the idea of interdependence. Researchers use NK fitness landscape (Kauffman, 1993, Siggelkow, 2001, Levinthal, 1997) to abstractly simulate the phenomenon of interdependence. Therefore, this research study doesn't collect any empirical data on variation, selection and retention.

Branches and loops are a simple index of the structure of the network, but they are hard for people to understand. Rather than questionnaire, I use phone interview, a more interactive way, to collect data. Interview data generally has higher quality than survey data (Pinsonneault and Kraemer, 1993). During the interview, I can make sure that interviewees understand concepts like branches and loops.

In the interview, I start by identifying a repetitive pattern of action that the interviewees do as part of their work. It needs to have a definite start and finish, and it should be some jobs that they do in their work. Second, I ask them to provide a general description of the process. Third, the interviewee and I break the process down into steps and at the same time we identify the sequence of steps: what happens first, what happens next and what happens last. Fourth, I ask them to estimate the frequency of alternatives or exceptions, and discuss with them performance incentives and quality controls, if any. After the interview, I ask them to fill out a one-page survey about people's perception of the processes that they described.

Based on the interview data, I draw the action network of the organizational process. I can calculate the size of the network and the number of branches and loops based on the action network. Then the network of action can be represented as a matrix, the elements in the matrix express conditional probabilities that one action will occur, given that another action has occurred. The matrix is used to calculate the complexity of the network. As mentioned in Chapter 2, the total number of branches and loops provides an index of the complexity of routine. If a routine has few branches and/or loops, the routine is simple. If a routine has many branches and/or loops, the routine is complex.

Table 5 summaries the descriptive statistics of interview data I have collected. Some computer simulation experiments are based the data from this table. An average routine has 12 actions, with 5 branches and 2 loops. The average digital intensity level is 5.51. I found that a typical organizational routine is generally pretty simple. Nearly half of the actions are digitized, either performed by digital artifacts or people using digital artifacts.

	Mean	Min	Max
Size	11.72	6	32
Branches	4.59	1	14
Loops	2.01	0	8
Digital Intensity	5.51	2	17

Table 5: Descriptive statistics of parameters

Chapter 7: Results and analysis

This chapter reports the results and analysis from multiple regressions which are based on simulation results. Results are presented in a different order for clarity. The independent variables in regression include complexity (C), variation (V), retention (R), and interdependence (SID and FID), and digitization (D), as well as the interaction terms (VxR and VxC) that I theorize to be meaningful. The dependent variable in regressions is the evolutionary trajectory (ET) or magnitude of change and direction of change. To facilitate the analysis of interaction effects, the variables were centered (Cohen et al. 2003). Table 6 shows the descriptive statistics for each variable reported in table 7.

	Mean	S.D.	Min.	Max.	C	V	R	HD1
Complexity (C)	0	10.460	-42.923	20.077				
Variation (V)	0	0.014	-0.024	0.025	-0.01			
Retention (R)	0	14.216	-25.006	23.994	-0.04	-0.12***		
HD (SR)	49.564	7.650	22	86	-0.01	-0.03	0.05	
HD (LR)	51.415	6.974	32	85	-0.01	-0.02	0.03	0.84***

Note: sample size =1000; HD: Hamming Distance; SR: short run =50 iterations; LR: long run = 500 iterations. Magnitude and direction of change are measured by hamming distance and complexity change respectively.

Table 6: Descriptive Statistics

As shown in table 7, model 1 and 3 has not interaction terms. The first order, direct effects are consistent with the predictions in Table 4. For example, in the short run, complexity has a strong influence on the evolutionary trajectory ($\beta = -0.405$, $p<0.001$). Variation also has a strong influence on the evolutionary trajectory ($\beta = 0.135$, $p<0.001$), while retention has the opposite effect on the evolutionary trajectory ($\beta = -0.134$, $p<0.001$). Complexity and variation have pretty consistent effects over time (in short and long run), but effect of retention is smaller in the long run. However, we need to consider interaction effects when interpreting these results.

Since coefficients of interaction between variation and retention are significant and quadratic terms are not significant, I will focus our discussion on the interaction effects.

Evolutionary Trajectory				
	Short Run		Long Run	
	Model 1	Model 2	Model 3	Model 4
Complexity (C)	-0.405***	-0.410***	-0.425***	-0.425***
Variation (V)	0.135***	0.128***	0.157***	0.146***
Retention (R)	-0.134***	-0.127***	-0.054 +	-0.047 +
Interaction (VxR)		0.107***		0.149***
Sample size (N)	1000	1000	1000	1000
R^2	19.97%	21.35%	20.92%	23.18%
Notes: standardized coefficients; p<0.10 +, p<0.05 *, p<0.01 **, p<0.001 ***.				

Table 7: Regression results (Variation and Retention)

I simulate experiments and analyze the simulation results progressively. I start with the baseline simulation model of variation and retention experiment, and then full model of variation, selection and retention, and finally extended model of VSR and digitization. To examine the propositions 2 and 3, I look at the interaction effects following the procedure by Aiken and West (1991). The interaction effects in evolutionary trajectory are plotted at the top row in Figure 7. X axis is standardized variation value from -1 to 1. Y axis is standardized evolutionary trajectory. The interaction effect between variation and retention is significant for the short run and the long run. In the short run (top left corner of Figure 7), the slope of the variation is small (0.021) for low level of retention and big (0.235) for high level of retention. In the long run (top right corner of Figure 7), we can observe similar trends, namely bigger slope for higher retention level. When retention is low, routine will become locked-in very quickly no matter how strong the variation is. Interaction happens when the effect of retention is not very strong (R at medium and high values). So the effect of variation is offset by the effect of retention. I can conclude that proposition 2 is supported.

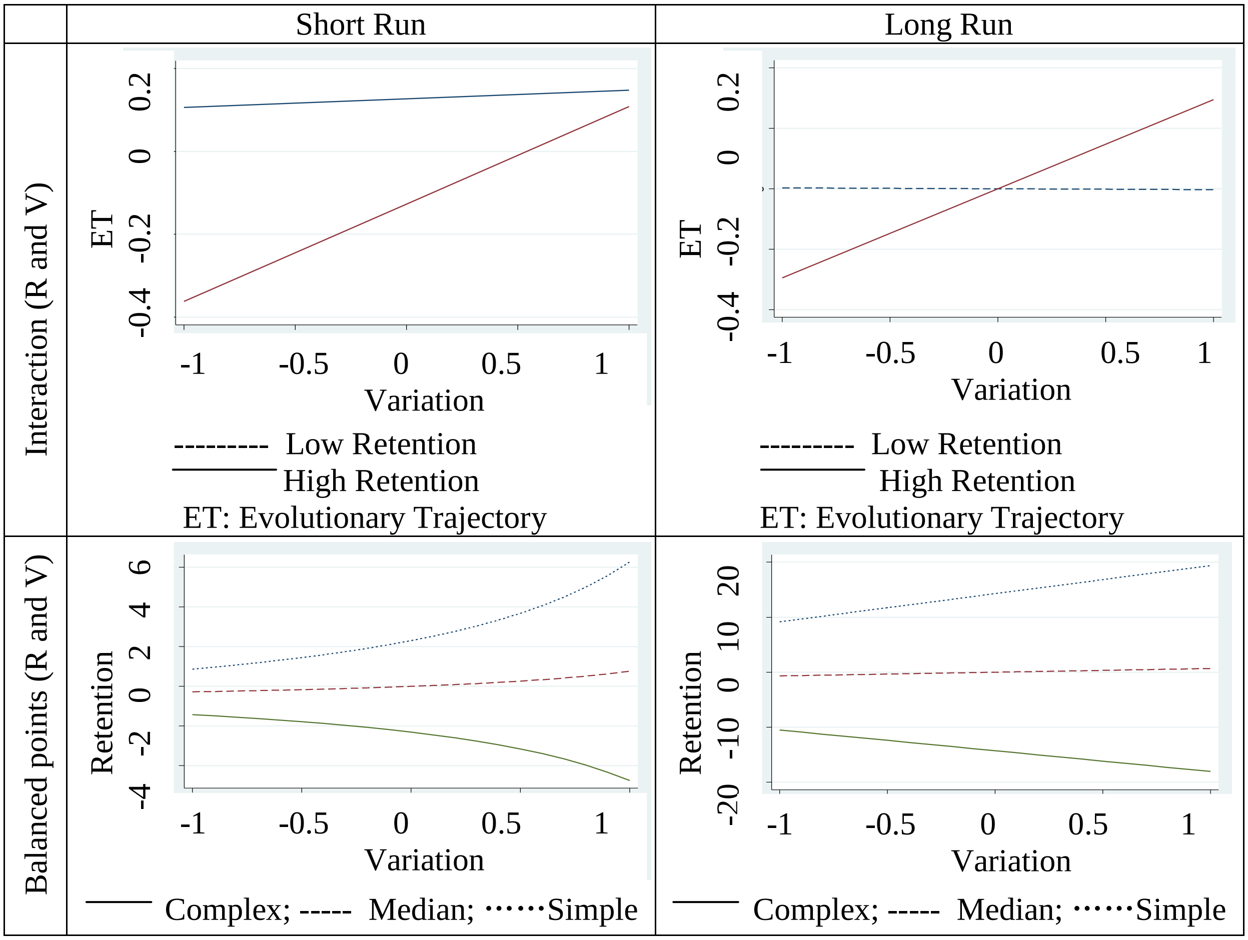


Figure 7: Interaction effects and balance points

Proposition 3 concerns the offsetting effects of variation and retention. When the direction of change is zero, it means that the matrix representing an action network is not getting simpler or more complex. When magnitude of change is zero, the complexity of matrix remains the same. Based on regression results on the magnitude of change, I am able to draw the balanced line (complexity-neutral frontier) between variation and retention for the short run and the long run. The interaction effect is significant in the short run but not significant in the long run, so the balanced line is a curve in the short run but a straight line in the long run, but the line maintains the same trend (see pictures at the bottom row in Figure 7). Therefore, proposition 3 is supported. For simple and median complex routine, variation needs to increase to maintain balance if retention increases. For a complex routine, variation needs to decrease a little, because the complex routine already has a lot of possible patterns of actions. Similarly, for a simple routine, high variation needs to work with high retention to incorporate more variations to maintain a neutral trajectory. For a complex routine, high variation needs to work with low retention to maintain a neutral trajectory.

Proposition 4a concerns effects of variation and selective retention in the full model, where selection is due to structural interdependence. In table 8, model 1 and 2 show that in the short run and the long run, the degree of structural interdependence has a negative effect on the magnitude of change. Proposition 4 is supported. Structural interdependence serves a similar role as retention: it causes a routine to evolve towards lock-in through a complexity-decreasing trajectory.

Magnitude of change	Short Run Model 1	Long Run Model 2		Short Run Model 3	Long Run Model 4
Complexity (C)	-0.352***	-0.364***	Complexity (C)	0.381***	0.943***
Variation (V)	0.111***	0.148***	Variation (V)	0.048+	0.031**
Retention (R)	-0.128***	-0.064*	Retention (R)	-0.013	-0.041***
Structural (SID)	-0.081**	-0.079**	Functional (FID)	-0.127***	-0.007
Interaction (VxR)	0.051 +	0.092**	Interaction (VxR)	0.042	-0.006
Sample size (N)	1000	1000	Sample size (N)	1000	1000
R^2 (%)	17.87%	18.74%	R^2 (%)	30.61%	37.27%
Notes: standardized coefficients; p<0.10 +, p<0.05 *, p<0.01 **, p<0.001 ***.					

Table 8: Regression results (Variation, Retention and Selection)

Proposition 4b concerns the effects of variation and selective retention, where selection is due to functional interdependence. Model 3 in table 8 shows that the degree of functional interdependence has a negative effect on the magnitude of change in the evolutionary trajectory. It means the higher functional interdependence, the less the amount of change. However, this effect is not significant in the long run (model 4), so proposition 4 is partially supported.

In model 4, unlike the others, the sign of complexity on the magnitude of change is positive. This is because when the evolutionary trajectory is almost definitely a decrease in complexity, higher complexity tends to offer more possibility for change. The effects of complexity, variation and retention are consistent with the results in table 7.

Evolutionary Trajectory:					
	Random Starting Matrix		18 non-zero entries Fixed Matrix		
	Short Run	Long Run		Short Run	Long Run
	Model 1	Model 2		Model 3	Model 4
Complexity (C)	-1.728***	-1.691***	Complexity (C)	---	---
Variation (V)	3.231	20.326	Variation (V)	37.335***	46.861***
Retention (R)	0.573***	-0.018	Retention (R)	-0.254***	-0.110***
Digitization (D)	-1.129**	-1.896***	Digitization (D)	-0.703***	-0.961***
Structural (SID)	-1.064**	-0.902*	Structural (SID)	-0.142	-0.191+
Interaction (VxR)	2.785	5.946**	Interaction(VxR)	0.979	1.652*
Interaction (VxD)	-43.982***	-48.233***	Interaction(VxD)	-13.589***	-15.043***
Sample size (N)	1000	1000	Sample size (N)	1000	1000
R^2 (%)	30.60%	32.95%	R^2 (%)	23.68%	17.09%
Notes: standardized coefficients; p<0.10 +, p<0.05 *, p<0.01 **, p<0.001 ***.					

Table 9: Regression results (Variation, Retention, Selection and Digitization)

To test the proposition 1 in the extended model of VSR and digitization, I add the digitization into the full VSR model. Table 9 shows the results of variation, retention, structural selection and digitization; table 10 shows the results of variation, retention, functional selection and digitization. Left two columns of these tables are the results from totally random matrices, and the right two columns of these tables are the results from restricted matrices. Complexity doesn't have an effect in model 3 and 4, because the total number of non-zero entry is fixed. Digitization has negative effects on the evolutionary trajectory in most of models in table 9 and 10. The standard coefficient of digitization ranges from -1.896 in model 2 in table 9 to -0.093 in model 3 in table 10. Therefore, proposition 1 is supported.

Evolutionary Trajectory:					
	Random Starting Matrix			18 non-zero entries Matrix	
	Short Run	Long Run		Short Run	Long Run
	Model 1	Model 2		Model 3	Model 4
Complexity (C)	-0.997***	-0.991***	Complexity (C)	---	---
Variation (V)	-2.052	-2.409	Variation (V)	8.161+	3.669
Retention (R)	-0.018*	-0.010	Retention (R)	-0.020*	-0.006
Digitization (D)	-0.044	-0.102**	Digitization (D)	-0.093**	-0.119***
Functional (FID)	-0.075+	-0.063*	Functional (FID)	-0.009	-0.004
Interaction (VxR)	0.359	0.183	Interaction (VxR)	0.081	-0.037
Interaction (VxD)	1.898	0.411	Interaction (VxD)	-2.401+	-1.267
Sample size (N)	1000	1000	Sample size (N)	1000	1000
R^2(%)	89.18%	92.62%	R^2 (%)	1.88%	1.36%
Notes: standardized coefficients; p<0.10 +, p<0.05 *, p<0.01 **, p<0.001 ***.					

Table 10: Regression results (Variation, Retention, Selection and Digitization)

Table 11 shows interactions results between variation and complexity. Top row is results for magnitude of change, and bottom row is the results for direction of change. The interaction effect between variation and complexity is significant except the long run when dependent variable is direction of change. In the short run, the slope of the variation is small (-0.066) for high level of complexity and big (0.308) for low level of complexity. In the long run, we can observe similar trends, namely bigger slope for low complexity level. When complexity is high, variation doesn't contribute much to the change. Variation has a strong effect for simple routine. Finally, proposition 5a and 5b are supported.

One point worth noticing is that variation become not significant in VSR and digitization models with random matrix. It is because digitization in the simulation experiments works after variations. Digitization acts like a filter on variation. In VSR and digitization models with restricted matrix, variation has very big effects, because simple matrix is very sensitive to variations. A little amount of variation can greatly change the simple routine. Complexity has no effects because all matrices have the same complexity level at the starting point of simulation.

Other variables such as complexity, retention, selection have consistent results comparing with other previously mentioned regression tables. Model 3 and 4 in table 10 have lower R-Square about 1 percent, this may be because evolutionary trajectory is almost always complexity-decrease in variation, retention, and functional selection, and restricted matrices are already very simple and they don't provide a lot of room for search.

Magnitude of change	Short Run		Long Run	
Hamming Distance	Model 1	Model 2	Model 3	Model 4
Complexity (C)	-0.680***	-0.689***	-0.779***	-0.785***
Variation (V)	0.123***	0.121***	0.029	0.037*
Retention (R)	-0.309***	-0.299***	-0.058**	-0.055**
Interaction (VxC)		-0.187***		-0.244***
Interaction (VxR)		0.140***		-0.006
Sample size (N)	1000	1000	1000	1000
R^2 (%)	56.75%	62.74%	60.69%	66.93%
Logistic Regression: Direction of change				
	Model 5	Model 6	Model 7	Model 8
Complexity (C)	-4.801***	-4.801***	-4.966***	-5.106***
Variation (V)	0.664***	0.377	0.926***	0.784**
Retention (R)	-0.429**	-0.388	0.053	-0.241
Interaction (VxC)		-0.917*		-0.651
Interaction (VxR)		0.626***		0.813***
Sample size (N)	1000	1000	1000	1000
Pseudo R^2 (%)	60.41%	63.46%	59.83%	62.97%
Notes: standardized coefficients; p<0.05 *, p<0.01 **, <0.001***				

Table 11: Regression and logistic regression results

Chapter 8: Discussion, contributions, limitations and conclusion

This chapter discusses the contributions of this dissertation, lists the limitations, highlights the key findings, and outlines several future research directions.

8.1 Discussion

The goal of my dissertation is to build a better theory of the evolutionary dynamics of digitized organizational routines. By theorizing about the effects of increased digitization on path dependence and interdependence mechanisms, this dissertation extends current theory on the evolutionary dynamics of organizational routines by taking into account the effects of three basic phenomena: digitization, path dependence and interdependence. Understanding the change and stability of a routine via the evolutionary trajectory allows me to explore the influence of variation, selection and retention on the trajectory. Representing organizational routines as networks of action allows me to express the trajectory of a routine in terms of the magnitude and direction of change. This model offers several contributions to the literature on organizational routines.

First, digital artifacts provide variation, retention and selection mechanisms which govern the evolution of organizational routine. This theorization of digital artifacts is in line with the call to put artifacts at the center of routine (D'Adderio, 2011), and therefore provides vocabulary to analyze the effects of digitization on organizational routines.

Digitization can provide a path dependence mechanism which is usually seen as a major source of routine stability. Full automation is a classic example. Digitization restricts variations in patterns of actions, and supports tracking and recording of actions patterns that occurred. Restrictiveness is an innate attribute of digital artifacts (Silver, 1988), and different digital artifacts have different restrictiveness and therefore reduce variation to different levels. Although some new digital artifacts with advanced functions like video conference may be less restrictive, digital artifacts in general reduce variations between two adjacent actions in a routine. Restrictiveness is not always a bad feature, because it can prevent misuse or unfaithful use of digital artifacts. Therefore, digital artifacts' restrictiveness characteristic is an important controller for managers to govern the stability or change of routines.

However, digital artifacts can also lead to innovation and "path creation" when the effects of variations outweigh retention. Innovation is likely to occur when the digital artifacts are less restrictive and can induce variations and support retention. For example, Taobao.com, a C2C platform in China, develops a messager called Ali WangWang to facilitate communication between buyers and sellers. The messager is both a technological innovation and administrative innovation, and it is less restrictive than traditional phone-call type customer service. The messager can store all the chats between buyers and sellers; buyers and sellers can add each other as friends; and buyers and sellers can chat in a relaxed way. It has become a new habit among Chinese online buyers to "chat" with the sellers through the messager to inquire about products prior to purchasing and repair, replacement, or return after the purchase. Moreover, digitization can also provide the interdependence mechanism among actions, which tends to constrain the sequence in which actions can occur. For example, we have to type in digital data before it can be reviewed, analyzed and mined. In short, digital artifacts influence the rate and direction of change in routine (D'Adderio, 2011), and path dependence and interdependence are mechanisms through which digital artifacts affect routines. Although path dependence and interdependence are not unique to digital artifacts, the effects of digitization are crucial as organizational routines are becoming increasingly more digitized.

Second, to assess the evolution of routine, this dissertation introduces methods for conceptualizing and measuring the magnitude and direction of change in organizational routines. By operationalizing the key concepts in terms of the network of actions, it becomes possible to test the propositions outlined here in empirical research. Unlike other applications of evolutionary theory in organizational research (e.g. Levinthal, 1997; Zollow and Winter, 2002), the propositions outlined here are relatively easy to test because the "generational" cycle is very short. The development of new organizational capabilities may have a long reproductive cycle of several months or years. However, some routines have a very short reproductive cycle, which can be minutes or hours, because each performance (or iteration) of the routine is a reproductive cycle. If there is enough variation, and low levels of retention, the evolutionary process can transform the routine very quickly. If variation is low, and retention is high, then the evolutionary trajectory is likely to be very stable.

Third, this dissertation offers a set of empirically testable propositions concerning the evolutionary process. When retention dominates in the evolutionary process, the trajectory leads towards reduced complexity and eventually to “lock-in”. When variability dominates, the trajectory tends towards greater complexity and path making, subject to the limitations of interdependence. One of the surprising findings of simulation is the “complexity-neutral frontier” between variation and retention where a routine could potentially evolve in either direction. The existence of alternative trajectories is theoretically significant because it contradicts the view that routines inevitably get locked-in to fixed patterns of action. Even in steady state (a trajectory that maintains a constant level of complexity), the model predicts that the specific patterns of action generated by a routine could be continuously changing.

Fourth, the dissertation uses the action network representing routine to predict the evolutionary dynamics of routines. The idea of action network provides a natural and convenient measurement of organizational routines, because organizational routine is usually defined as patterns of actions which are essential feature and the most observable aspect of organization routine (Pentland, 1999; Pentland et al., 2011). In the short run, the current structure predicts the trajectory of evolution. Eventually, over time, the direct effect of current structure will be eclipsed by the competing influence of variation, retention and selection.

Fifth, organizational routines are different at different hierarchical levels, in different firms, and in different industries. For example, there are managerial routines and operational routines, and purchasing routines and production routines. No matter how different they are, as long as they are digitized, their evolution is subject to the effects of path dependence and interdependence by digitization. I am sampling 1000 networks from the space of all possible networks of action - every combination of branches and loops - for the given choice set. Results from simulation are representative and can be apply to many different types of routines, although hierarchical level, firm type and industry type are moderators in empirical research.

Finally, contrary to the conventional understanding that path dependence alone causes lock-in, the dissertation shows that interdependence between actions can also explain lock-in. The combined effects of path dependence and interdependence offer a more robust explanation of this widely observed phenomenon.

8.2 Limitations and future research

Because this model is quite abstract, it is subject to several important limitations. For example, it is limited to a fixed set of actions. The dissertation is not considering the situation where new elements are added to or deleted from the choice set. For example, some digital artifacts can create new actions like online search for information, video conference. The use of some digital artifacts can remove old actions like distributing documents to offices. The dissertation is not considering the effect of new technological constraints and affordances, or other new possibilities for action. Future research can relax this assumption to explore the effects of new actions on the evolution of routines. More specifically, simulation model needs one more parameter, total choice set AA, which store all the possible actions including current actions and all possible new actions. The size of AA should be greater than the size of current choice set A. The size of current choice set A is not constant, and the actions in the choice set are not fixed.

Second, even though this dissertation collects empirical data, it doesn't empirically test all the propositions. I believe that simulation experiments do lay a solid basis for future empirical testing of the propositions. Since this dissertation is based on the idea of using action network to represent routines, detailed longitudinal workflow data would be a perfect fit for future empirical research. Researchers can easily measure the level of variations (the chance of action changes) from workflow data. However, measuring retention and different types of selections is still a challenge. It is possible to collect data on retention and selection through survey or interview. Both variation and retention could come from a lot of resources. For example, programs like ISO9000 and Six Sigma can minimize variation. Knowledge management programs probably promote higher retention. After measuring variation and retention level and current routine structure, researchers can identify the main evolution driver as shown in table 3 and predict what kind of trajectory will a routine follow.

Third, the dissertation has not considered the ways in which particular actions may be distributed among various actors (there is no division of labor or organizational structure). If certain actions are only carried out by certain actors, it would have implications for evolutionary processes involving those actions/actors. In particular, division of labor could be seen as a way of enforcing structural interdependence (e.g., a manager must sign off on phase 1 before phase 2 can start). In general, division of labor would probably tend to inhibit variations because the full range of actions would not be available at each point in time, as they are in the present model.

Fourth, the number of iterations in the simulation is an index for the passage of time, but the difference in time cycle for real routines makes the labels (long run and short run) potentially misleading. Feldman's (2000) university housing routines include student move-in and move out, which occur once per year. For those routines, the long run scenario would span 500 years. Other routines occur hundreds of times daily, so the "long run" might be over by lunchtime. In field research, these differences would obviously need to be considered.

Finally, the dissertation has used the simplest model that allows me to represent pattern-in-variety: a first-order Markov model. Analysis of data on a small number real routines indicates that the first order Markov model is justified (Pentland et al., 2010), but it would be interesting to consider higher-order models. While these are important limitations, they seem like fruitful directions for extending this work.

8.3 Additional research directions

The results of this simulation relate to and extend March's (1991) distinction between exploration and exploitation. Based on the relative strength of variation and retention, it is possible for researchers to predict the trajectory of organization routines. Relatively higher V will increase the tendency for exploration (change). Relatively higher R will in increase the tendency towards exploitation (stability). However, the results here suggest that effect of increased variation or retention will depend on the on the selection regime that is operating. In a situation where digital artifacts are used to automate or standardize processes, substantial exploration may not be possible.

Digital artifacts can help managers choose different combinations of variation, retention and selection, and therefore change routines in desirable direction. The next question is how to choose the appropriate IT governance arrangement (Sambamurthy and Zmud, 1999). When people want to explore prospects for digital artifacts in a routine, decision rights for IT activities should be decentralized, so that the benefits or costs of new patterns of action can be quickly evaluated. Therefore, we can hypothesize a complexity increasing trajectory works best with de-centralized IT governance, while a complexity decreasing trajectory works best with centralized IT governance. It is interesting to test this hypothesis in empirical research. It is also interesting to investigate the how different IT governance arrangements work in different evolutionary trajectories.

There are multiple types of digital artifacts in organizations, and people use these artifacts differently. It is interesting to explore how people used different types of digital artifacts to achieve the level of exploration or exploitation they want. As shown in Figure 8, certain digital artifacts can have convergent effects on routine evolution by increasing (or decreasing) variation level and decreasing (or increasing) the effects of retention/selection. Some digital artifacts can have divergent effects on routine evolution by increase or decrease variation and retention/selection level. It is interesting to find out what types of digital artifacts tend to have convergent effects and what types of digital artifacts tend to have divergent effects.

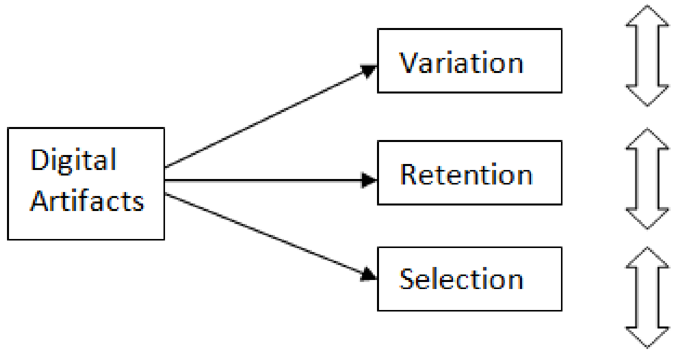


Figure 8: Effects of digital artifacts on variation, retention and selection

Path creation (Garud et al, 2010) is associated with innovation, new business processes, new products, or new business models. After researchers are familiar with the level of variation, retention and selection brought by some digital artifacts, it is also possible to predict whether path creation will happen. The evolutionary trajectory view can also be applied to study digital convergence or the evolution or digital artifacts (Yoo et al., 2009), because digital artifacts are not fixed, and they can also evolve over time.

Organizational capabilities are based on organizational routines and defined as routine bundles (Winter, 2003). The idea of evolutionary trajectory also applies to the study of organizational capabilities. It is possible to assess how an organizational capability evolves over time. It is also interesting to use a multilevel view to study how the different routines evolve and interact with each other and contribute to the change of organizational capabilities. This dissertation treats variation, and selective retention as a type of dynamic capability (Pavlou and El Sawy, 2006). During a routine's evolutionary trajectory, dynamic capability can manifest variation-dominant effects or retention-dominant effects. It is interesting to study the change or the evolutionary trajectory of dynamic capability overtime.

8.4 Conclusion

Organizational routines are ubiquitous in organizations and are becoming increasingly digitized, as technologies for process support and management continue to flourish. However, our theories on the change of digitized organizational routines are incomplete. This dissertation extends current theory on the evolutionary dynamics of organizational routines by taking into account the effects of three basic phenomena: digitization, path dependence and interdependence. My dissertation models routines as networks of action that are subject to an evolutionary process of random variation and selective retention. To access the evolutionary process, I use the idea of evolutionary trajectory which is measured by the magnitude and direction of change.

Digitization provides and influences path dependence and interdependence mechanisms that govern the change and stability of organizational routines. Digitization supports or restricts variation, retention, and selection which interact and shape the trajectory of routine evolution. More specifically, relatively higher Variation will increase the tendency for complexity-increase trajectory and routine change. Relatively higher Retention and/or higher interdependence will in increase the tendency towards complexity-decrease and eventually "locked-in".

These phenomena would be difficult to investigate in empirical research so I used simulation. Computer simulation is an increasingly significant method for theory building and theory testing in organization studies (Davis et al., 2007). They enable researchers to define starting conditions, take a complex set of assumptions, and observe and record detailed characteristics of organizational processes (Lant and Mezias, 1990). Therefore, simulations are well suited to build theory in a longitudinal process such as the evolution of routines. Here, this dissertation has emphasized simplicity and abstraction. The advantage of an abstract model is that it is potentially applicable across a wide range of empirical situations. This model offers a wide range of directly testable propositions. I look forward to seeing them tested in empirical research.

APPENDIX

APPENDIX

Overview of Interview and Interview questions

We will start by identifying a repetitive pattern of action you do as part of your work. It needs to have a definite start and finish. Ideally, it should involve more than one person (the other person might be a customer or a supervisor).

Once we have decided on the process to talk about, we will:

1) Get a general description of the process.

2) Break the process down into steps.

3) Identify the sequence of steps.

4) Estimate the frequency of alternatives or exceptions.

5) Discuss performance incentives and quality controls, if any.

6) Fill out a one-page survey (20 questions, agree/disagree).

Part 1: Get a general description of the process.

Q1. Let's start by getting a brief description of the organization.

How would you describe this organization (not the name, but what it does).

Q2. Now let's identify a particular process to talk about.

Can you tell me some things that you do in your work?

Q3. Which of those things do you do most often?

Q4. OK, let's focus on (name of the process): ______________________________

Q4a. What is the purpose or goal of the process?

Q4b. What is the outcome of the process? Is it a product or service?

Q4c. Can you give me a broad overview of this process, from start to finish:

Q5. How often is the process done: _____________(daily, weekly, monthly, or yearly)

Q6. I'd like to know how long it takes to complete, from start to finish.

(Total time spent on each action, not including time for wait, relax, eat or sleep)

Q6a. From start to finish, what's the shortest/fastest: _____________

Q6b. From start to finish, what's the longest/slowest: _____________

Q6c. From start to finish, what's the typical time: _____________

Q7. How important is this process to the organization?

(Extremely important, very important, important, not that important, not important)

Q8. Is there a lot at stake in how well this process works? For example, safety, revenue, or legal compliance?

Q9. In this location, how many people are involved? Can you list the different jobs (or roles)? For example, in a restaurant, there might be a hostess, waiter, busboy, cook, cashier…)

Q10. For each of those jobs or roles, how many different individuals would you say are involved in doing this routine in your organization? For example, 2 hostesses, 12 waiters…

Q11. In how many different locations is this process performed?

PART 2: Break the process down into steps

Now I'd like to break this process down into steps. There may be quite a few steps, so we may need to go slowly. I appreciate your patience.

Q12. First, let's pin down the start and the finish

Q12a. What happens FIRST? How do you know the process has started?

Q12b. What happens LAST? How do you know it has ended?

Q13. Now talk me through again, but let's go a little slower so I can write down each step. As we go, try to think of "what happens next?" Once we've got the list, we'll go through it again and I'll ask if that *always* happens next, or if there are special cases, alternatives or exceptions.

[get the action list – next page]

ACTION LIST & SEQUENCE

PART 3: Identify the sequence of steps

Now let's go through it again and focus on sequence. And if I left out any steps, we can add those in.

Q14. Starting with the first action, what happens next? Is that always what happens, or are there alternatives or exceptions? If there is an alternative, let's not worry about how often it happens. Right now I want to know if it's possible for the sequence to go another way or not.

Q14a. Are there any branches in the process?

Q14b. Are there any loops in the process?

[Draw lines between the actions to indicate sequence, branches and loops and refine the action list]

Example of branches and loops:

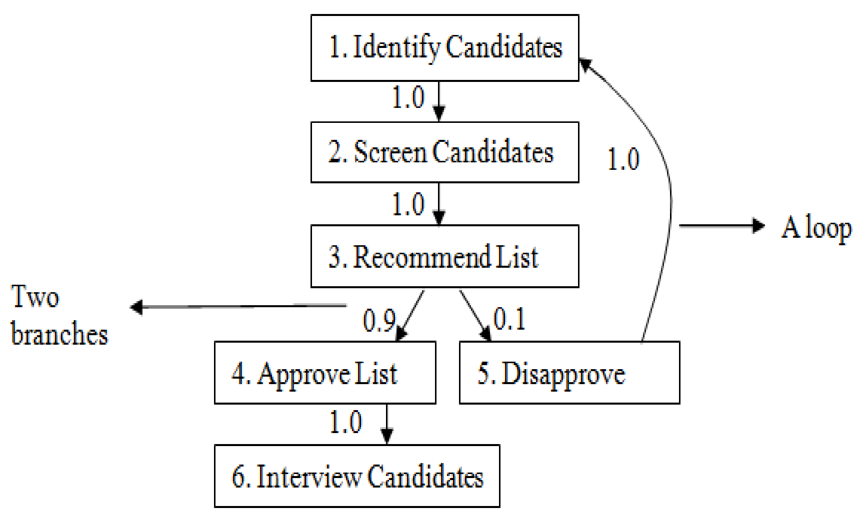


Figure 9: An example of two branches and one loop in academic hiring process

PART 4: Estimate the frequency of alternatives or exceptions

Q15. Now let's go through this one last time and focus on how *often* different alternatives happen. For each place where there is an alternative or exception, I'm going to ask you to estimate how often that happens. Try to make your best guess.

[Prompt with: 90-10? 80-20? 60-40? 50-50? Similarly for 3-way or 4-way branches.]

Q15a. For each step in the process, how varied is this step from situation to situation?

(from 0 to 100.)

Q15b. Is this step performed by people or by machine or by people using machine?

(IT, People or people using IT)

Q15c. Can this step (e.g. step 1) happen after the next steps (e.g. step 2, step 3, step 4 …)?

(please indicate which steps)

Q15d. How many other steps does this step depend on?

(from 0 to total number of steps)

Part 5: Measurements, incentives, and quality controls, if any

The hard part is over. Now I have a few quick questions about what the organization does, if anything, to make sure this process is working correctly.

Q16. Are there any measurements used to monitor this process (if any)? For example, time, cost, quality, waste?

Q17a. Are there any positive incentives to perform the process well?

Q17b. Are there any negative consequences if the process is performed poorly?

Q18. Is there a written checklist for this process? Yes / No

Q18a. If yes, is the checklist used while the process is being carried out? Yes / No

Q19. Is there a continuous improvement program in place, where the process is closely monitored (for example, Total Quality Management or Six Sigma)? Yes / No

Q20. Is this an ISO9000 certified organization?   Yes / No

Q21. When you do this work, how many previous situations do you keep in mind to help you do this work? (from 0 to .. ..)

Q22. If you know a better (cheaper, more efficient) way of doing this process, will you adopt it? (0 or 1)

Q23. How varied is the outcome of this process (a product or a service)? How many different products or services are based on this process? (from 0 to .. ..)

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