Digital Intensity and Variety in Design Routines *

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Abstract

Design routines are increasingly digitalized, but it is not clear whether this increased digital intensity will reduce, increase, or have no effect on routine variation. In this paper we report on a study of design routines across four organizational contexts to understand the effect of digital intensity on routine variation. By developing a view grounded in the Law of Requisite Variety, we sketch the foundation for the effect of theory of digital intensity on the “configural” variety of routines. That is, the variation associated with the socio-technical components of those routines. We test hypotheses through the application of a novel computational sequence analysis technique of four theoretically-sampled, world class organizations that design industrial products, semiconductor chips, software, and innovative buildings. Our findings suggest that digital intensity reduces configural variety in design routines in general and that this effect is moderated by different aspects of the design context. This research contributes to theoretical work on digitalization and design routines, contributes two new constructs and their operationalization (digital intensity and configural variety), and applies a novel computational mixed-methods approach.

Keywords: Digital intensity, configural variety, design routines, organizational routines, routine variation, sequence analysis, requisite variety

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Introduction

Design routines\(^1\) form a particular class of organizational routines that are concerned with mobilizing organizational knowledge to produce innovations. In this regard they are reproduced and evolving patterns of action (i.e., “routines” – see Pentland & Reuters 1994) that explicitly focus on visioning, shaping, and generating novel arrangements and artifacts (Simon 1996). Design routines are important for the study of innovation because they drive many innovation outcomes. Design routines are profoundly knowledge intensive, generative, and collaborative - they represent the key locus of change in organizational contexts (Farjoun 2010).

Today, design routines are enabled and supported by a rich variety of digital technologies (Bailey et al 2010). This has led many to refer to routines in terms of “sociomaterial ensembles,” to highlight that design activity is fundamentally intertwined with technological artifacts (Pentland et al 2011). The literature abounds with accounts of how digital technologies have been embedded in design routines and how they enable new forms of distributed collaboration, which results in new and diverse innovations (e.g. Argyres 1999; Malhotra et al 2001; Carlile 2002; Boland et al 2007; Bailey et al 2012). Although design routines are increasingly digitally-enabled, they vary in the scope and depth to which they appropriate and utilize digital technologies – what we call *digital intensity*. We define “digital intensity” as the overall portion of activity in a design routine that leverages digital artifacts.

Design routines vary in their digital intensity, and yet there is little work inquiring into the consequences of this variation in the composition and structuring of design routines. One dimension that is particularly relevant for the study of innovation involves the variety of the routines themselves. Drawing on cybernetic theory and the Law of Requisite Variety (Ashby 1956), if we were to conceive of a design routine as a form of complex “solution-generating system” (Beer 1979), one could argue that the number of states that are available to that system – the ‘variety’ of the system – would enable the system to solve more complex problems. Ashby’s Law of Requisite Variety indicated that a control system must have the same or a greater number of states (variety) than the controlled system in order to maintain stability of that system by “destroying” the variety in that system. In a design context, we are generally not referring to controlling a system or destroying variety, but instead looking to solve complex

\(^1\) Here we use the term “design” in a very general sense – as the process of transforming existing situations into more desirable ones (Simon 1996). As such, design routines can refer to product design and development, software engineering, architectural design, process improvement, etc.
problems through creative solutions. Thus we are looking to generate variety in order to match the variety of a problem. This formulation is consistent with Stafford Beer’s (1967, 1979) characterization of requisite variety. Rather than variety destroying variety, Beer (1979) indicated that variety “absorbs” variety.

As digitalization of design routines inevitably advances (Yoo et al 2012), the question we face is this: *does increased digital intensity in design routines result in more or less variety in those routines?* Put another way, does increased digital intensity make the routine more repetitive, or does it introduce greater variation in the routine? The existing literature is inconclusive in this regard. On one hand, digital technologies have been shown to consolidate tasks thereby reducing routine variation; on the other hand, digital technologies also expand capabilities thereby increasing routine variation (Pentland and Feldman 2005; 2008). One reason for this ambiguity is that the presence of digital elements in a routine has been treated in a relatively simple manner as a mere ‘presence’ or ‘absence’ of digital technology in the context where the routine is enacted. No measures have been developed to investigate where and how digital technologies enter into actual routine compositions. Consequently, we lack good measures of a routine’s digital intensity across different aspects of design activity. Not surprisingly, in the research that has been produced on the effects of digitalization, results about the effects of digital technologies are inconclusive.

Further, the answer to the effect of digitalization on routine variety may depend on a number of other conditions. For example, is the relationship between digital intensity and routine variety similar within organizations? Within particular organizational structures? Within similar product environments? Broad analyses into patterns of activity associated with routines are still in their nascent stage, and answers to these sorts of questions until recently seemed “a long way off” given the data and methodologies available (Pentland et al 2009). This, we contend, is no longer the case. A recently introduced computational approach for the study of organizational routines – “sociomaterial sequence analysis” (Gaskin et al forthcoming) – offers a new avenue for addressing these questions and engaging in related theory development.

In this study, we will make initial steps in addressing these questions and building associated theory. In particular, we investigate whether increased digital intensity in design routines have the general effect of increasing or reducing the variety of those routines. To measure the variety of a design routine, we develop and instrument the construct of *configural variety*. Configural variety refers to the variation in the composition of sociomaterial routines. We develop
configural variety as a meaningful way to operationalize variety in a design context. Our aim is to sketch an outline of an initial theory of the effects of digitalization on “configural” routine variety in different contexts. To this end we examine the effect of digital intensity on configural variety in four different contexts that vary across the environmental and organizational dimensions of: (1) greater and lesser environmental volatility (frequency of product and market fluctuations); and (2) more or less centralized decision structures (hierarchical versus networked). Drawing on Stafford Beer’s (1979) adaptation of the Law of Requisite Variety (Ashby 1956), we characterize these four contexts as either ‘variety matching’ (turbulent and networked; not turbulent and centralized), ‘variety attenuating’ (turbulent and centralized), and ‘variety amplifying’ (not turbulent and networked). Using this theoretical lens, we explore the influence of these environmental and organizational factors on routine variation by conducting theory-driven comparative, exploratory case studies in four complex organizations that design, develop, and engineer: (1) industrial products, (2) semiconductor chips, (3) software, and (4) innovative architecture.

Overall, we find that digital intensity tends to reduce design routine configural variety, suggesting that the impacts of digital technologies generally involve standardizing design tasks. In variety-attenuating design contexts, digital intensity is associated with reduced configural variety, whereas in variety-amplifying contexts digital intensity is associated with greater configural variety. Finally, variety matching contexts tend to do both at different stages in the design process. Beyond the theoretical contributions, this work contributes to the organizational literature by articulating and operationalizing the constructs of “digital intensity” and “configural variety,” and by employing a novel sequence analytic technique (sociomaterial sequence analysis).

The remainder of the paper is organized as follows. First, we review research on organizational routines, digitally-enabled design, and variety. Second, we outline a theory of the effects of digital intensity on the configural variety based on selected organizational contingencies. Then we outline our research design and provide details of the analysis method used to validate the

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2 Another type of variety is sequential variety (Pentland 2003); i.e., how routines are temporally ordered and how this varies from one context to another. We focus on configural variety in this study because we view each routine as an independent problem-solving system, and the configural variety is intended to measure the number of potential problem-solving states for each routine. Sequential variety, on the other hand, allows for investigating the ordering of routines, but not the number of potential states associated with the routines themselves.
theory. We conclude by providing a critical summary of our findings and discussing future research.

Theory Review

Organizational Routines as a Unit of Analysis

Broadly, routines can be thought of as technologies or techniques for doing something (Nelson 2009); they constitute embedded physical and social mechanisms that underlie all work. Herein, *physical* technologies refer to the apparatus, inputs and outputs, and procedures employing these to control what gets done and how. *Social* technologies refer to the human side of work: social organization and collaboration (Nelson 2009). Seen this way, organizational routines can be seen as accumulated capabilities garnered through repeated behaviors, which reflect an organization’s strengths to employ its physical and social technologies. In this regard, routines exhibit the organizational analog of individual habitual behavior.

The persistence of routines and the fact that each routine does something specific means that routines can be treated as replicable and combinable modules that employees can flexibly mobilize in accomplishing their tasks (Hodgson 2009). Accordingly, sets of routines present in an organization can be viewed as a generative and dynamic system that helps increase the variety in the organization’s responses (Pentland and Feldman 2005). By reconfiguring routines, organizations can continuously adapt and respond to changes in their internal structures and external dynamics. To accomplish this, dynamic routines exhibit a recursive relationship with organizational memory. On one hand, routines are enabled by, transfer, and manifest organizational memory (Becker and Lazaric 2009). On the other hand, routines—as repeatable modules—would not exist without organizational memory. Without organizational memory, organizational processes would exhibit a similar structure only by coincidence. Routines also enhance organizational memory by modularizing (chunking) organizational techniques for getting things done (Nelson 2009; Nelson and Winter 1982). Lastly, organizational routines evince the presence of a successful organizational memory: a routine—especially an evolving one—provides evidence that the organization is not only remembering how work is done, but learning how to do it better (Hodgson 2009).

Overall, routines can be approached as reproduced and evolving patterns of organizational action (Pentland & Reuters 1994) where the relationship between organizational memory and routine change can be framed as an evolutionary process of variation, selection and retention (Miller et al. 2010a; Miller et al. 2010b). Routines are a source of both stability and change.
(Farjoun 2010) similar to a human genome: on one hand routines increase the potential for routine variation; on other hand, routines manifest and are outcomes of organizational memory and thus decrease variation.

Finally, routines vary in term of their structuring and formalization (Nelson and Winter 1982; Galbraith 1979). A majority of studies around routines and their change have been conducted in standardized, administrative contexts (Pentland et al. 2010) that rely in their routine execution on highly structured and formalized information systems (Berente 2008; Volkoff et al. 2007). These studies show a tight connection between routine generativity and environmental variation and demonstrate that routines likely vary as new organizational processes unfold (Pentland 1995; Pentland and Reuter 1994). However, a certain class of organizational routines is targeted toward intentionally changing existing situations to more desirable situations (Simon 1996). These routines differ from their administrative cousins, because they are intentionally generative. Here, the change is not only a by-product of adaptation to environment, but also the explicit goal of the routine’s enactment. We call such routines “design routines” and will next characterize such routines, followed by theorizing about the relationship between digital intensity and configural variety in design routines.

**Digitally-enabled Design Routines as Generative Patterns of Action**

Due to their pivotal role in enabling organizational change, routines have long been viewed as a germane mechanism for, or “locus” of organizational innovativeness (Nelson & Winter 1982; Becker et al 2006). Innovation generally results from an organization’s response to new internal or external circumstances. The class of organizational routines that we referred to above as “design routines,” is particularly important to such innovation (Farjoun 2010). Design routines are concerned with identifying, mobilizing, integrating, and enacting organizational knowledge to develop innovations. We define a design routine accordingly as an organizational task engagement and related behavioral episode, which transforms a diverse set of representational and knowledge inputs into material (e.g., a building or a car) or other representational outputs (e.g., programming code) (Boland et al. 2007; Yoo et al. 2006). Design routines mostly serve a single and specific functional goal – that of generating specific types of design artifacts (such as creating blueprints, validating them, or materializing them). Unlike administrative routines, such as payroll – that serve transactional and functional goals and are highly structured and thereby operate with clearly defined inputs, outputs and transformation rules – such design routines are more fluid. They must deal with unknown and diverse inputs and uncertain and diverse outputs that result from learning and environmental volatility (Cross et al. 1996; March
and Smith 1995). Consequently, they must deal with novel and often unknown transformation challenges under unknown goals and constraints (Cross 2001).

Today, design routines are enabled by an increasing variety of digital technologies. From the extant literature we can learn that digital technologies are embedded in all facets of design work – designers, indeed, use rich arrays of digital, in addition to non-digital, artifacts to carry out their work to produce design artifacts (Bucciarelli 1994; Bailey et al 2010; Baxter & Berente 2010; Boland et al 2007; Yoo et al 2010a). Furthermore, complex design tasks bring a variety of specialists together in cross-disciplinary teams where they must reconcile the abundance of diverse technologies and related cognitive models (Bailey et al 2010; Berente et al 2010). They must span the barriers to communication and differences in interests using digital artifacts as boundary objects (Boland & Tenkasi 1995; Carlile 2002). These two uses suggest that digital technologies act both as infrastructures for collaboration and serve as an interactive medium for design activity. In the former role, digital technologies enable collaboration necessary for large-scale design innovation across multiple groups and organizations (Argyres 1999; Carlile 2002; Yoo et al 2006). In the latter role, digital technologies diversify and accelerate generate-test cycles associated with the development of design artifacts (Baba & Nobeoka 1996; Avital & Te’eni 2009; Bailey et al 2012).

The growing role of digital artifacts in design work echoes the broader effects of digitalization in organizations and society (Yoo et al. 2010). By digitalization we mean “a socio-technical process of applying digitizing techniques to broader social and institutional contexts that render digital technologies infrastructural” (Tilson et al 2010 pp. 749). In contemporary organizations, there are few domains that are not in some way digitized – including design work. As digitalization progresses, digital artifacts will replace strictly physical artifacts with less frequency. Instead, new digital artifacts tend to replace previous generations of legacy systems (Baxter & Berente 2010). Together – both as infrastructures and as mediums of design work – multiple, diverse digital artifacts in design environments form ecologies that can trigger cascading innovations across design products, processes, and modes of organizing (Boland et al 2007; Bailey et al 2010).

To summarize, the question of the impact of digitalization in design no longer hinges upon whether design routines are digitally-enabled. Rather, the question is the overall degree to which routines are digitally-enabled – a concept we label as “digital intensity.” More precisely, the digital intensity of a design routine can be defined as the overall portion of activity in a design routine that involves the deployment of digital artifacts. The digital intensity of a
routine can be expected to be associated with the composition of the routine. Next we provide background for one measure of this composition, “configural variety,” by reviewing the Law of Requisite Variety.

**Configural Variety and the Law of Requisite Variety**

Generally speaking, more diverse, specialized designers with more accompanying technological artifacts in a routine would allow for more degrees of freedom to accomplish complex and innovative design tasks. Conversely, the fewer the specialists and associated technological ecologies brought to bear on a problem, the fewer degrees of freedom that the design group possesses to accomplish the design activity. This intuitive idea can be clarified by drawing on cybernetic systems theory and using Ross Ashby’s (1956) “Law of Requisite Variety.” According to Ashby (1956), the term “variety” can be used to describe the number of possible states of a set. A set with more variety has a greater “range of possibilities” (p.129). Cybernetic theory is all about controlling a system, and a system with a high degree of variety is a system with a large number of potential states. In order to stabilize and control such a system, the controller would need to match or surpass this number of states. Ashby referred to this type of control as a form of “destroying” the variety in the controlled system. Ashby’s use of the notion does not directly translate to design contexts because oftentimes designers do not wish to destroy variety but to nurture variety through generate-test cycles (Simon 1996). Design is not so much about control as it is about creative problem solving.

Stafford Beer (1967) reformulated the idea of requisite variety in a way that is directly applicable to design practice. Rather than variety destroying variety, Beer (1979) indicated that variety absorbs variety, and this formulation allows for open ended results associated with complex problem solving. In order to control – that is, solve – a complex problem with a great deal of variety, the problem solver must have an equal level of complexity (variety). Beer was concerned with avoiding simplistic solutions to complex problems and argued for thinking in terms of complex solution generators, where the solution-generating system must equal or exceed the variety of the problem (Beer 1979).

Beer indicated that two processes can take place to create requisite variety: attenuation and amplification. To attenuate variety, a system reduces its variety in order to simplify and become

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3 Ashby’s precise formulation of variety was whether “(1) the number of numbers in a set; or (2) the logarithm to the base 2 of the number, the context indicating the sense used” (1956, p.126). We interpret this second formulation to get at the “relative” element of our usage – more or less variety – rather than any raw number.
more manageable. To amplify variety, a system increases its degrees of freedom to accommodate greater variety in requirements (Beer 1979). A system developed to adapt to complex and changing situations can be described as a “variety generator” (Beer 1995). Design routines can be viewed as necessary forms of variety generation as their purpose explicitly involves addressing the changing complexity of the environment (the design problem) and changing something to address this variety – either through increasing (amplifying) the variety of existing situations to match the variety of the problem, or decreasing (attenuating) the variety of the situation and thus reducing the complexity which the design will address.

In addressing a design problem, design routines must satisfy performance and quality standards by operating within time and budgetary constraints while confronting significant novelty and complexity due to evolving and ambiguous design tasks (Clarkson and Eckert 2005). According to the Law of Requisite Variety, the design routine must attend to this variety in some way. The possible states of a design routine are a function of its key components: humans (specialist), artifacts, and activities. As noted, designers will draw upon a variety of physical and digital tools (Bucciarelli 1994), where each tool supports or enables some aspect of the design task and related knowledge creation and transfer (Boland et al. 2007). At each step, tools support the creation or modification of design representations such as drawings, sketches, diagrams, models, requirements and detailed design specifications. Design routines also mobilize heterogeneous actors including a myriad of design professionals, users, managers, and so on – each performing specialist activities. As a result, multiple representations need to traverse across and touch different actors while designers and other stakeholders deploy physical and digital artifacts to communicate and coordinate design knowledge (Rosenman and Gero 1996).

Overall, representations are highly critical to, and for, design routines, which, while being enacted, trigger constant iterative activities across and within representations – both individually and socially (Berente et al. 2009). Accordingly, the configurations of design routines directly relate to the potential states that a design routine – as a variety generating system – can generate. Routines involving more diverse elements (which include social elements such as disciplinary specialists, as well as material elements such as their assorted representations, digital artifacts, and related activities) are likely to generate a greater number of potential outcomes than those with fewer variation in routine elements. We refer to this

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4 Note that Beer’s viable systems model actually looks at organizational systems in terms of four nested systems, with the highest – the “brain” – involving adaptation to an unknowably changing environment. Here we describe just a single system – simplifying this model in order to highlight only the key concepts that apply to our theorizing.
diversity of routine elements as the “configural variety” of a routine. More specifically, we define 

\textit{configural variety as the number of distinct configuration of social and material elements that comprise a set of design routines that produce a design outcome.}

Thus far, we have identified two foundational concepts to analyze the effects of contemporary design routines: their “digital intensity,” which reflects the degree to which routines involve various digital artifacts, and their “configural variety”, which represent the degrees of design freedom associated with generating a design variety. Next we will bring the two together in an initial sketch of a theory of the effects of digitalization on design routine’s configural variety.

**Toward a Theory of Configural Variety & Digitalization**

Past studies show that digitalization can, on one hand, consolidate tasks and reduce variations, or on the other hand expand digital capabilities and increase variation (Pentland and Feldman 2005; Pentland and Feldman 2008). Thus, digitalization provides an occasion for bifurcate effects by potentially increasing \textit{and} decreasing configural variety.

Digital tools are generally thought to streamline processes and consolidate design work (Attaran 2003). As such, many digital design tools have become work-flow platforms on which multiple joint and distinct tasks can be orchestrated. In addition, such platforms can expand by adding new elements to design routines. For example, in architectural design practices, new breeds of design tools such as building information management (BIM) systems can now perform advanced design tasks (such as collision conflicts) that were only available by highly specialized computer-aided design (CAD) tools for specific trades in the past (Yoo et al. 2006). In addition, these generic tools can now be configured flexibly to perform many alternative design tasks. Compare this to the prior use of specialized analog tools (such as drawings or physical prototypes) which were well-suited mostly to a single type of functionality and were thus functionally “rigid” or “closed”. Given these differences, when digital tools increasingly became the primary instruments for, and a media of, design work, variety within the routine composition is likely to be low, given that a single tool can now perform multiple functions. Thus fewer tools will be needed to accomplish the work. Conversely, when physical tools supplement the use of digital tools, the design routine variety (configural variety) is likely to increase, because more tools will be required to perform the same amount of designing functionality. Thus we propose:
**H1. Increases in the digital intensity of design routines will reduce their configural variety.**

That digital intensity would be expected to reduce configural variety of design routines, however defensible theoretically, is a broad, sweeping argument. Context matters in the assessment of the impact of digital technologies. How then does context influence design routine variation? Do design routines within an organization in a given context share a more similar pattern than organizations in a different context? Do design routines within each design context share more similar patterns than across contexts? Next we will classify such contexts for design routines and theorize about the relationship of digital intensity and configural variety.

**Classifying Design Contexts for Design Routine Variation**

Design routines are enabled and constrained not only by the digital artifacts at hand, but also by path dependent organizational, institutional and environmental factors that constitute what we call a *design context*. One might expect the impact of digital intensity on the configural variety of design routines to differ in different contexts. The first relevant design context involves the organization itself. Design routines within an organization in a given context will share a more similar pattern within their design routines when compared with routines from a different organization in another context. Routines within an organization operate with more similar organizational memory, culture, and environmental pressure due to path dependency (Becker and Lazaric 2009; Miller et al. 2010a; Miller et al. 2010b), thus reducing routine variety and promoting stability (Pentland 1995). Thus we propose:

**H2. Design routines vary less within an organization than across organizations.**

Beyond the bounds of an organization, we additionally consider two organizational dimensions – one internal and one environmental – that are expected to influence design routine variety in a given design context. These are *decision centrality* for the internal dimension and *environmental volatility* for the environmental dimension. We use decision centrality to refer to the extent to which the control of the design process is vested to a central body in contrast to a distributed authority. We use environmental volatility to refer to technology, industry, market volatility and associated levels of uncertainty surrounding the design process. We focus on decision centrality and environmental volatility in the context of design organizations for the following two reasons. First, these two dimensions of design contingencies are found in varying combinations in every design organization. Second, there exists a relationship between
centralization and volatility; namely, more volatile environments tend to encourage less centralized structures due to information overload (Casson 1994).

Any investigation into the impacts of design routines should address the issues related to design control; i.e., the allocation and exercise of rights to make decisions about the structure or features of the design artifact, or the design process. We chose this dimension, because more centralized decision authority is highly likely to dictate ostensive rules that control routine variation and also rules and norms that define specific criteria for the design outcome, thereby influencing routine composition (Galbraith 1973; Pentland and Feldman 2005; Volkoff et al. 2007). Design control has, therefore, traditionally been conceived to be synonymous with managerial prerogative (Yates and Project 1989), but will bear a markedly different character depending upon where the control is located along the continuum of decision centralization. This control may also change from time to time, or from project to project.

In general, the study of design control involves a broad understanding of the impacts of organizational structure, norms, and micro-level power in organizational behavior – like design work (Clegg et al. 2006). Organizations are generally thought to operate somewhere along a continuum, with centralized hierarchical organizational forms at the one extreme, and egalitarian networks at the other (Clegg et al. 2006). Due to the use of IT, firms can also act increasingly in combinations of the two forms of control, centralized and decentralized (what Clegg (2006) refers to as “polyarchies”). When examining decision centrality we need to focus on questions like: are decisions made top-down by a design manager, or are they made by consensus through a distributed network of minds?

We surmise that the structures and norms related to design processes are also conditioned by the environmental volatility of a given industry—a classic contingency factor in organizational research (Galbraith 1973; Lawrence and Lorsch 1967; Thompson 1967). In the case of design organizations, this involves the volatility of the design parameters, architectural principles and the level of uncertainty related to key design decisions and market demand. When examining environmental volatility we need to ask questions like: do the technologies underlying the product change fast or slow? Are there new variations in the products and product features? Do the consumers’ expectations change and at what rate? For example, a design organization that designs mobile phones operates in a more volatile environment than an organization that designs bicycles. Phone technologies, underlying service features and components and their interactions change constantly and rapidly; whereas bike technologies, features and components remain more constant. We predict that higher levels of technology, industry and market
volatility increase ambiguity and uncertainty about design decisions and their possible consequences. Accordingly we assume that design routines under higher levels of volatility need to respond to higher levels of variation in design outcomes and potential ways of reaching them – thus having the potential to influence routine variation.

Overall, by looking at both the centralization as well as the volatility of design tasks, we can identify four ‘Weberian’ ideal forms of design contexts: 1) stable hierarchical, 2) stable networked, 3) dynamic hierarchical and, 4) dynamic networked. Figure 1 describes the framework. As noted these classifications form a continuum. In addition, any design organization or its part may find itself crossing into different forms at different times.

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**Figure 1. Forms of Design Contexts**

In *stable hierarchical organizations*, design decisions are centrally made by a key design architect. Typically, these organizations execute well-defined design routines as they operate in relatively stable environments. We see this type of stable hierarchical design organization in manufacturing firms which design products for stable markets using mostly in-house resources. The designs are often based on a unique market niche or capability. Design projects that make tooling such as dies and molds might reflect stable hierarchical organizations. “X.T. Products” from Carlile (2002) is an example of such an organization. “X.T. Products (a pseudonym) designs and manufactures safety and environmental valves for automobile fuel systems and supplies them to both domestic and foreign automobile manufacturers.” In these cases, designers interact with customers in a limited set of ways and provide support for local manufacturing.

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5 These labels are for parsimony only. We recognize that stability and volatility are not attributes of the organization, but of the environment.
In stable networked organizations, design decisions are distributed among heterogeneous actors who typically represent different disciplines, trades or design communities. Some, but not all of these, may face rapid change. Teams in the Architecture, Engineering and Construction (AEC) industry, for example, typically operate in such stable networked design contexts. In a typical AEC project, an architect only provides “design intent” while design decisions are distributed as contractors and subcontractors decide how to build the building based on the design intent as represented in the initial design documents (Boland et al. 2007).

In dynamic hierarchical organizations, design decisions remain centrally controlled. These organizations, however, face much environmental unpredictability. Design organizations in the IT industry (such as microprocessor manufacturers or mobile phone manufacturers) fall into this category. The classical example is Apple and its hierarchical, relentless and highly focused design culture (Isaacson 2012). In order to execute the centrally made design decisions rapidly, these firms typically retain a repertoire of design routines and templates (Yoo et al. 2006) as they constantly enroll new knowledge resources while innovative requirements emerge and change (van der Merwe 2010).

Finally, in dynamic networked organizations, design decisions are distributed among heterogeneous and diverse actors where each group brings their own unique disciplinary knowledge to bear on a design task. In addition, new and changing knowledge resources are continually brought to bear in the design (Berente et al. 2010). In addition, each of these diverse actors faces rapid and unevenly distributed changes in their own disciplines (Yoo et al. 2008). Open-source communities are good examples of such dynamic networked design organizations. Several companies in the computer and IT industry can be found in this group (Galunic and Eisenhardt 2001).

We would expect routines between two centralized organizations to share more in common than routines between a centralized and a networked organization, because routines will be shaped in similar ways within a given decision structure (Casson 1994). Likewise, design routines within a volatile environment can be expected to demonstrate less variety when compared to each other than when compared to routines within a stable context (Galbraith 1973; Lawrence and Lorsch 1967; Thompson 1967). Next we develop hypotheses around centralized decision structures and environmental volatility.

**Centralized and Decentralized Structures**
Design routines within an organization in a given context will share a more similar pattern within their design. The impact of design contexts on the variations of design routines can be directly assessed by comparing the patterns of design routines along the two dimensions of volatility and decision centrality. Variation in routines is often conceptualized as organizational innovation (Nelson and Winter 1982; Nelson and Winter 2002; Pentland and Reuter 1994). Process innovations are changes to the way work is done, i.e., changes in organizational routines (Lyytinen and Rose 2003). In a meta-analysis of 23 studies of organizational innovation, Greenhalgh et al. (2004) found centralization to have a consistent negative effect on innovation—in other words, centralized organizations innovate less when it comes to processes. Decentralized, or networked, organizations are more likely to innovate because they draw upon a network of minds, each empowered to make decisions (Clegg et al. 2006). Therefore, their design routines are likely to vary more; whereas in centralized organizations, the design routines are more likely to follow ‘ostensive’ top-down guidelines, and thus to vary little from the espoused institutional rule. Additionally, centralized hierarchies enable task decomposition with limited access to information and autonomy (Radner 1992), which can reduce variation in routines. Thus we propose:

**H3a.** Configural variety in the design routines of organizations with centralized decision structures will be less than configural variety in the design routines of organizations with decentralized decision structures.

A moderating effect is suggested for decision centrality. We posit that the negative effect of digital intensity on routine variation will be more pronounced for centralized organizations than for networked organizations. Use of technology in centralized organizations tends to follow stricter procedures and is more tightly controlled either through organizational or software controls (Clegg et al. 2006; Orlikowski 2008). Therefore, the increased use of technology in centralized environments will have a strong negative effect on variation. Conversely, technology use in networked organizations is more often determined by the user, rather than by the institution, thus enabling a multiplicity of uses (Orlikowski 2008) that engenders variety. Therefore the consolidating and simplifying effect of increased digital intensity in networked organizations will be dampened by the less structured and less controlled nature of networked organizations. Thus we propose:

**H3b.** The negative effect of digital intensity on configural variety will be greater in organizations with more centralized decision structures than in organizations with decentralized decision structures.
**Environmental Volatility and Stability**

How do design routines within organizations operating in volatile environments compare to the patterns of routines within organizations operating in more stable environments? Environmental stability should be conducive to less experimentation and less frequent variation of design routines, because a predictable market requires little changes in processes with low levels of uncertainty (Damanpour and Gopalakrishnan 1998; Galbraith 1973; Peet and Watts 1996). Conversely, volatility in the environment will prevent organizations from sticking to what apparently works. Their change is compelled by external forces (Galbraith 1973; Hannan and Freeman 1977; Truex et al. 1999). Experimenting and making changes to routines is a risky move, but it is pursued because the market changes rapidly. Thus we hypothesize:

\[ H4a. \text{ Configural variety in the design routines of organizations operating in more volatile environments will be greater than configural variety in the design routines of organizations operating in more stable environments.} \]

We additionally explore how the impact of digital intensity on design routine variety is moderated by design context. Specifically, we expect that the effect of digital intensity on configural variety in a design routine in a volatile environment should have a more pronounced (stronger) effect than in a stable environment. In a volatile environment, the increased use of digital tools provides a way to simplify, standardize, and consolidate routines as a means to manage and counteract the volatility of the environment, and organizations that find themselves in the chaos of environmental turbulence are counseled to utilize technology for the sake of reigning in complexity (Ashkenas 2007; Ashkenas 2009; Keen 1987). Conversely, in stable environments, organizations often take advantage of increased use of digital technologies as a means to innovate by adding new capabilities to the tool belt of the organization (Cooper and Zmud 1990), and thereby add complexity to their organizational routines. Therefore, for organizations in stable environments, the consolidating and simplifying effect of increased digital intensity will be dampened by the ripples of using technology to innovate. Thus, we hypothesize:

\[ H4b. \text{ In the context of design routines, the negative effect of digital intensity on configural variety will be more pronounced in volatile environments than in more stable environments.} \]

**Variety Amplifying vs. Attenuating Organizations**


As noted, organizations can have a number of tactics for dealing with variety (Beer 1994). One approach is to attempt to match the variety with the appropriate organizational structure. For example, centralized, highly structured and bureaucratic forms of organization are well-suited to handling fairly stable environments (Mintzberg 1979). Standard processes and reporting structures do well to control the integrated machinery of stable work environments (Beer 1994). Similarly, less centralized, distributed organizational structures are well suited to more volatile contexts (Mintzberg 1979). Human intellect has higher variety than organizational processes and structures, and thus incorporating more distributed decision making can allow for the variety generation that volatile environments require (Beer 1994). We refer to each of these cases as “variety matching” contexts – where the organizational structure has the requisite variety for matching the volatility of the environment. Beer (1994) indicates, however, that in order to deal with complex situations, organizations may sometime wish to amplify the variety of the system in order to engage in more innovation and creativity than the environment requires – this could drive strategic advantage for firms who differentiate themselves based on more innovation in comparison with their peers. An example of such a “variety amplifying” organization would be one with a decentralized decision structure in a stable environment – stable networked organizations. Alternatively, organizations may deal with complexity by reducing the amount they deal with, essentially attenuating the variety of the environment through strict control of less of a variety. Beer refers to this as “variety attenuating.” An example of a variety attenuating situation could involve a highly centralized organization in a volatile environment – dynamic hierarchical organizations. Table 1 describes matching, amplifying and attenuating contexts.

<table>
<thead>
<tr>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variety Amplifying</td>
</tr>
<tr>
<td>Context where variety of the organizational structures are greater than typical for the environment</td>
</tr>
<tr>
<td>Strategy</td>
</tr>
<tr>
<td>Innovation / flexibility</td>
</tr>
<tr>
<td>Example</td>
</tr>
<tr>
<td>Stable Networked</td>
</tr>
</tbody>
</table>

An organization that seeks to amplify variety by its structure would seek to multiply the degrees of freedom in their design routines to generate a wider variety of solutions than the situation demands. Such organizations would extend the search space and engage in open-ended, exploratory activity (March 1991). Experimentation, iteration, and tactics for solution
generation beyond the requirements of a situation could be expected to run throughout the organization’s culture (Van de Ven 1986; Amabile et al 1996). This experimentation would be part of the organization’s “DNA” (Govindarajan & Trimble 2005). Managers that take a variety amplifying approach to solution generation would be more likely to use digital technologies to extend the degrees of freedom of a design effort. Therefore:

\[ H_{5a}. \text{Digital intensity in variety amplifying contexts will be positively associated with configural variety.} \]

Similarly, an organization in a variety attenuating situation is seeking to deal with a complex situation by reducing the degrees of freedom to which they attend (Beer 1994). In such a situation, the design routine as a solution generator will be targeted to a more focused search space, and exploit existing capabilities (March 1991). This organization would use digital technologies to streamline activity in accordance with centralized decision making in the organization. Therefore:

\[ H_{5b}. \text{Digital intensity in variety attenuating contexts will be negatively associated with configural variety.} \]

From this analysis of theory and literature, we have hypothesized a set of relationships between digital intensity and configural variety in a number of different contexts. Next we describe our empirical test of these hypotheses.

**Research Design**

**Exploratory Case Study**

Due to the lack of pertinent theory we adopted an exploratory multi-site case study approach (Yin 2011). We followed Eisenhardt’s (1989) recommendations for building generalizable theory from case study research following theoretical sampling (Eisenhardt 1989; Van de Ven 2007) based on the dependent variable (see Appendix B for a detailed explanation of our efforts). As the data collection efforts were guided by existing theory (Casson 1994; Galbraith 1973; Lawrence and Lorsch 1967; Thompson 1967; Yates and Project 1989), we sampled four design organizations that align well with the design contexts defined by (1) environmental volatility and (2) decision centrality. We next explain the sampling strategy and then discuss data collection and analysis.
**Sampling**

We sampled design process data reflecting routine variation from four large design organizations denoted next as Alpha, Beta, Delta, and Gamma (all pseudonyms). We selected one significant, successful and large project in each site. Each case reflects typical patterning of design routines for that type of design task as baseline for analyzing routine variation. In addition, they embed digital technologies to significant effect within the design process while representing essential and typical design tasks in their respective domains. All these projects also involved a large number of actors in the enactment of the design routines. Per Sydow et al. (2009), in terms of routine composition, each of the studied projects was in their formative stage, which means their routines could be expected to exhibit greater variation, as in each case, new digital capabilities were being embedded into the design processes. From the four cases, we captured 623 design routines, of which, 79% employed digital tools exclusively. Next we offer a brief description of the organizations and sampled design projects.

**Alpha: A Case of Stable Hierarchical Context**

Alpha Corp is a hydraulic design and manufacturing company specialized in designing and manufacturing hydraulic systems and their components – serving, among others, automotive and aerospace industries. Alpha represents a stable hierarchical organization as it designs most of its products in-house in hierarchically organized projects which may include some cross divisional and functional coordination. In 2009 Alpha finished designing a new and innovative hose system. The solution is thinner, stronger, and cheaper. The project began in 2007 and ran for about 2 years, and it involved around 5-6 different designers and experts. The project followed a stage-gate innovation process. The initial idea is refined through gates where, in each gate, the value and risk of the innovation is evaluated. The organization also uses a software supported environment for this process which extensively applies CAD/CAM tools, design repositories, and normal software suites (e.g., Excel). In addition, during this process hundreds of prototypes are fabricated according to specifications, and subjected to thorough testing. To reduce the number of tested prototypes, Finite Elements Analysis (FEA) tools were employed for the first time to eliminate infeasible prototype designs. The use of these new digital capabilities led to a product with characteristics (durability, thinness, cost) never achieved before. Lately, these new digital capabilities have become a fundamental element of design routines at Alpha.
Beta: A Case of Stable Networked Context

Beta Construction Company is a large, U.S.-based firm that designs and builds challenging structures and facilities for the advancement of modern society. Beta represents a stable networked organization as neither the architecture and components of the building, nor the market, has changed significantly over the last two decades. The company has built several challenging architectural designs by most revered architects including among others Frank Gehry, Danny Libeskind, and large civic structures like airports and museums, and challenging industrial structures like chip manufacturing plants. We selected a critical component in a large construction project – MEP coordination (Mechanical, Electrical, and Plumbing) – as the design process of interest. MEP always forms a critical path in complex construction projects. It is highly complex and potentially expensive (at roughly 30-35% of construction costs), because each subcontractor working on one technical subsystem (e.g., HVAC systems) must coordinate their work with other contractors, fitting the various MEP components together like one would fit together a three dimensional jigsaw puzzle. It is therefore also a design challenge that computer aided 3D virtual design has been able to simplify. Beta adopted virtual design practices in 2007 after completing successfully a large construction project that involved 3D capabilities. One area where it has used these capabilities since the beginning is the MEP coordination process. Beta has continuously changed this process over the past five years as new digital capabilities have been added, and old capabilities have been removed and replaced. Beta is still exploring within this process, adding and dropping tools and activities in order to find the best way to conduct virtual MEP coordination. Thus, we feel that MEP coordination at Beta is a prime candidate to examine for variation in design processes – it is explorative process innovation enabled by digital capabilities which is being constantly re-designed based on learning-by-trying. We sampled seven design processes that used MEP coordination dealing with complex building design between 2007-2011.

Gamma: A Case of Dynamic Hierarchical Context

Gamma is a large American OEM car manufacturer. Its operations are global and its design operations are also carried out in several parts of the world. Within Gamma we collected data from a large software development unit. This unit in Gamma represents a dynamic hierarchical design context (in contrast to other design units that design car components). This unit focuses on developing and integrating software that organizes all product information and associated processes for the OEM’s design and manufacturing. Because of this, the systems are large and complex and they touch nearly all parts of the organization. In this unit we followed the design
of a new Bill of Material (BOM) system which will integrate all product information from early concept design to manufacturing and maintenance. The project followed a traditional waterfall structure as dictated by Gamma’s life cycle development methodology that is founded on object oriented data modeling, use cases, and derivation of a software design architecture using object oriented design. The BOM project therefore followed sequential phases with gate decisions in between that involved gathering requirements, creating designs, coding and debugging, and testing the product. The final project also involved some iterations within development and testing phases. The project was initiated in the first quarter of 2009 and it was expected to enhance search in the BOM database. The project lasted for about two years. It is relatively large in size (over 20 man years), and its design and implementation involved 24 people working in two locations (U.S. and India).

**Delta: A Case of Dynamic Networked Context**

Delta Corporation is a leading semiconductor manufacturer. Here we followed one of the key design sites involved in the design of next generation microprocessor chips. The chip design involves all steps from initial concept development to designing the architecture and logic for the whole chip and its representation in silicon. This process takes around 36 months. We focused on the specification and design phase which covers around 18 months. Due to constant change and numerous design decisions distributed across a large number of design groups involved (logic design, physical design, validation, manufacturing), Delta represents a dynamic networked organization.

Based on Moore’s law, Delta uses a sequential two-stage design cycle model for systematically scaling up chip miniaturization. The first stage involves a design of new architecture (large architectural change), which typically involves 60-70% change in the functional logic of the microprocessor. The second stage involves optimizing the chip technology within an established architecture (local / process change). We collected data from the first type of design project (more challenging). The studied chip design consisted of multiple cores, which all included memory, central processor, caching, instruction fetching, and sequence optimization.

The chip design process consisted broadly of the following phases: (1) partitioning of the microprocessor into “chunks” or “modules”; (2) design process for changing functionality and control for each “chunk” (3) implementation (physical layout); and (4) integration (overall layout optimization). We collected data especially related to steps 2 and 3, where the key parts of the chip are designed. The data collection focused on designing and implementing one complex key chunk of the new architecture which dealt with instruction fetching, instruction pipelining
and memory caching. This chunk involved around 16 designers in two teams. The analysis followed typical design processes while following a structured data path design strategy. This strategy includes a significant amount of “handwork” in guiding the logic design and physical layout (for more detail see Choi et al 2011).

**Data collection**

A total of 51 interviews (of at least an hour each) were conducted to collect and validate design process data. All interviews were transcribed and then used as a reference to diagram the design projects as design process models. Archival data and observations were also utilized to triangulate the rendered process models. All models were validated with team leads at the respective organizations. For a summary of the project descriptions and associated data collection effort see Table 2.

<table>
<thead>
<tr>
<th>Organization: Industry</th>
<th>Project Description</th>
<th># of Interviews</th>
<th># of Interviewees</th>
<th>Duration of involvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha: Parts Manufacturing</td>
<td>New product development: Hose design</td>
<td>8</td>
<td>5</td>
<td>1/11/10 to 9/20/10</td>
</tr>
<tr>
<td>Beta: Construction</td>
<td>Virtual edifice design: MEP Coordination</td>
<td>6</td>
<td>5</td>
<td>3/30/10 to 4/13/11</td>
</tr>
<tr>
<td>Gamma: Automotive</td>
<td>Software development: “BOM Search”</td>
<td>17</td>
<td>14</td>
<td>1/13/10 to 12/6/10</td>
</tr>
<tr>
<td>Delta: Semiconductor computer chips</td>
<td>Chip Architecture</td>
<td>20</td>
<td>12</td>
<td>10/12/10 to 11/29/11</td>
</tr>
</tbody>
</table>

**Measurement**

The question next is how can we observe and tap into such configural variety? This demands that we observe key components in which a design routine can vary. Based on a review of the extant literature and field work we have solicited key varying elements of a design routine (Gaskin et al, forthcoming) i.e. its ‘genetic elements’ (Pentland and Feldman (2008). More specifically, a design process can be thought of as a sequence of routines that are necessary to complete a given design task. The routine’s elements are constitutive in the sense that without them, engaging in design would be impossible. Accordingly, we view routines through a genetic lens in a sense that the routines vary over time due to changes in participating elements and their composition. These variations are triggered by the changes in the environment or internal learning (such as adding new digital tools, inventing new design tasks, acquiring new skills etc.). Overall, routine elements and their compositions form “design DNA” that create the baseline for
routine variation (Gaskin et al forthcoming). In this “DNA” each design routine is a composition of seven components in that it is performed by some actors who consume and generate design artifacts by mobilizing some tools (Kock 2008). The tools—both physical and digital—are used to extend designer’s cognition and to generate alternatives (Boland and Tenkasi 1995; Simon 1996), or to communicate and coordinate activities (Malone and Crowston 1994), often as boundary objects (Carlile 2002). The tools accomplish this by enabling sets of affordances that are enacted by actors. Actors can be either individuals or groups, and they can be either collocated or distributed. All seven routine elements from Gaskin et al. (forthcoming) are summarized in Table 3.

<table>
<thead>
<tr>
<th>Element</th>
<th>Definition</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actor Configuration</td>
<td>The number and grouping of the actors involved in the activity</td>
<td>One individual</td>
</tr>
<tr>
<td>Activity Location</td>
<td>Where the activity takes place</td>
<td>Remote</td>
</tr>
<tr>
<td>Activity Type</td>
<td>The purpose of the activity</td>
<td>Validate</td>
</tr>
<tr>
<td>Tool Affordances</td>
<td>The specific way of appropriating the tool during the task execution</td>
<td>Analysis</td>
</tr>
<tr>
<td>Tool Modality</td>
<td>The underlying materiality of the functional affordances offered by the tool when carrying out the task</td>
<td>Digital</td>
</tr>
<tr>
<td>Design Artifact Type</td>
<td>The purpose of the artifact being used as an input, as being updated, or resulting as an output of an activity</td>
<td>Prototype</td>
</tr>
<tr>
<td>Data Flow</td>
<td>The use of an artifact in relation to a tool during a task</td>
<td>Input</td>
</tr>
</tbody>
</table>

Constructs like configural variety and digital intensity do not have well-known methods of measurement. For this simple reason we now offer a thorough discussion of how each of these constructs can be measured. We begin with configural variation, which takes two forms in our analysis: 1) variation between pairs of routines, and 2) variation from an entire set of routines.

**Variation between pairs of routines**

To validate our hypotheses, and advance a theory of routine variation, we have employed a sequence analysis method developed by Gaskin et al. (forthcoming) for analyzing routine variation between pairs of routines. This method treats representations of design routine components as “DNA” sequences. Accordingly, it uses a version of gene sequencing software, Clustal (Wilson 2001, 2006), to conduct multiple alignment sequence analysis through optimal matching for a set of routines. Principally, this method teases out how much variance there is between any pair of design activities in terms of their alignment within a set of routines.
One challenge in using this sequencing method is the articulation of taxonomy components that define and classify the routine elements. This articulation specifies: (1) what elements make up a routine, (2) how each element varies, and (3) how these routine elements relate to each other. Currently, the encoding method described by Gaskin et al. (forthcoming) identifies seven ‘genetic’ elements of design routines as shown in Table 3 above.

Following that taxonomy, we can encode routines (gleaned from interview data) into 7-tuples. Furthermore, all such routines and their compositions can be structured graphically into routine sequences; i.e., a sort of work-flow, which also permits the analysis of variety between routines (like iteration). This visualization capability (as shown in Figure 3) is currently implemented in MetaEdit+ (Jarke et al. 2010) – a visual meta-case environment. Thereafter the encoded routine data within MetaEdit+ can be structured into comparable raw routine sequences, much like the input for traditional (biological) DNA analysis. To illustrate, we may have the following pair of routines described in Table 4. The two routines in Table 4 differ only in regards to their tool affordance and dataflow. Thus, they are quite similar; i.e., there is not a lot of variation between them.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Activity Type</th>
<th>Configuration of Actors</th>
<th>Activity Location</th>
<th>Tool Modality</th>
<th>Tool Affordance</th>
<th>Artifact Type</th>
<th>Dataflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 Values</td>
<td>Generate</td>
<td>Many individuals</td>
<td>Colocated</td>
<td>Digital</td>
<td>Represent</td>
<td>Prototype</td>
<td>Output</td>
</tr>
<tr>
<td>R1 Codes</td>
<td>Gen</td>
<td>Inx</td>
<td>Col</td>
<td>Dig</td>
<td>Rep</td>
<td>Pro</td>
<td>Out</td>
</tr>
<tr>
<td>R1 Sequence</td>
<td></td>
<td>GenInxColDigRepProOut</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R2 Values</td>
<td>Generate</td>
<td>Many individuals</td>
<td>Colocated</td>
<td>Digital</td>
<td>Analysis</td>
<td>Prototype</td>
<td>Input</td>
</tr>
<tr>
<td>R2 Codes</td>
<td>Gen</td>
<td>Inx</td>
<td>Col</td>
<td>Dig</td>
<td>Ana</td>
<td>Pro</td>
<td>Inp</td>
</tr>
<tr>
<td>R2 Sequence</td>
<td></td>
<td>GenInxCodDigAnaProInp</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We will then analyze all sequences of design routines using ClustalTXY (Wilson 2006; Wilson et al. 2005; Winter and Szulanski 2001), a derivative of ClustalX and ClustalW (Larkin et al. 2007), both widely used biological sequence analysis applications to compare protein and nucleotide molecules (Aiyar 2000; Thompson et al. 2002). ClustalTXY is an expanded version that permits the analysis of multiple types of event sequences found in social sciences with varying base

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elements. The reliability of sequence analyses using Clustal has also been demonstrated by Wilson (2006).

To detect those variations, Clustal performs a pairwise alignment of the sequences. This is carried out by constructing a similarity matrix that is then converted into distance scores (for detailed computational method and algorithm see MacIndoe and Abbott (2004)). Next, Clustal compiles multiple alignments between pairs based on the branching pattern of a tree calculated from pairwise distances and other conventions that affect alignment scores (Wilson 2001), including a user-specified weight or cost matrix.

Variation from an entire set of routines

In H1, we explored whether an increase in digital intensity decreases design routine variety. Since digital intensity is inherent to a single routine, in order to determine the relationship between the digital intensity of a single routine and the variety of that routine, we must measure the variety of a single routine relative to a set of routines. To do this, we employed metric multidimensional scaling (MDS) (Borgatti et al. 2002; Cox and Cox 2001). A similarity matrix (produced in Clustal) is used as an input for MDS. MDS calculates coordinates for each routine in n-dimensional space that reduces the sum of squared residuals; thus, the Euclidean distance from an origin of (0,0) is a meaningful measure for the “raw” variance of a routine within a given set of routines (cf., Pentland et al. 2011). MDS then outputs an n-dimensional plot that minimizes the stress (residual sum of squares – something like “model fit”) (Kruskal 1964). Stress increases as the number of objects in the matrix increases, and it decreases with the number of dimensions used (Sturrock and Rocha 2000). In order to ease interpretation, we limited our analysis to a 2-dimensional plot. Our two-dimensional plot (Figure 1) resulted in a final stress of 0.338, well below the recommended minimum threshold for stress of 0.396 in 2D for a 100 object matrix (Sturrock and Rocha 2000). These results indicate that our complex plot, which included 623 objects, has less than a 1% chance of following a random structure (Sturrock and Rocha 2000) – i.e., it has a good fit.

7 For example, Wilson (2001) used Clustal to explore the variation in daily activity patterns among Canadian women using 3 base elements: activity type, location, and persons-present.

8 The weight matrix is used to specify scores or costs for aligning any pair of values from two sequences.
Our primary hypothesis requires us to determine the effects of digital embeddedness on the variation of routines. Therefore, in addition to calculating variation scores, we must be able to measure the level of digital intensity: the ratio of digital tools to total tools being used in a single routine. To illustrate how this value is calculated, consider Figure 2. Figure 2 illustrates three design routines. The first utilizes one digital tool and one physical tool (underlined at the bottom of the circles); thus, the digital intensity of this routine is equal to 0.50 (one digital tool divided by two total tools; $\frac{1}{2} = 0.50$). Accordingly, the second and third routines have digital intensity values equal to 0.33 and 1.00 respectively. With these methods of measurement accounted for, the tests for each hypothesis become rather straightforward.
Hypothesis Testing

With H1, we hypothesized that digital intensity would decrease routine variation. To test H1, we used the variation score obtained from MDS to perform a simple OLS regression with digital intensity as the predictor for observed variation.

With H2a, we hypothesized that design routines vary less within an organization than between organizations. The variation score was calculated for each organization by subtracting from 100% the average multiple alignment percent between all pairs of routines within that organization. The variation score between organizations was calculated by subtracting from 100% the average of the multiple alignment percent between all pairs of routines across both organizations (i.e., each pair included one routine from each of the two organizations being compared). In order to maintain consistency—comparing apples to apples—we included only scores between routines with the same type of activity. For example, we averaged the scores of
Generate activities with other Generate activities, but not with Validate activities. The total number of paired routine comparisons was 38,570 (see Table 5).

To test H2, an F-value was calculated for the differences in means between the paired variation score and the next closest variation score for each pair. Thus, to test whether the variation of routines at Alpha was greater than the variation of routines between Alpha and any other organization, we calculated an F-value for the difference between Alpha’s mean variation score and the mean variation score when paired with another organization.

With H3a and H4a, we hypothesized that, on average, routines would vary less in stable environments and under centralized decision structures. To test H3a and H4a, we simply averaged the variation scores for pairs of organizations. This approach does not make cross-organizational routine comparisons like H2. For H3a and H4a we only average the average variation scores from both organizations in the given context.

With H3b and 4b, we hypothesized about the moderating effect volatility and centrality would have on the relationship between digital intensity and routine variation. To test H3b and H4b we conducted a simple OLS regression to compute standardized coefficients and $R^2$ values for the effect of digital intensity on routine variation for each separate design context. We then employed the formula utilized by Kiel et al. (2000) to produce a t-statistic for the statistical difference between these effects.

With H5a and H5b we hypothesized about the different relationships digital intensity will have with configural variety depending on whether the context is variety amplifying or attenuating. Importantly, these two hypotheses account for these relationships over time. To do this, we divided each set of case data into 20 equal time periods. We then created averages for digital intensity as well as configural variety for each of the 20 time periods. To test the hypotheses, we conducted simple OLS regressions in each context and then examined the strength and direction of the effect.

**Findings**

Table 5 summarizes our hypotheses and the conclusions from our analysis of the data. This is followed by a description of how we reached these conclusions.
Table 6. Results Summary

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Description</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>Increase digital intensity -&gt; reduce configural variety</td>
<td>Supported</td>
</tr>
<tr>
<td>H2</td>
<td>Design routines within organization vary less than across organization</td>
<td>Supported</td>
</tr>
<tr>
<td>H3a</td>
<td>Design routines in centralized organizations will have less variety than networked organizations.</td>
<td>Supported</td>
</tr>
<tr>
<td>H3b</td>
<td>The negative effect of digital intensity on configural variety will be greater in centralized than network organizations.</td>
<td>Supported</td>
</tr>
<tr>
<td>H4a</td>
<td>Design routines in more volatile environments will have greater variety than stable environments.</td>
<td>Not Supported</td>
</tr>
<tr>
<td>H4b</td>
<td>The negative effect of digital intensity on configural variety will be greater in volatile than stable environments.</td>
<td>Supported</td>
</tr>
<tr>
<td>H5a</td>
<td>Digital intensity in variety amplifying contexts will be positively associated with configural variety.</td>
<td>Supported</td>
</tr>
<tr>
<td>H5b</td>
<td>Digital intensity in variety attenuating contexts will be negatively associated with configural variety.</td>
<td>Supported</td>
</tr>
</tbody>
</table>

Table 6 provides the basic descriptive statistics of our data. Keep in mind comparisons are only made between routines with similar activity types; thus, we cannot directly calculate the number of routine comparisons based on the number of routines (as the comparisons depend on the proportions of activity types).

Table 6. Descriptive Statistics

<table>
<thead>
<tr>
<th></th>
<th>Total number of routines</th>
<th>Count of routine comparisons</th>
<th>Average variation percent</th>
<th>Average standard deviation</th>
<th># of unique tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha</td>
<td>40</td>
<td>241</td>
<td>66%</td>
<td>0.140</td>
<td>27</td>
</tr>
<tr>
<td>Beta</td>
<td>131</td>
<td>2136</td>
<td>67%</td>
<td>0.152</td>
<td>26</td>
</tr>
<tr>
<td>Gamma</td>
<td>214</td>
<td>5027</td>
<td>69%</td>
<td>0.218</td>
<td>15</td>
</tr>
<tr>
<td>Delta</td>
<td>238</td>
<td>9440</td>
<td>96%</td>
<td>0.047</td>
<td>27</td>
</tr>
<tr>
<td>Alpha : Beta</td>
<td>171</td>
<td>1371</td>
<td>52%</td>
<td>0.139</td>
<td></td>
</tr>
<tr>
<td>Alpha : Delta</td>
<td>278</td>
<td>1661</td>
<td>54%</td>
<td>0.122</td>
<td></td>
</tr>
<tr>
<td>Alpha : Gamma</td>
<td>254</td>
<td>656</td>
<td>56%</td>
<td>0.085</td>
<td></td>
</tr>
<tr>
<td>Beta : Delta</td>
<td>369</td>
<td>4941</td>
<td>52%</td>
<td>0.146</td>
<td></td>
</tr>
<tr>
<td>Beta : Gamma</td>
<td>345</td>
<td>5113</td>
<td>52%</td>
<td>0.132</td>
<td></td>
</tr>
<tr>
<td>Delta : Gamma</td>
<td>452</td>
<td>7984</td>
<td>57%</td>
<td>0.101</td>
<td></td>
</tr>
</tbody>
</table>

The results support hypothesis H1, with a standardized regression coefficient of -0.368 (t=9.865, $R^2=0.135$, p<0.000). Thus, the more a routine was enabled by digital tools, the less
variety it displayed; whereas, the less it was enabled by digital means, the *more* configural variety it displayed.

Our results **support H2.** The analysis results are detailed in Appendix A and summarized in Table 6. In Table 6 the diagonal (within organization) percentages are, in all cases, less than the off-diagonal (cross-organization) percentages. The F-values for the difference between ranged from 167 to 3719⁹, and are thus all significant at p < 0.001.

**Table 6. Summary of Variation Within and Across Organizations**

<table>
<thead>
<tr>
<th></th>
<th>Alpha</th>
<th>Beta</th>
<th>Delta</th>
<th>Gamma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha</td>
<td>34%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beta</td>
<td>47%</td>
<td>33%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delta</td>
<td>44%</td>
<td>48%</td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td>Gamma</td>
<td>46%</td>
<td>48%</td>
<td>43%</td>
<td>31%</td>
</tr>
</tbody>
</table>

Our results show that organizations with similar contextual features consistently produce more similar patterns within the organization than when compared to organizations in different contexts. Incidentally, the abnormally low value for Delta is most certainly due to the iterative nature of their process. Delta engages in highly frequent iterations across sets of modularized routines, thus repeating the same set of routines in roughly the same way, many times over.

We next explored the impact of organizational decision structure on design routine varieties. Specifically, we hypothesized that decision centralization would decrease the variety in design routines. We found **support for H3a;** design routines vary less among centralized organizations (19%) than among networked organizations (32%). We also found that the negative effect of digital intensity on design routine variety was stronger in organizations with centralized decision structures (β=-0.584) than in organizations with decentralized decisions structures (β=-0.213); **supporting H3b** (see Table 7).

<table>
<thead>
<tr>
<th>Design context</th>
<th>Standardized Effect</th>
<th>R-squared</th>
<th>t-statistic for group differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Networked</td>
<td>-0.213***</td>
<td>0.045</td>
<td>2.843**</td>
</tr>
<tr>
<td>Centralized</td>
<td>-0.584***</td>
<td>0.341</td>
<td></td>
</tr>
<tr>
<td>Stable</td>
<td>-0.019</td>
<td>0.000</td>
<td>2.557*</td>
</tr>
<tr>
<td>Volatile</td>
<td>-0.504***</td>
<td>0.254</td>
<td></td>
</tr>
</tbody>
</table>

*** p-value < 0.001; ** p-value < 0.01; * p-value < 0.05

---

⁹ These values are quite high due to the large sample size.
We also found that design routines vary less for organizations in more volatile environments (average 17.5% variation within organization) than for organizations in more stable environments (34.5%); not supporting H4a. This discrepancy is discussed further in the next section. We also found that the negative effect of digital intensity on design routine variety was stronger in organizations operating in a more volatile environments ($\beta=-0.504$) than in organizations operating in more stable environments ($\beta=-0.019$); supporting H4b (see Table 7). For both H3b and H4b, in addition to the t-statistics to support the significance of the difference between the groups, we also observe the large difference between $R^2$. In networked and stable contexts the $R^2$ is minimal and without practical significance (despite statistical significance of the effect); whereas for centralized and volatile contexts the $R^2$ is distinctly larger and meaningful.

Figures 3a-d provide support for H5a and H5b. Specifically, variety amplifying contexts result in a strong positive correlation between digital intensity and configural variety; whereas, variety attenuating contexts result in a strong negative correlation. Interestingly, but not unexpectedly, the two firms in the variety matching contexts did not display any significant relationship between digital intensity and configural variety.

In testing H5a/b we also plotted out and visually inspected the results by standardizing the time frames. In visually inspecting these graphs, we find that in certain situations, the relationship between digital intensity and configural variety seems to change from the first portion of the process to latter portions. To test the significance of this observation, we conducted a post-hoc analysis to explore first-half/second-half relationships by dividing each set of routines in half and then performing the regression (see Table 8). While this leaves us with very small sample sizes ($n=10$ for each regression), we nevertheless arrive at some interesting results. Of particular interest, is that for Beta and Gamma, the signs for the relationship switch direction between first and second half.

<table>
<thead>
<tr>
<th>Organization (Type)</th>
<th>Beta first half</th>
<th>Beta second half</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha (Stable Hierarchical)</td>
<td>-0.202</td>
<td>-0.109</td>
<td>Weakened</td>
</tr>
<tr>
<td>Beta (Stable Networked)</td>
<td>0.612*</td>
<td>-0.265</td>
<td>Flipped</td>
</tr>
<tr>
<td>Delta (Dynamic Networked)</td>
<td>-0.869***</td>
<td>-0.962**</td>
<td>Strengthened</td>
</tr>
<tr>
<td>Gamma (Dynamic Hierarchical)</td>
<td>-0.513*</td>
<td>0.451</td>
<td>Flipped</td>
</tr>
</tbody>
</table>
Figure 3a. Variety Matching

Figure 3b. Variety Amplifying

Figure 3c. Variety Attenuating

Figure 3d. Variety Matching
Discussion

Two interrelated forces mark the contemporary organizational landscape: innovation and digitalization (Yoo et al 2012). Contemporary organizations need to continually innovate to survive, and the digital revolution is somehow complicit in accelerating the pace and transformational character of innovation in recent decades. Digital technologies as infrastructures enable the collaboration and coordination necessary for large-scale innovation across groups and organizations (Argyres 1999; Sambamurthy et al 2003; Yoo et al 2006) and digital technologies in the hands of with designers, developers, and engineers enable acceleration of generate-test cycles associated with development of innovative outcomes (Baba & Nobeoka 1996; Avital & Te’eni 2009; Bailey et al 2012). Together – as both infrastructures for collaborative innovation and artifacts supporting design work – multiple and various digital artifacts together form an ecology of digital technologies that enable cascading innovation across products, processes, and modes of organizing (Boland et al 2007; Bailey et al 2010). Existing research is abundant with examples of the role of digital technologies in fostering innovation.

The question becomes, however, whether digital technologies necessarily drive innovation. It is clear that digital technologies are inextricably implicated in organizational activity, but, to date, research does has not looked for broad patterns of the relationship between digital technologies and innovativeness. This may be due to a number of causes, including: (1) measuring innovation is very difficult. Innovation is a multidimensional concept that can refer to conceptions of novelty for the process, its output, or the impact of its output on a marketplace (e.g., Gatignon et al 2003). (2) The effect of digital technologies on design work is difficult to isolate. This is, in part, because the impact of digital technologies can involve a time lag of multiple years (Brynjolfsson & Hitt 2003). More importantly, however, all contemporary design work inevitably involves digital technologies – typically multiple digital technologies (Bailey et al 2010). Thus, isolating the effects of digital artifacts in empirical situations can be problematic. (3) Finally, analytic tools for understanding the shape of design practices in order to compare across context are still in their infancy (Pentland 2009). Thus, there is little to no work on the general conditions within which the digital technologies foster more or less innovativeness in design contexts.

In this paper, we investigate broad conditions for the impact of digital technologies on innovativeness in design work. As such we make a step toward resolving some of the issues associated with understanding the relationship of digital technologies on innovativeness. As such, we: (1) propose and develop the construct of “configural variety,” drawing upon Ashby’s
(1958) construct of requisite variety to understand the variety generating (i.e., more innovative) or variety limiting (i.e., less innovative) elements of design practice; (2) propose and develop the construct of “digital intensity” to conceptualize and measure the degree of digitalization in a design routine; and (3) draw upon a novel sociotechnical sequence analytic technique to measure the variety within and between routines.

Our first hypothesis, that digitalization reduces the configural variety of design routines was supported. This implies that the inclusion of digital technologies in design routines may broadly involve streamlining and consolidation of those routines. Reduction of variety limits the range of complex problems to which the routine can adequately attend (Beer 1979). One might consider this reduction of variety to move toward the “automate” end of the classic tension associated with the impact of information technology - between “automating” or “informating” organizational work (Zuboff 1988). However, this is not necessarily the case, because reduction of configural variety does not necessarily reduce the complexity to which a routine can attend if the digital technology offers a wide range of capabilities. A single, high-powered digital technology such as three-dimensional computer-aided design (Boland et al 2007) might allow for a variety of complex analyses. However, those analyses are limited to the capabilities of the program, and no single program – however powerful – can afford all of the capabilities contemporary designers require when engaged in complex design activity (Bucciarelli 1994; Bailey et al 2010). Unpacking the relationship between configural variety and the automating and informing character of digital technologies in design work is a next step for the analysis of design routines.

Our hypotheses regarding the contextual factors were also generally supported, indicating that organizational and environmental characteristics do matter when it comes to the impact of digital artifacts in design routines. However, H4a which involved volatile vs. stable environments was counter-supported. Perhaps the reason for the unexpected finding (routines in stable environments exhibit greater variety than in volatile environments) is that experimenting and making changes to routines is a risky move, especially when the market changes rapidly. Thus, organizations in volatile markets try to hold processes steady in order to balance out the instability in the market. This is consistent with the view that stability in one area of an organization allows for flexibility in another (Farjoun 2010). Take chip manufacturing for example—the type of work done at Delta. Chip manufacturing is a volatile market because new chips with new designs are constantly required to keep up with the demands of new software and of customers. Organizations cannot attend to the entirety of this volatile field, so they reduce the variety to which they attend by focusing more narrowly. The highly focused
attention of organizations such as Delta maintain a high degree of focused innovation to keep the pace of innovation in the environment at a high level. Because each design task forms important occasions to learn, due to their novelty, we see generativity as one source of variation in design routines. At the same time routines need to enforce stability, which is needed to create predictability and lower outcome variation across critical design dimensions. This raises the question: how stability and variability are both enabled and sustained through design routines and what factors affect these processes?

Using the metaphor of biological variation and change, one can characterize a design routine with this set of generative elements. Different compositions of these elements give birth to routine variation. Hereby, we can structurally delineate the extent of variation in the low-level design elements across each instance of a design routine. By doing so, we can show how alternative combinations of low-level design elements generate a range of variations in enacted design routines. This allows us to identify the organizational DNA of each design routine by showing how an organization’s design routines are the outcomes of combining and recombining, in situ, a limited set of genetic elements (Gaskin et al forthcoming).

Likewise, different design routines—characterized by different sequences of the same genetic elements—can be compared using computational techniques appropriate for sequential data analysis in biology. The evolutionary interpretation of organizational routines provides the theoretical backdrop to the inquiry that follows. It seeks to detect variation in design routines across design contexts where using the variation model underlying genetic analyses, we explore whether the growing embedding of digital capabilities influences variation in design routines, and whether changes in organizational contexts and environments influence the level of variation.

This work also lays the groundwork for theorizing into the attenuation of complexity (Beer 1994) as a viable approach to addressing a volatile situation. Organizations through their design routines need not attend to the entirety of the changing landscape, but only the portion on which they are focusing. Findings support this view – digital technologies our sampled “attenuating” organization was associated with reduced configural variety. Conversely, in the “amplifying” context we sampled an organization in the AEC industry where the pace of change is far more stable than semiconductors, but found that increased digitalization increases configural variety. This implies that in situations where the environment is stable, organizations that increase the variety of their routines to attend to more complexity than the environment, and thus innovate.
In this study we theoretically sampled four organizations based on the centralization of their decisions structures and the volatility of their environments. Findings generally supported our theorizing, but future research should do more to cast a broader net and look into a greater variety of organizations.

**Conclusion**

“Do different environments and organizations tend to produce the same patterns [in routines], or are there systematic differences? Do different organizations given similar environments, produce similar patterns? Are there characteristics of the persons or team responsible for the [routines] that may predict variation in patterns of actions? In other words, are routines shaped more by the external environment or by internal features of the organization? ...answers to these questions seem a long way off at the moment...” (Pentland et al. 2009).

Pentland et al. (2009) pose a question which we have sought to address: Do different environments and organizations tend to produce the same patterns, or are there systematic differences, and, do organizations in these environments use digital tools differently to shape their routines? In this paper we have addressed these questions by exploring how different environmental conditions and decision centralization shape routine variation. We have also examined how alternative configurations of actors, and the way they coordinate design, is carried out differently across different contexts due to digitalization. Lastly, we have explored the effects of digitalization on routine variation, and found that design routines executed primarily through digital tools exhibit less variation than when supplemented by physical tools, confirming the hypothesis of organizational standardization that is associated with the use of digital capabilities. We have moved forward our understanding of organizational routines by developing and validating a theory of organizational routine variation, and by highlighting how digital capabilities affect design routine variation.

We advance research focused on organizational routines by shedding new light on enacted design processes. This is in contrast to (normative) studies of ostensive routines that have dominated, for example, software engineering research (Brooks 2009). In particular, this is carried out through the use of sequence analysis techniques that recognize the effects of organizational context on routine variation. In doing so, we offer some initial answers to the questions posed by Pentland et al. (2009). We have also examined how alternative
configurations of actors, and the way they coordinate design, is carried out differently across different contexts due to digitalization.

Schumpeter believed that the understanding of innovation was the “greatest unmet scientific challenge” of our time, but he was never quite able to identify the specific mechanisms through which innovation comes about in organizational settings (Becker et al 2006). Organizational routines have since been proposed as those mechanisms that both transmit the historical and contextual knowledge of an organization, and at the same time evolve to accommodate and drive changes in the environment (Nelson & Winter 1982). Design routines are a particular class of routine that is particularly important to innovative activity (Farjoun 2010). Using a novel computational methodology, in this work we have moved our understanding of design routines one step further.

References

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Porter, M. E. *The technological dimension of competitive strategy* Division of Research, Graduate School of Business Administration, Harvard University, 1981.


### Appendix A: Detailed Percent Variation between Organizations

<table>
<thead>
<tr>
<th>Activity</th>
<th>Paired</th>
<th>Gamma</th>
<th>Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choose</td>
<td>56%</td>
<td>18%</td>
<td>0%</td>
</tr>
<tr>
<td>Execute</td>
<td>32%</td>
<td>29%</td>
<td>19%</td>
</tr>
<tr>
<td>Generate</td>
<td>26%</td>
<td>19%</td>
<td>0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Activity</th>
<th>Paired</th>
<th>Gamma</th>
<th>Beta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choose</td>
<td>-</td>
<td>18%</td>
<td>-</td>
</tr>
<tr>
<td>Execute</td>
<td>46%</td>
<td>29%</td>
<td>23%</td>
</tr>
<tr>
<td>Generate</td>
<td>44%</td>
<td>19%</td>
<td>43%</td>
</tr>
</tbody>
</table>
Appendix B: Summary of research design and method

Overall, Table 2 summarizes steps and associated deliverables in engaging in exploratory case study for explaining routine variation, which follows closely the recommendations of Eisenhardt (1989).

Table 2. Steps for Building Generalizable Theory for Routine Variation

<table>
<thead>
<tr>
<th>Research Step</th>
<th>Our Efforts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Explore constructs and questions of interest based on literature prior to making decisions regarding where/whom to sample.</td>
<td>We sought to analyze both external and internal factors for their effects on process variety. Accordingly we initially chose environmental volatility (external) and decision centralization (internal) as our primary antecedents. We desired to sample high performance organizations and highly digitally-enabled design processes to generate a plausible theory for the effects of digitalization.</td>
</tr>
<tr>
<td>2. Sample theoretically “useful” cases that fit into conceptual categories that will most likely maximize variance on the dependent variable.</td>
<td>We chose sites that fit into the 2x2 matrix that dichotomizes environmental volatility and decision centralization. We also chose the sites based on their high profile as design organizations and their extensive use of digital technologies.</td>
</tr>
</tbody>
</table>
selected cases from each site which were typical, significant, innovative and large enough to detect significant variation in design routines. We also sought to identify all routines from the start to the end of the design process. We were fortunate enough to obtain access to such appropriate cases from all four organizations.

3. Ground research in data by triangulating data collection using both quantitative and qualitative techniques.  
Our data collection included in-depth semi-structured interviews, observations, archival data, theme extraction, literature reviews, and self-reported recall data. These helped to maintain veracity and authenticity of recording the actual ‘enactment’ of routines. We engaged these approaches in several steps to guarantee the reliability and validity of the data (Silverman 2001). We used several coders to code the data into sequences and validated them with the participants. We deployed quantitative analysis techniques based on event sequence methods to detect and analyze routine variation as explained above and interpreted these results in light of the qualitative data and participant reports.

4. Overlap the collection and analysis of data in order to refine data collection approach so that the most useful\(^\text{10}\) data is gathered.  
We conducted multiple rounds of data collection and analysis for each case. After each site visit, data was analyzed and sent for feedback and interpretation, and accordingly our models were refined. When necessary, protocols were adjusted for subsequent site visits in order to ensure we would obtain data for each construct that would best explain the phenomena we sought to understand.

5. Once data is collected, conduct within-case and across-case analyses to extract patterns of similarity and divergence between the cases.  
Our theorizing and analysis in the current paper reflect this effort. We used the 2x2 sampling and analysis matrix as a baseline for pairwise comparisons across cases. We have reported the within case comparisons at more detailed level in other publications.

6. Iteratively tabulate evidence for each construct in a search for the reasons behind observed patterns.  
Discovered patterns directed further investigations into the interviews and into the diagramed processes in order to discover the reasons behind the observed patterns. These further investigations prompted new forms of analysis which required new constructs, measures, and techniques to explain these patterns and to obtain accurate estimates.

7. Compare findings to supporting and disconfirming literature in order to position, validate, and We supported our initial theorizing using the extant literature. Insofar as our theorizing and results differ from accepted assumptions or prevalent thought, we explain the reasons for

\(^{10}\) “Useful” data is not meant to imply ‘data that will support my a priori theory’. Useful means data that exhibits variance and patterns that will help researchers develop new and generalizable theory.
make more generalizable the theory.

choosing our position based on our field observations. Insofar as our results disconfirm our own theorizing (see H2a), we returned to the literature to seek potential explanations for such discrepancies.

| 8. Stop data collection and analysis when theoretical saturation has been reached (i.e., when additional efforts provide only marginal improvements). | This was done through iterative cycles of data collection and validation at each organization. After data was collected and diagramed, it was presented back to the participating organization for validation. This iterative process continued until we arrived at a final validated model. |

Appendix C: Barriers to measuring routine variation

One challenge in the study of routine variation has been the lack of methods to detect variation in organizational behaviors (routines) in the similar manner sociometrics or psychometrics capture variation in social structures or attitudes (Shadish et al 2001; de Vellis 2003). Variation in organizational routines is difficult to detect and analyze for three reasons. First, the concept of ‘organizational routine’ has, until recently, remained obscure and nebulously defined (Hodgson 2009). Second, the correct granularity and appropriate way to detect and classify routines and identify their elements as foundation for variation has been lacking (Pentland et al. 2009). This has made it difficult to systematically observe variation in routines, and henceforth theorize around the nature and sources of this variation.

These two issues — taxonomy and granularity — form a ‘catch 22’. Should organizational routines be captured at the activity level or just include specific types of activities? Or, should we also capture information about the actors, their roles, the tools they use, the methods they use for collaborating, before defining a routine? Or, should we capture more granular information about data flow, design objects, and even algorithmic processes before settling for the concept of routine? On one hand settling on a specific level of granularity is difficult without first advancing a justified taxonomy of organizational routines. On the other hand developing taxonomy requires a prior decision on granularity. No definitive solution to this dilemma has yet to emerge. To overcome it this research, some (Gaskin et al. 2010; Gaskin et al. 2011; Salvato and Rerup 2011) have emphasized flexibility in resolving this issue and argue for the benefits of having multi-level granularity, or, multi-level analysis. This has triggered the need to capture increasingly detailed contextual information on how routines and their elements
are composed – as a means to detect richer nuances in systematic variation and build higher level abstractions of them.

The third barrier in the study of routine variation deals with methods of analyzing variation in routines. Until recently, the primary methods for collecting data and analyzing routines was qualitative observations and narratives (Becker and Lazaric 2009). These rich micro-level idiographic accounts (e.g., Henderson 1991; Majchrzak et al. 2000) neither detect the systematically varying patterns of routines across multiple contexts nor help to understand the long-term changes which seemingly innocent local changes in routine composition—such as employing a simple digital tool in one routine—have on shaping configural variety in routines. Similarly, the dominant variance-based measurement approaches that rely on psychometric or econometric techniques (e.g., Massini et al. 2005) are inadequate. Due to their perceptual nature and use of simple scales (like Likert scales) they fail to systematically account for routine variation in that they offer a limited ‘perceptual’ window to tap into true process variation which is fundamentally defined by how routines are composed and how these compositions vary over time and space (Mohr 1982). Consequently, traditional variance-based measurement approaches used in social science are inadequate to capture and compare, either systematically or in a scalable way, variety in routines.

Recent advances in computational sequence analytic techniques that emerged in genetics and genomics in the 1980’s, however, combined with advances in digital tracing techniques (computer logs) can provide one means for rigorous and extensive quantitative analyses of routine variation (Gaskin et al. 2010; Pentland et al. 2009; Salvato 2009a, b). For example, Pentland et al. (2009) recently analyzed structural variation of workflows associated with over 2000 invoicing processes in a single organization. Their analysis covers descriptive statistics, formal network analysis of flow structure, and sequence analysis to detect variation in invoicing sequences. Sequence analysis, in particular, offers novel insights into routine variation, including the detection of patterns of similarity or difference between multiple sequences of routines or routine components, or comparisons of their sequential ordering.
Appendix D. Affordances and Tool Modality

We further explored, through descriptive statistics, what each type of tool was used for at each organization. Table 4 shows for each affordance, what proportion of the design work is performed using digital or physical tools.

Table 4. Percent Affordance Enacted through Digital or Physical Modality

<table>
<thead>
<tr>
<th></th>
<th>Analysis</th>
<th>Control</th>
<th>Coop</th>
<th>Represent</th>
<th>Storage</th>
<th>Transform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digital</td>
<td>60%</td>
<td>-</td>
<td>90%</td>
<td>100%</td>
<td>100%</td>
<td>40%</td>
</tr>
<tr>
<td>Physical</td>
<td>40%</td>
<td>-</td>
<td>10%</td>
<td>0%</td>
<td>0%</td>
<td>60%</td>
</tr>
<tr>
<td>Beta</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digital</td>
<td>86%</td>
<td>100%</td>
<td>60%</td>
<td>83%</td>
<td>95%</td>
<td>88%</td>
</tr>
<tr>
<td>Physical</td>
<td>14%</td>
<td>0%</td>
<td>40%</td>
<td>17%</td>
<td>5%</td>
<td>12%</td>
</tr>
<tr>
<td>Delta</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digital</td>
<td>87%</td>
<td>100%</td>
<td>87%</td>
<td>20%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Physical</td>
<td>13%</td>
<td>0%</td>
<td>13%</td>
<td>80%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Gamma</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digital</td>
<td>95%</td>
<td>-</td>
<td>92%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Physical</td>
<td>5%</td>
<td>-</td>
<td>8%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>