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THEORY & REVIEW

UNIFYING THE ROLE OF IT IN HYPERTURBULENCE AND COMPETITIVE ADVANTAGE VIA A MULTILEVEL PERSPECTIVE OF IS STRATEGY

Ning Nan

Management Information Systems Division, Sauder School of Business, The University of British Columbia,
2053 Main Mall, Vancouver BC V6T 1Z2 CANADA {ning.nan@sauder.ubc.ca}

Hüseyin Tanriverdi

Department of Information, Risk, and Operations Management, Red McCombs School of Business,
The University of Texas at Austin, Austin, TX 78712 U.S.A. {huseyin.tanriverdi@mccombs.utexas.edu}

Appendix A

Overview of IS Strategy Literature Streams

Literature Stream	Sample References	Level of Analysis	Main Arguments	How Is it Synthesized into Our Theorization?
IT and industry competitiveness	Fine 1998; Mendelson and Pillai 1998; McAfee and Brynjolfsson 2008	Collective (industry)	Turbulences in a competitive environment can be endogenously generated from IT-based firm strategic actions.	It provides the foundation for the collective-level conception in our multilevel perspective.
IT-business alignment	Benbya and McKelvey 2006; Tanriverdi et al. 2010; Vessey and Ward 2013	Collective and firm	A co-evolutionary theoretical lens is appropriate for capturing the dynamic nonlinear relationships between turbulent environments and business strategy, as well as IT's role in supporting business strategy.	It provides the foundation for a bi-directional (coevolutionary) causal relationship between hyperturbulence and firm strategic actions, and the changing role of IT to enable competitive advantage.
Resource-based view of IT	Nevo and Wade 2010; Wade and Hulland 2004	Firm	IT is manifested by specific firm assets and enterprise information systems.	It provides the foundation for our conception of component IT innovation.
Digital innovation	Tiwana et al. 2010; Yoo et al. 2010	Firm (product)	Digital innovation allows business products and processes to continuously create and recreate themselves by combining modularized productive means via standardized interfaces.	It provides the foundation for our conception of architecture IT innovation.
Dynamic capabilities	El Sawy et al. 2010	Firm	Turbulent environments require dynamic and improvisational capabilities.	It provides the foundation for our conception of firm adaptive capabilities.

Literature Stream	Sample References	Level of Analysis	Main Arguments	How Is it Synthesized into Our Theorization?
Enterprise Agility	Sambamurthy et al. 2003; Overby et al. 2006; van Oosterhout et al. 2006	Firm	Agility is an important subset of dynamic capabilities. It's the ability to sense and respond to changes in the environment.	It provides the foundation for our conception of the opportunity for IT to contribute to firm adaptive capabilities and ultimately competitive advantage.
Digital options	Sambamurthy et al. 2003	Firm	Digital options are building blocks of dynamic capabilities. They coevolve with agility.	It provides the foundation for our conception of firm adaptive capabilities and ABM representation of productive means.
Competitive intelligence	Pant and Sheng 2015; Zheng et al. 2012	Firm	Competitive intelligence is integral to the sensing component of agility. It can help firms to more accurately identify the changes in the competitive landscape	It provides the foundation for our conception of the opportunity for IT to contribute to firm adaptive capabilities and ultimately competitive advantage.
Absorptive capacity	Cohen and Levinthal 1990	Firm	Absorptive capacity is integral to dynamic capabilities. It is the continuous acquisition, search, management of knowledge.	It provides the foundation for our conception of the ongoing and recurrent applications of firm adaptive capabilities.
Strategy search as hill climbing (NK model)	Levinthal 1997; McKelvey 1999	Collective and firm	A firm's effort to coevolve with competitive environment can be visualized as hill climbing in a rugged landscape.	It provides the foundation for our conception and ABM representation of firm adaptive capability and strategic interaction.

Appendix B

Agent-Based Model Validation and Sensitivity Analysis

We took three actions to ensure validity of our agent-based model design. First, we chose conservative parameter values so that without experimental treatments the baseline parameter setting alone is unlikely to produce the expected simulation results. For example, previous agent-based strategy modeling research (e.g., Ethiraj and Levinthal 2004; Ethiraj et al. 2008; Levinthal 1997; Rivkin and Siggelkow 2007) showed that the number of interconnection links among productive means is positively related to the difficulty for firms to achieve and maintain superior performance. By restricting the initial value of interconnection links to small numbers (1 interfirm link and 2 intra-firm links) we can attribute simulation results to the theoretical propositions codified in the experimental treatments rather than the baseline parameter values.

Second, the simulation results regarding our P1 and P2 are qualitatively consistent with the well-known "creative destruction" argument (Schumpeter 1942) and IT's impact on industry competitiveness (McAfee and Brynjolfsson 2008) respectively. Furthermore, the probabilities for a firm to remain in a performance stratum in our simulation are quantitatively comparable (see Table B1 below) to those in the empirical study by Wiggins and Ruefli (2002). Consistent qualitative and quantitative results provide grounds for belief that the agent-based model can serve as a theorization tool for further development and testing of our propositions.

Finally, we performed sensitivity tests of the simulation results across a range of values for each parameter in the model. Results are summarized in the Table B2. These results indicate that qualitative insights from our model are robust against changes in parameter values.

Table B1. Probabilities for a Firm to Transit Between Performance Strata from One Time Period to the Next

From \ To	Top 15% Stratum	Middle 70% Stratum	Bottom 15% Stratum
Top 15% stratum	0.764 (0.784)	0.181 (0.195)	0.003 (0.021)
Middle 70% stratum	0.042 (0.038)	0.890 (0.919)	0.036 (0.042)
Bottom 15% stratum	0.015 (0.030)	0.208 (0.208)	0.847 (0.762)

Note: Numbers outside parentheses are simulation results while those in parentheses are from Table 7 in Wiggins and Ruefli (2002).

Table B2. Summary of Sensitivity Tests

Parameters	Values Tested	Results
Number of digits in a firm's string	• 20 • 60	Varied number of digits has no systematic effect on firm performance ranking change. Firm performance increases slightly with the number of nodes.
Number of intra-firm links and interfirm links originated from each digit	• 4 intra-firm and 1 interfirm links • 1 intra-firm and 4 interfirm links	The average firm performance ranking change increases with higher number of interfirm links. Firm performance increases slightly as the total number of links increases.
Number of firms	• 10 • 40	The average firm performance change increases with the number of firms. Varied number of firms has no systematic effect on firm performance.
Number of digits in each bundle of component IT innovations	• 10 • 40	The effect of component IT innovations on firm performance ranking change becomes slightly more pronounced with increased number of digits. Firm performance decreases with increased number of digits.
Number of links from each digit in a bundle of component IT innovation to existing digits in incumbent firms	• 2 • 5	Varied number of links from component IT innovations to incumbent firms has no systematic effect on firm performance ranking change. Firm performance increases with the increased number of links.
Digit values in a bundle of component IT innovation	• Randomly set at 0 or 1 with equal probability	The average firm performance ranking change is consistent the result from the initial value of all 1s (average ranking change from 0 to 8 innovations: 0.58, 0.68, 0.76, 0.90, 1.00, 1.14, 1.20, 1.37, 1.46).
Module size	• 2 • 10	The average firm performance ranking change reduces slightly as module size increases. Firm performance decrease slightly as module size increases.
Number of clock ticks in a simulation session	• 50 • 200	Effect of component IT innovations on firm performance ranking change diminishes with increased number of clock ticks. Architectural IT innovation's effect on firm performance ranking change does not diminish with increased clock ticks. Number of clock ticks has no systematic effect on firm performance.
Number of simulation sessions in each experimental condition	• 10 • 50 • 250	Number of simulation sessions has no systematic impact on firm performance ranking change or firm performance.

Appendix C

Post Hoc Analysis Results

		P3[†]	P3 Extension[†]	P3 Extension	P4	P4 Extension	P4 Extension
Number of component IT innovations	*β*	0.13	0.13	0.07	-0.03	-0.008	
	p	< 0.001	< 0.001	0.12	< 0.001	< 0.001	
Pervasiveness of architectural IT innovations	*β*	0.36	0.42		-0.01		0.02
	p	< 0.001	< 0.001		< 0.001		< 0.001
Number of component IT innovations * pervasiveness of architectural IT innovations	*β*	-0.02	-0.02				
	p	0.046	0.034				
(Number of component IT innovations)^2	*β*		-0.05	0.003			
	p		< 0.001	0.62			
(Number of component IT innovations)^2 * pervasiveness of architectural IT innovations	*β*		-0.01				
	p		0.055				
IT-enabled informational input	*β*				0.08	0.06	0.002
	p				< 0.001	< 0.001	0.73
Constant	*β*	3.61	3.96	0.56	0.58	0.62	0.56
	p	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
N		3025	3025	2707	3025	2707	2702
F		63.57	42.80	27.67	245.29	77.74	213.71
R^2		0.06	0.06	0.02	0.20	0.05	0.14

[†]Independent variables in these models are centered around mean to prevent the multicollinearity concern.
Dependent variable: the average firm performance ranking change in the collective of firms.

Appendix D

Pseudo-Code of the Agent-Based Model

Let the model user set the number of component IT innovations
\\ This is an experiment treatment for proposition testing

Let the model user set the pervasiveness of architectural IT innovations
\\ This is an experiment treatment for proposition testing

Let the model user set firm path creation to true or false
\\ This is an experiment treatment for the post hoc analysis of IT generativity

Let the model user set distributed tuning to true or false
\\ This is an experiment treatment for the post hoc analysis of IT generativity

Setup firms {
\\ This procedure creates firms and defines their attributes.
    Create 20 firms with each firm possessing 40 productive means (i.e., a string of 40 digits)
    Set the value of each digit in a firm's string as either 0 or 1 with equal probability
    Set IT-enabled information input of each firm as true or false with equal probability
}

Setup interconnection links {
\\ This procedure implements the pervasiveness of architectural IT innovation

    IF pervasiveness of architectural IT innovation > 0 [
    Set the number of repeats = pervasiveness of architectural IT innovation
    Repeat the number of repeats [
    Assign each firm's leftmost 5 digits that have not been assigned to a module to a new module
    ]

    ]
    Set K=2 + (pervasiveness of architectural IT innovation * 2)
    Ask each digit in a firm's string to create K outgoing links to digits in the same module
    IF there is no other digit left in the same module for links, set the outgoing links to digits outside the module
    Set each link as synergistic or conflicting with equal probability

    Set C= 1 + pervasiveness of architectural IT innovation
    Ask each digit in a firm's string to create C outgoing links to digits in other firms' corresponding modules (a corresponding model occupies the same digit positions as the focal digit's module)
    Set each link as synergistic or conflicting with equal probability
}

Setup fitness payoff schedule {
\\ This payoff schedule is unknown to firms.

    Ask each digit {
        For each of my outgoing link {
        If the link is synergistic [
        Set fitness (0, 0) = 0 \\ the first number in the parentheses is the focal digit's value,
        \\ the second number in the parentheses is the alter digit's value
        Set fitness (0,1) = a random number from [0,1] distribution
        Set fitness (1,0) = a random number from [0,1] distribution
        Set fitness (1,1) = fitness (0,1) + fitness (1,0) + a random number from [0,1] distribution
        ]

If the link is conflicting [
Set fitness (0,0) = 0
Set fitness (0,1) = a random number from [0,1] distribution
Set fitness (1,0) = a random number from [0,1] distribution
Set fitness (1,1) = a random number from [-2,0] distribution
]
}
}
}

Run one tick of the model clock {

IF number of component IT innovations > 0 [**Introduce-component-IT-innovation**]
IF number of component IT innovations > 0 and pervasiveness of architectural IT innovation > 0 and it is the 10^{th} clock tick [**Introduce-component-IT-innovation**]
Ask firms to [**Compete-and-adapt**] \\ call the Compete-and-adapt procedure
IF firm path creation is TRUE [**Path-creation**]
IF distributed tuning is TRUE [**Distributed-tuning**]

Record-result \\ call the Record-result procedure at the end of each simulation run
Tick \\ increase the internal clock ticks by one
}

Repeat [Run one tick of the model clock] 100 times \\ This produces recurrent firm strategic
\\ actions and the time paths of their nonlinear effects

Compete-and-adapt {
\\ This procedure implements a firm's behavioral rules: internal search, external imitation, and
\\ responding to innovations.
Randomize the order of executing the three behavioral rules below [
// below is the internal search rule
Ask each firm {
Choose a pair of digits in its string of digits
IF this firm has IT-enabled informational input
[**RESET** the values of the selected pair of digits according to the synergistic/conflicting nature of the interconnection link between them]
ELSE
[**RESET** the values of the selected pair of digits randomly]
If firm performance after resetting the pair of digits > firm performance before
[**Keep** the new values]
Else [revert to the previous values]
\\ end of the internal search rule.

\\ below is the external imitation rule
IF pervasiveness of architectural IT innovation > 0 [
ASK each firm [
Choose one of my modules as the to-be-replaced module
Select the set of other firms whose fitness is greater than mine
Select the exemplar modules that are in the selected firms, occupy the same digit positions as the to-be-replaced module, and have higher fitness than the to-to-replaced module
IF this firm has IT-enabled informational input
[**Select** the one exemplar module that has the best match in terms of distribution and nature of interconnection links]
ELSE
[**Select** one module randomly from all exemplar modules]
]
]
\\ end of the external imitation rule

```
        \\ below is the responding to component IT innovation rule
        IF number of component IT innovation > 0 [
        Ask each firm [
        IF this firm has IT-enabled informational input
        [RESET the values of the digits affected by a component IT innovation according to the synergistic/conflicting nature of the interconnection links between my digits and the component innovation's digits]
        ELSE
        [RESET the values of the digits affected by a component IT innovation randomly]
        ]
        ]
        \\ end of the responding to component IT innovation rule
        ]
        ]
    }
}

Path-creation {
    Ask each firm [
        Find low-performing digits whose fitness contributions are one standard deviation below the average fitness contributions of all digits in all firms
        Reset each low-performing digit value as either 0 or 1 with equal probability
        Reset each interconnection link of low-performing digits as synergistic or conflicting with equal probability
]
}

Distributed-tuning {
    Ask randomly selected 10% of all interconnection links [
        Find my equivalent links (i.e., links whose two node digits occupy the same digit positions as mine)
        Find the majority link nature of my equivalent links
        Reset my link nature to the majority link nature with 50% probability
]
}

Calculate-fitness {
    Set each digit's fitness contribution = MEAN (all this digit's outgoing links' actualized fitness values)
    ]
    Set each firm's fitness = MEAN (all this firm's digits' fitness values)
}

Introduce-component-IT-innovation {
    Create the model user specified number of component IT innovations [
    Create 5 digits in each component IT innovation [
    Set digit value to 1
    Create an outgoing link to a randomly selected digit in one of incumbent firms [
    Set the nature of the outgoing link to conflicting
    ]
    ]
    ]
}

Record-result {
\\ This procedure will specify all the data values we want to collect from the simulations.
    Record each firm's performance ranking
    Record each firm's fitness
    Record number of digit value changes in each firm
    Record current experimental treatment
    Record current clock tick
}
```

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