Internet Appendix to "Labor-Technology Substitution: Implications for Asset Pricing"

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Abstract

This appendix is divided into two sections. The first section provides supplementary tables. The section section develops and calibrates an extended model of the "technology-switching" model presented in Section I of the main text.

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A. Supplementary Tables

Table A.1
Most and Least Routine Occupations

This table reports the 10 occupations with the highest routine-task intensity scores and the 10 occupations with the lowest, as of 2014.

SOC	Occupation Title	RTI Score
	Panel A: Top 10 Occupations with the Highest Routine-Task Intensity Score	
43-9051	Mail Clerks and Mail Machine Operators, Except Postal Service	1.66
43-4071	File Clerks	1.65
51-9031	Cutters and Trimmers, Hand	1.64
51-3093	Food Cooking Machine Operators and Tenders	1.62
51-9022	Grinding and Polishing Workers, Hand	1.61
51-6062	Textile Cutting Machine Setters, Operators, and Tenders	1.57
43-6012	Legal Secretaries	1.54
43-4021	Correspondence Clerks	1.47
53-7011	Conveyor Operators and Tenders	1.47
23-2091	Court Reporters	1.42
	Panel B: Bottom 10 Occupations with the Lowest Routine-Task Intensity Score	
39-9031	Fitness Trainers and Aerobics Instructors	-2.98
33-1021	First-Line Supervisors of Fire Fighting and Prevention Workers	-2.95
17-2021	Agricultural Engineers	-2.73
19-3092	Geographers	-2.73
11-9021	Construction Managers	-2.61
13-1141	Compensation, Benefits, and Job Analysis Specialists	-2.53
21-1094	Community Health Workers	-2.53
53-5031	Ship Engineers	-2.41
25-2012	Kindergarten Teachers, Except Special Education	-2.38
53-4011	Locomotive Engineers	-2.28

Table A.2
Robustness for Table 3: Diff-in-Diffs Tests Around Recessions

This table reports the difference-in-differences results of investment in machines before and after the 2001 and the 2008-2009 recessions for firms with difference share of routine-task labor, *RShare*. The dependent variable is *Investment in Machines*, which is the real growth rate of machinery and equipment at cost (Compustat item FATE). *RShare* is the ratio of the firm's total wage expense on routine-task labor relative to its total wage expense, and it is defined in the year before the recessions, i.e., 2000 and 2007. $Post_t$ is a dummy variable that equals 1 if the year is within one, two, or three years after the beginning of recessions (including the recession year), and 0 if the year is within one, two, or three years before recessions, for results in columns (1) to (2), (3) to (4), and (5) to (6), respectively. Firm characteristics controls include Tobin's Q, market leverage, cash flows, cash holdings, and total assets in the previous year. See the Appendix in the main text for definitions of firm characteristics variables. All standard errors are clustered at the firm level and reported in parentheses. *, **, and *** represent significance at the 10%, 5%, and 1% level, respectively. The sample period is 1998-2003 and 2005-2010.

	1-Year Window		2-Year Window		3-Year Window	
	(1)	(2)	(3)	(4)	(5)	(6)
RShare × $Post_t$	0.110***	0.075*	0.110***	0.090***	0.088***	0.071**
	(0.040)	(0.041)	(0.032)	(0.029)	(0.031)	(0.029)
Firm Characteristics	N	Y	N	Y	N	Y
Firm FE	Y	Y	Y	Y	Y	Y
Ind×Year FE	Y	Y	Y	Y	Y	Y
Observations	6,498	6,498	12,571	12,571	18,153	18,153
Adjusted R^2	0.741	0.770	0.525	0.562	0.472	0.512

Table A.3
Robustness for Table 3: Controlling for Cross-Terms

This table shows the response of investment in machines to aggregate shocks for firms with different shares of routine-task labor, *RShare*, controlling for the interaction between firm characteristics and the aggregate shocks. The dependent variable is *Investment in Machines*, which is the real growth rate of machinery and equipment at cost (Compustat item FATE). . *RShare* is the ratio of the firm's total wage expense on routine-task labor relative to its total wage expense. *Shock* is the growth rate of real GDP value added. All variables are standardized so that the mean equals 0 and the standard deviation equals 1. *Ind* is the Fama-French 17 industry classification. See the Appendix in the main text for definitions of firm characteristics. All standard errors are clustered at the firm level and reported in parentheses. *, **, and *** represent significance at the 10%, 5%, and 1% level, respectively.

Dep. Var.	Investment in Machines					
	(1)	(2)	(3)	(4)	(5)	(6)
RShare_{t-1}	0.003	0.002	0.001	0.003	0.002	0.003
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
$\text{RShare}_{t-1} \times \text{Shock}_t$	−0.012**	−0.011**	−0.012**	−0.006	−0.009*	−0.010*
	(0.006)	(0.006)	(0.005)	(0.005)	(0.005)	(0.006)
Cash Flow_{t-1}		0.044**				
		(0.020)				
$\text{Cash Flow}_{t-1} \times \text{Shock}_t$		−0.018				
		(0.020)				
Mkt.Lev_{t-1}			−0.267***			
			(0.013)			
$\text{Mkt.Lev}_{t-1} \times \text{Shock}_t$			−0.075***			
			(0.010)			
$\text{Cash Holding}_{t-1}$				0.229***		
				(0.020)		
$\text{Cash Holding}_{t-1} \times \text{Shock}_t$				0.069***		
				(0.014)		
Log Tobin's Q_{t-1}					0.278***	
					(0.014)	
Log Tobin's $\text{Q}_{t-1} \times \text{Shock}_t$					0.059***	
					(0.013)	
Log Asset_{t-1}						−0.324***
						(0.038)
Log $\text{Asset}_{t-1} \times \text{Shock}_t$						−0.097***
						(0.018)
Firm FE	Y	Y	Y	Y	Y	Y
Ind×Year FE	Y	Y	Y	Y	Y	Y
Observations	37,503	37,503	37,503	37,503	37,503	37,503
Adjusted R^2	0.357	0.358	0.383	0.373	0.392	0.364

Table A.4
Robustness for Table 4: Using Establishment *RShare*

This table shows shows the response of routine-task employment to aggregate shocks at the establishment level. Panel A shows results using establishments that can be matched to firms in the Compustat database. Panel B shows results using all establishments to check weather results in Panel A are driven by sample selection biases. *Chg.* $RShare^{Est,Emp}_{t-3,t}$ and *Chg.* $RShare^{Est}_{t-3,t}$ are the 3-year changes in the establishment's employment-based share of routine-task labor and share of routine-task labor, respectively. An establishment's employment-based share of routine-task labor is the ratio of its total number of routine-task employees to its total number of employees. In all variable constructions, routine-task labor is defined at $t-3$ and maintains the same definition for three years to form the time-series changes of the variables, which restricts the sample period for this test to be 1996-2014. $RShare_{t-3}$ is the establishment's *RShare* three years before. $Shock_{t-3,t}$ is the growth rate of real GDP value-added from $t-3$ to t. *Ind* is the establishment's industry following the SIC 2-digit classification before 2001 and the NAICS 3-digit classification after 2001. *State* is the state in which the establishment is located. *Firm* is the establishment's parent firm in Panel A, and the establishment's Employment Identification Number (EIN) in Panel B. Standard errors are clustered at the establishment level and reported in parentheses. *, **, and *** represent significance at the 10%, 5%, and 1% level, respectively.

	Chg. $Emp^{R}_{t-3,t}$	Chg. $RShare^{Est,Emp}_{t-3,t}$	Chg. $RShare^{Est}_{t-3,t}$
	(1)	(2)	(3)
Panel A: Compustat Firm Matched Sample			
$RShare_{t-3}$	-0.638^{***}	-0.900^{***}	-0.912^{***}
	(0.007)	(0.006)	(0.006)
$RShare_{t-3} \times Shock_{t-3,t}$	0.017^{***}	0.029^{***}	0.018^{***}
	(0.006)	(0.005)	(0.005)
Firm FE	Y	Y	Y
Ind×Year FE	Y	Y	Y
State×Year FE	Y	Y	Y
Observations	79,344	79,344	79,344
Adjusted R^2	0.286	0.437	0.454
Panel B: Full Sample			
$RShare_{t-3}$	-0.727^{***}	-0.959^{***}	-0.966^{***}
	(0.003)	(0.003)	(0.003)
$RShare_{t-3} \times Shock_{t-3,t}$	0.037^{***}	0.040^{***}	0.037^{***}
	(0.003)	(0.002)	(0.002)
Firm FE	Y	Y	Y
Ind×Year FE	Y	Y	Y
State×Year FE	Y	Y	Y
Observations	1,232,590	1,232,590	1,232,590
Adjusted R^2	0.266	0.456	0.495

Table A.5

Robustness for Table 5: Value-weighted Portfolio Sorting Within Industry

This table reports the time-series average of stock returns as well as alphas and betas from the conditional CAPM for five portfolios sorted on the share of routine-task labor (*RShare*) within industry. At the end of each June, firms in each Fama-French 17 industry are sorted into five value-weighted portfolios based on their *RShare*. *Excess Returns* are monthly returns minus the 1-month Treasury bill rate. Panel A reports the results using all firms in the sample. Panel B and C report the results using subsample of firms with size below and above median firm size of the year, respectively. Newey-West standard errors (Newey and West (1987)) are estimated with four lags and reported in parentheses. All returns are annualized by multiplying by 12 and are reported in percentages. *, **, and *** represent significance at the 10%, 5%, and 1% level, respectively. The sample covers stock returns from July 1991 to June 2014.

	L	2	3	4	H	H−L
			Panel A: All Firms			
$E[R] - r_f$ (%)	9.24**	9.14**	8.06**	8.70***	8.51**	−0.73
	(3.82)	(3.92)	(3.26)	(2.98)	(3.58)	(2.07)
Avg. MKT β	1.11***	1.04***	0.89***	0.88***	0.91***	−0.20*
	(0.05)	(0.07)	(0.06)	(0.04)	(0.07)	(0.10)
			Panel B: Small Firms			
$E[R] - r_f$ (%)	16.57***	13.02**	12.85***	12.05**	11.47**	−5.10**
	(5.71)	(5.05)	(4.94)	(5.16)	(4.72)	(2.43)
Avg. MKT β	1.76***	1.54***	1.55***	1.59***	1.40***	−0.36***
	(0.16)	(0.13)	(0.11)	(0.13)	(0.11)	(0.09)
			Panel C: Large Firms			
$E[R] - r_f$ (%)	9.18**	8.84**	8.30**	8.68***	8.79**	−0.39
	(3.79)	(3.70)	(3.37)	(2.98)	(3.57)	(2.17)
Avg. MKT β	1.12***	1.04***	0.84***	0.87***	0.90***	−0.23**
	(0.04)	(0.06)	(0.06)	(0.05)	(0.07)	(0.08)

Table A.6
Robustness for Table 5: Sorting Across All Firms

This table reports the time-series average of stock returns for five portfolios sorted on share of routine-task labor, *RShare*, across all firms (instead of within industry in Table 5 of the main text). At the end of each June, firms are sorted into five equally-weighted portfolios based on their *RShare*. *Excess Returns* are monthly returns minus the 1-month Treasury bill rate. *Excess Unlevered Returns* are monthly unlevered returns, defined as in equation (20) in the main text following Liu, Whited, and Zhang (2009), minus the 1-month Treasury bill rate. *DGTW-Adjusted Returns* are monthly returns adjusted following Daniel, Grinblatt, Titman, and Wermers (1997). *RShare* is lagged by 18 months. Newey-West standard errors (Newey and West (1987)) are estimated with four lags and reported in parentheses. All returns are annualized by multiplying by 12 and are reported in percentages. *, **, and *** represent significance at the 10%, 5%, and 1% level, respectively. The sample covers stock returns from July 1991 to June 2014.

	L	2	3	4	H	H−L
			Panel A: Excess Returns			
$E[R] - r_f$ (%)	15.20***	12.14***	13.46***	11.81***	10.38**	−4.82**
	(4.98)	(4.45)	(4.55)	(4.50)	(4.38)	(1.96)
			Panel B: Excess Unlevered Returns			
$E[R^{Unlev}] - r_f$ (%)	13.19***	9.79***	10.75***	9.29**	8.61**	−4.58***
	(4.41)	(3.70)	(3.67)	(3.61)	(3.52)	(1.72)
			Panel C: DGTW-Adjusted Returns			
$E[R^{DGTW}]$ (%)	4.63***	1.73	2.59*	1.16	−1.34	−5.98***
	(1.64)	(1.09)	(1.35)	(1.48)	(1.47)	(1.58)

Table A.7
Robustness for Table 6: Sorting Across All Firms

This table reports the unconditional CAPM time-series regression results in Panel A and conditional CAPM regression results in Panel B for five portfolios sorted on share of routine-task labor (*RShare*) across all firms (instead of within industry in Table 6 of the main text). At the end of each June, firms in each Fama-French 17 industry are sorted into five equally-weighted portfolios based on their *RShare*. *RShare* is lagged by 18 months. Newey-West standard errors are estimated with four lags for the unconditional CAPM monthly estimations and with one lag for the conditional CAPM yearly estimation, reported in parentheses. CAPM alphas are annualized by multiplying by 12 and are reported in percentages. *, **, and *** represent significance at the 10%, 5%, and 1% level, respectively. The sample covers stock returns from July 1991 to June 2014.

	L	2	3	4	H	H−L
Panel A: Unconditional CAPM						
MKT β	1.25***	1.16***	1.13***	1.11***	1.03***	−0.22***
	(0.05)	(0.04)	(0.07)	(0.07)	(0.07)	(0.06)
α	5.30*	2.89	4.48*	3.00	2.21	−3.08
	(2.77)	(2.29)	(2.51)	(2.54)	(2.53)	(1.98)
R^2	0.71	0.76	0.73	0.74	0.68	0.12
Panel B: Conditional CAPM						
Avg. MKT β	1.59***	1.50***	1.35***	1.35***	1.30***	−0.29***
	(0.12)	(0.10)	(0.07)	(0.10)	(0.09)	(0.07)
Avg. α (%)	4.67	0.92	4.75	2.54	1.06	−3.61
	(4.85)	(3.97)	(3.80)	(3.36)	(3.66)	(2.41)
Avg. R^2	0.75	0.81	0.80	0.80	0.77	0.35

Table A.8
Cash Flow Beta and Discount Rate Beta

This table shows the decomposition of the market betas for five portfolios sorted on share of routine-task labor. At the end of each June, firms in each Fama-French 17 industry are sorted into five equally weighted portfolios based on their *RShare*. *RShare* is lagged by 18 months. β_{CF} and β_{DR} are the cash flow beta and the discount rate beta, constructed following Campbell and Vuolteenaho (2004). See the Internet Appendices to Campbell and Vuolteenaho (2004) and Weber (2013) for more detailed descriptions of the estimation procedure. β is the sum of the two betas. The estimation period for the cash flow news and the discount rate news are from July 1962 to June 2014. The estimation period for the betas is from July 1991 to June 2014. *, **, and *** represent significance at the 10%, 5%, and 1% level, respectively.

	L	2	3	4	H	H-L
β_{CF}	0.87***	0.78***	0.78***	0.75***	0.74***	−0.13***
	(0.09)	(0.09)	(0.10)	(0.10)	(0.09)	(0.02)
β_{DR}	0.66***	0.59***	0.60***	0.59***	0.56***	−0.10***
	(0.10)	(0.09)	(0.09)	(0.09)	(0.09)	(0.03)
β	1.53***	1.37***	1.39***	1.35***	1.29***	−0.23***
	(0.15)	(0.14)	(0.15)	(0.15)	(0.14)	(0.05)

Table A.9
Robustness for Table 7: Using Alternative Measures of *RShare*

This table reports the predictability of firms' share of routine-task labor (*RShare*) on their annual stock returns in Panel A, and their conditional betas in Panel B. I define three alternative measures of firms' share of routine-task labor, *Alt.RShare*. *RShare (Top Quartile Cutoff)* and *RShare (Top 30% Cutoff)* are defined similar to the *RShare* defined in the main text, but classify routine-task labor as the top 25% and 30% of workers in the routine-task intensity distribution of the year, respectively. *Routine-Task Intensity* is the average routine-task intensity of all occupations of the firm, weighted by the total wages paid to each occupation. *Routine-Task Intensity* measure is free of the subjective choice of cutoffs in characterizing a firm's exposure to routine-task labor. Conditional betas are calculated following Lewellen and Nagel (2006) for each year t. Realized annual stock returns are aggregated from July of year t to June of year $t+1$ in percentage. *Alt.RShare* is lagged by 18 months. *Ind* indicates the Fama-French 17 industries. See the Appendix in the main text for definitions of firm characteristics. Standard errors are clustered at the firm level and reported in parentheses. *, **, and *** represent significance at the 10%, 5%, and 1% level, respectively. The sample covers stock returns from July 1991 to June 2014.

Alt. RShare	RShare (Top Quartile Cutoff)		RShare (Top 30% Cutoff)		Routine-Task Intensity	
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Annual Stock Returns						
Alt.RShare$_{t-1}$	-5.31^{***}	-7.59^{***}	-3.38^{*}	-4.59^{**}	-2.29^{***}	-2.99^{***}
	(1.94)	(2.07)	(1.77)	(1.85)	(0.85)	(0.89)
Firm Control	N	Y	N	Y	N	Y
Ind×Year FE	Y	Y	Y	Y	Y	Y
Observations	41,080	41,080	41,080	41,080	41,080	41,080
Adjusted R^2	0.10	0.11	0.10	0.11	0.10	0.11
Panel B: Conditional Betas						
Alt.RShare$_{t-1}$	-0.54^{***}	-0.53^{***}	-0.42^{***}	-0.36^{***}	-0.25^{***}	-0.21^{***}
	(0.08)	(0.08)	(0.07)	(0.07)	(0.03)	(0.03)
Firm Control	N	Y	N	Y	N	Y
Ind×Year FE	Y	Y	Y	Y	Y	Y
Observations	41,080	41,080	41,080	41,080	41,080	41,080
Adjusted R^2	0.07	0.08	0.07	0.08	0.07	0.08

B. Extended Model

The simple "technology-switching" model in the main text makes several simplifying assumptions in order to show the core mechanism clearly. First, the model assumes that each firm is essentially a single project. Hence, the firm's *RShare* is either 0 if the firm is automated or $\frac{c_R}{c_R+c_N}$ if the firm is unautomated. In the data, firms' *RShare* is a much more continuous variable. Second, the model excludes growth options by assuming that firms' production scale cannot be expanded or reduced. Hence, investment in this model is induced solely by countercyclical technology switching, while investment in general is very procyclical. Third, the model setup implies a non-stationary economy in terms of firms' *RShare*, since after a sufficient length of time, all firms switch from being unautomated to automated.

As an example to extend this model to capture additional features of the real world, I embed this technology-switching model in a production-based model as I briefly summarize here.

In this extended model, I follow the setup in Berk, Green, and Naik (1999), Gomes, Kogan, and Zhang (2003), and Kogan and Papanikolaou (2014) by assuming that each firm has multiple projects and the firm can increase the number of projects by adopting new projects. The cash flows of each project are subject to aggregate-level, firm-level, and also project-level shocks. The only new ingredient in this extended model, compared to the literature, is that there are two types of projects—automated and unautomated projects, just like the firms in the simple model. Due to idiosyncratic shocks, firms differ from each other in numbers of automated and unautomated projects, making *RShare* vary continuously in the cross-section. Firms' exercise of their growth options (to adopt new projects) is subject to the net-present-value rule, and is thus procyclical. The stationarity of the economy in terms of firms' *RShare* is achieved by imposing a mechanism for the exercise of growth options. In particular, I assume that building a new automated project takes more time (to adapt to the new technology) than building a new unautomated project. This assumption makes the firm prefer to adopt a new unautomated project to a new automated project when the firm is doing extremely well. In equilibrium, while existing unautomated projects are switched, new unautomated projects are undertaken, resulting in a stationary distribution of the two types of projects. Finally, I calibrate this extended model and support the model's quantitative fit with the data.

B.1. Technology

There are a large number of infinitely lived firms that produce a homogeneous final good. Firms behave competitively, and there is no explicit entry or exit. Firms are all-equity financed, hence firm value is equal to the market value of its equity.

B.1.1. Projects

Each firm owns a finite number of individual projects. Firms create projects over time through investment, and projects expire randomly.[1] The cash flows generated by project j of firm i at time t are given by

$$A_{i,j,t} = e^{x_t + z_{i,t} + \epsilon_{j,t}}, \tag{IA.1}$$

where x_t is the aggregate shock that affects the cash flows of all existing projects, and $z_{i,t}$ and $\epsilon_{j,t}$ are the firm-specific shock and the project-specific shock, respectively. While aggregate uncertainty contributes to the aggregate risk premium, the firm- and project-specific shocks contributes to firm heterogeneity in the model. Similar to Gomes, Kogan, and Zhang (2003), I assume that shocks evolve according to mean-reverting processes to capture their path-dependency property. Different from Gomes, Kogan, and Zhang (2003), I assume that the rate of mean-reversion are the same for all levels of shocks for tractability. Specifically,

$$\begin{aligned} dx_t &= -\theta x_t dt + \sigma_x dB_{xt} \\ dz_{i,t} &= -\theta z_{i,t} dt + \sigma_z dB_{zt} \\ d\epsilon_{j,t} &= -\theta \epsilon_{j,t} dt + \sigma_\epsilon dB_{\epsilon t}, \end{aligned} \tag{IA.2}$$

where $\theta \in (0,1)$ is the rate of mean-reversion and B_{xt}, B_{zt}, and $B_{\epsilon t}$ are Wiener processes independent of each other. Hence, the dynamics of $a_{i,j,t} = \log(A_{i,j,t})$ evolve according to

$$da_{i,j,t} = -\theta a_{i,j,t} dt + \sigma_a dB_t, \tag{IA.3}$$

[1] Firms with no existing projects can be viewed as firms waiting to enter the product market. In this sense, my model endogenously takes into account the entry and exit of firms.

where $\sigma_a = \sqrt{\sigma_x^2 + \sigma_z^2 + \sigma_\epsilon^2}$ and $B_t = (\sigma_x B_{xt} + \sigma_z B_{zt} + \sigma_\epsilon B_{\epsilon t})/\sigma_a$, which is also a Wiener process. In the following analysis, I suppress the firm index i and project index j for notational simplicity unless otherwise indicated.

A project is characterized as follows. First, each project requires an initial investment of I at the project's initiation date. Second, each project requires fixed units of non-routine-task labor such as managers to perform the non-routine tasks, which demands a total wage of c_N per unit of time. Finally, each project also requires factor input to perform routine tasks, and the project generates cash flows when both non-routine tasks and routine tasks are performed.

A project's routine tasks can be performed by either fixed units of routine-task labor or fixed units of machines. If the firm hires routine-task labor, it pays a total wage of c_R per unit of time, and the project starts producing immediately. Production incurs a fixed cost of f per unit of time. I refer to projects using routine-task labor as *unautomated projects*. If the firm invests in machines, the firm pays I_M at the initiation date, but it takes the firm T units of time to adapt the technology embodied in the machines for its project, during which time the project does not generate any cash flows.[2] After the first T periods, the project starts generating cash flows and incurs a fixed cost of f per unit of time. Using machines does not incur additional fixed costs.[3] I refer to projects using machines as *automated projects*. All capital, once purchased, has zero resale value.

Given the above setup, the operating profits for an unautomated project are

$$\pi_U(t) = A_t - c_R - c_N - f, \tag{IA.4}$$

and the operating profits for an automated project initiated at time t_0 are

$$\pi_A(t_0;t) = \begin{cases} -c_N & t \leq t_0 + T \text{ (technology-adoption periods)} \\ A_t - c_N - f & t > t_0 + T \text{ (production periods).} \end{cases} \tag{IA.5}$$

[2] I assume that projects have heterogeneous needs for technology. Hence, each project requires some time to customize the technology for its own needs.

[3] Alternatively, we can allow for a fixed cost of using machines, but regard the cost as part of f. In this case, c_R is the excess cost of using routine-task labor to using machines.

B.1.2. Firm Dynamics

Given that each project uses a fixed amount of input factors, changes in a firm's capital and labor in the model are represented by changes in the *number* of the firm's unautomated and automated projects. Such changes are assumed to arise for one of three reasons. First, at any point of time, projects can expire independently at a rate of δ. Second, following Kogan and Papanikolaou (2014), a new project can exogenously become available to the firm according to a Poisson process with an arrival rate of λ. At the time of arrival, the project-specific shock of the new project is at its long-run average value, that is $\epsilon_t = 0$. Such investment opportunities cannot be postponed or preserved. If the firm decides to undertake the new project, it can choose to initiate either an unautomated or an automated project.

Third, a firm can endogenously switch its existing projects' type at any time. If the firm decides to switch a project from unautomated to automated, it lays off the project's routine-task labor and invests I_M in machines. I assume that technology has evolved to a stage such that automating unautomated projects is profitable. That is, I assume that I_M is significantly lower than the present value of all future wages paid to routine-task labor, $I_M \ll \frac{c_R}{r+\delta}$.[4] For simplicity, I assume that the process of the project-specific shock is not affected after a project's type is switched. Given that machines have zero resale value and routine-task labor is significantly more costly than machines, switching from automated projects to unautomated projects is never optimal.[5]

A firm's existing projects are the sum of its unautomated projects and its automated projects. Suppose at time t that a firm has $n_{U,t}$ unautomated projects and $n_{A,t}$ automated projects. Then, the firm's share of routine-task labor (*RShare*) is defined as the ratio of the total wages paid to its routine-task labor relative to its total wage expense:

$$RShare(t) = \frac{c_R n_{U,t}}{c_N(n_{U,t} + n_{A,t})}. \tag{IA.6}$$

[4] The literature on investment-specific technological shocks argues that a large part of the technological progress after World War II took place in equipment and software and can be inferred from the decline in the quality-adjusted price of new capital goods. See Greenwood, Hercowitz, and Krusell (1997), Papanikolaou (2011), and Kogan and Papanikolaou (2014) for more details.

[5] I do not allow the firm to switch an automated project to a new automated project to ensure that the general assumption applies to both unautomated and automated projects that the firm cannot endogenously suspend production for purposes other than adopting labor-saving technology. Technically, I assume that if the firm switches an automated project to a new automated project, the firm does not need to take another T periods to learn the technology for the project, and the project starts incurring production costs immediately. Under this assumption, such choice is never optimal.

B.2. Valuation

Following Berk, Green, and Naik (1999) and Zhang (2005), I specify the stochastic discount factor explicitly as

$$\frac{d\Lambda_t}{\Lambda_t} = -rdt - \sigma_\Lambda dB_{xt}, \tag{IA.7}$$

where r is the interest rate and σ_Λ is the price of risk.

B.2.1. The Value of Automated Projects

Since automated projects do not have any options, their value is simply the discounted value of their future profits. For an automated project initiated at t_0,

$$\begin{aligned} V_A(t_0;t) &= E_t \int_0^\infty e^{-\delta s} \frac{\Lambda_{t+s}}{\Lambda_t} \pi_A(t_0, t+s) ds \\ &= \int_{t'}^\infty A_t^{e^{-\theta s}} e^{g(s)} ds - \frac{c_N + e^{-(r+\delta)t'} f}{r+\delta}, \end{aligned} \tag{IA.8}$$

where $t' = \max(t_0 + T - t, 0)$ is the time to wait (for the project to generate cash flows) and $g(s) = (-\delta - r)s - \frac{\sigma_x \sigma_\Lambda}{\theta}\left(1 - e^{-\theta s}\right) + \frac{\sigma_a^2}{4\theta}\left(1 - e^{-2\theta s}\right)$. Appendix A.1 in the main text provides a proof.

B.2.2. The Value of Unautomated Projects

The value of an unautomated project can be divided into the value of assets in place, $V_U^{AP}(t)$, and the value of switching options, $V_U^{SO}(t)$:

$$V_U(t) = V_U^{AP}(t) + V_U^{SO}(t). \tag{IA.9}$$

The value of assets in place is simply the discounted value of future profits:

$$\begin{aligned} V_U^{AP}(t) &= E_t \int_0^\infty e^{-\delta s} \frac{\Lambda_{t+s}}{\Lambda_t} \pi_U(t+s) ds \\ &= \int_0^\infty A_t^{e^{-\theta s}} e^{g(s)} ds - \frac{c_R + c_N + f}{r+\delta}. \end{aligned} \tag{IA.10}$$

The value of the switching option can be calculated as the discounted value of the optimal payoff:

$$V_U^{SO}(t) = \text{Payoff}(t+\tau) \hat{\mathbb{E}}_t[e^{-(r+\delta)\tau}], \tag{IA.11}$$

where τ is the optimal stopping time for the firm to switch technology and $\hat{\mathbb{E}}_t[\cdot]$ is an expectation operator under the risk-neutral probability measure. The payoff function is

$$\begin{aligned}\text{Payoff}(t) &= V_A(t;t) - V_U^{AP}(t) - I_M \\ &= \frac{c_R + f[1 - e^{-(r+\delta)T}]}{r+\delta} - I_M - \int_0^T A_t^{e^{-\theta s}} e^{g(s)} ds \\ &= P(A_t).\end{aligned} \tag{IA.12}$$

Hence, the switching option can be viewed as an investment opportunity with a fixed benefit, a fixed direct cost, but a variable opportunity cost that is low if the project is doing poorly. Following Dixit and Pindyck (1994), I prove the following in Appendix A.2 of the main text:

Proposition 1 (Optimal exercise of switching options): *A firm optimally switches a project from unautomated to automated when the project's cash flows, A_t, are below a threshold A^*, where A^* satisfies*

$$\frac{d\,[P(A^*)O(A_t, A^*)]}{dA^*} = 0 \qquad \forall A_t \geq A^*, \tag{IA.13}$$

where $O(A_t, A^*) = \hat{\mathbb{E}}_t[e^{-(r+\delta)\tau}]$ is the optimal discounting of the option payoff.

The analytical expression of $O(A_t, A^*)$ is provided in Appendix A.2 of the main text.

Corollary 1 (Cross-section of investment for technology switching): *Keeping all else equal, a firm with a high RShare invests more in machines than a firm with a low RShare if the economy experiences a negative shock, that is, $dx_t < 0$.*[6]

Proof: This follows directly from Proposition 1.

Corollary 2 (Cross-section of routine-task employment under negative aggregate shocks): *Keeping all else equal, a firm with a high RShare reduces more of their routine-task labor than a firm with a low RShare if the economy experiences a negative shock, that is, $dx_t < 0$.*

Proof: This follows directly from Proposition 1.

Finally, the value of the unautomated project is

$$V_U(t) = \int_0^\infty A_t^{e^{-\theta s}} e^{g(s)} ds - \frac{c_R + c_N + f}{r+\delta} + P(A^*)O(A_t, A^*). \tag{IA.14}$$

[6] "Keeping all else equal" in this corollary means that we are comparing two firms with the same number of projects and the same set of cash flows for their projects. The only difference is that the high-*RShare* firm has more unautomated projects than the other firm.

B.2.3. The Value of Growth Opportunities

Given that the investment opportunities cannot be postponed, firms optimally decide to undertake new projects based on the NPV rule. The optimal exercise of the growth options is thus characterized by comparing the incremental value of undertaking a new unautomated project, $V_U(t+s) - I$, undertaking a new automated project, $V_A(t+s; t+s) - I_M - I$, and not undertaking a project.

The optimal exercise of switching options indicates that firms prefer undertaking new automated projects over undertaking new unautomated projects if $A_t < A^*$.[7] Let A^{**} be the threshold for firms to undertake a new project. A^{**} is determined by making the investment in the new project a zero NPV project, that is, A^{**} is the solution to

$$V_A(t;t) - I_M - I = 0 \tag{IA.15}$$

or the solution to

$$V_U(t) - I = 0. \tag{IA.16}$$

I summarizes these results in the following proposition.

Proposition 2 (Optimal exercise of growth options): *A firm optimally undertakes a new project when the cash flows of the new project, $A_t = e^{x_t+z_t+0}$, are above a threshold A^{**}. A^{**} is the minimum of the solutions to equations* (IA.15) *and* (IA.16)*.*

If $A^{**} < A^*$, firms undertake an automated project when $A^{**} < A_t \leq A^*$ and undertake an unautomated project when $A_t > A^*$.

If $A^{**} \geq A^*$, firms undertake an unautomated project when $A_t > A^{**}$.

Corollary 3 (Procyclical aggregate investment): *All firms are more likely to invest in new projects if the economy experiences a positive shock, that is, $dx_t > 0$.*

Proof: This follows directly from Proposition 2.

This corollary helps to generate procyclical aggregate investment in the model.

Corollary 4 (Cross-section of investment for growth): *If $A^{**} < A^*$, conditional on undertaking new projects, firms with high idiosyncratic shocks, z_t, are more likely to undertake new*

[7] To see this, suppose that a firm undertakes a new unautomated project when $A_t < A^*$. Then, by Proposition 1, the firm will immediately switch the project to automated.

unautomated projects, and firms with low idiosyncratic shocks are more likely to undertake new automated projects.

Proof: This follows directly from Proposition 2.

The intuition of this corollary is straightforward. Because new unautomated projects can start generating cash flows more quickly than new automated projects, they are preferable to be undertaken for expansions when firms are doing well.[8] This corollary has two implications in the model. First, it helps generate a stationary distribution of the two types of projects, since in equilibrium, while existing unautomated projects are switched to automated ones, new unautomated projects are also undertaken.

Second, this corollary also generates predictions in the cross-section of machinery investment in good times. Because high-*RShare* firms, on average, are more likely to have high firm-specific shocks, they are more likely to hire routine-task labor instead of investing in machines during good times than low-*RShare* firms.

Corollary 5 (Cross-section of routine-task employment under positive aggregate shocks): *If $A^{**} < A^{*}$, keeping all else equal, a firm with a high RShare and a high firm-level shock is more likely to hire routine-task labor than a firm with a low RShare and a low firm-level shock if the economy experiences a positive shock, that is, $dx > 0$.*

Given that the project-specific shock of any new project is at its long-term mean, the present value of growth opportunities is a function of the aggregate shock and the firm-specific shock:

$$\begin{aligned} PVGO(t) &= E_t \int_{s=0}^{\infty} \lambda \frac{\Lambda_{t+s}}{\Lambda_t} \max\left[V_U(t+s) - I, V_A(t+s;t+s) - I_M - I, 0\right] ds \\ &= G(x_t, z_t). \end{aligned} \tag{IA.17}$$

B.2.4. Firm Value

At any time t, a firm may have $n_{U,t}$ unautomated projects and $n_{A,t}$ automated projects that the firm previously undertook. Let $V_{U,l}(t)$ denote the value of the lth unautomated project that the firm undertook, where $l = 1, 2, ..., n_{U,t}$. Let $t_k \leq t$ denote the time when

[8] This argument is consistent with Berger (2012), who argues that firms grow "fat" during booms and streamline their production during recessions.

the kth automated project was undertaken, and $V_{A,k}(t_k;t)$ the value of the kth automated project, where $k = 1, 2, ..., n_{A,t}$. Firm value equals the value of all existing projects plus the present value of growth opportunities:

$$V(t) = \sum_{l=1}^{n_{U,t}} V_{U,l}(t) + \sum_{k=1}^{n_{A,t}} V_{A,k}(t_k;t) + PVGO(t) \tag{IA.18}$$

B.3. Firm Risk

The equity beta of a project or a firm is defined as the scaled covariance of its value and the stochastic discount factor,

$$\beta = -\frac{\text{Cov}\left(\frac{dV}{V}\frac{d\Lambda}{\Lambda}\right)}{\text{Var}\left(\frac{d\Lambda}{\Lambda}\right)}. \tag{IA.19}$$

From equation (IA.18), we know that a firm's beta is the weighted average of the betas of its existing projects and the beta of its growth opportunities,

$$\beta_f = \sum_{l=1}^{n_U} \frac{V_{U,l}}{V}\beta_{U,l} + \sum_{k=1}^{n_A} \frac{V_{A,k}}{V}\beta_{A,k} + \frac{PVGO}{V}\beta_{PVGO}. \tag{IA.20}$$

Given that multiple channels drive the cross-sectional comparison in betas between firms with a high and a low *RShare*, I calibrate the model in the next section to examine whether the switching options channel is a dominating channel under economically reasonable parameters.

B.4. Calibration

I simulate the model to examine whether the switching option channel is powerful enough to generate lower risk premia for high-*RShare* firms in the cross-section under economically reasonable parameters. In addition, this test also helps to examine whether the predictability of *RShare* on stock returns is robust to the dynamic setting in which *RShare* evolves endogenously.

To conduct the calibration, I do the following steps: First, I discretize the continuous model. Second, I obtain the values of parameters by matching several economic moments. Third, I plug the parameter values into the model and simulate the model to generate stock returns for five portfolios sorted on share of routine-task labor.

The processes for stochastic discount factor Λ_t, and the shocks, e^{x_t}, e^{z_t} and e^{ϵ_t} are discretized using the following approximations:

$$\begin{aligned} \Lambda_{t+\Delta t} &= \Lambda_t e^{(-r-\frac{1}{2}\sigma_\Lambda^2)\Delta t - \sigma_\Lambda \sqrt{\Delta t}\xi_{xt}} \\ e^{x_{t+\Delta t}} &= \left(e^{x_t}\right)^{e^{-\theta\Delta t}} e^{\sigma_x \sqrt{\frac{1-e^{-2\theta\Delta t}}{2\theta}}\xi_{xt}} \\ e^{z_{t+\Delta t}} &= \left(e^{z_t}\right)^{e^{-\theta\Delta t}} e^{\sigma_z \sqrt{\frac{1-e^{-2\theta\Delta t}}{2\theta}}\xi_{zt}} \\ e^{\epsilon_{t+\Delta t}} &= \left(e^{\epsilon_t}\right)^{e^{-\theta\Delta t}} e^{\sigma_\epsilon \sqrt{\frac{1-e^{-2\theta\Delta t}}{2\theta}}\xi_{\epsilon t}}, \end{aligned} \tag{IA.21}$$

where $\Delta t = 1/12$ is one month, and ξ_{xt}, ξ_{zt} and $\xi_{\epsilon t}$ are standard normal random variables that are independent with each other and over time.

I specify a grid of 10 points for each of the processes, and linearly interpolate the value functions based on the grids. The grid points are chosen by first specifying an upper bound and lower bound of the state variable and equally spanning the interval.

Profits in each period are thus

$$\begin{aligned} \pi_A(t) &= (A_t - c_N - f)\Delta t \\ \pi_U(t) &= (A_t - c_R - c_N - f)\Delta t. \end{aligned} \tag{IA.22}$$

The value of V_A and V_U^{SO} can be easily calculated based on the analytical functional forms. I calculate A^* by searching a large space of A_t.

The relation between project's value, dividend, profit, and investment is

$$V_t = d_t + E(\frac{\Lambda_{t+\Delta t}}{\Lambda_t} V_{t+\Delta t}), \tag{IA.23}$$

where $d_t = \pi_t - I_t$, and A_t is the state variable.

The value of growth options are calculated following Berk, Green, and Naik (1999), who simulate 400 time periods in order to obtain a good approximation of the integration. I discretize the present value of growth opportunities as

$$PVGO_t = \frac{\lambda \Delta t}{J} \sum_{j=1}^{J} \sum_{n=1}^{\infty} PVGO_{j,n}, \tag{IA.24}$$

where $PVGO_{j,n}$ is the jth realization of the growth opportunity at time $t + s\Delta t$. Note that $n = 0$ is not included here (those opportunities that come up at t are already taken or passed). The growth opportunity counts starting from $t + \Delta t$ on.

Panel A of Table B.1 summarizes the parameter choices. My model setup shares many similar features with Kogan and Papanikolaou (2014), who also develop a model at the project level. Hence, I adopt the parameter values used by Kogan and Papanikolaou (2014) as many as possible. Specifically, I adopt the parameter values in Kogan and Papanikolaou (2014) for volatilities of x_t, z_t and ϵ_t, rate of mean-reversion, risk-free rate, and project obsolescence rate.[9] The required time for technology adoption is absent in the model of Kogan and Papanikolaou (2014). I thus set the required time to be three quarters following the time-to-build literature (e.g., Kydland and Prescott (1982) find that a reasonable range for the average construction period is three to five quarters).

Given that Kogan and Papanikolaou (2014) have two factors in their pricing kernel while my model only has one, I choose the price of risk to match the equal-weighted aggregate risk premium. Because I assume a constant price of risk in my stochastic discount factor for tractability, I need an unrealistically high value for the price of risk to match the risk premium.[10] In addition, my model has a much simpler setting for growth opportunities compared to the model of Kogan and Papanikolaou (2014), I thus set the project arrival rate to match the aggregate dividend growth rate.

The literature offers less guidance on the cost of different production factors at the project level. I thus match several moments to pin down these parameters. The per-project cost for using routine-task labor, c_R, and non-routine-task labor, c_N, are chosen to match the aggregate share of routine-task labor in my sample. The rest of the operating cost, f, is chosen to match the correlation between gross hiring and GDP growth. Cost of project initiation, I, and cost of machines per automated project, I_M, are chosen to match the correlation between gross investment and GDP growth. See Panel B of Table B.1 for the moments.

Plugging these parameter values into equations (IA.13), (IA.15), and (IA.16), we obtain the optimal thresholds for exercising switching options and growth options. Under these

[9] Kogan and Papanikolaou (2014) use 0, 0.35, and 0.5 as the rates of mean-reversion for the aggregate shocks, firm-level shocks, and project-level shocks, respectively. My model requires the rate of mean-reversion to be the same for all levels of shocks. Thus, I choose the rate of mean-reversion to be 0.35 in my simulation.

[10] It is well-known in the literature that a countercyclical price of risk in the stochastic discount factor is crucial for generating high risk premium. See alternative specifications of stochastic discount factor in Zhang (2005) and Jones and Tuzel (2013).

parameter values, $A^* = 0.75$ and $A^{**} = 0.81$, while the 40th, 50th, and 60th percentiles of A_t are 0.63, 1.00, and 1.58, respectively.

Table B.1
Parameter Values and Calibration Moments

This table presents the parameter values used in the calibration of the model.

Panel A: Parameter Values		
Parameters	Symbol	Value
Technology		
Volatility of aggregate shock	σ_x	0.13
Volatility of firm-specific shock	σ_z	0.15
Volatility of project-specific shock	σ_ϵ	1.25
Rate of mean reversion	θ	0.30
Project		
Operating cost except for labor compensation	f	1.25
Compensation for non-routine-task labor	c_N	0.25
Compensation for routine-task labor	c_R	0.35
Investment for project initiation	I	3.50
Investment in machines per automated project	I_M	0.10
Required time for technology adoption	T	0.75
Project obsolescence rate	δ	0.10
Project arrival rate	λ	12
Stochastic discount factor		
Risk-free rate	r	0.03
Price of risk of aggregate shock	σ_Λ	1.30

Panel B: Calibration Moments		
Moments	Data	Model
Aggregate economic moments		
Mean of aggregate dividend growth	0.02	0.02
Volatility of aggregate dividend growth	0.12	0.18
Aggregate share of routine-task labor	0.14	0.14
Aggregate labor share in GDP	0.55	0.24
Correlation between gross investment and GDP Growth	0.48	0.49
Correlation between gross hiring and GDP Growth	0.74	0.59
Asset pricing moments		
Mean of equal-weighted aggregate risk premium	0.14	0.15
Volatility of equal-weighted aggregate risk premium	0.26	0.14

Using the above parameter choices, I simulate the model at monthly frequency ($dt = 1/12$) for 1,000 firms over 1,200 periods. I drop the first 600 periods to eliminate dependence on initial values. I simulate 100 times and calculate the standard errors across simulations.

Table B.2 reports portfolio sorting of stock returns by firms' share of routine task labor (*RShare*) using model simulated data. The excess returns monotonically decrease from 14.20% to 11.96% per year from the lowest *RShare* quintile to the highest *RShare* quintile.

Comparing the highest and the lowest *RShare* quintile portfolios yields a −2.24% return spread per year, which is somewhat smaller than what I find in the data, −3.10%. One reason could be that the simulation under the parameter values cannot generate enough cross-sectional dispersion in terms of *RShare*. The *RShare* of the five portfolios ranges from 0.06 to 0.22 in the model, but from 0.02 to 0.39 in the data. The market beta shows a similar monotonically decreasing pattern and has a spread of −0.18 for the long-short portfolio. In summary, these results suggest that switching options serve as an economically significant channel that dominates countering forces such as the operating leverage channel and leads to lower risk premium for high-*RShare* firms in the model.

Table B.2
Five Portfolios Sorted on *RShare* using Model Simulated Data

This table reports the asset pricing tests for five portfolios sorted on share of routine-task labor (*RShare*) using model simulated data. The model is simulated at monthly frequency for 1,000 firms over 1,200 periods for 100 rounds. The first 600 periods are dropped to eliminate dependence on initial values. See the Appendix for more details about the calibration. Excess returns and CAPM alphas are annualized by multiplying by 12 and are reported in percentages. *, **, and *** represent significance level of 10%, 5%, and 1%, respectively.

	L	2	3	4	H	H−L
			1. Excess Returns			
$E[R]-r_f$ (%)	17.02***	16.07***	14.91***	14.74***	14.56***	−2.46***
	(1.71)	(1.65)	(1.55)	(1.49)	(1.46)	(0.12)
			2. Unconditional CAPM			
MKT β	1.13***	1.11***	1.02***	0.96***	0.95***	−0.17***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
α (%)	−0.14	−0.11	−0.13	−0.19	−0.09	0.04
	(0.10)	(0.11)	(0.11)	(0.10)	(0.10)	(0.15)
R^2	0.99	0.99	0.99	0.99	0.99	0.53

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