Systematic Risk in Supply Chain Networks

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Joint work with
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Systematic risk in economy

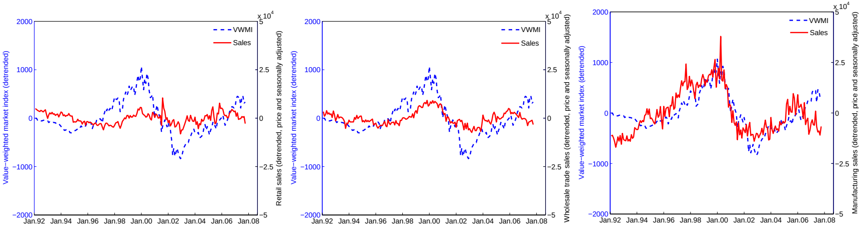


Figure : Retail, wholesale, and manufacturing sales and the VWMI market index time series, with trends removed. Systematic risk estimates are 0.33, 0.42, 0.50, respectively.

Industry	Upper tier (3)	Middle tier (2)	Lower tier (1)
Consumer products	3M Co. (0.89)	Procter & Gamble (0.64)	Costco Wholesale Corp. (0.482) Target Corp. (-0.182) Wal-Mart Stores Inc. (-0.190)
Electronics	Applied Materials Inc. (0.63)	Advanced Micro Devices (0.36) Intel Corp. (0.52)	Hewlett-Packard Co. (0.14)

Research questions

- Why certain industries and firms are robust to economic downturns, while others suffer?
- What are the mechanisms of shock propagation trough supply network?
  - Production decisions;
  - Aggregation of demand from multiple customers;
  - Aggregation of demand over lead time.
- What are the implications of the systematic risk?
  - Cost of capital
  - Supplier selection
  - Supply chain investments

Systematic risk

- Sales series: $S_{i,t}$
- Market return series: r_t
- Lead time or planning horizon T
- Sales uncertainty over lead time T: $SU_{i,(t,t+T]} = S_{i,t+T} - S_{i,t}$
- SU is associated with the financial market: $SU_{i,(t,t+T]} = a_i + b_i r_{(t,t+T]} + \epsilon_{i,(t,t+T]}$

Definition

Systematic risk in sales of firm/industry i over lead time T:

$$\rho_S(i, T) = \mathbb{C}\mathbf{orr}(SU_{i,(t,t+T]}, r_{(t,t+T]}),$$

where $SU_{i,(t,t+T]} = S_{i,t+T} - S_{i,t}$.

Agenda for the rest of the talk

- Literature
- Data sources
- Drivers of the systematic risk
- Industry and firm level evidence
- Managerial implications

Literature

- Risk management/hedging under systematic risk
  - Gaur and Seshadri (2005), Van Mieghem (2008), Chod et al. (2010)
- Bullwhip effect/production smoothing
  - Cachon et al. (2007), Chen and Lee (2012), Bray and Mendelson (2011)
  - Bray and Mendelson (2012)
- Network economics/finance/operations
  - Leontieff (1936, 1986), Acemoglu et al. (2012, 2013)
  - Cohen and Frazzini (2008), Menzly and Ozbas (2010)
  - Bellamy et al. (2014), Birge and Wu (2014), Wang et al. (2014)

Data

(i) Monthly surveys of manufacturing, wholesale trade, and retail trade sectors conducted by the U.S. Census Bureau;

(ii) Estimated annual gross margins reported by the U.S. Census Bureau for manufacturing, wholesale trade, and retail trade sectors;

(iii) Price deflators data (Bureau of Economic Analysis);

(iv) Input output tables from the Bureau of Labor Statistics for 195 industries for years 1993-2010;

(v) Firm level data on major customers for manufacturing, retail, and wholesale trade companies, constituents of the SP500 index (Bloomberg);

(vi) Firm level quarterly sales, inventory, and cost of goods sold data for manufacturing, retail, and wholesale trade companies, constituents of the SP500 index (S&P Compustat);

(vii) Historical daily returns and levels of the value-weighted market index including distributions (CRSP);

(viii) Historical daily returns and closing market capitalizations of U.S. public-listed firms in manufacturing, wholesale trade, and retail trade sectors (CRSP).

Illustration: industry level data

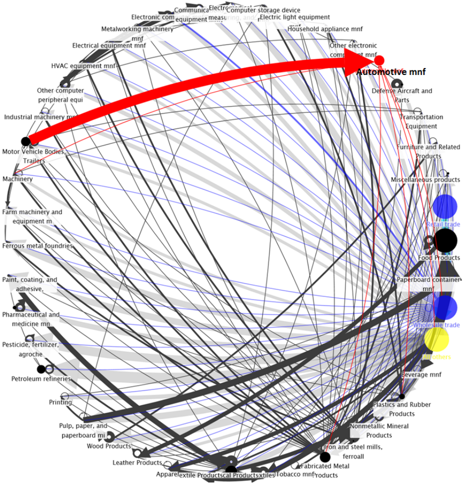


Figure : A representation of inter-industry flows in the US economy, based on the material requirements matrix derived from the IO tables for year 2002. Node radius is proportional to the industry output, arrow size is proportional to the share of the supplier. Highlighted in red are the flows to the Automotive manufacturing industry. Main suppliers to this industry include Motor vehicle bodies and trailers, Machinery, Fabricated metal, Rubber and Plastic manufacturers.

Illustration: firm level data

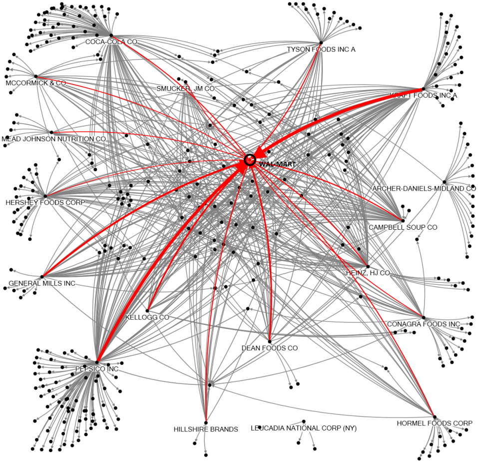


Figure : A representation of flows in between Food products manufacturers and their customers, for year 2013. Arrow size is proportional to relationship volume. Highlighted in red are the flows to from food manufacturers to Walmart.

Production decisions

- Production of an industry i in period t (Cachon et al., 2007)

$$P_{i,t} = S_{i,t} + B_{i,t},$$

where $S_{i,t}$ is the volume of price-adjusted sales (shipments) out of industry i in month t. $B_{i,t} = I_{i,t} - I_{i,t-1}$ is inventory buildup in month t ($I_{i,t}$ is the end-of-month inventory of industry i for month t).

- Systematic risk in production $\rho_P(i, T) = \mathbb{C}\mathbf{orr}(P_{i,t+T} - P_{i,t}, r_{(t,t+T]})$
- Production may have greater systematic risk than sales if uncertainty in inventory build up is sufficiently correlated with $r_{(t,t+T]}$.

Proposition: Amplification of systematic risk in production decisions

Let $BU_{i,(t,t+T]} \triangleq B_{i,t+T} - B_{i,t} = a_i^B + b_i^B r_{(t,t+t]} + \epsilon^B_{i,(t,t+T]}$, $\epsilon^B_{i,(t,t+T]}$ is drawn from the same distribution as $k\epsilon_{i,(t,t+T]}$ for some $k \geq 0$, and $\mathbb{C}\mathbf{orr}(\epsilon^B_{i,(t,t+T]}, \epsilon_{i,(t,t+T]}) \geq 0$. If $b_i^B > kb_i$, then $\rho_P(i, T) > \rho_S(i, T)$.

Aggregation over customers

- Upstream industry 0 is serving N customers
- M_{k0} - input from industry 0 required to produce \$1 output of industry k

Proposition: Amplification of systematic risk due to aggregation of orders

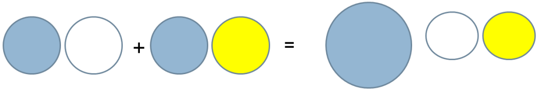
The systematic risk at the upstream level is amplified with respect to industry i, i.e., $\rho_S(0,T) > \rho_P(i,T)$ if and only if

$$\frac{\left(\sum_{k=1}^{N} b_k M_{k0}\right)^2}{b_i^2} \geq \frac{\left(\sum_{k=1}^{N} b_k M_{k0}\right)^2 + \sum_{k=1}^{N}\left(M_{k0}\frac{\sigma_k}{\sigma_r}\right)^2}{b_i^2 + \frac{\sigma_i^2}{\sigma_r^2}}.$$

Corollary

The systematic risk always increases if customers are identical. Moreover $\lim_{N\to\infty} \rho_S(0,T) = 1$ if customers are identical.

- Intuition



Aggregation over lead time

- Let $SU_{i,t} = S_{i,t} - S_{i,t-1}$, $r_t = \ln VWMI_t / VWMI_{t-1}$.
- $SU_{i,t} = a_i + b_i r_t + \epsilon_{i,t}$, and $\rho_S(i,1) = \mathbb{C}\mathbf{orr}(SU_{i,t}, r_t)$.

Proposition

If $SU_t = a + br_t + \epsilon_t$ and ϵ_t is independent from $r_{t-1}, r_{t-2}, \ldots$ for all $t = 1..T$, then $\rho_S(i,T) = \rho_S(i,1)$.

- Correlation with lagged returns is crucial for risk amplification

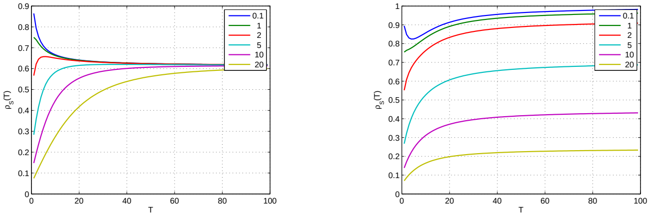


Figure : Systematic risk as a function of lead time: (1) no decay in correlation with lagged returns; (2) geometric decay ($\alpha = 0.8$) in correlation with lagged returns, for various levels of $\gamma = \sigma_\epsilon / \sigma_r$

Summary statistics

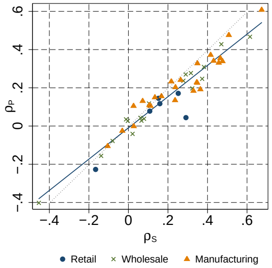
		Mean	Std.dev	Min	Max	# obs
Industry level data, years 1993-2007						
Customer dispersion	ratio	7.370	4.854	1.051	22.396	645
Sales	$mil/month	15095.66	40422.37	321.49	259000	645
Sales change ($T = 12$ months)	$mil	520.949	2073.883	-4182.4	15000	645
Rate of return ($T = 12$ months)	ratio	0.108	0.146	-0.175	0.364	645
Sales st.dev.	$mil	446.116	834.944	5.836	5661.224	645
Inventory	$mil	27925.39	71734.19	744.07	480000	645
Gross margin	ratio	0.25	0.47	0.17	0.45	645
Fraction of final demand in output	ratio	0.317	0.350	-0.743	0.922	645
Av. sales in past 12 months	$mil	14718.21	39067.1	323.551	253750	645
Beta	ratio	0.8678	0.3017	0.4403	1.7713	43
Firm level data, years 2009-2013						
Number of customers	count	48.13	56.17	1	414	992
Customer dispersion	ratio	5.23	5.08	1	27.47	992
Sales	$mil/quarter	4771.92	7709.23	98.91	64545.02	992
Sales change ($T = 4$ quarters)	$mil	84.53	1467.04	-19491.33	20699.37	992
Rate of return ($T = 4$ quarters)	ratio	0.052	0.280	-0.584	0.459	992
Sales st.dev.	$mil	368.56	766.34	3.17	10234.43	992
Inventory	$mil	1935.26	2873.70	0	38723.16	992
Gross margin	ratio	0.41	0.23	0	0.96	992
Num. of firms in the same NAICS3	count	23.8	17.85	1	50	992
Av. sales in past 4 quarters	$mil	4882.94	7806.59	187.89	70379.75	992
Beta	ratio	1.0584	0.4402	0.2718	2.2565	239

Industry-level: Production decisions

- Recall the industry level estimates of the systematic risk

Industry	Systematic risk
Retail trade	0.33
Wholesale trade	0.42
Manufacturing	0.50

- Production decisions attenuate the systematic risk



ρ_P	Coef.	Std.Err	95% C.I. LL	95% C.I. UL
ρ_S	0.817***	0.035	0.748	0.887
Intercept	-0.010	0.010	-0.030	0.011

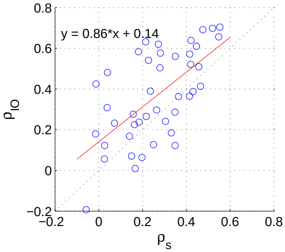
$N = 49$, $Prob. > F = 0$, $Adj.R^2 = 0.920$

Figure : Systematic risk in production (ρ_P) vs. systematic risk in sales (ρ_S) for non-overlapping segments in retail, wholesale trade, and manufacturing; $T = 12$ months.

Industry-level: Aggregation over customers

- Systematic risk in imputed sales $\rho_{IO}(i, T) = \mathbb{C}\mathbf{orr}\left(\sum_{i\in\mathcal{I}} M_{ij}(P_{i,t+T} - P_{i,t}), r_{(t,t+T]}\right)$.
- Key comparisons

Industry	Systematic risk		
	ρ_S	ρ_P	ρ_{IO}
Retail trade	0.33	0.17	0.20
Wholesale trade	0.42	0.29	0.37
Manufacturing	0.50	0.44	0.52 (median)



ρ_{IO}	Coef.	Std.Err	95% C.I.	
			LL	UL
ρ_s	0.8558	0.1628	0.5269	1.1846
Intercept	0.1405	0.0504	0.0388	0.2422

$N = 43,\ Prob. > F = 0,\ Adj.R^2 = 0.3879$

Figure : Systematic risk in sales (ρ_S) vs. systematic risk in imputed sales (ρ_{IO}) for 43 industries and industry segments, $T = 12$ months. Linear fit is reported.

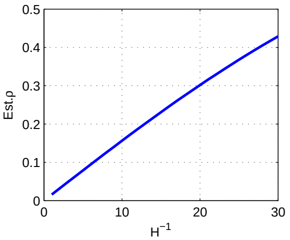
Industry-level: Aggregation over customers

- Customer base dispersion $H_j^{-1} = \left(\sum_i \left(\frac{M_{ij} g_i}{\sum_i M_{ij} g_i} \right)^2 \right)^{-1}$, where g_i is the total output of industry i.

$$SC(i,t,T) = \alpha_1 r(t,T) + \alpha_2 H^{-1}(i,t) + \alpha_3 (r(t,T) \times H^{-1}(i,t)) + \alpha_4 SS(i,t) + \alpha_5 INVT(i,t) + \alpha_6 GM(i,t) + \alpha_7 FD(i,t) + \alpha_8 ASV(i,t) + \alpha_9 \tau(t) + u(i) + \epsilon(i,t,T).$$

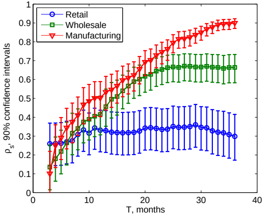
Variable	Coef. (Robust Std.Err.)
Return $\times$ Cust.Disp.	241.635** (107.914)
Return (r)	39.575 (763.772)
Cust. Disp. (H^{-1})	-4.289 (34.041)
Sales Std.Dev. (SS)	0.527 (0.330)
Inventory ($INVT$)	0.033 (0.034)
N customer ($NCUST$)	–
Gross margin (GM)	1734.176 (3433.164)
Final dem. perc. (FD)	293.728 (337.134)
Competition ($NFIRM$)	–
Size (ASV)	-0.031 (0.049)
τ	1.082 (7.590)
σ_u	556.000
σ_ϵ	1021.868
R-sq overall	0.709
# obs.	645

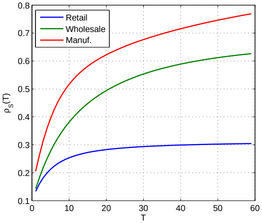
*-$p < .1$, **-$p < .05$, ***-$p < .01$



Industry-level: Aggregation over time

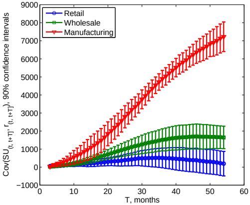
- Does the systematic risk increase with T?





- Correlation of errors with lagged returns drives the effect
  - Geometric decay: $\alpha_{RET} = 0.69$, $\alpha_{WHS} = 0.90$, $\alpha_{MNF} = 0.96$.

- Covariance

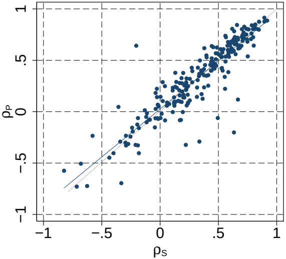


Firm-level: Production decisions

- Continue to observe amplification of the systematic risk from retail, to wholesale, and manufacturing

Industry	Systematic risk (mean, median)	
Retail trade	0.23	0.19
Wholesale trade	0.28	0.35
Manufacturing	0.36	0.41

- Firm level production decisions attenuate the systematic risk



ρ_P	Coef.	Std.Err	95% C.I. LL	95% C.I. UL
ρ_S	0.933***	0.028	0.878	0.988
Intercept	-0.026*	0.014	-0.001	0.053

$N = 238, \; Prob. > F = 0, \; Adj.R^2 = 0.823$

Figure : Systematic risk in production (ρ_P) vs. systematic risk in sales (ρ_S) for SP500 constituent retail, wholesale trade, and

Firm-level: Aggregation over customers

$$SC(i,t,T) = \alpha_1 r(t,T) + \alpha_2 H^{-1}(i) + \alpha_3 (r(t,T) \times H^{-1}(i)) + \alpha_4 SS(i,t) + \alpha_5 INVT(i,t) + \alpha_6 NCUST(i) + \alpha_7 GM(i,t) + \alpha_8 NFIRM(i,t) + \alpha_9 ASV(i,t) + \alpha_{10}\tau(t) + NAICS2(i) + \epsilon(i,t).$$

Variable	Coef. (Robust Std.Err.)
Return × Cust.Disp.	106.485*** (11.460)
Return (r)	416.376* (212.043)
Cust. Disp. (H^{-1})	15.406 (16.944)
Sales Std.Dev. (SS)	0.071 (0.474)
Inventory ($INVT$)	-0.012 (0.029)
N customer ($NCUST$)	1.527** (0.562)
Gross margin (GM)	303.539** (96.233)
Final dem. perc. (FD)	–
Competition ($NFIRM$)	4.415** (1.319)
Size (ASV)	$3 * 10^{-5}$(0.009)
τ	8.037 (28.298)
σ_u	435.463
σ_ϵ	1418.926
R-sq overall	0.057
# obs.	992

*-$p < .1$, **-$p < .05$, ***-$p < .01$

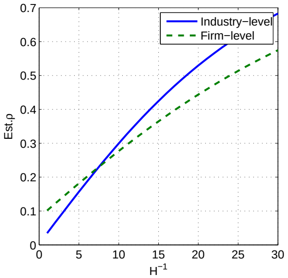


Figure : Firm level analysis of customer dispersion systematic risk. Left: estimation results, fixed effects, robust standard errors.

Firm-level: Aggregation over lead time

- Does the systematic risk increase with T?

$$(1): \quad \rho_S(i,t) = a_i + bT_{i,t} + \epsilon_{i,t}$$
$$(2): \quad |\rho_S(i,t)| = a_i + bT_{i,t} + \epsilon_{i,t}$$

Table : Firm level systematic risk as a function of the function of T, for retail, wholesale trade, and manufacturing firms constituents of SP500, robust standard errors, firm-level fixed effects.

		Coef.	Std.Err	95% C.I. LL	95% C.I. UL
ρ_S	T	0.012***	0.001	0.009	0.014
	Intercept	0.198***	0.009	0.180	0.216
$\lvert\rho_S\rvert$	T	0.028***	0.001	0.026	0.030
	Intercept	0.222***	0.006	-0.209	0.234

- One quarter increase in lead time increases risk by $\approx 3\%$.

Summary of empirical results

Table : Amplification of the systematic risk

Mechanism	Industry-level	Firm-level
Production decisions	☒	☒
Aggregation	✓	✓
Lead time	✓	✓

Cost of capital

$$\beta_i = a + b_1(\rho_S)_i + b_2(\sigma_s)_i + b_3(\rho_S \times \sigma_s)_i + \epsilon_i.$$

Table : Estimates of relationship between Beta, ρ_S, and σ_s.

	Industry-level		*Firm-level*	
	Base model	Full model	Base model	Full model
ρ_S	0.653**(0.267)	-0.799*(0.407)	0.426***(0.078)	0.570***(0.117)
σ_s	-	-1.340*(0.725)	-	1.459***(0.333)
$\rho_S\sigma_s$	-	10.916***(2.742)	-	1.508** (0.729)
Intercept	0.692***(0.084)	0.890***(0.107)	0.914***(0.038)	0.737***(0.053)
N	43	43	239	239
$Prob > F$	0	0	0	0
$Adj.R^2$	0.106	0.434	0.109	0.187

*-$p < .1$, **-$p < .05$, ***-$p < .01$

- If the equity risk premium is 6% Damodaran (2012), the estimates of the relationship between beta and ρ_S suggest that for every increase in ρ_S by 0.1, the cost of equity increases by 0.25-0.39% per annum.

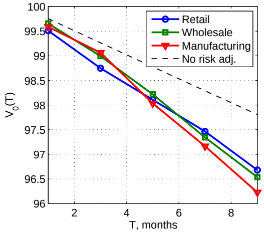
Supplier selection and valuation of supply chain investments

- Supplier selection result: addition of the new customer will increase the systematic risk of the supplier by 14% (from 0.0880 to 0.1005), *ceteris paribus*
- Value of future random payoff S as viewed from time 0:

$$V_0(T) = \frac{\mathbb{E}(S) - \Omega \mathbb{C}\mathbf{ov}(S, r)(T)}{1 + r_f},$$

where $\Omega = \frac{\mathbb{E}(r) - r_f}{\mathbb{V}\mathbf{ar}(r)}$ is the market price of risk

- $\mathbb{C}\mathbf{ov}(S, r)(T)$ depends on T and customer structure



NAICS M3 Code	Industry	Planning horizon, months 1	3	5	7	9
44.45	Retail trade	99.51	98.75	98.11	97.47	96.68
42	Wholesale trade	99.65	98.99	98.22	97.34	96.54
MTM	Manufacturing	99.59	99.06	98.03	97.17	96.23
-	No systematic risk adjustment	99.75	99.26	98.78	98.29	97.81

Figure : Risk adjustment factors as a function of lead time.

Conclusions

- Why certain industries and firms are robust to economic downturns, while others suffer?
- We define the systematic risk of an industry or a company and study its potential drivers
  - Production decisions
  - Aggregation of customer orders
  - Leadtime in operational decisions
- Industries and firms appear to attenuate the systematic risk in production decisions
- Disperse and wide customer base and longer leadtimes are associated with the increased systematic risk
  - Higher systematic risk is priced into the cost of capital
  - Supplier selection affects the systematic risk of the supplier
  - Supply chain investments change the risk profile of the company and should be executed with care

Thank you!

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The paper is forthcoming in *Management Science*