Economic Resilience of the Firm: A Production Theory Approach[†]

March 26, 2018

Noah Dormady[††]
Assistant Professor
John Glenn College of Public Affairs
The Ohio State University
Faculty Affiliate
Critical Infrastructure Resilience Institute
University of Illinois

Alfredo Roa-Henriquez
Doctoral Candidate
John Glenn College of Public Affairs
The Ohio State University

Adam Rose
Research Professor
Price School of Public Policy
University of Southern California
Faculty Affiliate
Critical Infrastructure Resilience Institute
University of Illinois

Abstract:

As a result of catastrophic events, firms and other organizations are faced with input shortages and price shocks. Firms can respond to these events using a variety of "resilience" actions, or tactics. Here we provide a microeconomic foundation for analyzing a comprehensive range of these tactics, incorporating both inherent and adaptive concepts of resilience. We classify these tactics and derive optimality conditions for production with the use of each class of resilience in the context of a nested Constant Elasticity of Substitution (CES) function consisting of aggregated Capital (K), Labor (L), Infrastructure (I), and Materials (M). The framework has broad applicability, including measurement and scoring of resilience, cost-effectiveness assessment of resilience tactics individually and as a group, calculation of resilience indices, and supply-chain management.

Keywords:

Economic Resilience; Production Theory; Inherent and Adaptive Resilience; Disasters

JEL Classifications:

D2; L29; L39; M21; Q54

[†] *Acknowledgements*: The authors gratefully acknowledge funding from the U.S. Department of Homeland Security's Critical Infrastructure Resilience Institute (CIRI) (Grant No. 2015-ST-061-CIRC0).
[††] Corresponding Author: 1810 College Rd., Columbus OH, 43210; email: dormady.1@osu.edu; Ph.: 614-688-1668.

1. Introduction

Research on resilience has proliferated in recent years. Numerous definitions, tactics, metrics, and indices have been proposed. However, most of them are formulations with little or no formalized theoretical underpinnings. This is as true for economic resilience as it is in other fields. Unfortunately, this subjects recent research advances to criticisms of being arbitrary, inconsistent, and missing key elements.

Lacking is a comprehensive framework for the analysis of how enterprises, or firms, cope with disasters. The most prevalent definition of resilience in economics at the microeconomic level focuses on how firms use remaining resources as effectively as possible and invest in repair and reconstruction so as to accelerate recovery (Rose, 2004; Kajitani and Tatano, 2009; Graveline and Gremont, 2017). Economic production theory provides an ideal framework for the analysis of resilience at this micro level. It characterizes how firms use inputs in optimal combinations to achieve goals such as production targets or the maximization of profits. Thus far, however, the use of this framework has barely been explored. Rose and Liao (2005) analyzed how firms substituted for and conserved on critical inputs whose supply was disrupted in the aftermath of a disaster. However, these are only two of a dozen general classes of resilience actions, or tactics, that firms can use to respond to unforeseen shocks. Rose (2009, 2017) suggested the use of this framework for other resilience tactics and noted some of the complications that should be addressed but did not perform a rigorous applied micro theory analysis.

The concept of economic resilience as articulated and formally analyzed by Rose and Liao (2005) and others has helped spawn a far-reaching literature in several fields that seeks to incorporate this concept into their own. Some examples include research on enterprise resilience (e.g., Sanchis and Poler, 2013), supply-chain resilience (e.g., Hosseini and Barker, 2016), community resilience (e.g., Cutter, 2016), regional macroeconomic resilience (e.g., Martin and Sunley, 2015), reliability engineering (e.g., Pant et al., 2012), and adaptation to climate change (e.g., Pelling, 2010). Still, none of these analyses provides a formalized theoretical approach from an economic perspective, and they generally include only one or a few resilience tactics. Thus, progress would be enhanced by a general analytical framework capable of analyzing key characteristics and implications of a comprehensive set of individual resilience tactics. For example, as businesses identify an increasing number of resilience tactics, it behooves them to have a standardized approach for analyzing and measuring the cost-effectiveness of the alternatives so as to better determine the optimal mix of production inputs. As Hosseini, Barker and Ramirez-Marquez (2016) conclude from a recent comprehensive survey of resilience research, tangible resource allocation models capable of analyzing tradeoffs among dimensions of resilience are greatly needed.

The purpose of this paper is to present a comprehensive production theory framework for analyzing economic resilience at the level of the individual firm across dimensions of resilience. We derive optimality conditions for eleven core resilience tactics using a typology of four distinct cases that covers them all. We use a Kuhn-Tucker formulation to generalize the analysis to cases in which a critical input may not be available at all. The analysis provides insights into trade-offs and complementarities in the application of resilience tactics. It also provides the basis for the measurement of the effectiveness and costs of these various tactics.

The contributions of this paper extend beyond the microeconomic level. For example, it helps strengthen the foundation of supply-chain resilience, which has gained increasing attention in this *Journal* (Tang and Tomlin, 2008; Hosseini and Barker, 2016; Kamalahmadi and Parast, 2016; Brusset and Teller, 2017; Chowdhury and Quaddus, 2017). Much of this literature is spawned by the need to cope with disruptions of critical inputs, which is exactly the focus of microeconomic resilience (though only on the direct input considerations and not the indirect ones that distinguish supply-chain analysis). We provide a theoretical analysis of eleven resilience tactics, including input substitution, relocation, import substitution, relocation, technological change and improvements in management effectiveness in a production theory context.

2. Background

2.1 Defining Economic Resilience

Although there are many definitions of resilience, Rose (2009, 2017) and others have found more commonalities than differences. We offer the following general definitions of resilience, which capture the essence of the concept, and then follow them with definitions that capture the essence of economic considerations. Following Rose (2004, 2007, 2017), we distinguish two major categories, or dimensions, of resilience:

- In general, Static Resilience refers to the ability of the system to maintain a high level of functioning when shocked (Holling, 1973). *Static Economic Resilience* is the efficient use of remaining resources at a given point in time. It refers to the core economic concept of coping with resource scarcity, which is exacerbated under disaster conditions.[1]
- In general, Dynamic Resilience refers to the ability and speed of the system to recover (Pimm, 1984). *Dynamic Economic Resilience* is the efficient use of resources over time for investment in repair and reconstruction. Investment is a time-related phenomenon—the act of setting aside resources that could potentially be used for current consumption in order to re-establish productivity in the future. Static Economic Resilience does not completely restore damaged capacity and is therefore not likely to lead to complete recovery.

Another important delineation in economic resilience, and resilience in general, is the distinction between inherent and adaptive resilience (Rose, 2004; Tierney, 2006; Cutter, 2016). Inherent resilience refers to resilience capacity already built into the system, such as the ability to utilize more than one fuel in an electricity generating unit, the workings of the market system in offering price signals to identify scarcity and value, and established government policy levers. Adaptive resilience is exemplified by

[1] This definition has been cited by two papers on supply-chain resilience in this *Journal* (Hosseini and Barker, 2016; Chowdhury and Quaddus, 2017).

undertaking conservation that was not previously thought possible, changing technology, devising market mechanisms where they might not have previously existed (e.g., reliability premiums for electricity or water delivery), or devising new government post-disaster assistance programs. We acknowledge that resilience is a process, whereby steps can be taken before the disaster to build resilience capacity, but resilient actions do not take place until afterward (see also analogous distinctions in the definition of resilience in the supply-chain literature by Azadegan and Jayaram, 2018). Also, unlike other fields such as engineering, the focus of economic resilience is not on property damage, which has already taken place, but rather the reduction in the loss of the *flow of goods and services* emanating from property, or *capital stock*. The former is often measured in terms of the level of production at the micro level and supply-chain analysis or gross domestic product (GDP) at the macro level, and is typically referred to as business interruption, or BI. BI just begins at the point when the disaster strikes but continues until the system has recovered.

2.2 An Operational Metric

The next step is to translate these definitions into something that can be measured. Following Rose (2004, 2017), for static resilience, the metric is the amount of BI prevented by the implementation of a given resilience tactic or set of tactics comprising a resilience strategy divided by the maximum potential BI.

Several studies have measured resilience using this and related metrics. Rose et al. (2009) found that potential BI losses were reduced by 72 percent by the rapid relocation of businesses following the September 11, 2001 terrorist attacks on the World Trade Center. Rose and Wei (2013) found that a reduction in potential BI from a nine-month closure of a major US seaport could be as high as 66 percent from the implementation of several types of resilience, most notably ship rerouting, use of inventories, and production rescheduling. Xie et al. (2015) estimated that BI losses could have been reduced by 30 percent and recovery time by one year with an increase in investment funds and acceleration of their timing in the aftermath of the Wenchuan earthquake in China.

Other studies have found extensive potential of economic resilience. Kajitani and Tatano (2009) found extensive resilience possibilities among Japanese manufacturing firms in response to utility lifelines disruptions caused by disasters. Specialized studies have developed methodologies for examining the potential of specific resilience strategies, such as the use of inventories (Barker and Santos, 2009).

2.3 Resilience and Firm-level Actions

Despite the many disparate definitions of resilience—ecological, economic, organizational behavior, engineering—they each identify a similar general conceptualization of rebounding after a disaster or shock event (Rose, 2009; 2017). The canonical resilience path, attributed most commonly to Holling (1973) and many subsequent contributions (e.g., see Bruneau et al., 2003; Zobel, 2011; Hosseini, Barker and Ramirez-Marquez, 2016), is provided below in Figure 1 with an application to a firm or organization.

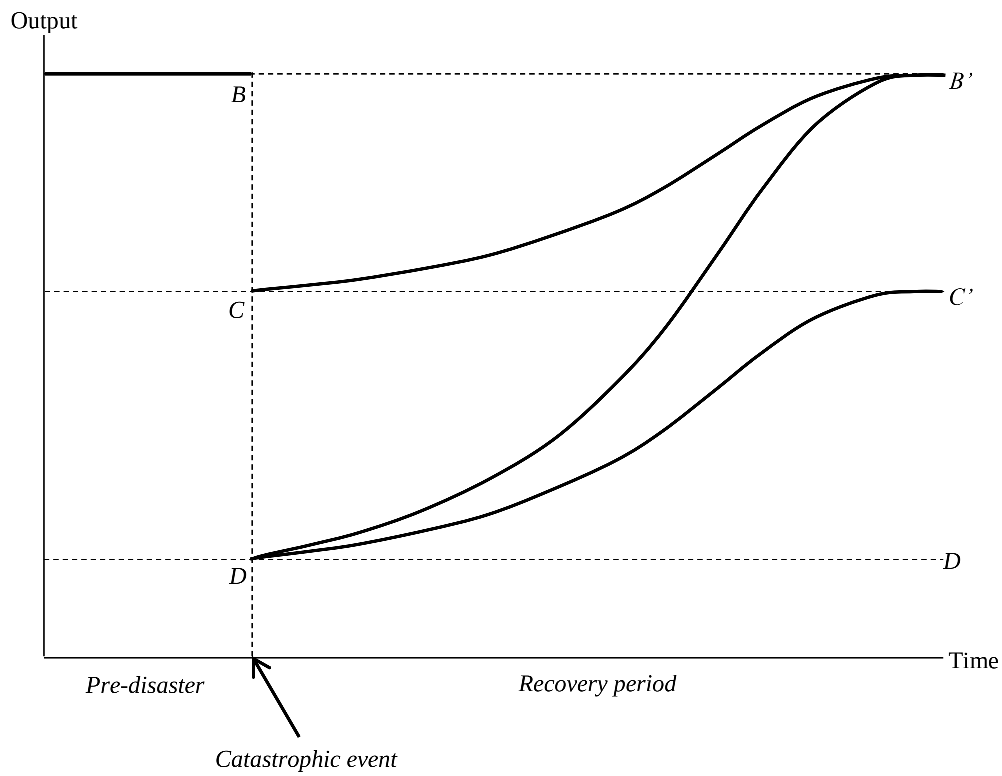

Figure 1. Resilience in Firm Recovery

Here, the output of the firm is plotted on the y-axis, and time is plotted on the x-axis. Point B identifies the firm's output before the shock, and points C and D identify two of many possible output levels the firm may face in the immediate aftermath of the shock. The recovery path of the firm—either returning to a new normal at or below, the pre-disaster output level—is identified for three of among

Table 1. Resilience Tactics/Actions and General Definitions

Resilience Tactic	Definition (Activities Involved)	Related Terminology in Supply-Chain Literature
Conservation	Maintaining intended production or service levels using lower amounts of an input or inputs (e.g., achieving the same level of production using less water, electricity or workers, without substituting other inputs for them).	*Green Supply Chain* (Govindan et al., 2014); *Recoverable Manufacturing Systems* (Guide Jr. et al., 2000)
Resource Isolation	Modifying a portion of business operations to run without a critical input (e.g., following a disaster an office building could still be operational without water). This can include isolation before the event or extra effort to isolate it post-event.	*Flexible Production Processes* (Graves & Tomlin, 2003; Stecke & Kumar 2009; Bode et al., 2011)
Input Substitution	Replacing a production input in short supply with another (e.g., replacing electricity by natural gas, piped water with bottled or trucked water, whole milk with powdered milk, employees for tasks previously performed by machinery).	*Input Redundancy* or *Production Flexibility* (Martha & Vratimos, 2002; Sheffi, 2005; Tang, 2006; Pettit et al., 2013)
Inventories	Continuing business operations even when a critical input is in short supply by using emergency stockpiles and ordinary working supplies of production inputs (e.g., water tanks, canned goods, stock-piled materials in general).	*Inventories* or *Strategic Stock* (Sheffi & Rice, 2005; Tang, 2006; Bode et al., 2011); *Inventory Buffers* (Lee, 2004; Kleindorfer & Saad, 2005)
Excess Capacity	Using plant or equipment that was idle before a disaster in place of a damaged plant and equipment (e.g., bringing on-line physical assets not previously in use; such assets might include computers, equipment, vehicles, and vacant buildings).	*Excess Capacity* (Lee, 2004; Kleindorfer & Saad, 2005); *Flexible Supply Base* (Tang, 2006); *Organizational Slack* (Bourgeois, 1981); *Volume Flexibility* (Tomlin, 2006)
Relocation	Moving some or all of the business activity to a new location (either temporary or permanent), including shifting data from onsite to "cloud" storage.	*Production Rerouting* (Tomlin, 2006; Rose et al., 2018)
Management Effectiveness	Improving business efficiency in the aftermath of a disaster (e.g., allowing for flexibility in business operations/procedures to minimize red tape during recovery, offering flexible working hours, minimizing reporting requirements or monitoring to facilitate more efficient or responsive operations).	*Efficient HR Management* (Coutu, 2002; Stecke & Kumar 2009)
Import Substitution	Importing needed production inputs when not available from the usual local or regional suppliers, including new contractual arrangements (e.g., buying materials or supplies from other regions or countries).	*Multiple/Redundant Suppliers* (Lee, 2004; Kleindorfer & Saad, 2005)
Technological Change	Improvising all or part of the production process without requiring a major investment expenditure (e.g., replacing two food preparation kitchens with one, replacing a paper accounting system with an automated one).	*Alternate Technology* (Pettit et al., 2013)
Production Recapture	Making up for lost production (not just selling inventories) by working overtime or extra shifts (e.g., adding an additional shift for employees or having them work additional overtime hours).	*Overtime* or *Double Shifts* (Sheffi & Rice, 2005)
Resource Pooling/Sharing	Hastening recovery through mechanisms such as bargaining (e.g., renegotiating supply contracts), selective exchange of resources (short-term agreements for a defined period of time with other organizations, e.g., utilization of facilities in exchange for provision of any service or any other resource), creating new partnerships (e.g., building relationships with other businesses to share information and/or expertise), and joint ventures (e.g., to bid for public contracts).	*Buffering* (Menzar & Nigh, 1995; Bode et al., 2011); *New Alternative Sourcing Arrangements* (Lee & Wolfe, 2003; Tomlin, 2006); *Collaborative Information Exchange* (Pettit et al., 2013)

many possible recovery paths. A firm may also rebound sufficiently to a new normal above pre-disaster levels, not illustrated in Figure 1. We utilize this nomenclature for specific reference points to identify specific production parameters on a firm's isoquant and production function below.

In general, the tactics and strategies that firms can take to improve either static or dynamic resilience can include a variety of business operations. Note that the application to disasters is based on the issue of how businesses react when one or more of their inputs are disrupted or damaged. We choose to delineate the tactics into eleven discrete activities in relation to inputs and the firm's response, as provided in Table 1. Building on Rose (2009), the table provides a naming convention for each static resilience tactic along with refined definitions and examples.

The table provides terminology for related or similar tactics in the resilient supply-chain literature so that readers more familiar with the supply-chain terminology can compare them with the economic resilience tactics. It is important to note that the supply-chain literature addresses the concept of resilience actions primarily from the planning side (i.e., prior to a disaster). This includes common resilient supply-chain tactics such as diversification (Chopra and Sodhi, 2004; Kleindorfer and Saad, 2005; Tang, 2006), integration (Frohlich and Westbrook, 2001; Narasimhan and Kim, 2002; Vickerey et al., 2003; Das et al., 2006; Hendricks, Singhal and Zhang, 2009), and supply and demand-side flexibility (Tsay and Lovejoy, 1999; Van Miegham and Dada, 1999; Tang and Tomlin, 2008).

Pre-disaster planning strategies are often referred to as "mitigation" in the resilience literature, as they do not directly pertain to *adaptive* resilience (i.e., how a firm responds to unforeseen disruption after it begins). However, some proactive planning actions move beyond mitigation toward actually building resilience capacity (a form of inherent resilience in our terminology, more recently referred to as "anticipative" resilience in the supply-chain literature, see Azadegan and Jayaram, 2018). Examples of this include increasing inventories or lining up alternative suppliers. In this paper we explicitly model only the set of tactics that a firm could implement in the event of an unforeseen disruption, but model both *inherent* and *adaptive* resilience. And, we do so for cases in which firms both do, and do not, experience a change in relative prices associated with the disruption. Thus, without a loss of generality, our models are adaptable to both pre- and post-disaster tactics of relevance to both microeconomic and supply-chain resilience. However, our tactics represent only a subset of the broader supply-chain resilience tactics, focusing on how individual firms cope with disruptions of inputs from their direct suppliers. Our focus is on a single firm as a subset of the characterization of major disruptions to the supply chain, such as stage-spanning bottlenecks and floating bottlenecks (Graves and Tomlin, 2003). We acknowledge the broader issues of strategy such as process flexibility in multi-product supply chains, but this is far beyond the scope of this paper (see, e.g., Graves and Tomlin, 2003).

3. A Background on Production Theory

3.1 Production Functions

Economists have developed sound theories to explain the workings of most aspects of the economy. Theories are abstractions by definition, but they serve the purpose of providing a consistent framework of analysis that focuses on fundamental causal relationships. One such body of knowledge is known as *production theory*—how firms (businesses) operate. At the core is the concept of the production function, or how firms combine various inputs to generate their products. Specification of these functions provides insight into the combination of inputs and their productivity, substitution between inputs, and how input relationships with outputs vary according to scale. Various "functional forms" are available, the most ideal of which allow for a variety of possibilities and numerical values in these key relationships. Production functions have been refined over time to include a variety of determinants other than basic generalized inputs of labor, capital, and natural resources. This first included intermediate inputs, infrastructure, inventories, spatial considerations, and management characteristics, and then environmental inputs. More recently, it has included behavioral considerations, which are especially important when considering resilience. These focus primarily on human factors such as perceptions and motivations. The generalized production function approach is presented in the following implicit form:

$Q^t = f(A, K, L, N, M, I, V, E, S, G, B)$

where,

A = technology
K = capital
L = labor
N = natural resources
M = materials (intermediate goods)
I = infrastructure
V = inventories
E = environment
S = spatial considerations (location)
G = management
B = behavior (information processing, perceptions, biases)

Despite the strengths of this approach, firms do not just maximize output but have to produce under constraints such as cost considerations. Hence, a constrained optimization problem, such as the minimization of cost subject to an output constraint, is the more relevant problem for the manager because it is more consistent with the operational problem faced by firms (Varian, 1992). In this sense, there exists a *duality* between the production and cost functions. This implies that given a production function with *n* factors such as the one described above with known factor prices, it is possible to find a minimum cost function for the firm. Once the firm has found its minimum cost function, it is possible, under certain regularity conditions, to derive factor demand equations (Shephard, 1970; Diewert, 1971).

The arguments of the implicit production function can be mapped onto our resilience tactics, some directly and some requiring explanation. For example, inventories have a direct mapping as does the management term mapping onto our management effectiveness tactic. Spatial considerations map onto our relocation tactic. The technology term relates to technological change and arises through the conservation of any of the inputs (e.g., energy efficiency improvements, higher capacity utilization levels). All of the inputs are subject to some degree of input substitution. In the analysis below, we do not explicitly model the effects of environmental or behavioral factors/inputs. However, the former can be analyzed in a similar manner to those inputs that we do consider, while the latter might best be considered as coming into play in the implementation of various resilience tactics, thereby affecting the extent to which their potential is accurately evaluated and made effective.

3.2 The Constant Elasticity of Substitution Production Function

In order to more explicitly explain the production decisions of firms, several different functional forms of production models have been estimated. The most prevalent are the Cobb-Douglas (CD), the Constant Elasticity of Substitution (CES), and the translog production functions (Greene, 2012). The Cobb-Douglas function has been extensively used for empirical estimation despite strong conditions imposed on its functional form (i.e., it requires that the elasticity of substitution always be unity). Improving upon this restriction, Arrow et al. (1961) developed a family of functions, the Constant Elasticity of Substitution (CES) production function, which emerged as a more general functional form incorporating a full range of cases in which the elasticity of substitution is constant between a group of inputs but can take on values between zero and infinity. The technology characterized by a CES production function provides an example of isoquants that look well-behaved (i.e., convex to the origin and monotonically increasing with respect to output), which are the result of assuming properties such as linear homogeneity, homotheticity and diminishing marginal returns, facilitating the empirical estimation of the production function and its analysis. Although the translog is the most frequently used flexible functional form in empirical analysis (predominantly due to its flexibility for econometric estimation),[2] the CES has become quite popular in general equilibrium models and has also been gaining importance in econometric work despite its nonlinear features and the fact that no transformation reduces its functional form to one that is linear in the parameters (Greene, 2012).

Different versions of the CES have been proposed (Uzawa, 1962; McFadden, 1963) that allow different constant elasticities between each pair of factors but, at the same time, impose strict conditions on the elasticities of substitution and make them less useful in empirical applications (Sato, 1967). These restrictions can be overcome by transforming the ordinary CES into a hierarchal decision process corresponding to a set of nests, or tiers, for which the elasticity of substitution must be constant for each

[2] Translog stands for Trascendental Logarithmic. This is a more general production function than the CES, as it does not impose any constraints on the elasticity of substitution (Christensen, Jorgenson, & Lau, 1973).

nest, but need not be of equal numerical value across nests (Perroni & Rutherford, 1995; Rose & Liao, 2005). The basic idea of nesting CES functions is to have two or more levels of CES functions, where each of the inputs of an upper-level CES function might be replaced by the dependent variable of a lower-level CES function. For this function, factors are combined according to the CES at one level to form higher level factors, which are combined again to produce output.

In this way, the CES function allows a modeler to incorporate production inputs of a firm in a flexible way to develop a production model that adequately captures the key inputs of analysis. A nesting structure can thus be developed that facilitates analysis of resilience by incorporating the input designations most relevant. Here, we make use of this flexibility and introduce a constant elasticity of substitution (CES) production function that has the following nested form for four aggregate inputs; capital (K), labor (L), infrastructure (I), and materials (M).

$$q = A_1\left[\alpha_1\left(A_L L\right)^{-\rho_1} + \left(1-\alpha_1\right)KIM^{-\rho_1}\right]^{-1/\rho_1} \tag{1}$$

$$KIM = A_2\left[\alpha_2 M^{-\rho_2} + \left(1-\alpha_2\right)KI^{-\rho_2}\right]^{-1/\rho_2} \tag{2}$$

$$KI = A_3\left[\alpha_3 K^{-\rho_3} + \left(1-\alpha_3\right)I^{-\rho_3}\right]^{-1/\rho_3} \quad , \tag{3}$$

where q is output, A_i is the factor-neutral technology parameter ($A_i > 0$); A_L is the labor-specific technology parameter; α_i, is the share parameter ($0 \le \alpha_i \le 1$); σ_i is the constant elasticity of substitution ($\sigma_i = \frac{1}{1+\rho_i}$); KIM is the capital, infrastructure, and materials combination; and KI is the capital and infrastructure combination. The elasticity of substitution measures the "ease" by which one input can be substituted for another without cost penalty and is graphically characterized by the curvature of the isoquant. An example is a hospital responding to a labor shortage by using cellular/remote diagnoses. The factor-neutral technology parameter, or total factor productivity, measures efficiency in terms of the proportion of output that is not explained alone by the amount of inputs used in production and is graphically represented by a parallel shift in the isoquants. For instance, conservation is identified when a firm is able to obtain the same level of output with reduced or interrupted electricity, which would be reflected in a total factor productivity exceeding a value of 1.0 (see e.g., Rose and Liao, 2005). More examples of each tactic are provided in Section 4.

Production functions like the CES, therefore, allow for the estimation of production relationships between key inputs and their sub-nests. Regarding estimation, there is a two-way relationship (i.e., duality) between a production function and a cost function in the sense that, under certain conditions, the existence of the production function implies the unique existence of its dual, which facilitates estimation because data needed to estimate the dual are often more readily available than are data for estimating the production function directly. Duality is more tractable when the production function is homothetic (i.e., the slopes of the isoquants are invariant to proportional increases in each production factor) because the dual can be expressed as a separable cost function (Silberberg and Suen, 2000). However, the estimation of more complex production functions such as nested CES have required the implementation of local linear approximations, grid search procedures and global optimization algorithms (Henningsen & Henningsen, 2012). Here we utilize these relationships in the context of a KLIM function to introduce a theoretical approach for the analysis of static economic resilience—those actions that firms can take with existing resources on hand in the aftermath of a disaster or hazard to utilize resources as efficiently as possible, thereby facilitating rebounding or recovery of production output.

4. Resilience in Firm Production Decisions

4.1 Mapping Firm Production Decisions to Resilience

Consider a nested CES production function such as the one that was defined in the previous section, and also consider the first tier as comprised only of two factors: Labor, *L*, and the Capital-Infrastructure-Material aggregate, *KIM*, which we will refer to as *K* for the sake of simplification. As shown in Figure 2, the maximum number of units of *K* and *L* available to the firm before the shock are K_0 and L_0, respectively. Before a shock (e.g., Superstorm Sandy, Hurricane Katrina, Northridge Earthquake), the firm is producing at a given level of output (identified by isoquant q_0) and is using a combination of inputs of K, L, I and M optimally. This pre-disaster optimal input mix can be identified at point B in Figure 2 (and matched to point B in Figure 1).

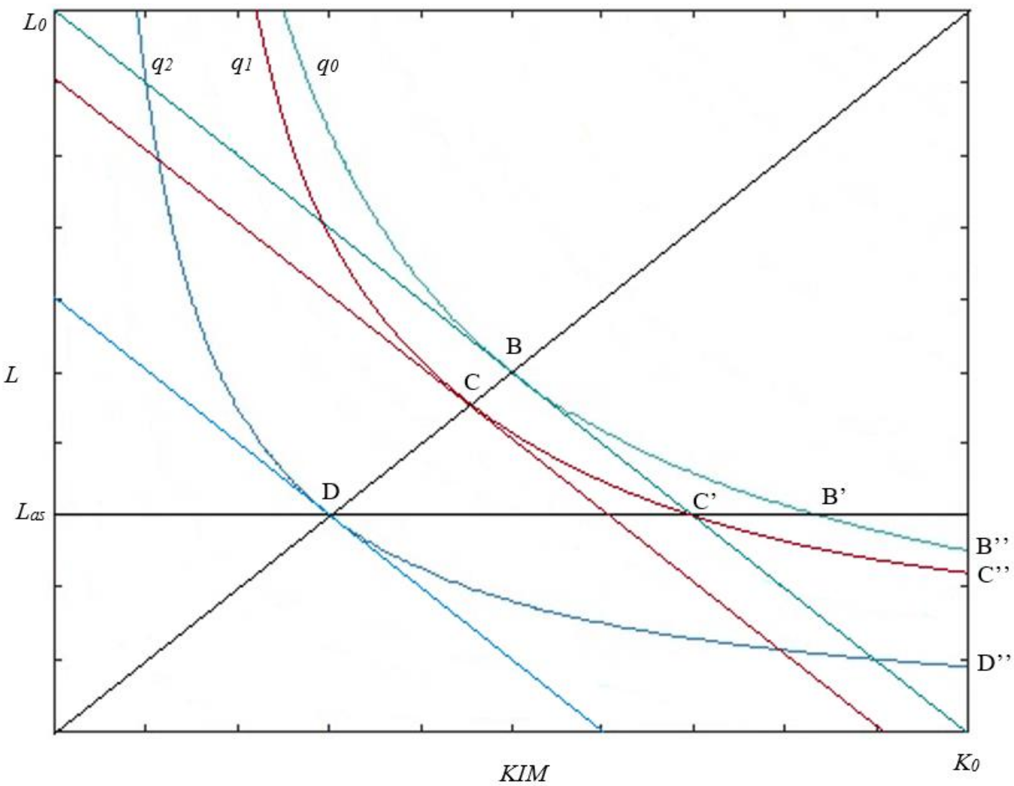

Figure 2. Isoquant Map for Firm-level Resilience Actions with and without Disaster-Induced Input Constraint

In this sense, if q_0 represents pre-disaster output in our CES function, *A* the total factor productivity parameter, α the factor share parameter, ρ the substitution parameter, and P_L and P_K represent price of Labor and price of the Capital-Infrastructure-Material aggregate, respectively, the optimal solution (i.e., optimal level of labor, L^*, and the *KIM* aggregate, K^*) of the cost minimization problem of the firm becomes:

$$K^{*}=\frac{\left(\frac{q_0}{A}\right)}{\left[\alpha\left[\frac{(1-\alpha)P_L}{\alpha P_K}\right]^{\rho/(\rho+1)}+(1-\alpha)\right]^{-\frac{1}{\rho}}} \tag{4}$$

$$L^{*}=\frac{\left(\frac{q_0}{A}\right)}{\left[\alpha+(1-\alpha)\left[\frac{\alpha P_K}{(1-\alpha)P_L}\right]^{\rho/(\rho+1)}\right]^{-\frac{1}{\rho}}} \tag{5}$$

In the absence of a disaster, L^* and K^* would identify optimal production inputs of labor and KIM, respectively. However, in the aftermath of a disaster, output may be severely curtailed, altering the optimal production input mix. In the absence of a demand shock, output curtailment is directly attributable to input constraints on K, L, I or M. Consider an input constraint on labor consistent with the recent Superstorm Sandy experience in which many employees could not travel to their place of work or were preoccupied with attending to their families or damaged dwellings. In Figure 2, we can observe a post-shock labor constraint, L_{as}. After the shock, the firm observes a curtailment in the level of accessible labor, which can be measured by the difference between L_0 and L_{as}.[3] Post disaster production may remain at its original pre-shock level (i.e., isoquant q_0), may fall to a slightly lower level of output (isoquant q_1), or may fall considerably to an even lower production level (isoquant q_2). As a result, the optimization problem becomes:

$$\text{Min } P_{L_{as}}L+P_K K \tag{6.a}$$

$$\text{s.t. } A\left[\alpha\left(A_L L\right)^{-\rho}+(1-\alpha)K^{-\rho}\right]^{-1/\rho}\geq q_{as} \tag{6.b}$$

[3] Here we demonstrate a labor curtailment. Capital, materials or infrastructure curtailments are also possible. For these others , inputs can easily be swapped and used in slightly different nesting structures to those presented above. Additionally, a constraint representing a fixed and inflexible Capital-Infrastructure-Material aggregate, *KIM*, in the post-disaster short run, is important for extreme cases in which firms use a specific tactic (e.g., relocation) and post-disaster output ends up being larger. In this sense, the constraint does not prevent this situation to occur for reasons other than increase in plant size, infrastructure or materials availability.

$$L \le L_{as} \tag{6.c}$$

$$K \le K_0 , \tag{6.d}$$

where q_{as}, L_{as}, and $P_{L_{as}}$ denote post-shock output, labor and cost of labor, respectively. Additionally, A_L denotes a labor-specific technology parameter, which allows us to incorporate changes in labor productivity,[4] with the remaining parameters already defined. We formulate the Lagrangean function and obtain Kuhn-Tucker first-order conditions (FOC), as follows:

$$\begin{aligned} \ell = -P_{L_{as}} L - P_K K + \mu_1 \left(A\left[\alpha A_L^{-\rho} L^{-\rho} + (1-\alpha) K^{-\rho} \right]^{-1/\rho} - q_{as} \right) \\ - \mu_2 \left(L - L_{as} \right) - \mu_3 \left(K - K_0 \right) \end{aligned} \tag{7}$$

$$-P_{L_{as}} + \mu_1 \left(A\left[\alpha A_L^{-\rho} L^{-\rho} + (1-\alpha) K^{-\rho} \right]^{\frac{-1-\rho}{\rho}} \right) \left(\alpha A^{-\rho} A_L^{-\rho} L^{-\rho-1} \right) - \mu_2 = 0 \tag{8}$$

$$-P_K + \mu_1 \left(A\left[\alpha A_L^{-\rho} L^{-\rho} + (1-\alpha) K^{-\rho} \right]^{\frac{-1-\rho}{\rho}} \right) \left[(1-\alpha) A^{-\rho} K^{-\rho-1} \right] - \mu_3 = 0 \tag{9}$$

$$\mu_1 \left(A\left[\alpha A_L^{-\rho} L^{-\rho} + (1-\alpha) K^{-\rho} \right]^{-1/\rho} - q_{as} \right) = 0 \tag{10}$$

$$\mu_2 \left(L - L_{as} \right) = 0 \tag{11}$$

$$\mu_3 \left(K - K_0 \right) = 0 \tag{12}$$

These Kuhn-Tucker conditions are a generalization of the FOCs for an interior solution that allow for corner solutions (i.e., when one of the inputs is not utilized).

Based on equations 8 through 12, we can now introduce an approach to derive optimal production decisions of firms for each resilience tactic. In this way, we can incorporate both *inherent resilience* and *adaptive resilience*. The former can be represented as a movement along an isoquant, and the latter as an

[4] We assume a model with labor-augmenting productivity (i.e., Harrod neutral). When this parameter is not included in any solution, we have assumed its value to be 1.

isoquant shift, due to a change in technology or factor productivity (see Rose and Liao, 2005). And, both can occur simultaneously. As it turns out, nearly all post-disaster static resilience actions are a special case of input substitution. That is, the relationship between inputs that are utilized, and how, when another input, or inputs, are constrained or affected in some way by the disaster. Therefore, all resilience actions can be mapped onto one of four general cases provided in Table 2.

Table 2. Firm Resilience and Production Effects of Resilience Tactics

	No Price Effects	**Price Effects**
No Productivity Effect (Inherent Resilience)	**Movement Along an Isoquant:** *Input Substitution* *Import Substitution* *Relocation* *Resource Isolation* *Resource Pooling* (Case 1)	**Movement Along an Isoquant & Change in the Isocost Function:** *Input Substitution* *Import Substitution* *Recapture* *Relocation* *Resource Isolation* (Case 2)
Productivity Effect (Adaptive & Inherent Resilience)	**Shift in an Isoquant & Movement Along an Isoquant:** *Conservation* *Import Substitution* *Input Substitution* *Management Effectiveness* *Relocation* *Resource Pooling* *Technological Change* (Case 3)	**Shift in an Isoquant, Movement Along an Isoquant & Change in the Isocost Function:** *Conservation* *Import Substitution* *Input Substitution* *Management Effectiveness* *Relocation* *Technological Change* (Case 4)

In the first case, resilience actions involve input production decisions in an environment in which prices are not affected, either exogenously due to the disaster or endogenously due to the implementation of the tactic. In the second case, resilience actions involve production decisions in an environment in which relative input prices are affected, and this is modeled as a change in the firm’s isocost function. In the third case, the productivity of an input(s) is affected, but the relative price of inputs is not affected. And finally, in the fourth case, the firm’s productivity is affected in conjunction with a change in the relative price of inputs. Table 2 provides a summary of how each tactic is modeled and which tactics are applicable to each of the four cases.

For uniformity, we demonstrate each case in the prevalent post-disaster context of a labor shock (e.g., employees unable to travel to work due to a physical transportation constraint, employees occupied attending to families and homes, or loss of life). We note, importantly, that the approach can easily be modified to accommodate conditions of alternative input shocks, and we discuss a variety of modeling options for each case below.

We also facilitate easy comparison between the canonical resilience curves provided in Figure 1 and the isoquant maps as provided in Figures 2-5 for each of the respective cases. In this way, each production relationship can be matched to an output level on the resilience curve so that the reader can clearly identify the connection between resilience and production decisions. In all figures, pre-disaster firm output is identified as point B. The post-disaster output in the absence of resilience actions is identified as either C or D, depending upon the severity of the effect of the disaster on the firm. And, post-disaster output after the implementation of resilience actions is identified as B' and C', respectively. The analysis below becomes extended as the complexity of the cases increases.

4.2 Case 1: The firm observes no change in input price ($P_{L_{as}} = P_L$), or productivity (A_L=1) after the shock

Here we illustrate a straightforward resilience case in which the firm faces a disaster-induced shock to a core production input (labor). In this case the shock to the availability of labor does not induce scarcity pricing in wages. Additionally, we assume no change in the productivity of labor, which would be consistent with a situation in which the disaster does not affect the marginal product of labor.

Figure 2 shows how the *KIM* aggregate varies after the shock. In this case, post-disaster level of output might fall to q_1, q_2, or remain at its pre-disaster level q_0. If output falls from q_0 to q_1, the range of possible solutions would be found along the portion of the isoquant designated by (arc) C'C''. If there are no changes in labor productivity and relative prices among production factors after the disaster, the optimal solution would consist of movements along the isoquant to point C' where total cost would be equal to the pre-disaster total cost but the production level would be slightly lower. If output falls from q_0 to q_2, possible solutions would be found along the arc DD'', but the optimal solution would be located at point D, where total cost would be lower than the pre-disaster total production cost and the production level would also be considerably lower. Finally, if production remains at the same pre-disaster level q_0, possible solutions would be found along the arc B'B'', but the substitution and optimal solution would consist of moving along the isoquant to point B', where total cost would be higher than the pre-disaster total production cost. These solutions can be computed when μ_1 and μ_2 are simultaneously greater than zero (i.e., constraints on output and labor are active), but $\mu_3 = 0$, with the following demand functions of labor and the *KIM* aggregate:

$$L^* = L_{as} \tag{13}$$

$$K^* = \left[\frac{\left(\frac{q_{as}}{A} \right)^{-\rho} - \alpha L_{as}^{-\rho}}{1-\alpha} \right]^{-\frac{1}{\rho}}, \tag{14}$$

where q_{as} corresponds to q_0, q_1, and q_2. In this sense, if output falls to q_1 after the disaster, inherent resilience can be measured by subtracting the *KIM* aggregate level at point C' from that at point B'. However, if the post-disaster output falls to q_2, inherent resilience can be computed by subtracting the *KIM* aggregate at point D from that at point B'.[5]

In this case, a disaster-induced shock to labor could have resulted in substantially reduced output for the firm. However, through substitution of the KIM aggregate for labor, the adverse effects of the binding labor constraint is at least partially overcome (output q_1 or q_0 instead of q_2). This inherent

[5] As Figure 2 has been drawn, it is possible to inherently (i.e., without any change in technology or productivity) achieve the pre-disaster level of production after the shock. As this is not always the case, the firm needs to carry out adaptive actions to achieve the initial output. For instance, if the constraint on labor were located below B'' but above C'', it would not be possible to achieve q_0 inherently.

resilience effect would be consistent with a variety of resilience tactics of a firm and for shocks to other production inputs besides labor. *Input substitution* and *import substitution* themselves are axiomatic, as they are themselves defined by the use of alternative inputs to offset the constrained or scarce input. In the wake of many disasters such as hurricanes, earthquakes and floods, firms can incur damage to materials or capital equipment. Utilization of labor to manually offset damaged equipment or materials is also consistent with this resilience case, as it employs the substitution of existing inputs to reduce the severity of curtailments in another input.

Similarly, in many disaster situations, firms incur damage to their physical plant (i.e., property damage) or damage to critical lifeline infrastructure (e.g., water, power, telecommunications, waste removal). When firms opt for *relocation,* either due to property damage or the loss of reliable infrastructure, they are engaging in substitution of land. We note that under the conditions of Case 1, we implicitly assume an equal rental rate on the new/relocated property. In Case 2 we relax this assumption and allow for a change in the isocost function, such as would occur in relocation from shoreline realty to less costly inland realty, or when a disaster induces scarcity pricing in the absence of slack in the commercial property market. Case 2 also allows us to incorporate the potentially higher cost of imported goods if a tactic of import substitution is utilized.

In our framework, land can be sub-aggregated within a production input such as capital. In the aftermath of Superstorm Sandy, for example, the New Jersey shoreline incurred flooding through stormwater inundation, roads and bridges were damaged making it difficult for employees and customers to travel to places of business, and critical infrastructure was disrupted. A number of firms chose to lease or buy new physical plant or storefront inland and away from the damaged shoreline. Similarly, Rose et al. (2009) conducted a computable general equilibrium analysis of the economic impacts of the September 11, 2001 terrorist attacks and found that one of the predominant reasons that economic losses were not substantially greater, was the glut of available office space in the New York area at the time.

An extreme application of this particular resilience case occurs when a firm is able to continue operating at some reduced level in the absence of an input entirely—referred to as *resource isolation*.

Offices, for example, can continue operating in the absence of running water unless prohibited by local code enforcement. They can substitute drinking water with bottled water and onsite restrooms with trips to offsite restroom facilities. In the absence of a critical raw material, production-based firms can continue operating on those production lines that do not require the curtailed input, essentially isolating production. In our framework, *resource isolation* can be modeled as a corner solution for firms that do not have segmented production amenable to resource isolation.

This resilience case is similarly applicable to *resource pooling*, or the sharing of resources or information among firms in communities, trade associations or other networks. In the case of shared information, firms can learn about substitution opportunities from similarly-situated firms and replicate those actions. In the aftermath of Hurricane Katrina, technical operational expertise was shared with New Orleans transit operators by transportation operators in Boston, who experience near outages from cold weather events routinely. The Metro Boston Transit Authority (MBTA) sent expert personnel to New Orleans to assist onsite and facilitate the information exchange (Dormady and Ellis, 2018). In the case of pooled physical resources, firms can acquire substitute materials from neighboring firms and obtain gains from trade. An example in the above-mentioned water outage application is observed when a neighboring firm that is not faced with a water outage allows neighboring firms and their customers to utilize its restroom facilities. Public utilities have similarly pooled linemen and other technical personnel to facilitate transmission and distribution system recovery. Resource pooling of physical resources can offset shortfalls in key production inputs, predominantly production materials, though labor and capital equipment can also be pooled.

From a modeling standpoint, pooled raw materials would be modeled much like import substitution, though no political borders are crossed in the process of exchange. It should be noted that pooled resources can also serve to temporarily improve a binding input constraint. In the given labor constraint example, this would be modeled as an increase in L_{as} by the amount of the resource pooled, allowing for inherent resilience to move firm output to a higher isoquant, with an associated substitution away from KIM.

4.3 Case 2: The firm observes an increase in input price ($P_{L_{as}} > P_L$) but productivity remains the same after the shock (A_L=1)

In this case, as in the previous case, the firm may observe post-disaster output reductions below q_0 , at q_1 or q_2. Here we extend the first case to allow for a change in cost of a key production input in the post-disaster environment by allowing for a change in the isocost function. In the aftermath of a disaster, firms may observe an increase (or potentially decreases) in costs of key inputs for a variety of reasons including scarcity, hoarding, demand changes, price gouging, etc. Here we build upon the example of the first case by modeling an increase in the price of labor accompanying the labor constraint. This would be consistent with a post-disaster environment in which there was either a demand side, or supply side, or both, effect on the price of labor.

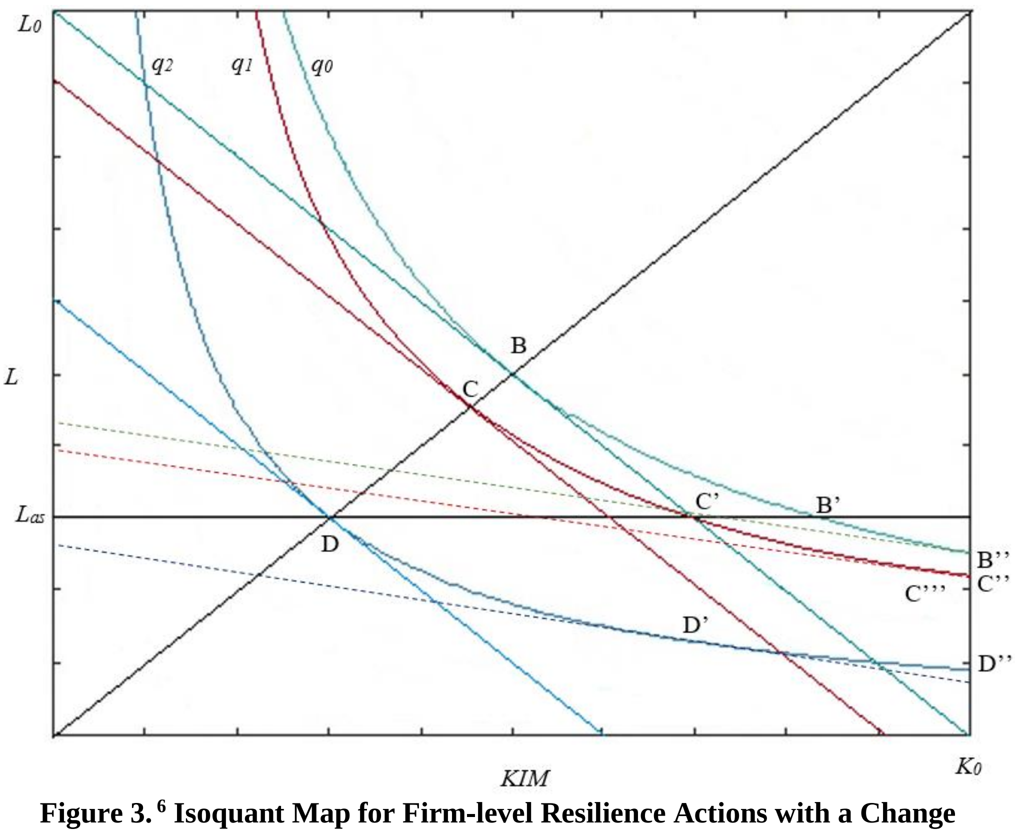

Figure 3.[6] **Isoquant Map for Firm-level Resilience Actions with a Change in Relative Prices–Inherent Resilience**

[6] We note that the horizontal line illustrating the labor constraint in Figures 3-5 may appear to have a positive slope. This is only an optical illusion, however.

We also assume that the new price relationship between production factors is equivalent to rotating the isocost line around point C' until reaching the (left-hand) "tangency" point B,'' which happens to be a corner solution.[7] Here the optimal solution would be point D' if the post-disaster level of output decreases to q_2. It would be point B'' if the post-disaster level of production remains at q_0. And, it would be point C''' if the post-disaster level of output falls to q_1. For q_1 and q_2, the optimal solution is calculated when $\mu_1 > 0$ but $\mu_2 = \mu_3 = 0$, which implies:

$$K^* = \frac{\left(\frac{q_2}{A}\right)}{\left[\alpha\left[\frac{(1-\alpha)P_{L_{as}}}{\alpha P_K}\right]^{\rho/(\rho+1)} + (1-\alpha)\right]^{-\frac{1}{\rho}}} \tag{15}$$

$$L^* = \frac{\left(\frac{q_2}{A}\right)}{\left[\alpha + (1-\alpha)\left[\frac{\alpha P_K}{(1-\alpha)P_{L_{as}}}\right]^{\rho/(\rho+1)}\right]^{-\frac{1}{\rho}}} \tag{16}$$

For q_0, we compute the optimal solution when μ_1 and μ_3 are simultaneously greater than zero but $\mu_2 = 0$ (i.e., constraints on output and the *KIM* aggregate are active), as follows:

$$K^* = K_0 \tag{17}$$

$$L^* = \left[\frac{\left(\frac{q_{as}}{A}\right)^{-\rho} - (1-\alpha)K_0^{-\rho}}{\alpha}\right]^{-\frac{1}{\rho}}, \tag{18}$$

where q_{as} corresponds to q_0 and q_1 and the post-disaster price of labor, $P_{L_{as}}$, is higher than the pre-disaster price, P_L. As in the previous case, if post-disaster output falls to q_1, inherent resilience can be computed

[7] One important improvement that the Kuhn-Tucker approach provides above a previous approach such as Rose and Liao (2005) is its ability to model corner solutions.

by measuring the distance from C''' to B''. Nonetheless, if the post-disaster output falls to q_2, inherent resilience can be measured by calculating the distance between points D' and B''.

This second case is applicable to several specific resilience actions. As in the previous case, the utilization of *input substitution* and *import substitution* are obvious. Firms that can substitute other inputs or use imports can do so and avoid a potentially larger output loss. In using either tactic, a firm might observe higher prices of the substituted input for a variety of reasons, both due to the disaster and not. These would result in a slope change in the isoquant map to accommodate a higher cost of utilizing imports. Additionally, a firm utilizing *relocation* due to infrastructure restoration delays or property damage may observe a leasing price differential between its prior location and its new location. A change in the isocost function would similarly accommodate the leasing or purchase price difference.

In a similar way, *resource isolation* may also be accompanied by post-disaster changes in input prices. A firm utilizing the tactic to either continue operating in the absence of an input or shifting production to a product line that does not require the curtailed input, may simultaneously be accompanied by a change in the relative price of the curtailed input. In the event that the isolation is due to the absolute absence of the input (i.e., the input is completely unavailable), a change in the isocost function for that input would not affect the firm's optimal production decision, as it would simply result in a corner solution provided in Case 1. In other words, even if the price of the input increased, the firm would not observe it because the firm could not access the input anyway. On the other hand, if the isolation was due to a curtailed input that was still available to some degree and the firm engaged in isolation to shift production away from that input, it is likely that the price of that input would increase for other firms in the region as well, and all firms in the region would observe a similar change in relative prices. In either case, the firm would be shifting its production away from the use of the input either in response to the constraint, in response to the price change, or both simultaneously.

Another application of the second case is the tactic *production recapture.* A firm that runs extra shifts in an effort to recapture lost production may simultaneously observe a change in relative prices, due say, to paying overtime wages. Whereas the increase in costs associated with running extra shifts should not endogenously affect the relative prices of inputs to the firm, its consumption levels can affect marginal costs of inputs that would affect relative prices. This is particularly the case for infrastructure and labor inputs. In the case of electricity, water and gas, public utilities commissions often approve graduated, or tiered pricing tariffs. Adding an extra shift could very likely result in higher marginal costs of those inputs (e.g., a jump from 9 cents/kWh to 11 cents/kWh beyond a consumption level of 200,000 kWh on a commercial tariff).[8] In the case of labor, adding extra shifts even in an environment in which the constrained input is not labor, could likely necessitate overtime pay or higher overhead. This can be seen in Figure 3 as the isocost function shifts downward in relation to the labor axis.

4.4 Case 3: The firm observes no change in input price ($P_{L_{as}} = P_L$), but observes an increase in labor augmenting productivity after the shock ($A_L > 1$)

Adaptive resilience can be effectively modeled as a productivity improvement (Rose and Liao, 2005). Whereas inherent resilience is driven by explicit actions of a firm to alter production processes or to substitute among inputs, adaptive resilience is consistent with a more efficient utilization of remaining resources due to ingenuity, innovation or extra effort. This has been observed repeatedly in post-disaster situations in which firms, individuals and communities roll up their sleeves and work markedly toward a hastened recovery (Alesch et al., 2001; Chang and Falit-Baiamonte, 2002; Cutter 2017), and in the process, discover new or improved ways of operating and managing resources (Rose and Liao, 2005; Wein and Rose, 2011).

Productivity improvements in a post-disaster environment manifest themselves as adaptive input substitution (see Rose and Liao, 2005). In this case, the firm can potentially return to its pre-disaster production level (or greater) because an increase in the productivity of an input results in a nonparallel

[8] The opposite effect could occur in the case of time-of-use (TOU) pricing such as smart-metered billing. Smart meters enable tariff rates to be pegged to actual wholesale grid price on the independent systems operator (ISO) or regional transmission operator (RTO) markets. A firm that adds extra shifts in off-peak hours and whose electricity rate is pegged to the wholesale market price is likely to observe lower marginal costs of electricity because it would be buying electricity at the lower off-peak price. In this case, the isocost function would shift in the opposite direction, with lower relative infrastructure prices.

shift in the isoquant toward the origin and, in turn, a higher relative level of output for the same input combination. The move to a higher output level isoquant is represented graphically in Figure 4 by an isoquant that is shifted toward the origin (i.e., uses fewer inputs to achieve the same or greater output). This effect is common in post-disaster situations and occurs when employees roll up their sleeves and operate in a heightened capacity in an effort to make up for the absence of coworkers. With the same or fewer inputs available after a disaster, adaptive resilience enables a firm avoid larger losses in output or incur none at all.

This particular situation is depicted in Figure 4. Previously, when the level of output falls to q_1 after the disaster, the total cost of producing optimally at C' was equal to the pre-disaster optimal cost. Nonetheless, the firm is not able to achieve the same pre-shock output level. However, when there is a technological change or productivity improvement in relation to labor, we can observe a shift in the isoquant. Labor-augmenting technical change shifts the isoquants to the left—indicating the same level of output with a reduced level of input *L*—and a change in isoquant slope (marginal rate of technical substitution) is thus observed. As a result, should the output level fall to q_1, the firm could achieve a new output level, q_0' in Figure 4, by utilizing production factors at E', with a total cost that is higher than its new optimum at point E. On the other hand, if the output level should fall to q_2 following the shock, it would be possible for the firm to achieve a new output level, (q_1' in Figure 4) with demand for inputs given at F', which is located to the right of the optimal solution derived from the isoquant q_2 (i.e., point D). This new solution is computed as a result of a parallel movement from q_0' to q_1', and a subsequent substitution from F to F').

Adaptive resilience can be measured as the ratio of averted loss (i.e., horizontal distance between C' and E' if output falls to q_1 after the disaster) to maximum potential loss (i.e., horizontal distance between C' and B'). Additionally, it can also be measured as the ratio of averted loss (i.e., horizontal distance from point D to point F' or the distance from D to E' if the post-disaster level of production is q_2) to maximum potential loss (i.e., horizontal distance between D and B').

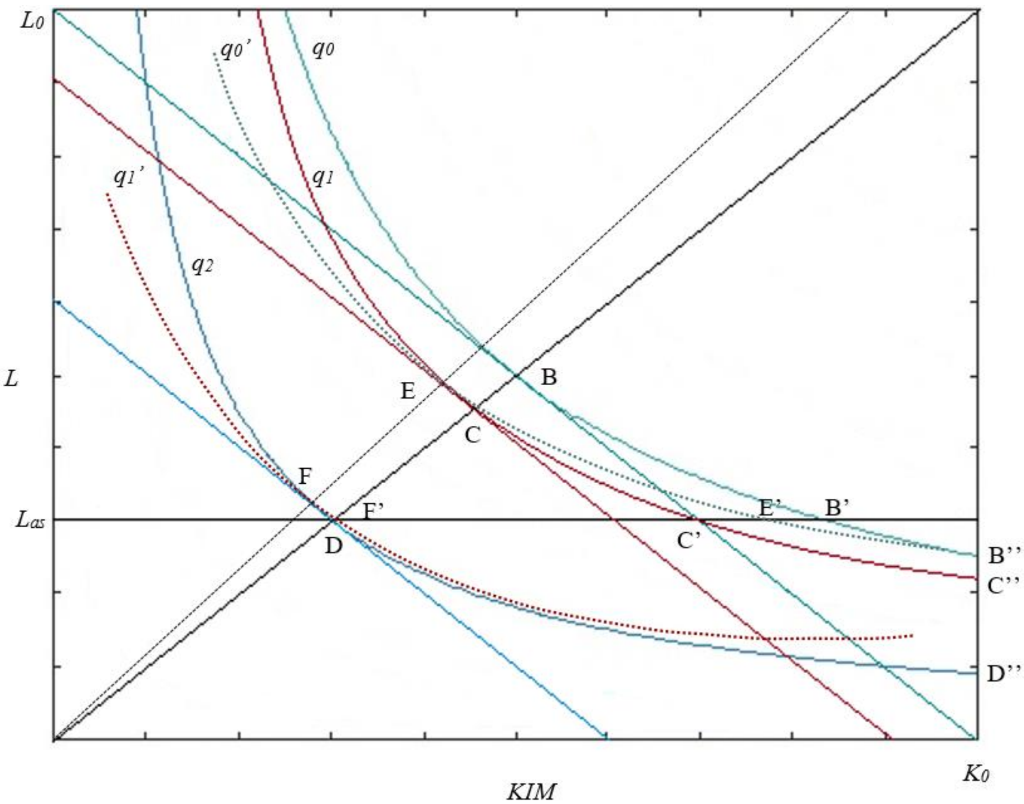

Figure 4. Isoquant Map for Firm-level Resilience Actions—Adaptive & Inherent Resilience (Labor-Augmenting Technological Change)

In this sense, if the firm exhibits labor-augmenting productivity (i.e., labor is measured in efficiency units and the number of efficiency units per worker, A_L, rises), having the same number of workers implies more effective labor. As a consequence, if the production falls to q_1 or q_2 after the disaster, we can recognize the labor augmenting productivity by deriving the CES production function with respect to labor and capital as follows:

$$q_L = \frac{\partial q}{\partial L} = A_L^{-\rho} A^{-\rho} \alpha \left(\frac{q_{as}}{L_{as}} \right)^{1+\rho} , \tag{19}$$

$$q_K = \frac{\partial q}{\partial K} = A^{-\rho} \left(1-\alpha\right) \left(\frac{q_{as}}{K_{q_{as}}} \right)^{1+\rho} , \tag{20}$$

where q_L and q_K represent marginal productivity of labor and capital, respectively, q_{as} corresponds to q_1 and

q_2, and $K_{q_{as}}$ characterizes the level of the *KIM* aggregate used at q_1 and q_2. Firms respond to labor-augmenting productivity based on the value of the elasticity of substitution, σ, which is calculated through the CES substitution parameter as: $\sigma = 1 / (1+\rho)$.

Labor-augmenting productivity affects the ratio of marginal products and the elasticity of substitution, as follows:

$$\frac{q_K}{q_L} = A_L^{\frac{1-\sigma}{\sigma}} \frac{1-\alpha}{\alpha} \left(\frac{K}{L} \right)^{-1/\sigma} \tag{21}$$

When labor-augmenting productivity increases while holding the *KIM* aggregate-labor relationship constant, the marginal productivity of *K* rises relative to that of labor if $A_L^{(1-\sigma)/\sigma}$ increases. This happens when the elasticity of substitution is less than unity (i.e., $\sigma < 1$), indicating that labor and the *KIM* aggregate are relatively less substitutable. On the other hand, if the elasticity of substitution is greater than 1 (i.e., $\sigma > 1$), this not only indicates a higher relative degree of substitutability between labor and the *KIM* aggregate but also that the relative marginal productivity between *K* and *L* decreases (i.e., the marginal productivity of labor rises).

When μ_1 and μ_2 are simultaneously greater than zero but $\mu_3 = 0$, optimal solutions at E' and F' are given by:

$$L^* = L_{as} \tag{22}$$

$$K^* = \left[\frac{\left(\frac{q'}{A} \right)^{-\rho} - \alpha A_L^{-\rho} L_{as}^{-\rho}}{1-\alpha} \right]^{-\frac{1}{\rho}}, \tag{23}$$

where q' refers to q_0' or q_1', and the post-shock cost of labor remains constant after the disaster as was defined previously.

In terms of the applicability of Case 3 to specific resilience tactics, adaptive resilience can be observed alongside the use of virtually any tactic as firms have the potential for productivity improvements in essentially all production inputs. Given this, Case 3 is most applicable in terms of modeling four specific tactics: *Conservation*, *Management Effectiveness*, *Relocation*, and *Technological Change*. Explicit efforts to conserve production inputs, such as materials (M) or infrastructure (I) can be modeled as materials or infrastructure augmenting productivity improvements. For example, a firm's conservation of electricity consumption would be illustrated as an inward shift in the isoquant in relation to the infrastructure input that represents the same or greater output with fewer infrastructure inputs.

In a similar way, *Management Effectiveness* efforts to reduce red tape that result in more effective labor (L), improved utilization of materials (M) or capital (K) would be modeled in a similar manner as an improvement in the productivity of those respective inputs. Likewise, *Relocation* could similarly result in productivity increases (or decreases) of land. The firm's new location could be accompanied by greater reliability of infrastructure (I) (e.g., a move to an office/factory supported by faster fiber optic cables or Volt/Var optimization controls). The firm's new location could similarly support improvements associated with industrial agglomeration or knowledge networks, resulting in technological improvements in labor (L) or other inputs. Finally, *Technological Change*—explicit post-disaster efforts to improve upon pre-disaster production processes without major investments—would be modeled in the same manner as a productivity improvement in one or more production inputs.

4.5 Case 4: The firm observes an increase in both input price ($P_{L_{as}} > P_L$) and labor-augmenting productivity after the shock (A_L>1)

We can now extend the application of inherent resilience to include an environment in which the firm also observes a change in relative prices. Here we extend the previous labor application to include a change in the relative price of labor. From equation 21 above, we can find the *KIM* aggregate – labor ratio as follows, which arises from the equilibrium condition that the ratio of marginal productivities equals the ratio of factor prices:

$$\frac{K}{L} = {A_L}^{1-\sigma}\left(\frac{1-\alpha}{\alpha}\right)^{\sigma}\left(\frac{P_{L_{as}}}{P_K}\right)^{\sigma} \qquad (24)$$

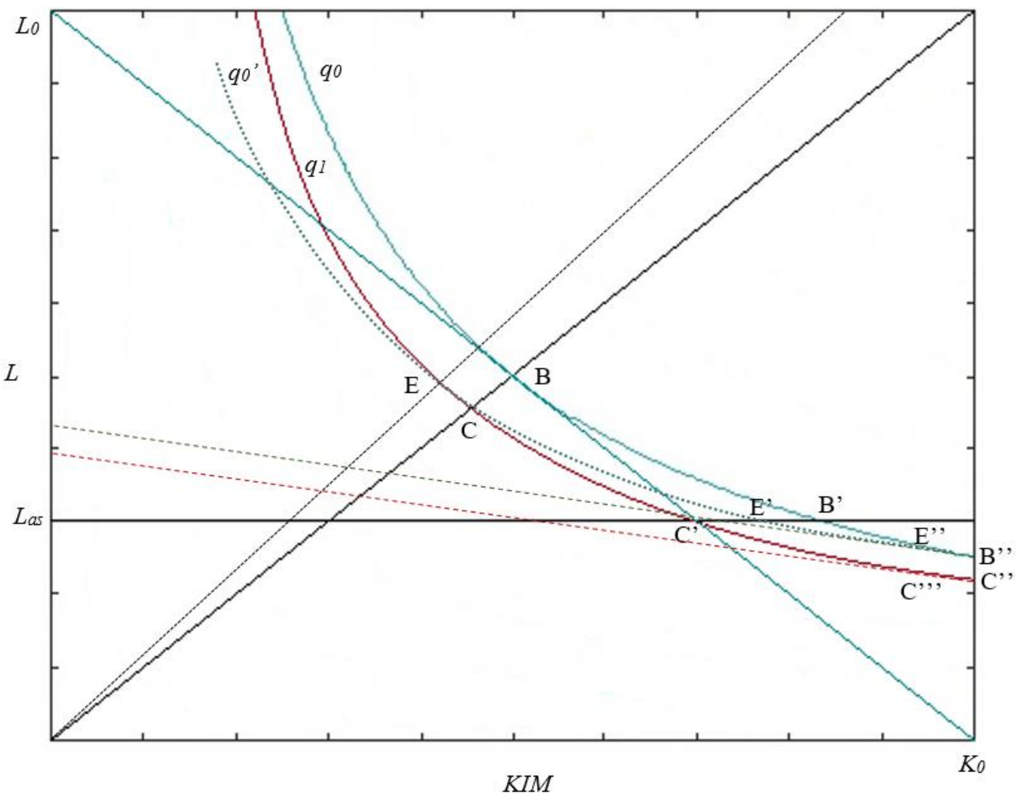

Figure 5. Isoquant Map for Firm-level Resilience Actions with a Change in Relative Prices—Adaptive & Inherent Resilience (Labor-Augmenting Technological Change)

In order to avoid cluttering Figure 5, we have exemplified this situation by only identifying pre-shock output q_0, post- shock output q_1, and the new q_0 when there is a shift in the isoquant map as a result of a change in labor productivity and an increase in the post-shock price of labor.

An increase in the price of labor will lead to an increase in the *KIM* aggregate – labor ratio. Additionally, if the elasticity of substitution is greater than 1, an increase in labor-augmenting productivity will lead to a reduction in the *KIM* aggregate – labor ratio. By the same token, if the elasticity of substitution is less than 1, an increase in labor augmenting productivity will result in an increase in the *KIM* aggregate – labor ratio. Without labor augmenting productivity, we previously observed the optimal solution at B''. After the technical change, we observe the new optimal solution at E'', where the new isocost line is tangent to the new q_0 (i.e., q_0'). Adaptive resilience is then measured as the distance from C''' to E''. The optimal solution at E'' is computed when $\mu_1 > 0$ but μ_2 and μ_3 are simultaneously equal to zero (i.e., constraint on output is active) according to the following equations:

$$K^* = \frac{\left(\frac{q_0'}{A}\right)}{\left[\alpha A_L^{-\rho/(\rho+1)}\left[\frac{(1-\alpha)P_{L_{as}}}{\alpha P_K}\right]^{\rho/(\rho+1)} + (1-\alpha)\right]^{-\frac{1}{\rho}}} \tag{25}$$

$$L^* = \frac{\left(\frac{q_0'}{A}\right)}{A_L\left[\alpha + (1-\alpha)A_L^{-\rho/(\rho+1)}\left[\frac{\alpha P_K}{(1-\alpha)P_{L_{as}}}\right]^{\rho/(\rho+1)}\right]^{-\frac{1}{\rho}}} \tag{26}$$

The extension provided by Case 4 allows us to model both inherent and adaptive resilience in environments in which firms observe a change in relative prices, either due to an exogenous change in prices stemming from the disaster or due to production-related decisions of the firm that affect its marginal cost of an input. As discussed in Case 2, the latter is likely to occur when conservation results in a lower marginal rate for energy or relocation results in a change in the rental rate on land; though numerous other scenarios are likely depending upon the nature of the firm and the post-disaster environment it faces. The application of Case 4 is again broadly applicable to essentially all resilience tactics a firm might engage in, and allows for the optimization of production inputs in the very likely case of changing relative prices.

4.6 Cost-Effectiveness Assessment

The cost and effectiveness of tactics derived from the analysis above are inputs into the resilience metric in relation to business interruption presented in Section 2.2, specifically the values in the numerator. The denominator is the loss a firm faces in the absence of a tactic's implementation. The maximum loss takes place in the absence of using the tactic. Analytically it is measured as the difference between the post-shock output before the tactic is implemented (points C or D in Figures 1-5) and the initial position (point B). The loss prevented is the difference between this level and the loss associated with the new equilibrium in the presence of the resilience tactic.

5. Extensions and Complications

In the previous sections we have presented a formal foundation for the theoretical and empirical analysis of static economic resilience in the context of production theory. The implicit assumption is that producers maximize output subject to production technology and cost constraints (or minimize costs subject to technology and output targets), inputs are homogeneous, and at least some inputs are substitutes. There are also implicit assumptions inherent in the production function.

In actuality, the manipulation of the production function in anticipation of, during, or in the aftermath of a shock caused by a man-made, natural, or technological disaster, involves a set of resilience tactics that are applied to the various inputs or product output. These resilience tactics differ in many instances from the ordinary production decisions operators or managers make in determining input levels or substituting among inputs. The analysis below attempts to shed light on some practical considerations and determine the extent to which they affect the decision process, the extent to which they need to be modeled in future work, and the extent their existence complicates empirical estimation.

Table 3 provides some key complications in relation to individual resilience tactics for the most prevalent conditions and common applications of the tactics as we have identified them. The first of these complications arises when actions taken prior to the event have carryover effects to future periods of time beyond the post-disaster recovery period (i.e., Long-Term Applicability), identified in Column 1. This is important in assessing the value of the tactic beyond the current disaster, as well as for the application of the tactic to environments that face multiple catastrophic events. Interestingly, among all of the examples only stockpiles of materials, such as fuels, represent a "one-shot" application, and only if the inventories are actually utilized.

Column 2 indicates whether actions must be taken with regard to the resilience tactic prior to the disaster (i.e., Pre-Shock Action) in order to build resilience capacity. It indicates that this is the case for some resilience tactics, such as inventories and excess capacity, and is the case for some applications of input isolation and relocation, such as establishing redundant or mirrored data repositories.

On the other hand, the third column indicates whether the resilience tactic can be applied following the shock (i.e., Post-Shock Action). In most cases the answer is yes, or at least minimally so. Exceptions relate to excess capacity and material inventories, which cannot be adjusted by resilience to cope with the shock once it has begun. The predominant focus of the production theory approach as presented in this paper has been on these tactics that can be implemented post-shock. This highlights a major contribution of the approach presented here in relation to the many supply-chain resilience contributions (identified above) that predominantly focus on resilience actions that must be put in place prior to a shock. These are often referred to as mitigation, or proactive planning, in the supply-chain literature (Tomlin, 2006; Stecke and Kumar, 2009).

Because some tactics need to be put in place (for future use) before the disaster, indicates that either a two-stage (two time-period) analysis is a logical extension of the approach presented here. This would require some measurement of temporal value, or exogenous discount rate, for the future resilience value of prior opportunity costs. One approach would be the combination of advanced stochastic operations research models that solve for the optimal inventory with a production theoretic model such as those presented here.

Column 4 indicates whether the implementation of the tactic can affect productivity (i.e., Productivity Enhancement Possibility). Various forms of conservation are productivity enhancing, and potentially costless or even cost-saving in the aftermath of the disaster, as are technological change and management effectiveness tactics. Others such as relocation to temporary quarters are likely to reduce productivity, though as identified in Section 3 above, they can also improve productivity. The “minimal” entries for tactics such as input substitution indicate a second-best situation with respect to original input combinations.

The next column in addresses whether the resilience tactic is applicable to more than one input simultaneously, as expressed as Multiple Input Applicability. Obviously input substitution involves input pairs, and excess capacity refers primarily to the capital input (we assume that the infrastructure input is beyond the control of the firm except in the use of relocation). Those entries listed as "no" refer to the fact that most tactics are applied to a single input, but several tactics do have multiple input applicability, such as relocation, technological change, and some management effectiveness.

Table 3. Prevalent Resilience Tactics and Production Relationships

Resilience Categories	Longer-Term Applicability	Pre-Shock Action	Post-Shock Action	Productivity Enhancement	Multiple Input Applicability	Applicability Limitations
Conservation						
-automated controls	on-going	no	yes	yes	yes	limit
-reduce non-essential use	on-going	no	yes	yes	yes	limit
Input Substitution						
-back-up generators	on-going	yes	yes	minimal	K, M	isoquant
-cross-training	on-going	yes	minimal	minimal	L types	isoquant
Import Substitution						
-mutual aid agreements	on-going	yes	minimal	minimal	no	isoquant
-re-routing of goods	on-going	no	yes	minimal	no	isoquant
Inventories (Stockpiles)						
-fuel supplies	one shot	yes	no	no	no	storage capacity
-labor pool	on-going	yes	minimal	no	no	storage capacity
Excess Capacity						
-system redundancy	on-going	yes	no	minimal	K only	no
-maintenance set-aside	on-going	yes	no	minimal	K only	no
Resource Isolation						
-decrease dependence	on-going	yes	minimal	yes	yes	physical limit
-segment production	on-going	yes	minimal	no	yes	physical limit
Relocation						
-back-up data centers	on-going	yes	yes	minimal	yes	no
-physical move	on-going	no	yes	minimal	yes	regional capacity
Production Recapture						
-information clearinghouse	on-going	no	yes	yes	n/a	K capacity
-restarting procedures	on-going	no	yes	minimal	n/a	K capacity
Technological Change						
-change processes	either	no	yes	yes	yes	no
-alter product characteristics	either	no	yes	yes	yes	no
Management Effectiveness						
-emergency procedures	either	yes	yes	yes	yes	no
-succession/continuity	either	no	yes	yes	no	no
Resource Pooling						
-information sharing	one shot	no	yes	yes	yes	no
-cross-pooling inputs	either	no	yes	minimal	yes	market capacity

The last column of the table indicates whether explicit limitations on the capacity of resilience tactics might need to be included formally. It should be noted that cost is not considered an explicit constraint, but obviously limits the implementation of all the tactics. Tactics such as excess capacity, some aspects of relocation, technological change and management effectiveness, do not require constraints. There is a limit to the amount of conservation that can be obtained, as there are limits on storage capacity for inventories and physical limits to how much of the firm's operation can be isolated from dependence on critical inputs. The limitation on input substitution is the production technology itself, as best represented by the isoquant. One can also consider a similar relationship between imported and regionally produced goods.

Another potential complication is that of the applicability of our tactics to cases of multi-product firms. We first make a distinction between a (single) production process that produces joint product outputs and a factory with multiple production processes, some of which may produce joint products. Applicability in practice depends to a great extent on the separation of the processes. For example, back-up generators might be used to power an entire factory or just a single process. Specialized material inputs might only be applicable to a subset of processes, but, even if applicable to only one, that single process may produce joint products. Thus, all of our resilience tactics are in fact applicable to multi-product firms. The analysis above can simply be extended by combining joint product outputs into a single composite, adding another dimension of substitution between inputs across products, or in an explicit joint-product production function.

One additional complication that merits discussion, and that this paper has not breached in any way, is the issue of complementarities. Complementarities, or synergies, arise in business when two or more production inputs or activities used in combinations generate output levels that exceed the total contribution of their inputs separately. An example is when two employees work well together and produce a higher quality or greater quantity of work products than each of them would have done independently. This can occur for any technological mix of inputs (e.g., land, labor, capital). This can also occur when two or more resilience tactics complement one another and result in a relative improvement in firm recovery.

For purposes of both modeling and assessing resilience, in the case of complementarities, it would be difficult to observe a change in recovery and attribute the resilience to either tactic independently. While empirical estimation through econometric analysis could offer some degree of statistical control to evaluate the independent contribution of any one tactic through evaluating cross-sectional variation of a large sample of firms, it would be quite difficult to map out multiple input combinations (i.e., an isoquant) of a firm simultaneously. Dormady et al. (2017) have introduced one potential survey-based approach to this, based on querying affected firms about their recovery path regarding the relative contribution of each tactic. Additionally, negative complementarities can arise when two or more tactics have a contradictory, or cancelling out, effect. A potential approach would be a vector-based one in which the effects on the resilience of multiple tactics could be mapped out in terms of both direction and magnitude.

On top of all of this, the core challenge of complementarities that affects both theoretical and empirical estimation of resilience is the endogeneity between complementarities and adaptive resilience (i.e., identifying the productivity improvement of a single tactic when it is used in combination with other complementary tactics that can jointly affect productivity). Both effects would show up as a shift in the isoquant. Additional research is needed on this front.

6. Conclusion

This paper has provided a formal microeconomic analysis of the economic resilience of the individual firm in the context of production theory. We developed a typology of resilience tactics that enabled us to condense the analysis of about a dozen alternatives into four cases. We then derived optimality conditions for resilience tactics using a Kuhn-Tucker formulation, since disasters can interrupt the entire flow of various production inputs.

This paper fills an important gap in literature. The vast majority of research on economic resilience lacks a solid theoretical foundation. Nearly all of the limited number of studies to date that have selected and analyzed resilience tactics have done so in the absence of a formalized theory like the one provided here. Almost none have formally analyzed the optimal use of these tactics individually or in relationship to one another. Attempts to formulate and apply resilience metrics have similarly been done in the absence of formalized theory.

Our production theory framework serves as a basis for deriving and testing hypotheses about effectiveness and cost of resilience. Its incorporation into a formal production theory context should facilitate econometric estimation of the effectiveness of individual tactics, their various applications, as well as competing and complementary relationships among the tactics.

The paper's contribution extends beyond its microeconomic focus. It can serve as the basis for the economic component of broader community resilience analyses and to strengthen the basis of research on supply-chain resilience. Our metrics can be useful in compiling an economic and even more comprehensive community resilience index. Although we have focused on static resilience at the microeconomic level, the analysis provides insight into dynamic economic resilience (primarily investment in repair and reconstruction of damaged capital stock) and to resilience at the meso (industry/market) and macro (economy-wide) levels.

Our analysis can also serve as an additional foundation for future supply-chain resilience research. At its most basic level, the analysis can apply to each firm in the chain. While we acknowledge that, at the most disaggregated level, supply chains are composed of firms that can each implement their own resilience actions, we also acknowledge that the complexity and interdependence of supply chains extends well beyond a single firm. A case in point is when a firm undertakes static economic resilience initiatives, but has its actions undercut by the action, or inaction of its suppliers. A prime example is the San Francisco Airport during the Loma Prieto earthquake, which paid the non-interruptibility premium for its electricity service, but its major fuel supplier did not and came close to being unable to deliver its product to the airport. We reiterate that recent supply-chain resilience research has identified a need for resource allocation models (e.g., Hosseini et al., 2016), and we offer our model as a contribution to this objective.

Relatedly, individual tactic cost and effectiveness metrics at the level of the firm, presented here, can be extended in future research to include the entire supply chain. While pre-planning resilience actions can reduce losses and build resilience capacity, many firms in post-disaster environments stumble because unforeseen circumstances eluded their ability to fully prepare for them. They then end up having to rely on a mix of adaptive tactics that, at the time, are perceived to be the most cost-effective, but in a second-best sense.

The direct extension of our approach is empirical estimation of the cost-effectiveness of static resilience tactics. The next step is empirical estimation of the cost-effectiveness of these tactics throughout the entire supply chain, taking into account multi-product and multi-stage considerations.

References

Azadegan A., Jayaram J. 2018. Resiliency in supply chain systems: A triadic framework using family resilience model. In: Khojasteh Y. (eds) Supply Chain Risk Management. Springer, Singapore

Alesch, D.J., Holly, J.N., Mittler, E., Nagy, R., 2001. Organizations at risk: What happens when small businesses and not-for-profits encounter natural disasters. Public Entity Risk Institute PERI.

Arrow, K.J., Chenery, H.B., Minhas, B.S., Solow, R.M., 1961. Capital-labor substitution and economic efficiency. Review of Economics and Statistics 43 (3), 225-250.

Barker, K., Santos, J.R., 2010. Measuring the efficacy of inventory with a dynamic input–output model. International Journal of Production Economics 126 (1), 130-143.

Bode, C., Wagner, S., Petersen, K., Ellram, L., 2011. Understanding responses to supply chain disruptions: Insights from information processing and resource dependence perspectives. Academy of Management Journal 54 (4), 833-856.

Bourgeois, L.J., 1981. On the measurement of organizational slack. Academy of Management Review 6 (1), 29-39.

Bruneau, M., Chang, S.E., Eguchi, R.T., Lee, G.C., O'Rourke, T.D., Reinhorn, A.M., et al., 2003. A framework to quantitatively assess and enhance the science of the seismic resilience of communities. Earthquake Spectra 19 (4), 733-752.

Brusset, X., Teller, C., 2017. Supply chain capabilities, risks, and resilience. International Journal of Production Economics 184, 59-68.

Chang, S.E., Falit-Baiamonte, A., 2002. Disaster vulnerability of businesses in the 2001 Nisqually earthquake. Global Environmental Change Part B: Environmental Hazards 4 (2), 59-71.

Chopra, S., Sodhi, M., 2004. Avoiding supply chain breakdown. Sloan Management Review 46 (1), 53-62.

Chowdhury, M. M. H., Quaddus, M., 2017. Supply chain resilience: Conceptualization and scale development using dynamic capability theory. International Journal of Production Economics 188, 185-204.

Christensen, L.R., Jorgenson, D.W., Lau, L.J., 1973. Transcendental logarithmic production frontiers. Review of Economics and Statistics 55 (1), 28-45.

Coutu, D.L., 2002. How resilience works. Harvard Business Review 80 (5), 46-55.

Cutter, S., 2016. The landscape of disaster resilience indicators in the USA. Natural Hazards 80, 741-758.

Cutter, S., 2017. The perilous nature of food supplies: Natural hazards, social vulnerability, and disaster resilience, Environment 59 (1), 4-15.

Das, A., Narasimhan, R., Telluric, S., 2006. Supplier integration—finding an optimal configuration. Journal of Operations Management 24, 563-582.

Diewert, W. E., 1971. An application of the Shephard duality theorem: A generalized Leontief production function. Journal of Political Economy 79 (3), 481-507.

Dormady, N., Ellis, R. 2018. Energy-transport sector interdependence in extreme events: The case of a hurricane event in Boston. Current Sustainable Renewable Energy Reports, Special Issue: Energy Markets: 1-13.

Dormady, N., Rose, A., Rosoff, H., Roa-Henriquez, A., 2017. A survey approach to measuring the cost-effectiveness of economic resilience to disasters. In M. Ruth & S. Reisemann (Eds.) Resilience of Socio Technical Systems. Cheltenham: Edward Elgar. Forthcoming.

Frohlich, M.T., Westbrook, R., 2001. Arcs of integration: An international study of supply chain strategies. Journal of Operations Management 19, 185-200.

Govindan, K., Azevedo, S.G., Carvalho, H., Cruz-Machado, V., 2014. Impact of supply chain management practices on sustainability. Journal of Cleaner Production 85, 212-225.

Graveline, N., Grémont, M., (in press). Measuring and understanding the microeconomic resilience of businesses to lifeline service interruptions due to natural disasters. International Journal of Disaster Risk Reduction.

Graves, S. C., Tomlin, B. T., 2003. Process flexibility in supply chains. Management Science 49 (7), 907-919.

Greene, W.H., 2012. Econometric analysis. Boston, MA: Prentice Hall.

Guide Jr, V. D. R., Jayaraman, V., Srivastava, R., Benton, W. C. (2000). Supply chain management for recoverable manufacturing systems. Interfaces 30 (3), 125-142.

Hendricks, K.B., Singhal, V.R., Zhang, R., 2009. The effect of operational slack, diversification, and vertical relatedness on the stock market reaction to supply chain disruptions. Journal of Operations Management 27, 233-246.

Henningsen, A., Henningsen, G., 2012. On estimation of the CES production function—Revisited. Economics Letters 115 (1), 67-69.

Holling, C.S., 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics 4 (1), 1-23.

Hosseini, S., Barker, K., 2016. A Bayesian network model for resilience-based supplier selection. International Journal of Production Economics 180, 68-87.

Hosseini, S., Barker, K., Ramirez-Marquez, J., 2016. A review of definitions and measures of system resilience. Reliability Engineering and System Safety 145, 47-61.

Kajitani, Y., Tatano, H., 2009. Estimation of lifeline resilience factors based on surveys of Japanese industries. Earthquake Spectra 25 (4), 755-776.

Kamalahmadi, M., Parast, M.M., 2016. A review of the literature on the principles of enterprise and supply chain resilience: Major findings and directions for future research. International Journal of Production Economics 171, 116-133.

Kleindorfer, P., Saad, G., 2005. Managing disruptions risk in supply chains. Production and Operations management Journal 14, 53-86.

Lee, H., 2004. The triple-A supply chain. Harvard Business Review 82, 102-112.

Lee, H., Wolfe, M., 2003. Supply chain security without tears. Supply Chain Management Review 7 (1), 12-20.

Martin, R., Sunley, P., 2014. On the notion of regional economic resilience: Conceptualization and explanation. Journal of Economic Geography 15 (1), 1-42.

McFadden, D., 1963. Constant elasticity of substitution production functions. Review of Economic Studies 30 (2), 73-83.

Menzar, M., Nigh, D., 1995. Buffer or bridge? Environmental and organizational determinants of public affairs activities in American firms. Academy of Management Journal, 38 (4), 975-996.

Narasimhan, R., Kim, S.W., 2002. Effect of supply chain integration on the relationship between diversification and performance: Evidence from Japanese and Korean firms. Journal of Operations Management 20, 303-323.

Pant, R., Barker, K., Sobel, D., 2012. Static and dynamic metrics of economic resilience for interdependent infrastructure and industry sectors. Reliability Engineering and System Safety 125, 92-102.

Pelling, M. 2010. Adaptation to climate change: From resilience to transformation. London: Routledge.

Perroni, C., Rutherford, T.F., 1995. Regular flexibility of nested CES functions. European Economic Review 39 (2), 335-343.

Pettit, T.J., Croxton, K.L., Fiksel, J., 2013. Ensuring supply chain resilience: Development and implementation of an assessment tool. Journal of Business Logistics 34 (1), 46-76.

Pimm, S.L., 1984. The complexity and stability of ecosystems. Nature 307 (5949), 321-326.

Rose, A., 2004. Defining and measuring economic resilience to disasters. Disaster Prevention and Management 13 (4), 307-314.

Rose, A., 2007. Economic resilience to natural and man-made disasters: Multidisciplinary origins and contextual dimensions. Environmental Hazards 7 (4), 383-95.

Rose, A., 2009. A framework for analyzing and estimating the total economic impacts of a terrorist attack and natural disaster. Journal of Homeland Security and Emergency Management 6 (1), Article 6.

Rose, A., 2017. Benefit-cost analysis of economic resilient actions. In S. Cutter (Ed.) Oxford Research Encyclopedia of Natural Hazard Science, New York: Oxford.

Rose, A., Liao, S., 2005. Modeling regional economic resilience to disasters: A computable general equilibrium analysis of water service disruptions. Journal of Regional Science 45 (1), 75-112.

Rose, A., Oladosu, G., Lee, B., Beeler-Asay, G., 2009. The economic impacts of the September 11 terrorist attacks: A computable general equilibrium analysis. Peace Economics, Peace Science and Public Policy 15 (2), Article 6.

Rose, A., Wei, D., 2013. Estimating the economic consequences of a port shutdown: The special role of resilience. Economic Systems Research 25 (2), 212-232.

Rose, A., Wei, D., Paul, D. 2018. Economic Consequences of a Disruption of Oil Imports: The Role of Seaports in U.S. Energy Security. Energy Policy 115, 584–615.

Sanchis, R., Poler, R., 2013. Definition of a framework to support strategic decisions to improve enterprise resilience. International Federation of Automatic Control Proceedings 46 (9), 700-05.

Sato, K., 1967. A two-level constant-elasticity-of-substitution production function. The Review of Economic Studies 34 (2), 201-218.

Sheffi, Y., 2005. The resilient enterprise: Overcoming vulnerability for competitive advantage. MIT Press.

Sheffi, Y., Rice Jr, J.B., 2005. A supply chain view of the resilient enterprise. MIT Sloan Management Review 47 (1), 41.

Shephard, R.W., 1970. Theory of cost and production functions. Princeton, NJ: Princeton University Press.

Shirali, G.H.A., Mohammadfam, I., Motamedzade, M., Ebrahimipour, V., Moghimbeigi, A., 2012. Assessing resilience engineering based on safety culture and managerial factors. Process Safety Progress 31 (1), 17-18.

Silberberg, E., Suen, W., 2000. The structure of economics: A mathematical analysis. New York: McGraw-Hill.

Stecke, K.E., Kumar, S., 2009. Sources of supply chain disruptions, factors that breed vulnerability, and mitigating strategies. Journal of Marketing Channels 16, 193-226.

Tang, C.S., 2006. Robust strategies for mitigating supply chain disruptions. International Journal of Logistics: Research and Applications 9 (1), 33-45.

Tang, C., Tomlin, B., 2008. The power of flexibility for mitigating supply chain risks. International Journal of Production Economics 116, 12-27.

Tierney, K., 2006. Businesses and disasters: Vulnerability, impacts, and recovery. In H. Rodriguez, E. L. Quarantelli, and R. R. Dynes (Eds.) Handbook of Disaster Research. New York, NY: Springer. Pp. 275- 296

Tomlin, B., 2006. On the value of mitigation and contingency strategies for managing supply chain disruption risks. Management Science 52 (5), 639-657.

Tsay, A., Lovejoy, W., 1999. Quantity flexible contracts and supply chain performance. Manufacturing and Service Operations Management 1 (2), 89-111.

Uzawa, H., 1962. Production functions with constant elasticities of substitution. The Review of Economic Studies 29 (4), 291-299.

Van Mieghem, J., Dada, M., 1999. Price versus production postponement: Capacity and competition. Management Science 45 (12), 1631-1649.

Varian, H.R., 1992. Microeconomic analysis. New York, NY: W.W. Norton.

Vickery, S.K., Jayaram, J., Droge, C., Calantone, R., 2003. The effect of an integrative supply chain strategy on customer service and financial performance: An analysis of direct versus indirect relationships. Journal of Operations Management 21, 523-539.

Wein, A., Rose, A., 2011. Economic resilience lessons from the ShakeOut earthquake scenario. Earthquake Spectra 27 (2), 559-573.

Xie, W., Li, N., Wu, J., Hao, X., 2015. Disaster risk decision: A dynamic computable general equilibrium analysis of regional mitigation investment. Human and Ecological Risk Assessment: An International Journal 21 (1), 81-99.

Zobel, C.W., 2011. Representing perceived tradeoffs in defining disaster resilience. Decision Support Systems 50 (2), 394-403.