Supply Chain Integration, Product Modularity and Market Valuation: Evidence from the Solar Energy Industry

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Abstract

Supply chain integration is increasingly seen as a method to obtain flexibility, and consequently, to provide competitive advantage for firms within a supply chain. Product modularity, either in concert with or independent of such integration, can also produce flexibility for firms within a supply chain. In this proof-of-concept research we explore whether the supply chain network affects each constituent firm's market valuation and how decisions regarding the level of supply chain integration and the usage of product modularity are associated with the value of the supply chain. We develop a method to identify and measure the supply chain's effect on each constituent firm's market valuation. Results indicate that greater integration is associated with a higher supply chain valuation, whereas increasing aggregated product modularity across the supply chain relates to a lower supply chain value. However, when combined, the interaction of aggregated product modularity and supply chain integration is positively associated with the supply chain's valuation.

Keywords: *Product modularity; supply chain integration; network; market valuation*

Received: June 2010; accepted: October 2012 by Edward Anderson and Geoffrey Parker after three revisions.

1. Introduction

In recent years, the emphasis in product development and delivery has shifted from value created largely within the bounds of an individual firm to collaborative value-creation efforts across firms in a supply chain (Lee and Billington 1992; Fisher 1997; Fung, Fung, et al. 2007). Consequently, managers see effective product and supply chain integration as a means of obtaining competitive advantage for all firms within a supply chain (Houlihan 1985; Davis 1993; Ragatz, Handfield et al. 1997; Fine 2000; Parker and Anderson 2002). Indeed, firms are reporting on this value created from their supply chains. For example, the president of Li & Fung Group, speaking to investors, has pointed to "the extraordinary value [that] Li & Fung can add to one's supply chain of products and services" (So 2009). Yet, the veracity of such company pronouncements has not been examined through systematic analysis.

If firms are indeed competing in product markets based on their value-added supply chain capabilities, then we would expect to see superior supply chain performance reflected in the constituent firms' capital market valuations. However, determining this is not a straightforward exercise. Firms can set up products and processes in multiple ways to achieve flexibility and create value in the supply chain. In particular, modular designs (Baldwin and Clark 2000) can either be used in concert with supply chain integration or in a stand-alone manner. Our work aims to assess the impact of flexibility in the supply chain gained through integration and product modularity, and quantify the value they generate in both product markets and in the supply chains themselves.

We draw upon theories of flexibility to postulate the linkages between firms' supply chain decisions and their market valuation. Flexibility has been identified empirically as a key measure of supply chain performance (Beamon 1999), with firms choosing suppliers not only for their low costs, but also for their speed and flexibility (Fisher 1997). Valuation by capital markets is a common measure of firm performance, but to our knowledge, has not been used to assess the performance of an end-to-end supply chain. Hendricks and Singhal (2005) investigated the effects of supply chain disruptions on the long-term stock market valuation of firms in the supply chain. They found empirically that individual firms that experienced supply chain disruptions had 33–40% lower stock returns relative to their industry benchmarks over a 3-year period. Analytically, Huchzermeier and Cohen (1996) ascertained that the value of firm flexibility is determined through the overall capacity of the supply chain and the network linkages to its supply chain partners. However, we see a gap in the research on supply chain performance – it does not explicitly measure the value of supply chain flexibility gained through integration, product modularity, and allied network linkages.

Our contribution to bridging this gap in the literature is twofold. First, we offer a framework to explain the relationships between supply chain integration, product modularity constructs, and the supply chain's valuation. Second, we assess the value of a supply chain by developing a new method that proportionally aggregates the performance of individual firms within a supply chain through their stock market valuations. This method allow us to test our framework by examining evidence from 42 solar energy firms and their 42 unique supply chains for the financial year 2007. In doing so, we find that, 1) greater supply chain integration is associated with a higher supply chain value, 2) increased aggregated product modularity across the supply chain relates to a lower supply chain value, 3) the interaction of aggregated product modularity and supply chain integration is positively associated with the supply chain's value, and 4) we show that the value of the supply chain network impacts the market valuation of the constituent firms within the network.

Our paper unfolds as follows. We review the extant literature on product modularity and supply chain integration and develop constituent hypotheses in Section 2. Constructs, measures, and methods are described in Section 3. Results are presented in Section 4. We discuss management and policy implications, industry effects, and limitations of the work in Section 5. We conclude in Section 6 with questions for follow-up research on supply chain integration, product modularity, and market valuation.

2. Theoretical Perspective

2.1 A Supply Chain Integration – Product Modularity – Market Valuation Framework

As highlighted in the introduction, a diverse set of elements such as product modularity (Baldwin and Clark 2000) and supply chain integration (Parker and Anderson 2002) impact the market valuation problem (Huchzermeier and Cohen 1996; Hendricks and Singhal 2005). We take an integrative view of these elements to devise a Supply Chain Integration – Product Modularity – Market Valuation framework (Figure 1). This framework elucidates the interplay between the multiple constructs we associate with market valuation. Particularly, the valuation of each firm within the supply chain and the aggregated valuation of the supply chain are interdependent. Thus, the overall benefits and costs of a supply chain should be reflected in the market value of each constituent firm. These supply chain effects, however, would not appear if a firm's valuation is considered in isolation. Consequently, the relationship between the level of flexibility within a firm and the flexibility achieved through supply chain integration must be considered simultaneously. The effects of these linkages within the supply chain are discussed subsequently in Section 2.5.

Integration of the supply chain provides flexibility to better match supply and demand at different junctures along the supply chain. Independent of supply chain integration, product modularity provides a firm with production flexibility by allowing product components to be recombined in different ways to serve different functions in different products (Schilling and Steensma 2001). The implementation of product modularity is often considered simultaneously with the level of supply chain integration. For example, the development of modular products can lead to supply chain disintegration (Langlois and Robertson 1992), and products with a modular architecture need little supply chain integration (Parker and Anderson 2002). Specifically, Fine, Golany et al. (2005) found that product architecture and supply chain architecture tend to be aligned along an integrality-modularity spectrum. In this paper, we specifically differentiate these two concepts. *A modular (or nonmodular) product is an attribute of the firm whereas integration (or disintegration) is an attribute of the supply chain.* We also construct an aggregated measure of supply chain value that is separate from the market valuation of each constituent firm in the supply chain. *The aggregated valuation of a supply chain is the value of each constituent firm plus the value created by the linkages, based on the flow of materials, between the constituent firms in the supply chain*.

2.2 The Value of Supply Chain Integration

The supply chain is an interconnected series of value-adding activities from suppliers through manufacturers, to the final customer. These activities include planning and controlling raw materials, components, and finished products (Stevens 1989). Supply chain managers take a holistic view of these activities and aim to improve performance by integrating their operations to create value for both customers and suppliers (Tan, Lyman et al. 2002) - the higher the degree of supply chain integration, the more superior the firm's performance will be (Frohlich and Westbrook 2001). Although each constituent firm is faced with the management of an extended network that creates interdependence and requires coordination between its supply chain partners, successful supply chain integration can create competitive advantage for all participating supply chain firms (Power 2005).

Supply chain integration increases the flexibility of the end-to-end chain by reducing time delays between the chain's firms, both in the downstream delivery of goods and in the upstream transmission of information (Frohlich and Westbrook 2001). Arguably, a fully integrated supply chain behaves as a single entity, that is, the firms in the chain are vertically integrated, enabling information exchange, reducing production-related errors, and enhancing quality and performance throughout the chain (Novak and Stern 2008). Integration of the supply chain is a theory construct that we later measure in terms of the level of vertical integration (see Section 4.2 for further details). Such supply chain integration increases flexibility by reducing the uncertainties in supply and demand, and increases overall control of business operations (Towill, Childerhouse et al. 2002). Superior implementers of supply chain flexibility are rewarded with increased financial performance (Vickery, Calatone et al. 1999), cost savings and/or improved customer responsiveness (Fisher 1997). The financial economics literature also recognizes that greater flexibility offers firms an enhanced ability to manage uncertainty and reduce risk (Kogut and Kulatilaka 1994; Kulatilaka and Trigeorgis 2004). This extant research proposes that the performance, and hence the aggregated value of supply relationships, depend heavily on the level of integration. Thus, our first hypothesis is:

H1: The level of supply chain integration is positively associated with the aggregated value of the supply chain.

2.3 The Value of Product Modularity Aggregated Across the Supply Chain

The concept of modularity classifies a complex system's hierarchical and decomposable design and production into unique components or modules (Simon 1962; Langlois and Robertson 1992;

Sanchez and Mahoney 1996). Modules are characterized by independence across their defined boundaries and interdependence within the boundaries (Sosa, Eppinger et al. 2004), and are "loosely coupled" so that changes made to one module have minimal impact on the others. Thus, new configurations can be achieved with no overall loss of the system's functionality or performance (Baldwin and Clark 1997). This decoupling of modules is achieved through the adoption of standardized interfaces (Baldwin and Clark 2000) and the use of interchangeable components that enable the configuration and assembly of a wide variety of end products (Schilling 2000). Therefore, modular products are adaptive and give the firm flexibility to respond quickly to unanticipated threats and opportunities as the competitive environment shifts (Thomke and Reinertsen 1998; Baldwin and Clark 2000; Galunic and Eisenhardt 2001). This ability to rapidly reconfigure modular products enables a firm to increase product variety and to meet diverse and constantly changing customer requirements (Fine 1998; Salvador, Forza et al. 2002) without having to forecast which products or product attributes will be most valued in the short and long term (Pil and Holweg 2004). In addition, a firm can leverage the capabilities of its network of suppliers by outsourcing particular modules rather than producing them in its own facilities, and can shift production among suppliers as conditions change (Takeishi and Fujimoto 2001; Pil and Cohen 2006).

Prior studies have linked product modularity with performance. Baldwin and Clark (2000) identify the value of product modularity in the form of flexibility options. Companies that have high levels of product modularity also appear to have better product performance (Lau, Yam et al. 2010). Product modularity can reduce production costs through the economies of scale that arise from utilizing modules with multiple applications (Pine, Victor et al. 1993; Baldwin and Clark 2000) and by reducing production volume and inventory, since modular designs have fewer unique components (Jacobs, Vickery et al. 2007). In concert with product modularity, standardization also enables firms to attain operational efficiencies through reduced coordination costs (Collier 1981; Danese, Romano et al. 2004) and enables high quality, repetitive manufacturing at lower cost (Ro, Liker et al. 2007). Ulrich (1995) asserts that a standard component is generally less expensive than a component designed and built for only one product because it can be produced in higher volume, allowing greater economies of scale and shared learning. This learning can also enable cospecialization with a complementary product, further reducing production costs (Anderson and Parker forthcoming). In contrast, studies have revealed that offering greater product variety and customization to meet the increasing demand for differentiated products can lead to increased manufacturing and component costs (Fisher, Ramdas et al. 1999), and implementing standards for compatible designs can raise production costs (Katz and Shapiro 1986).

Although firms generally apply modularity to product design, firms also have employed it to design supply chains (Sanchez 1999). The level of modularity aggregated across the supply chain influences both the flexibility of supply and the ability to deliver different product variations This aggregated product modularity is a supply chain construct that reflects the overall level of product modularity across the supply chain. Similarly, supply chain decisions include consideration of mass customization strategies (Fixson 2005) and recognition of compatibility standards that lead to improved performance (Langlois and Robertson 1992). Consequently, firms within the supply chain that use product modularity, while considering the complementary use of standards and customization, can positively influence the overall value of the supply chain. However, given the potential increased costs and the ease of defection from the supply chain (Camuffo, Furlan et al. 2007), capital markets may also discount the use of product modularity in assessing the value of a supply chain. Consistent with this research on the varying impact of the costs and benefits of product modularity, we offer competing hypotheses for the relationship between a supply chain's aggregated product modularity and its aggregated value:

H2A: Controlling for the level of standards and customization, aggregated product modularity is positively associated with the aggregated value of the supply chain.

H2B: Controlling for the level of standards and customization, the aggregated product modularity is negatively associated with the aggregated value of the supply chain.

2.4 The Interaction of Supply Chain Integration and Product Modularity

Recent studies have investigated the relationship between the degree of product modularity, the nature of vertical interorganizational relationships, switching costs and organizational performance (Jacobs, Vickery et al. 2007; Lau, Yam et al. 2007; Ro, Liker et al. 2007; Hoetker, Swaminathan et al. 2007; Gomes and Joglekar 2008).

Scholars have offered two differing views on the interaction of supply chain integration and product modularity. One group of studies proposes that modularity in product design reduces the need for integrated supply relationships because modular products lower the need for coordination and control through standardization and hence reduce interfirm dependence (Sanchez and Mahoney 1996; Sosa, Eppinger et al. 2004; Baldwin 2008; Cabigiosu and Camuffo 2011). Suppliers that design and produce a modular component can economize on information sharing and reduce customer uncertainty as a change in the design of one component does not require changes in the designs of the other associated components (Schilling 2000; Langlois 2003). A modular product design also gives the supplier autonomy and flexibility to develop a series of short-term supply chain relationships to sell modules to various customers simultaneously. Input suppliers of modular products can also readily find new buyers because switching costs are low (Hoetker, Swaminathan et al. 2007; Lau, Yam et al. 2010).

On the other hand, an alternate group of studies maintains that modularity in product design increases the need for "thick" supply relationships — those that require extended interaction times, comprehensive efforts, and joint investment by both customers and suppliers (Hsuan 1999; Brusoni and Prencipe 2001). Suppliers of modular products need to maintain open access to component-specific knowledge via intense supply relationships (Zirpoli and Camuffo 2009). Such investments can require that each constituent firm and its suppliers acquire similar systems (such as computer-aided design) and organizational processes (for example, problem solving routines) so as to take advantage of their joint capabilities (Thomke 2006). Both customers and suppliers must engage in closely coupled relationships for ease of communication and coordination (Fine, Golany et al. 2005) and continuously improve products, processes, control opportunism, and share risk (Howard and Squire 2007).

It remains a matter of debate as to how supply chain performance varies based on the degree of product modularity and supply chain integration. For this, we offer two competing hypotheses:

H3A: The interaction between supply chain integration and aggregated product modularity is positively associated with the aggregated value of the supply chain.

H3B: The interaction between supply chain integration and aggregated product modularity is negatively associated with the aggregated value of the supply chain.

2.5 The Value of the Supply Chain Network

Researchers have considered the value of the firm in relation to industry sectors (Schmalensee 1985), the level of business diversification (Wernerfelt and Montgomery 1988), and strategic groups (Porter 1979). Although investment in flexibility is a long-term decision with no immediate benefits (e.g., profitability), it creates value that is captured in the forward-looking market valuation. The firm's increase in value via operational flexibility stems from its ability to respond quickly and profitably to uncertain events when they arise in the future (Kogut and Kulatilaka 1994; Kulatilaka and Trigeorgis 2004). However, firms can also benefit from their supply chain network and the access it provides to an extended set of suppliers' assets (Lavie 2007). Thus, value from the supply chain network can be achieved by exploiting the synergies derived from coordination of the many firms in the network (Huchzermeier and Cohen 1996), and by pooling capacity to more readily meet customer demand (Fung, Fung et al. 2007).

Porter (1985) recognized that the linkages within chains are crucial to competitive advantage but that firms often overlook them because of the sophisticated level of understanding required. Like the value chains defined by Porter, where goods or services obtain value as they move through the supply chain, the transformation of a product through the supply chain from raw materials to the end-customer, also affects or is affected by other supply chain firms. These links between firms are not trade-offs, but dependent on the configuration of the chain, and can be mutually enhancing, benefitting the firm, and its suppliers and customers. In addition, critical resources can span firm boundaries and value can be embedded in the resources and routines between firms (Dyer and Singh 1998). Thus the supply chain' value not only incorporates the market valuation of all constituent firms in the supply chain, but also includes the value that the supply chain network provides to each constituent firm. This aggregated supply chain valuation is a supply chain construct that reflects this overall value of the supply chain. Based on this, we hypothesize that:

H4: The aggregated value of the supply chain is positively associated with the market valuation of each constituent firm.

2.6 Fixed Effects

In addition to the flexibility factors that we hypothesize relate to a firm's and a supply chain's valuation, we also control for key variables that research has shown to affect firm valuation. For example, more profitable firms are more likely to have a higher market capitalization than less profitable firms (Loughran and Ritter 1997). The amount of revenue generated - a measure of size and performance - also impacts shareholder value (Christopher and Ryals 1999). Prior performance is also a key factor in the valuation of a firm (Lang and Lundholm 1993). We hypothesize that profitability, revenue, and prior performance of the firms within a supply chain are positively associated with firm's and the supply chain's overall valuation.

The rate of technological change is an important factor in the adoption of product modularity. In a rapidly changing environment, firms must make additional calculations for investments on how long the module is expected to be relevant (Fine 2000; Parker and Anderson 2002). Therefore, we include research and development (R&D) intensity as a control for technological change. We hypothesize that an increase in the level of R&D intensity is positively associated with the firm's and the supply chain's valuation.

The level of production costs is closely linked to the use of product modularity and the level of integration, in that they can both generate economies of scale across the supply chain and potentially reduce production costs (Christopher and Ryals 1999). We control for production costs by including a measure for cost of goods sold (COGS) intensity and hypothesize that lower production costs are associated with higher firm and supply chain valuations.

One of the main considerations in supply chain design is the fixed costs of the network (Lee and Billington 1992). Firms can gain advantage from decreasing fixed assets, particularly in competitive and uncertain markets (Miller and Shamsie 1996), and the reduction of fixed asset investment through rationalization of production facilities in the supply chain can improve shareholder value (Christopher and Ryals 1999). We control for the supply chain's fixed-asset intensity level and hypothesize that a lower proportion of aggregated fixed assets is related to a higher valuation of the supply chain. Note that the supply chain controls are an aggregation of the firm level variables within that supply chain proportioned by the weight of the links that connect the chain, as defined in the aggregation algorithm discussed in Section 3.3. Finally we consider the type of product technology utilized. If the technology is unique, supply chain partners cannot share the functionality with other firms (Anderson and Parker forthcoming). Thus, we hypothesize that the type of technology employed is related to the supply chain's valuation.

3. Context, Measures and Method

3.1 Industry Context: The Solar Energy Supply Chain

We test our hypotheses using a financial data set of public firms in the solar energy industry for the 2007 financial year. Clean technologies have experienced an accelerated adoption cycle with the increasing attention on climate change, rising oil prices and a supportive global regulatory environment. Solar in particular is predicted to be a significant energy technology over the next four decades. The solar energy sector is characterized by a large amount of investment in technologies and fast-paced innovation. While still a young industry, solar energy's supply chain is quickly advancing with new firms entering, and established players integrating backward and forward (Suskewicz 2008). Several technologies are competing to become dominant in the solar energy field: concentrated solar power through reflecting mirrors, and photovoltaic (PV) generation through either thin-film or crystalline cells (NREL 2011). For the purpose of this study, we focus on the more common PV generation as it has a well defined supply chain network. We control for the different technology and materials employed in manufacturing thin-film versus crystalline silicon energy cells. Thin-film energy cells can be used to make cheaper PV solar modules, but they are less efficient and require more physical space to generate the same amount of power as crystalline silicon energy cells.

Some of the key drivers of the solar PV industry (Englander, Mehta et al. 2009) include: access to high-quality raw materials; vertical integration; cost reduction through increased technology-driven efficiency in the production of thin-film cells, and less waste in processing crystalline silicon wafers. The solar PV industry is also differentiated between firms that focus on building productive assets and firms that employ "asset light" strategies supported by proprietary technologies and multiple partnerships (Clegg and McNamara 2008). The importance of integration, technology, and use of assets for success in the solar PV supply chain parallel the theoretical factors identified earlier as influential in the supply chain's valuation. In addition, the solar PV industry's ability to readily access materials and its emphasis on partnerships signifies the importance of the network in this industry. The solar PV industry also has a particularly global supply chain with installation and production occurring across Europe, Asia and North America. The key players within each position of the supply chain and their estimated market share are summarized in the Electronic Companion Table A1.

The supply chain for crystalline PV cell production involves four distinct processes: the attainment of raw silicon, the conversion of raw silicon to silicon wafers, the production of solar cells, and the creation of the solar modules that are ultimately installed as panels on rooftops to convert solar energy to electricity. The supply chain for the production of thin-film cells involves a subset of these processes: the production of solar cells and the assembly of the solar modular, as no silicon is required in thin-film production. As this study concentrates on market valuation, we focus only on the publicly traded companies within the solar PV supply chain. However, to capture the potential flexibility across the whole supply chain network, we estimate the share of market for the individual public firms, and the overall share of market for the private (non-publically traded) firms, which we classify as 'Other'. The market share data is either provided by investment analysts' reports or is estimated based on the known production capacity for the firm compared to the size of the solar PV market. Given the lack of a readily available representation of the solar PV supply chain network, we determine the network by identifying the supply chain linkages reported in 119 newswire announcements of solar PV supply contracts in Factiva for the year 2007. We supplement this data with information on customer and supplier relationships provided in the firms' 2007 annual reports. The solar PV supply chain network is represented by 42 publicly traded companies based in Asia, Europe and the North America involved in 42 unique supply chains (Figure 3). We estimate the weighting of the supply chain linkages based on the size of the contract and known market share for each firm in the supply chain.

3.2 Measures

Dependent Variable: To calculate the supply chain's valuation we aggregate the market value of the firms within the supply chain based on the method described in Section3.3. We use the firm's market capitalization — closing share price x common shares outstanding at the end of financial year 2007 — as the measure of firm market value. We use this simpler method of measuring value, rather than the more developed Tobin's q, because the former is exogenous to the independent variables.

Explanatory Variables

The data for product modularity, customization, and standards are compiled from the number of references each of the 42 firms made to these concepts in their 2007 annual reports. The content analysis method used to capture this information is described in Section 3.5.

To operationalize supply chain integration we use a measure of vertical integration. Vertical integration is the most explicit way for investors to assess the level of integration of a firm across the four distinct processes of the supply chain. We devise a scale from 1 to 4 which is assigned based on how many adjoined processes in the supply chain are delivered by a single firm. A supply chain that consists of one vertically integrated firm across all four processes has a score of 4. For example, in Figure 3, REC's chain is assigned a supply chain integration value of 4 because it provides all four of the processes of the supply chain. If a firm is vertically integrated across any three adjoining supply chain processes it receives a score of 3. For example, the Walker-Solarworld-Solarworld-Solarworld chain in Figure 3 receives a supply chain integration value of 3. The same logic holds for a firm that plays in two adjoined processes. A chain that consists of four unique firms receives a score of 1.

Network Design: As described earlier, the supply chain network design is a key input to our analysis. Although in itself it is not an explanatory variable, the supply chain network is estimated through the proportion of firm valuation and dependent measures that are captured by a particular supply chain (Simpson 1958, Graves and Willems 2003). To define each unique end-to-end supply chain, we first identify the share of market for the materials at each supply chain position. We then, for each link in a particular supply chain, identify the proportion of the total amount of materials for that position transferred between all firms that are directly linked in the chain (for details of this method, see Section 3.3).

Controlling for Fixed Effects: To control for profitability, we use operating margin, defined as the ratio of operating profit to revenue. Revenue, a control for performance and size of the firm, is measured as the annual revenue produced during financial year 2007. Prior performance is controlled for using the market capitalization at the end of financial year 2006. Production costs are measured by the ratio of costs of goods sold to revenue (COGS intensity). We use the level of R&D intensity, defined as the ratio of expense in R&D to revenue, as a proxy for the rate of technology innovation. Fixed-asset intensity refers to the proportion of assets tied up in a firm's long-term investments (e.g., property, physical plant and equipment) and is measured by the ratio of fixed assets to total assets. As noted above, this data is captured at the firm level and then aggregated using the algorithm for each of the 42 supply chains as defined in Section 3.3. Technology is represented by a dummy variable for whether the supply chain produces silicon-based or thin-film energy cells (determined from information obtained in 2007 annual reports and/or company websites).

3.3 Model Specification

Supply chains are complex, expansive networks in which each firm can have multiple upstream suppliers and/or downstream customers (Harland 1996; Lazzarini, Chaddad et al. 2001). To assess the value of a firm within a supply chain, and the overall value of the supply chain itself, we consider each firm and each individual supply chain in the context of the overall network of supply chains. We first present the equation for the relationship between firm valuation and the related firm flexibility factors of modularity, customization and standards, while controlling for fixed effects that influence firm valuation, plus an error term to capture any omitted firm specific and broader economic or industry effects. Note that to correct for skewed data we take the natural log transformation in both the firm and subsequent supply chain equations for the continuous variables. Firms' investment in items such as R&D and COGS are often considered by researchers in a multiplicative manner when measuring firm performance. See, for example, Gaur, Fisher et al. (2005) and Lévesque, Joglekar et al. (2012) who explore the theoretically appropriate use of a log-linear model. Based on the conceptual framework and the prior detailed measures for our variables, the firm model is specified as:

$$LnFirmMarketCap_i = \beta_0 + \beta_1 {*} FirmProductModularity_i + \beta_2 {*} FirmStandards_i$$
$$+ \beta_3 {*} FirmCustomization_i + \beta_4 {*} LagLnFirmMarketCap_i + \beta_5 {*} LnFirmRevenue_i$$
$$+ \beta_6 {*} LnFirmOperatingMargin_i + \beta_7 {*} LnFirmCOGSIntensity_i$$
$$+ \beta_8 {*} LnFirmR\&DIntensity_i + \varepsilon_{1i} \qquad (1)$$

The combined level of these flexibility factors across all the constituent firms in a supply chain contribute to its valuation, as well as the level of overall supply chain integration. We propose a new aggregation method to estimate the valuation of an entire supply chain: that is the combined market valuations of the constituent firms, proportioned by the volume of materials that flows through the links that connect the firms (see Figure 2 for an illustrative example). In line with Graves and Willems (2000), we borrow from the field of network analysis to model a supply chain network using node and arc concepts from graph theory. We represent the network structure of the firms with nodes, and the flow of materials between the firms with arcs. Our application is similar to Billington, Callioni et al.'s (2004) classification of the Hewlett-Packard supply chain where the arcs track the amount of goods that flow between the nodal firms connected by arcs. Therefore, if the aggregated value of each supply chain variable X_k is $T(X_k)$, the supply chain model is specified as:

$$LnT(FirmMarketCap_k) = \gamma_0 + \gamma_1 * SC\ Integration_k + \gamma_2 * T(FirmProductModularity_k)$$

$$+ \gamma_3 * T(FirmStandards_k) + \gamma_4 * T(FirmCustomization_k)$$

$$+ \gamma_5 * SCIntegration_k * T(FirmProductModularity_k) + \gamma_6 * Lag\ Ln\ T(FirmMarketCap_k)$$

$$+ \gamma_7 * Ln\ T(FirmRevenue_k) + \gamma_8 * Ln\ T(FirmOperatingMargin_k)$$

$$+ \gamma_9 * Ln\ T(FirmCOGSIntensity_k) + \gamma_{10} * Ln\ T(FirmR\&DIntensity_k)$$

$$+ \gamma_{11} * Ln\ T(FirmFixedAssetIntensity_k) + \gamma_{12} * SC\ Technology_k + \varepsilon_{2k} \qquad (2)$$

Here $T(X_k) = {}_j(\,{}_i(X(i) * FO(i,j) * OC\ i,j,k) + M(j))$, for all k as described previously. (3)

The operator T stands for the aggregated valuation of the parameters (X). V stands for the value of that parameter at a node. M represents a correction for the value of that parameter at a terminal node. FO stands for the fraction of the parameter flowing outbound. OC stands for outbound connection. The details behind the aggregation are further defined in an algorithm included in the accompanying Electronic Companion. In equation 2, we also control for known fixed effects that influence the value of the supply chain, and an error term to capture any omitted supply chain specific and broader economic or industry effects.

3.4 Method

The determination of the dependent variables and some of the independent variables in Equations 1 and 2 are interdependent. It is reasonable to expect that equations sharing observable characteristics would also share unobservable characteristics and this would correlate the error terms (Moulton 1990). The error terms in firm valuation equations include factors that are common to all firms (e.g., the economy, energy policy), as well as firm-specific factors (e.g., size, age) (Greene 2003). If the error terms are correlated within supply chains, then small levels of correlation can downwardly bias the standard errors from the separate ordinary least squares estimations. This bias can result in spurious findings of statistical significance in variables of interest (Moulton 1990). To estimate the parameters consistently, we need to consider this correlation among the errors of Equations 1 and 2. Zellner (1962) proposed the seemingly unrelated regression (SUR) method for simultaneously solving a system of equations where the error terms are contemporaneously but not serially correlated. For example, SUR is commonly employed to test the value of returns for an aggregate portfolio of stock market assets (Greene 2003). We employ Stata's SUR command to simultaneously test Equations 1 and 2 and we test each equation separately using the ordinary least squares (OLS) regression for comparison.

To account for any heteroskedasticity, we employ Huber White's robust standard errors for all OLS and SUR analyses. We also check if multicollinearity could be driving our results. An examination of variance inflation factors and condition indices (Kutner, Nachtsheim et al. 2004) suggest that multicollinearity is not an issue. This examination of the econometric specification validity and related assumptions underlying the statistical model indicates that our results are robust.

3.5 Data

The accounting information is collected from COMPUSTAT. We mine evidence on product modularity, standards, and customization through content analysis of the business sections of each firm's annual report, since scales for measuring these constructs are not readily available. According to Holsti (1969), content analysis is a "technique for making inferences by objectively and systematically identifying specified characteristics of message" (p. 2). The annual report expresses the firm's undertakings, achievements, and performance during a financial year. Although the annual report does not provide direct verification that a firm is delivering what it announces with regard to product modularity, customization, standards, performance, and the like, it is one of the key documents referenced by investors and is deemed to provide dependable and valid data. In fact, the firm must publish information in its annual report that is consistent with other publicly available sources (e.g., product catalogs and product demonstrations). For example, products reported to be ‘modular products’ must be shown to be modular in company sales catalogues. In addition, the audited annual reports are compared by analysts to their personal dealings with the firm; for instance analysts hold meetings with CEOs, CFOs and key managers, and ask questions to check for accuracy at investor briefings. If the information in the annual report is not true, then the firm knows that such illegal reporting will have adverse consequences. Therefore, we deem any mention of product modularity, standards, and customization to be a true indication of their importance to the firm.

We determine the frequency of references to each term of interest, by assessing where the term occurs in the annual report and examine the context for correct meaning. We removed all irrelevant uses, and references regarding forward-looking statements, risk factors, duplicates, and negative connotations. In the content analysis methodology, the frequency of the keyword occurrences reflects the degree of emphasis placed on that concept (Weber 1990). Further details of the content analysis methodology employed are provided in the Electronic Companion.

4. Empirical Results

To test our hypotheses, we use results from both the OLS and SUR analyses. The OLS and SUR results for the firm (Equation 1) are shown in Table 1 and are correspondingly identified in Models 1a and 1b. The OLS and SUR results for the supply chain (Equation 2) are shown in Table 2 and are presented in Models 2a and 2b respectively. After establishing the validity of using the SUR to assess the value of the supply chain, we use Model 2b (see Table 2) to test Hypotheses 1, 2 and 3, and Models 1a and 1b (in Table 1) to test Hypothesis 4.

4.1 Analysis

As previously discussed, we expect the errors from the firm and supply chain models (i.e., Equations 1 and 2) to contemporaneously correlate. We test for this bias by simultaneously analyzing the two equations using the SUR approach. We compare the results from the SUR to OLS regression results for the firm equation in Table 1 (Models 1a and 1b respectively) and for the supply chain equation in Table 2 (Models 2a and Model 2b respectively). We note that the coefficients and standard errors change between the SUR and OLS in both the supply chain and the firm results, although the size, direction, and significance are similar. The adjusted R^2 decreases from the SUR to the OLS models for both the supply chain and the firm models, confirming that the errors contemporaneously correlate. This validates the use of SUR approach.

4.2 Tests for Hypotheses

We observe in Table 2 that the coefficient for supply chain integration (after adjusting for the log value of the dependent variable, i.e. the inverse log of the significant coefficient) is positively significant at 5%. This indicates that vertical integration between two firms results in a 28% increase in the geometric mean of the supply chain’s valuation, and provides support for Hypothesis 1 that the level of supply chain integration is positively associated with supply chain valuation. The value of the product modularity coefficient (after adjusting for the log value of the dependent variable) is comparatively large and negatively significant at the 5% level, thus providing strong support for Hypothesis 2B so countering support for Hypothesis 2A. In other words, while controlling for the level of customization and standards, the aggregated product modularity across the supply chain is negatively associated with supply chain valuation. However, the variables associated with product modularity — the level of standards and customization — are not significant.

The coefficients for supply chain integration and product modularity are individually significant in Table 2, although they have opposite relationships to supply chain valuation. However, when we examine the combined impact of these two variables, we see that the value of the interaction coefficient is four times the scale of integration coefficient alone and significant at the 10% level (p-value = 0.056). This interaction of product modularity and supply chain integration in the supply chain lifts the association with the supply chain value by over 20 times that of the relationship between supply chain integration and supply chain valuation, thus providing support for Hypothesis 3A, which is that aggregated product modularity across the supply chain moderates, in a positive manner, the association between supply chain integration and supply chain valuation.

The results of our SUR analysis shown in Table 1 show a reduction in the explanatory power of the firm level equation (Model 1b) compared to the OLS regression (Model 1a) when simultaneously accounting for the supply chain equation's value. This signifies a correlation between the error terms of the firm and supply chain equations. The drop in the adjusted R^2 between Models 1a and 1b provides support for Hypothesis 4 that a 'supply chain effect' exists at the firm level.

4.3 Testing for Fixed Effects

We examine the controls in Table 2 for the supply chain equation (Model 2b). It shows that only the prior performance of the supply chain and the aggregated COGS intensity are significantly associated with supply chain value. Aggregated revenue, operating margin and fixed asset intensity are not significant, demonstrating that the aggregated size, profitability and assets within the supply chain are not related to the value of solar energy supply chains. The aggregated R&D intensity (our proxy for the rate of technological change) was not significant. Very likely, the rate of technology innovation is constant for all 42 firms in our supply network and is an overall factor of the “clock-speed” of the industry (Fine 2000) for solar energy firms. The specific supply chain control for technology is not significant, but this could be due to the lack of variation as the sample contains only two technology types.

5. Discussion

We have tested the Supply Chain Integration - Product Modularity - Market Valuation framework to explore the relationships between product modularity, supply chain integration, and the value captured in a supply chain. We next discuss the managerial implications, industry effects and limitations of these findings.

5.1 Managerial Implications

A key theme for this special issue is the comparison of the structure, effectiveness, and capability of integration in distributed development environments with more traditional vertically integrated organizations. Our results, based on testing Hypothesis 3, suggest that given the synergy between product modularity and supply chain integration, managers of vertically integrated firms ought to strive for modular design of components. Product modularity creates value, supporting the argument that product modularity brings down internal and external coordination costs (Novak and Eppinger 2001). For example, Sunways AG, an integrated manufacturer of solar cells and modules, stressed the importance of its backward integration into “modular silicon production operations,” yielded a market capitalization increase of 11% in 2007.

Two streams of literature offer guidelines for shaping the integration of product and supply chain network design. The first stream is based on supply chain cost minimization which utilizes Simpson’s (1958) assumption that outgoing service time at the demand stage is zero (it provides off-the-shelf inventory to exogenous customers) and that raw material stages receive an incoming service time of zero (so they receive off-the-shelf inventory from suppliers not modeled in the network). In the second stream Graves and Willems (2003) build on these assumptions to offer management guidelines for optimal safety stock placement to achieve desired service levels; they argue that "decisions that are made in product design determine the topology, as well as key economics, of the supply chains" (p.95). However, the guidelines proposed in this study incorporate the inventory flows across end-to-end supply chains, where the key variable that is optimized in our observation is not the cost, but the value created for the firm. Recall from Section 4 that raising product modularity in vertically integrated firms enhances capital market valuation. Thus, managers within a firm's internal supply chain will do well, both for cost reduction *and* for value maximization, by promoting more modular products that minimize the safety-stock placement costs. Undoubtedly, this principle of promoting modular designs requires more nuanced analysis when the supply chain encompasses multiple firms. Such nuanced valuation analysis should account for the level of uncertainty, desired service levels, aggregated product modularity, and allied risk mitigation mechanisms, such as assignment of safety stocks across firm boundaries. Within this context we explore two specific managerial questions:

- **How to Account for Supply Chain Integration within Supply Chain Value?**

We observed that greater supply chain integration is related to a higher supply chain valuation. In fact, the analysis shows that supply chain integration can create a 28% lift in value, providing empirical validation of Frohlich and Westbrook's (2001) findings and in line with the results of Lau, Yam, et al. (2010). The measure for supply chain integration captures the number of supply chain positions that a firm holds, so a highly vertically integrated firm will achieve a positive association with valuation. For example, our analysis indicates that REC, a global firm in our dataset with presence at each position on the solar PV supply chain, gained $1.5 billion of its predicted market value from being vertically integrated.

- **How to Modularize Product Design to Maximize Supply Chain Value?**

We note from our analysis that increased aggregated product modularity, when combined with supply chain integration, is associated with a higher supply chain value, whereas reduced aggregated COGS intensity is associated with a higher supply chain value. Thus, tradeoffs occur between the use of product modularity, supply chain integration, and production, storage, and delivery costs that affect the supply chain's valuation in the solar energy industry.

One of the key themes for this special issue is the impact and limits of modularity and standards in enabling coordination. Hendricks and Singhal (1997) show that the market values new product introduction. However, their event-study–based assessment precludes the establishment of tradeoffs. Our results show that the stock market recognizes that the use of product modularity and supply chain integration comes with a cost. Indeed, the best way to implement product modularity is to combine it with supply chain integration when this would also reduce production costs. These tradeoffs differ from classic profit-maximization–based strategies that assume product modularity will raise the overall revenue through network effects (Parker and Van Alstyne 2005). Value maximization models in the production and supply chain realm (e.g., Babich and Sobel 2004) have yet to shed light on these tradeoffs. We identify this as an opportunity for follow-up modeling work.

5.2 Industry Effects

With particular relevance to the solar energy industry, the importance of integration within the supply chain is evident. Financial analysts following the solar energy industry predicted that vertical integration would be a key trend for 2007; our results show that integrated supply chains indeed have achieved a higher market value. Academics debate whether such analysts' reports affect valuation negatively (Benner 2010). However, beyond the prognostications of these analysts, our results identify the existence of tradeoffs associated with supply chain integration through operational levers such as product modularity and production costs.

Beyond operational insights, our findings can inform policy makers. While governmental bodies such as the Advanced Research Projects Agency – Energy (ARPA-E) and the U.S. Department of Energy look to support specific technologies, both through seed money and policy-making, they could also consider our supply chain valuation results. Assessment of robust policy alternatives is identified as a useful avenue for follow-up work. The clear delineation of technologies and data on the differing degrees of vertical integration make the solar energy industry a particularly appropriate sector to test our hypotheses. Studies of other industry sectors, such as photonics or bio-tech manufacturing, that come with a clear demarcation of supply chain roles and allied measures of flexibility, could also shed light on locus of innovation and market value creation. However, we restricted this study to one sector to avoid the influence of industry effects and to maintain the feasibility of identifying all possible supply chains.

5.3 Limitations

A related issue on the methodology side is our specification of weighted additions for establishing supply chain variation. Other specifications are also possible; for example, we could have specified the aggregation $T(X_k)$ in Equation 3 as a maximization function shown by $Max(X_k)$. The additive formulation is justified over the maximization function because it includes larger information content and accounts for the market share. In our view, we offer a novel methodological contribution for aggregation of supply chain parameters (with Equations 1 and 2) and allied SUR analysis. This approach has support based on research for assessing returns of a portfolio of stock market assets (Greene 2003) and analyzing foreign direct investment flows between countries (Borensztein, De gregorio et al. 1998). A related challenge in using firm level valuation data to impute both firm and supply chain performance is the possibility of a single firm developing and delivering multiple lines of products across industry sectors. However, such diversification is rare in the solar energy supply chain. A majority of firms in our sample offer one dominant product and have well established supply chain structures. We correct for any such effects by weighing all key constructs with their proportional solar energy output for each supply chain link (as captured in Equation 3). This use of weights and linkages also allowed us to exclude non-publically–traded firms (as shown by the term 'Other' in Figure 3). Verifying the robustness of our methodology (e.g., by comparing alternative specifications) is another avenue for follow-up research.

6. Conclusion

This work is a proof-of-concept study that seeks to untangle the effects of supply chain integration and product modularity on capital market valuation. This can be a challenging task because in many cases researchers cannot identify the full network of the supply chain because of incomplete or unavailable information and the highly dynamic nature of the supply chain network. Indeed, many studies utilizing secondary data are based on incomplete information in that they consider only public firms. We developed a technique where, through a firm's public announcements on supply contracts and production capacity, we could make estimates on individual market shares and the amount of material flow in the network. Future research could assess the impact of shortages in supplies or excess capacity on the valuation. It would also be of interest to examine the significance of the supply chain position on the individual firm's value.

For example, research could explore whether producing or distributing products in a particular supply chain network is more lucrative.

In contrast to the more common inventory-based view of supply chain performance, our intention was to explore the value of a network of firms. A number of researchers including Fiegenbaum and Karnani (1991), Frohlich and Westbrook (2001), Wu and Choi (2005), and Stevenson and Spring (2007) have called for additional investigation from the perspective of the supply chain network. Our work offers a methodology to fulfill this call. We do so, in particular, by developing and utilizing a quantitative method of valuing the supply chain, and then applying SUR to quantify the impact of supply chain integration.

Acknowledgements. We thank Janelle Heineke, Nalin Kulatilaka and Vinod Singhal for their valuable input and reviews as we developed the ideas within this paper. Earlier versions of this research have been presented at the POMS conference, the MSOM and INFORMS meetings and at the Judge Business School and Queens University Belfast seminar series. We are grateful to the participants for their comments, in particular Jaideep Prabhu and Arnoud de Meyer for their feedback on the model specifications and the theoretical structure.

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Figure 1.Supply Chain Integration–Product Modularity–Market Valuation Framework

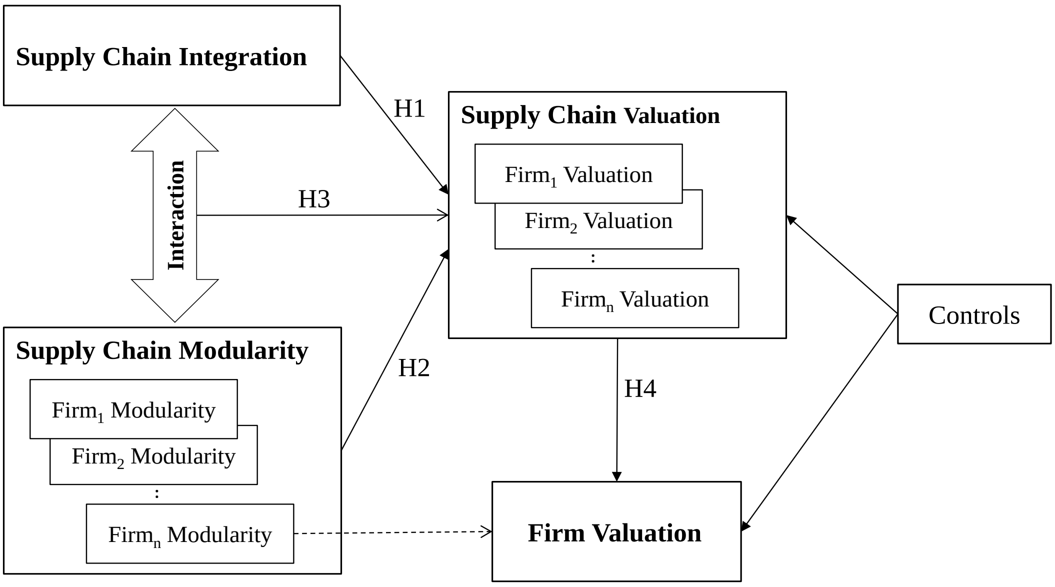
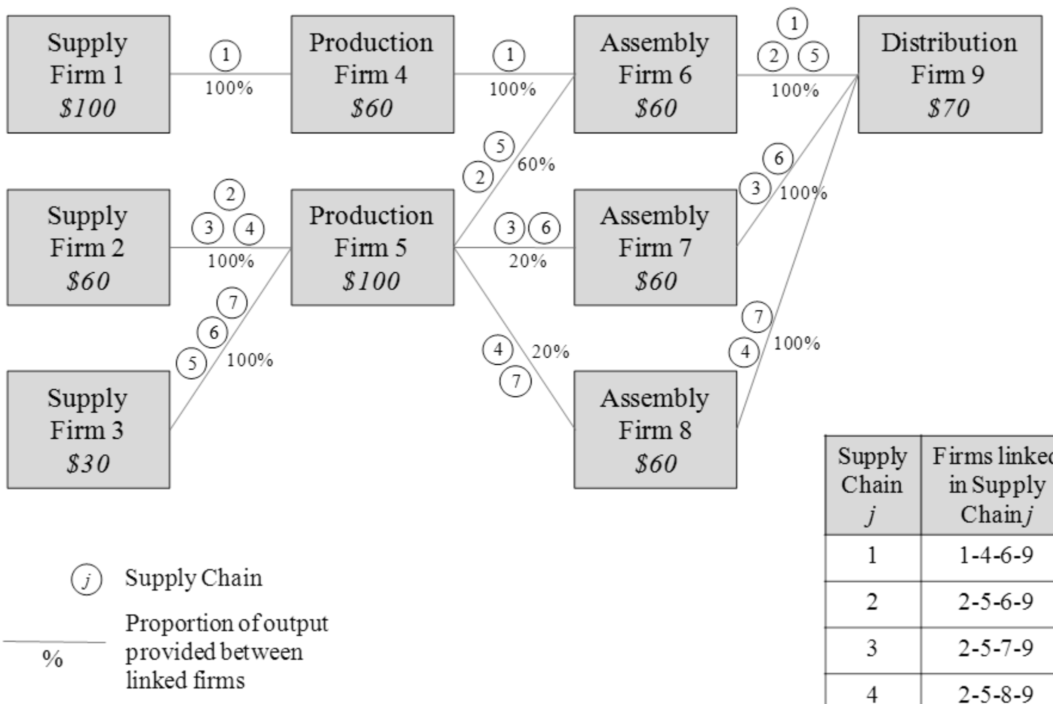


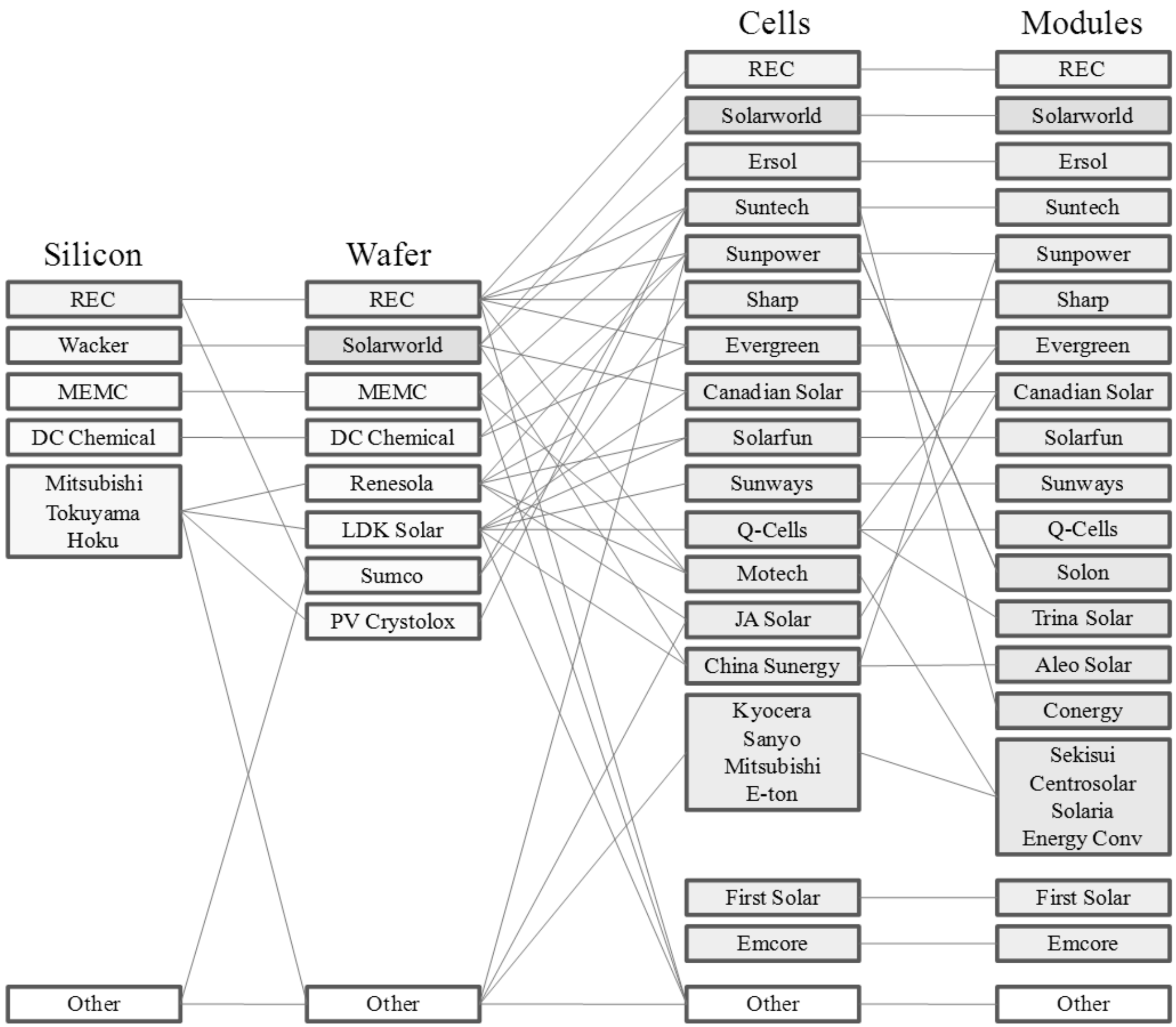
Figure 2. An illustration of End-to-End Supply Chain Configurations



Supply Chain *j*	Firms linked in Supply Chain *j*	Value of Supply Chain *j*
1	1-4-6-9	$190
2	2-5-6-9	$80
3	2-5-7-9	$70
4	2-5-8-9	$70
5	3-5-6-9	$70
6	3-5-7-9	$60
7	3-5-8-9	$60

As an example of applying the supply chain value algorithm, the value of Supply Chain 5 is 33.3% of the value of Firm 3 (as the chain is shared by three outgoing firms), plus 50% of 60% of the value of Firm 5 (as 60% of value shared by 2 outgoing chains), plus 33.3% of the value of Firm 6 (as shared by three outgoing chains) and 14.3% of the value of Firm 9 (as shared by seven incoming chains). The total value of Supply Chain 5 is $10 + $30 + $20 + $10 = $70.

Figure 3. Relationships in the Solar PV Industry Supply Chain Network for 2007



Relationships identified based on multiple industry and analyst reports detailing production capacity, and 119 newswire announcements on supply contracts. 'Other' represents privately owned companies.

Table 1. OLS and SUR Regression Results for Individual Firms

Dependent Variable: Ln Firm Valuation					
	Model 1a (OLS)		**Model 1b (SUR)**		
Independent Variables	Coeff	SE	Coeff	SE	
Firm Modularity Variables					
Firm Product Modularity	0.095	0.48	0.130	0.27	
Firm Standards	0.159 **	0.06	0.141	0.10	
Firm Customization	0.129 **	0.05	0.135 ***	0.05	
Firm Control Variables					
Lag Ln Firm Valuation	0.579 ***	0.13	0.611 ***	0.11	
Ln Firm Revenue	0.358 **	0.16	0.307 **	0.12	
Ln Firm Operating Margin	0.733 ***	0.26	0.840 ***	0.27	
Ln Firm COGS Intensity	-1.362 **	0.56	-1.318 **	0.54	
Ln Firm R&D Intensity	-0.018	0.08	-0.004	0.09	
Constant	0.490	0.75	0.605	0.80	
Model Fit					
R^2	0.818		0.816		
Adjusted R^2	0.774		0.772		
Observations	42		42		
F model/Chi^2	25.14 ***		194.65 ***		
Change in Adjusted R^2			0.002		Hypothesis 4 supported

Robust standard errors
*** p<0.01, ** p<0.05, * p<0.1

Table 2. OLS and SUR Regression Results for Supply Chain

Dependent Variable: Ln Supply Chain Valuation					
	Model 2a (OLS)		**Model 2b (SUR)**		
Independent Variables	Coeff	SE	Coeff	SE	
Supply Chain Intergration Variable					
SC Integration	0.249	0.16	0.244 **	0.11	Hypothesis 1 supported
Supply Chain Modularity Variables					
Aggregated Firm Product Modularity	-9.138 *	5.06	-10.230 **	5.18	Hypothesis 2B supported
Agrregated Firm Standards	-0.09	0.14	-0.056	0.14	
Aggregated Firm Customization	-0.011	0.06	-0.014	0.04	
Supply Chain Interaction Variable					
Aggregated Firm Product Modularity * SC Integration	4.38 *	2.51	4.935 *	2.59	Hypothesis 3A supported
Supply Chain Control Variables					
Aggregated Lag Ln Firm Valuation	0.819 ***	0.14	0.817 ***	0.11	
Aggregated Ln Firm Revenue	0.090	0.15	0.131	0.14	
Aggregated Ln Firm Operating Margin	0.081	0.53	0.019	0.46	
Aggregated Ln Firm COGS Intensity	-0.283	0.18	-0.312 *	0.16	
Aggregated Ln Firm R&D Intensity	-0.036	0.08	-0.044	0.08	
Aggregated Ln Firm Fixed Asset Intensity	-0.109	0.15	-0.103	0.12	
SC Technology	-0.375	0.58	-0.444	0.36	
Constant	1.052	1.42	0.859	0.91	
Model Fit					
R^2	0.869		0.868		
Adjusted R^2	0.815		0.813		
Observations	42		42		
F model/Chi^2	19.29 ***		297.17 ***		
Change in Adjusted R^2			0.002		

Robust standard errors
*** p<0.01, ** p<0.05, * p<0.1