NEW PRODUCT DEVELOPMENT AND INNOVATION THROUGH JOINT
KNOWLEDGE CREATION AND TRANSFER IN A DYADIC SUPPLY CHAIN
RELATIONSHIP

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Dedication

Words fail in this dedication to my wife Holly. She has endured this endeavor with stoicism and grace.

I would also like to thank my parents for instilling in me a love of learning at an early age.
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NEW PRODUCT DEVELOPMENT AND INNOVATION THROUGH JOINT KNOWLEDGE CREATION AND TRANSFER IN A DYADIC SUPPLY CHAIN RELATIONSHIP

ABSTRACT

RICHARD JOHN MILLER

The development of radical and incremental products in the context of supply chain relationships is changing the competitive paradigms for individual firms. The knowledge required for innovation is no longer the sole responsibility of a single firm. As firms use their supply chain’s knowledge stocks to innovate and develop products, the decisions regarding its internal and joint resource investments, the types of innovation, and how the firm and the supply chain respond to market turbulences must also change. In order to understand the dynamic behavior of this complex system, a System Dynamics simulation model of a focal firm, a supplier firm, and their joint area is developed and tested.

This study is an initial effort to develop and model a framework of dynamic supply chain relationships based on the radical and incremental innovation investments of a focal and supplier firm and knowledge transfer within the supply chain. The model is validated and tested across 16 diverse scenarios that contain 40 unique runs and 640,000 iterations. The model is also extended to two different industries utilizing market based purchases of product innovations. Using this extensive testing, we create a dynamic
learning environment to explore the effects of knowledge transfer and innovation investment strategies on the profits of firms and supply chains. The creation of this learning environment provides a major contribution to the literature by being the first to analyze innovation strategies and knowledge transfer in a dynamic supply chain relationship.

The extant literature focuses on recommending an initial set of conditions for supply chain members, but does not provide an understanding of the reactions of the supply chain after the change in strategy has been made. This study fills this gap by including the feedback mechanisms of the investment strategies, which provides firms and supply chains with both the initial set of recommendations and the reactions of the supply chain partners to the changes. The reactions of the supply chain partners are critical to developing a richer understanding of supply chain relationships because investment decisions can have negative impacts on the supply chain and create reinforcing feedback loops. Through the learning environment, several negative aspects are identified and recommendations are provided that enable firms and supply chains to avoid these issues.
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CHAPTER I

INTRODUCTION

The shift in competitive paradigms from individual firms to supply chains is changing the role of firms as they attempt to develop new and improved products and processes (Petersen, Handfield, & Ragatz, 2005). Innovation is no longer the sole responsibility of a single firm; firms must now extend their knowledge resources beyond their own boundaries. As they move from a competitive model of solely utilizing their own knowledge resources to utilizing the resources of other firms, models of knowledge transfer must also change. Creating alliances and collaboration for innovation is a relatively new concept among supply chain partners, and requires new studies to reveal how firms can use their supply chain networks to their advantage in developing new products and services.

A firm needs to make a decision of where it can acquire knowledge and resources for innovation. A firm can either generate all of its knowledge and resource requirements
internally or utilize firms in its supply chain network (Petersen et al., 2005). Once a firm makes a decision to use external resources it must find a firm or a supply chain network that has knowledge and resources that are complementary and beneficial; this is known as relational resources (Dyer & Singh, 1998). Relational resources allow firms to generate performance that neither firm would be able to accomplish alone. This mutual combination of relational resources allows the supply chain network to generate relational rents that exceed what either firm could generate on its own (Dyer & Singh, 1998).

The decision of how to utilize a supply chain network for relational resources is not a static decision. To sustain competitive advantage a firm and supply chain network must continuously review their previous decisions on the allocation of resources to react to changes. A firm and supply chain network need be able to respond to a variety of internal and external conditions. This dynamic decision process has not been captured through cross-sectional research of supply chain networks (Sarimveis, Parinos, Tarantilis, & Kiranoudis, 2008). While cross-sectional methodology provides insight into potential factors and causes of knowledge and innovation, it does not provide a temporal insight into the dynamic nature of policy decisions, resource allocations, and feedback mechanisms. In the literature, system dynamic modeling (Forrester, 1968; Morecroft, 1985) is suggested as a possible method to be used to alleviate the limitations of cross-sectional analysis. For example, Garcia, Calantone, and Levine (2003) suggest system dynamic modeling to investigate the role of knowledge and innovation within a single firm. Their analysis shows that internal and external factors affect the policy decisions and resource allocations on a dynamic basis with respect to time. Similarly, using system
dynamic modeling, the impacts of endogenous and exogenous variables are analyzed for
their impact on investment in radical and incremental innovation (Garcia et al., 2003).
Scenarios can also be created with system dynamic modeling to explore managerial
implications of decisions regarding conditions of knowledge creation and transfer within
a supply chain network over time.

The current system dynamics modeling of supply chain networks focuses on
logistics, inventory management, and information technology (Sarimveis et al., 2008),
and only captures the transfer of goods and information between firms in a supply chain
network but not innovation and knowledge transfer. Garcia et al. (2003) uses system
dynamic modeling for innovation and New Product Development (NPD) policies, but the
study focuses on a single firm, rather than in a dyadic supply chain relationship.

The purpose of the current study is two-fold. First, we contribute to the literature
by offering a comprehensive model that represents the dynamic nature of policy decisions
regarding knowledge creation and transfer among supply chain partners, resource
allocations, and feedback mechanisms over time. Secondly, we contribute to the
understanding of the impact of endogenous and exogenous factors on radical and
incremental innovation in a system dynamic model. The contributions will provide a
more complete understanding of the role of innovation and knowledge in the context of
supply chain management.
CHAPTER II

LITERATURE REVIEW

2.1 Knowledge Stocks

As new products and processes are developed and introduced, a firm needs to monitor and review them periodically. During the review period a firm has three decisions for each product and process: do nothing, improve, or replace the product. A product may not need any improvement or replacement, so the it left in its current form. Typically in an incumbent organization, the knowledge contained within the existing products and processes is used to created new or improved products (Grant, 1996a). In the literature, these products are referred to as sustaining technologies and the knowledge residing within the product and process is referred to as knowledge stocks (Garcia et al., 2003), embedded knowledge (Madhavan & Grover, 1998), organizational memory (Moorman & Miner, 1997), or knowledge inventories (Levinthal & March, 1993).

In general, a firm’s knowledge stock increases with the development of new products. Through the application of knowledge stocks to existing products and
processes, embedded knowledge is transformed into *embodied knowledge*, which in turn generates new knowledge that is embedded with the yet to be launched products (Madhavan & Grover, 1998). A firm builds up its knowledge stocks in this fashion until it is challenged by exogenous factors in the market or endogenous factors within the firm.

Knowledge stocks can increase through innovation, but can also decrease as the knowledge stocks age and become obsolete with the introduction of a new innovation. The new innovation can be a launch of a new product through internal innovation or by a competitor. Also, the knowledge stocks can be reduced through consumer preferences changing, making the product no longer demanded in the market.

One of the desired outcomes of innovation is to generate rents. Rent can be defined as the return on an innovation investment that exceeds the cost of maintaining the products and processes. Generation of rents allows a firm to invest the excess, or *slack resources*, in the future innovation of products and processes. Slack resources can be defined as the pool of resources that exceeds the minimum investment cost to maintain the current level of innovation and NPD (Nohria & Gulati, 1996: 1246). As products age, the value of the rents decrease and potentially become negative. The firm can either replace or improve the existing products to maintain and grow its rents.

2.1.1 Types of Innovation and Firm’s Knowledge Stocks

Innovation can be described as two ends of a continuum: radical and incremental innovation. There is no consensus on a definition in the extant literature and there are many different terms to describe similar types of innovation (Li, Vanhaverbeke, & Schoenmakers, 2008). Radical innovation has a similar meaning as double-loop (Argyris & Schon, 1978), explorative (March, 1991), and generative innovation (Baker & Sinkula,
Incremental innovation is similar in meaning to single-loop (Argyris & Schon, 1978), exploitative (March, 1991), and adaptive innovation (Baker & Sinkula, 2007; Senge, 1990).

Radical innovation produces products and processes that are not similar to existing ones. Levinthal and March (1993: 105) describe this type of innovation as, “…the pursuit of new knowledge, of things that might come to be known.” Pursuing new knowledge can lead to a larger increase in knowledge stocks but also poses a higher risk of an unsuccessful innovation (March, 1991). Because radical innovation is generating a product or process that the customers are not familiar with, it has a lower probability of success as compared to incremental innovation. The lower probability of success can be offset with a larger increase to the knowledge stocks for a successful innovation (Levinthal & March, 1993; March, 1991). After its launch, the new product or process can become a candidate for incremental innovation at a later time.

Incremental innovation produces an improved product or process. It allows a product or process to move along the same production function, i.e. reduce costs, improve quality, or decrease manufacturing time (Roy, Sivakumar, & Wilkinson, 2004). Levinthal and March (1993: 105) describe this type of innovation as, “… the use and development of things already known.” Incremental innovation of a product or process has a higher probability of success than radical innovation. Because incremental innovation is improving an existing knowledge stock, the increase to the knowledge stock after a successful launch will be lower than a radical innovation (Levinthal & March, 1993; March, 1991). After its launch, the incrementally improved product or process can become a candidate for incremental innovation.
There are two differing views on the creation of knowledge stocks through innovation. One view states that the innovation process does not define the knowledge stock. The type of innovation, radical or incremental, will, however, increase its respective knowledge stock (He & Wong, 2004). A second view treats knowledge as a non-differentiated stock generated from either the investment of slack resources in radical or incremental innovation process (Li et al., 2008). Regardless of innovation type, all knowledge increases a single knowledge stock. The non-differentiated knowledge stock view will be the basis of our study.

2.1.2 Balancing Radical and Incremental Innovation

Maintaining a balance between radical and incremental innovation, known as ambidexterity (Tushman & O'Reilly, 1996), is important for a firm (Baker & Sinkula, 2007; He & Wong, 2004; Levinthal & March, 1993; March, 1991). Ambidexterity is the ability to use each type of innovation to maximize the benefit or rent to a firm. Setting this balance is an important decision because a firm that exclusively relies on radical innovation cannot capitalize on the investment. New products or processes do not have a chance to gain rents from the market before a replacement product or process is being developed. Likewise, a firm that exclusively relies on incremental innovation can have difficulties with product and process obsolescence (Levinthal & March, 1993) which impact the level and the accumulation rate of rents.

The endogenous and exogenous factors, such as market dynamics, acting on the firm will have an impact on the radical and incremental innovation decision. The balance between these innovation types is not a static decision and must be continuously reviewed and possibly adjusted to react to changes in the endogenous and exogenous
factors. To react to these factors, a firm can choose a rent maximization decision based on its allocation of slack resources in radical and incremental innovation.

Part of the radical and incremental balance decision depends on the minimum rent generation of the firm. The amount of investment made in radical and incremental innovation allows the firm to respond to changes in their knowledge stocks, product and process portfolios, and endogenous and exogenous factors. Allocating resources between each type of innovation is referred to as *radical and incremental investment fraction* (Garcia et al., 2003). As rent generation expectations increase, the level of radical innovation investment should increase. Similarly, a lower level of rent generation expectations should lead to an increased level of incremental innovation investment (Levinthal & March, 1993). Higher success rate of incremental innovation also provides a ‘safer’ investment of slack resources (Garcia et al., 2003).

Slack resources are viewed as both beneficial and detrimental to firms (Herold, Jayaraman, & Narayanaswamy, 2006). Nohria and Gulati (1996) empirically test the level of slack resources and innovation within firms and find a curvilinear relationship. Firms possessing too little slack resources are not able to make minimum investments in innovation to replace their existing knowledge stocks. Likewise, firms possessing too many slack resources forgo investments in radical innovation and rely on improving the existing products and processes. This reliance on incremental innovation causes the knowledge stocks to age and thus produce lower rents. Firms with neither too few nor too many slack resources show the best performance.
2.1.3 Exogenous Factors Affecting Knowledge Stocks

Firms cannot control all factors in their environment. Two potential impacts from the external environment are market and technological turbulence. Turbulence of the environment, through the pace of market change (Hanvanich, Sivakumar, & Hult, 2006; Hult, Ketchen, & Arrfelt, 2007) and technological change of products and processes (Hanvanich et al., 2006) can have an impact on innovation. As environmental turbulence increases, the rate of change required to maintain a competitive advantage also increases, requiring more emphasis on radical innovation. A more stable environment enables firms to focus more on incremental innovation that would bring them lower risk and faster response time (Levinthal & March, 1993; March, 1991).

2.1.3.1 Market Turbulence

Market turbulence is a measure of the change in customer preferences for products and processes. Knowledge that is contained within the products and processes affected by market turbulence does not necessarily become obsolete; however, changes in demand occur. For example, a shift in a customer demand may switch to another product that is less expensive, better meets the customers’ requirements, or has some other trait that the customer values more than an existing product (Hanvanich et al., 2006). Knowledge stocks that are affected by market turbulence lose their ability to generate rents for a firm.

An example of market turbulence is the movement of customers away from low fuel efficiency vehicles in times of high fuel prices. The knowledge stocks for producing low fuel efficiency vehicles have not been decreased because of the increase in fuel prices. Firms are just as capable of producing vehicles with their existing knowledge
stocks, but the market values high fuel efficiency vehicles. Shifting demands have caused low fuel efficiency knowledge stocks to be able to produce lower rents than high fuel efficiency knowledge stocks. Thus, market turbulence provides a change in rent generation capabilities for a firm, shifting the investment of slack resources.

2.1.3.2 Technological Turbulence

Technological turbulence is a measure of the change in the underlying technology of products and processes (Hanvanich et al., 2006). Technological turbulence can reduce the level of knowledge embedded within a product through obsolescence. The reduction in knowledge stocks reduces the ability of a firm to innovate and produce rents from new and improved products and processes. Environments that have high technological turbulence should require a firm to invest more slack resources in radical innovation. The larger increases in knowledge stocks associated with radical innovation can offset the reduction.

An example of technological turbulence is the camera film industry. New technologies are reducing existing knowledge stocks through obsolescence for companies such as Kodak. Knowledge stocks embedded in film products are being replaced by digital media. The investments in incremental innovation for their existing technologies did not replace the loss of knowledge stocks caused by digital media. By not investing adequate resources into radical innovation, their knowledge stock’s ability to produce rents is reduced. Future investments of slack resources need to be focused on radical innovation to replenish their knowledge stocks. Through radical innovation investment they can launch new products that can produce enough rents to sustain and grow the company.
2.1.4 Endogenous Factors Affecting Knowledge Stocks

In addition to exogenous factors affecting a firm, endogenous issues also affect knowledge stocks and knowledge transfer processes. The difference between exogenous and endogenous factors is where the factor can be controlled. Endogenous factors originate within a firm, giving a firm some control over them. Firms set the level of rent required to maintain and invest in new product development through a goal orientation. Firms also have partial control over the forgetting rate of knowledge stocks.

2.1.4.1 Knowledge Loss Due to Aging and Forgetting

After a launch, knowledge that is embedded within a product starts to age. The amount of aged knowledge is both a function of the time since the task was last completed and the forgetting rate. A product or process selected for incremental innovation has some lost knowledge due to forgetting. As the development is undertaken some of the forgotten knowledge can be regained in a future product (Tukel, Rom, & Kremic, 2008).

Aging knowledge stocks have an impact on investment strategies in radical and incremental innovation. As forgetting rates increase, reductions in knowledge stocks require investment of slack resources to replenish knowledge stocks and the level of radical innovation investment should increase. Likewise, a lower forgetting rate allows for a decreased investment in radical innovation to replenish knowledge stocks. This should lead to an increased level of investment in incremental innovation.

2.1.4.2 Retained Knowledge of Abandoned Products and Processes

Not all radical and incremental innovation products or processes are successfully launched. Many times a product or process is not at the level of competition to enter the
market place. Products or processes that are not completed have a residual level of knowledge stock that can be used at a later time. Knowledge that is contained with these abandoned products can be stored through various knowledge management protocols such as lessons learned, databases, and benchmarking (Liebowitz & Megbolugbe, 2003). Firms might also seek patents for the product concept or for the technology developed with the intention of protecting the knowledge and maintaining ownership rights.

2.2 Resources and Knowledge in Single Firms and in Supply Chain Networks

NPD and innovation efforts within a supply chain network can benefit from the availability of knowledge generated by supply chain members. Both the knowledge stock of an individual firm and joint knowledge stocks of a supply chain network are resources available to each member for the development of new products. In the literature, the generation and use of joint knowledge stocks within a firm and a supply chain network can be explained using resourced based view (RBV), knowledge based view (KBV), and relational view (RV).

2.2.1 Resource Based View

RBV (Barney, 1991; Rumelt, 1984; Wernerfelt, 1984) shifted the analysis of the firm from that of its external environment to its internal resources. A firm is no longer viewed as a component of the market, but a set of resources that the firm can control (Lavie, 2006). A firm can control the allocation and investment of its internal resources to respond to the market (Dierickx & Cool, 1989) and generate rent.

A firm must purchase resources from the market at a cost similar to that of the competition. Typically, resources that are available to a firm are also available to the
competition (Barney, 1991). However, the mutual availability of resources alone does not adequately describe why one firm does better than the competition. It is the manner in which a firm allocates and uses its resources that determines not only its competitive capabilities, but also the amount of rent it can create. The RBV states that a firm can develop a competitive advantage through *idiosyncratic resources* by bringing them together in a manner which is difficult to imitate and enables them to generate a rent over the competition (Dierickx & Cool, 1989). Firms must have the capability to identify and utilize the resources to provide for the innovation of new and improved products (Leonard-Barton, 1992; Teece, Pisano, & Shuen, 1997).

Another concept of RBV is time compression diseconomies (Dierickx & Cool, 1989). Time compression diseconomies are path dependent accumulations of resources that make resources difficult to imitate. A competing firm cannot simply purchase the same set of resources and instantaneously produce rents equal to the original firm’s, because the resources contain both embedded and tacit knowledge that takes time to develop. The ability to produce rents is due in part to the history of a firm in using the resources. The knowledge contained within the resources can be accumulated over time as new knowledge is added, creating a knowledge stock (Grant, 1996b). Development of an equivalent level of resources by a competitor may require the recreation of knowledge stocks. However, the time to develop these resources causes a delay of when the resources are available to the competition (Dierickx & Cool, 1989).

2.2.2 Knowledge Based View

Grant (1996a; 1996b) and Spender (1996) expanded on RBV’s theory to focus on a particular type of resource; knowledge. This extension of RBV is the view that
knowledge accumulation in a firm is a means of providing rents. The emphasis of KBV is on the coordinating structure of a firm regarding the decision to gain knowledge from the market or vertical hierarchies (Grant, 1996b). This choice of make versus buy, with respect to knowledge, is an important decision for a firm (Kogut & Zander, 1992). The decision of which source of knowledge to pursue can lead a firm to a more efficient generation of knowledge (Grant, 1996b; Kogut & Zander, 1992). A firm can either expand its boundaries through vertical integration or use the market to access another firm’s knowledge through a market contract, joint venture, alliance, or a supply chain network.

In deciding to gain knowledge from external partners, a firm must also be aware of their partner trying to internalize the knowledge being utilized. If a partner is able to successfully internalize the knowledge then the relationship may no longer be required because of opportunistic knowledge transfer (Hamel, 1991). The knowledge that has been transferred makes the relationship no longer beneficial to one of the parties involved. While the opportunistic knowledge transfer is an issue, the literature also focuses on the strategic advantage that can be gained through cooperative knowledge transfers (Grant & Baden-Fuller, 2004). It is commonly suggested that firms establish governance mechanisms to monitor and minimize the opportunistic knowledge transfer in order to maintain robust relationships (Dyer & Singh, 1998).

2.2.3 Relational View

RV extends RBV’s theory beyond a single firm to include alliance partners because all resource opportunities for a firm are not contained within its organization (Dyer & Singh, 1998). This extension provides for the inclusion of resources available
beyond the boundary of a firm. Extending the available resources and knowledge for a firm to include those within the supply chain network can create *collaborative advantage* (Kanter, 1994). Utilizing other firms within the supply chain network allows a firm to generate additional rents, or *relational rents*. Relational rents are defined as, “… a supernormal profit jointly generated in an exchange relationship that cannot be generated by either firm in isolation and can only be created through joint idiosyncratic contributions of the specific alliance partners” (Dyer & Singh, 1998: 662). Relational rents can be created through a variety of mechanisms. There are four components that can develop relational rents: inter-firm assets and capabilities, complementary resources, inter-firm knowledge sharing routines, and absorptive capacity.

Relational assets can be joint products that a supply chain network is developing. These assets are created through the effort of the supply chain network and only produce rents within the relationship. In addition to generation of relational rents, the joint products also contain embedded knowledge that is available to the supply chain network. If the relationship is terminated, time compression diseconomies and the idiosyncratic nature of resources and capabilities creates uncertainty if the level of rent can be reached in another relationship (Dyer & Singh, 1998).

The knowledge that each firm possesses should not be identical to the knowledge contained within the supply chain network (Grant & Baden-Fuller, 2004). If a supply chain network possess similar knowledge then the ability to produce rents from this knowledge is limited. Non-identical knowledge is a necessary, but not sufficient condition for complementary resources. Also, knowledge sharing is key because the knowledge required for radical and incremental innovation is contained within the supply
Likewise, a firm needs to also capture knowledge that is contained within the joint products of the supply chain network to provide for future innovation. Part of this ability is explained through *absorptive capacity*.

Cohen and Levinthal (1990: 128) define absorptive capacity as, “the ability of a firm to recognize the value of new, external information, assimilate it, and apply it to commercial ends.” One issue with the definition of absorptive capacity is the requirement that knowledge be used to commercial ends. The reliance on using the knowledge to commercial ends limits the impact that knowledge can have on firms. Through improving capabilities and inter-firm knowledge sharing, absorptive capacity can positively impact the performance of firms, but not necessarily to commercial ends.

The automobile industry provides an example of the effects of absorptive capacity. The Toyota Production System (TPS) has been the source of imitation by many manufacturing companies. Knowledge of TPS is available through many sources, but few companies can utilize this knowledge to commercial ends (Spear & Bowen, 1999). Possessing knowledge about TPS is a necessary, but not a sufficient condition to apply the principles to existing knowledge stocks and innovate new products.

### 2.3 Innovation and NPD Through Joint Supply Chain Network Knowledge Stocks

RV predicts that firms can improve their rent generation through relationships. This competitive model has shifted innovation from one firm developing new products alone to one of using supply chain members to assist in the development. In support of this shift in innovation Hult et al. (2000) found that firms no longer control all of the knowledge of their products or services. A firm is no longer in control of its knowledge, thus a shift in the management of knowledge is required (Kale & Singh, 2007). A firm
must make a decision on the balance of internal versus external creation of knowledge. A firm has different structures to manage this externalization of their knowledge stocks which vary based on the transfer and control within the supply chain network.

2.3.1 Strategic Relationships

Firms, through strategic relationships, can create rents that exceed what an individual firm would be able to achieve (Carr & Pearson, 1999; Chen, Paulraj, & Lado, 2004; Chen & Paulraj, 2004a; Ellram, 1990). Establishing a strategic relationship is not the only choice that a firm must make. The structure of the relationship can also impact the role of knowledge and how knowledge is shared within the relationship (Grant & Baden-Fuller, 2004).

For example, in market relationships the knowledge transfer between firms is discretely specified by a contract. Once the contract is completed firms have no future obligations to one another (Ring & Van de Ven, 1992; Williamson, 1985). All competing firms have the potential to access the same resources through the market. The access and the interactions of firms being dictated through the contract does not allow firms to create idiosyncratic transfers of knowledge. This inability to form idiosyncratic transfers does not allow firms to create relational rents (Dyer & Singh, 1998).

Strategic relationships, on the other hand, can take on forms that function beyond a market relationship. Alliances, joint ventures, and supply chain networks are considered to be three forms of non-market based strategic relationships. Alliances can refer to both equity and non-equity sharing agreements between firms (Hamel, 1991) and definitions vary (Soosay, Hyland, & Ferrer, 2008; Vyas, Shelburn, & Rogers, 1995). Joint ventures are strategic relationships in which a combination of two or more firms’
resources create a new entity (Inkpen & Crossan, 1995). A third form of strategic relationship is a supply chain network where firms jointly innovate and develop products. The supply chain network differs from the alliance and joint venture because if a firm decides that the cost of the relationship outweighs the benefits it is able to terminate the relationship at any time.

Many different constructs of supply chain management have been used to define the supply chain relationship (Gibson, Mentzer, & Cook, 2005). This study draws on some key constructs for innovation that have been used to define supply chain management concepts: long-term relationships, communication, and supplier involvement (Chen & Paulraj, 2004a). These three constructs provide a basis for firms to share knowledge, innovate, and develop new products.

2.3.1.1 Supply Chain Network Structures

The structure of a supply chain network impacts the number of layers or interconnected relationships that are analyzed. At least two levels of a relationship must be used for the analysis of a supply chain network. The number of levels can either be described as dyadic, two firms, or a network structure in which more than two firms are analyzed simultaneously (Gulati, Nohria, & Zaheer, 2000). The network structure provides the most realistic level of analysis (Knight & Pye, 2005). But, the complexity of a network analysis can be difficult to manage. Dyadic structures reduce the realism of the model but allows for more detailed analysis of both firms involved.

2.3.1.2 Supply Chain Network Involvement in Innovation

The level of interaction within a supply chain network affects the inter-firm involvement in the innovation process. Table I shows terminology developed by
Petersen, Handfield, and Ragatz (2005: 378) to describe a joint involvement of a buyer and supplier firm through the level of interaction and mutual dependence between firms. Involvement at the white and black box levels has one firm taking a more dominant role in the development process by providing the guidance and direction for the development process. The gray box level has each firm contributing a more balanced amount.

Table I Terminology for Supplier Integration

<table>
<thead>
<tr>
<th>Supplier Involvement</th>
<th>None</th>
<th>White Box</th>
<th>Gray Box</th>
<th>Black Box</th>
</tr>
</thead>
<tbody>
<tr>
<td>No supplier involvement.</td>
<td>Supplier makes to print.</td>
<td>Informal supplier integration. Buyer</td>
<td>Formalized supplier integration. Joint</td>
<td>Design is primarily supplier driven, based on</td>
</tr>
<tr>
<td></td>
<td>Supplier makes to print.</td>
<td>‘consults’ with supplier on buyer’s design.</td>
<td>development activity between buyer and supplier.</td>
<td>buyer’s performance specifications.</td>
</tr>
</tbody>
</table>

Black box involvement is a firm providing a supply chain network with a list of specifications for the finished product. These specifications then become the mechanism of knowledge transfer by describing the desired outcome of the final product. The firm conducting the development uses its internal knowledge stocks to create the process or product. The supply chain network firm has a high degree of autonomy with the design as long as it meets the specifications. The knowledge used for the originating firm is the final product that is desired. Although the knowledge of how to develop the product is not contained within the firm, the knowledge is available within the supply chain network, so the product can be developed.

White box development is similar, but a firm utilizes its internal knowledge stocks and queries the supply chain network as needed. White box involvement uses
little of the knowledge from a supply chain network. The knowledge required to develop
the product is contained within the firm, but knowledge of such items as customer usage,
packaging, regulatory compliance, marketing, and other issues is contained within the
supply chain network. Comments are taken into consideration, but the white box firm
determines if any are implemented. Both white and black box involvement provide little
communication outside of beginning or ending inputs and comments from the supply
chain network.

Gray box involvement uses a collaborative approach with each firm providing
more equal levels of knowledge both at the beginning and throughout the innovation.
Gray box involvement utilizes both firms to provide input and communication into a
product from start to completion of an innovation. Because each firm is providing inputs
and is actively involved with the innovation, the knowledge created is more equally
spread to those involved.

2.3.1.3 Performance Measures in Supply Chain Networks

A variety of performance measurements have been used to determine the affect of
different changes and configurations in supply chain management and can be divided into
two areas: non-financial and financial performance. The non-financial performance
measurements are used to investigate a specific aspect of a firm that is improved due to
the supply chain relationship, such as cycle time (Hult et al., 2000; Hult, Ketchen, &
Slater, 2002; Hult et al., 2007; Martin & Patterson, 2009), inventory reduction (Martin &
Patterson, 2009), new product success (Baker & Sinkula, 1999a, 1999b), or knowledge
transfer to improve supplier performance (Modi & Mabert, 2007). While these measures
are important to a firm and its supply chain, they do not measure the overall performance
of a firm and the profits that it is able to generate because of its supply chain relationships.

Financial performance measurements are often operationalized as return on assets (Craighead, Hult, & Ketchen, 2009; D'Avanzo, von Lewinski, & Van Wassenhove, 2003) and profit growth (Flynn, Baofeng, & Xiande, 2010). Chen and Paulraj (2004b) argue that only having a single indicator of firm performance diminish the understanding of the interactions and dynamics of a firm and supply chain. While measuring the profits of a firm does rely on a generalized performance indicator of a firm, it can also be argued that without profits, a firm’s longevity is questionable. In addition, only measuring non-profit aspects of the firms and supply chains does not provide an understanding of their financial performance. For instance, Martin and Patterson (2009) measured non-financial and financial performance and found no link between SCM practices and a firm’s financial performance. Therefore, we propose using multiple firm and supply chain performance measurements, such as knowledge transfer, knowledge stock levels, recovering dormant products, etc. as components related to profits. However, our main focus is on the ability of the focal and supplier firm to generate profits and be able to fund future innovations, both within their firms and the joint area.

2.3.2 Joint Knowledge Stocks and the Boundaries of Firms in Supply Chain Networks

The boundaries of each firm define the difference between a firm’s internal stock of knowledge and resources to stocks that are possessed by other firms in the supply chain network. The boundaries of each firm overlap with the joint knowledge that has been created through collaborative innovation. Each firm maintains an internal stock of knowledge and products that have been created through radical and incremental
innovation. Each firm also maintains a separate stock of slack resources that their products have produced.

The boundaries of a firm are also important to the investment of resources. With a clear separation of boundaries, each firm controls its allocation of resources to invest in developing internal and joint product innovations. While each firm contributes to the joint product innovation, the joint knowledge stock is not within a firm’s boundary. Thus, to benefit from the joint knowledge stocks for its own product development and the generation of subsequent profits, a firm must transfer the joint knowledge stocks to their own.

2.3.3 Knowledge Transfer Processes

Johnson, Sohi, and Grewal (2004) propose two types of knowledge stocks, *functional knowledge stocks* and *interactional knowledge stocks*. Functional knowledge stocks are embedded in products and interactional knowledge stocks are embedded in processes that firms use to interact with a supply chain network. The interactional or *process knowledge stocks* enable the supply chain firms to access the joint knowledge stocks. The process knowledge stocks are developed and maintained by the investment of a firm’s slack resources. Upon transfer of the knowledge stocks, a firm can then use the knowledge for its internal radical and incremental innovations.

In the context of supply chain network relationships, firms do not solely invest slack resources into the development of products. Joint knowledge stocks can be transferred to a firm’s internal knowledge stock through investment in the *knowledge transfer process*. Transferred knowledge stocks are important to each firm because on termination of a relationship joint knowledge stocks are lost. Transferred knowledge
stocks, on the other hand, are available for future relationships, but are subject to time
diseconomies of scale (Dyer & Singh, 1998).

Knowledge transfer is impacted by the difficulty of a firm in assimilating the
knowledge (Lee, Lee, & Lee, 2003). More technologically advanced knowledge or
knowledge that requires a higher level of absorptive capacity can reduce the effectiveness
of the knowledge transfer process. As the difficulty of knowledge transfer increases a
firm can increase the investment in process knowledge stocks or utilize their internal
product knowledge stocks.

Process knowledge stocks have the same properties as product knowledge stocks.
Firms need to decide on the fraction of resources that are allocated to radical and
incremental innovation of processes to maintain and increase process knowledge stocks.
Slack resources invested in processes reduce the available slack resources for product
innovations. The firm’s decision to invest in product innovation produces knowledge
internally while an investment in process innovation increases the flow of knowledge
from the joint knowledge stocks.

2.4 System Dynamics

Through the use of systems dynamics, policy decisions and their corresponding
feedback can be analyzed. Decisions of a firm and a supply chain network exhibit
dynamic complexity (Forrester, 1968; Morecroft, 1985; Sterman, 2001), which assumes
that decisions are historically dependent. For instance, radical and incremental
innovation investment fraction decisions for the current time period are a function of
decisions from previous time periods.
Using system dynamics to analyze innovation is not intended to be used as a predictive tool to forecast the future, but rather a learning environment through which analysis of policy decisions can be examined (Sterman, 2000). Interactions of feedback mechanisms of firm and supply chain decisions can also be used to examine the impact of such decisions on the system. Also, sensitivity of variables can be examined to determine the impact of decisions on the remainder of the model and with respect to time. System dynamics also allows for the analysis of what impact policy decisions can have on themselves through the use of feedback mechanisms. As policy decisions are enacted they can start to change the system itself. Policy decisions must be revisited at each iteration to access their impact on the system. As a policy decision’s impact changes the system, it may no longer be valid and may require adjustment.

A system dynamics model can recognize this shift in innovation policy and can adjust slack resource investments away from radical and into incremental innovation. For innovation decisions, a radical innovation policy may be enacted to generate a new product. Once the innovation has been completed a firm’s investment in innovation may change to include more incremental innovation investment to maintain and improve the product after it has been launched. As time continues to pass, an incremental innovation investment decision may cause rents to decrease as emphasis has been shifted away from radical innovation of new products.

2.4.1 The Role of Feedback Mechanisms

Cross-sectional research studies are a snap shot of what is impacting firms and supply chain networks at a particular point in time. To overcome this issue, longitudinal studies can be conducted to provide a temporal perspective (Meredith, 1998). Both
cross-sectional and longitudinal studies are passive methods in which the researcher is an observer. These methods are crucial in the collection of data and the triangulation (Lewis, 1998) of information to develop understanding of theories. Due to issues of conducting experiments within the context of a live business environment (Meredith, 1998), feedback mechanisms can be difficult to capture. The role of feedback is critical to understanding its impacts on decision and policy choices. Endogenous and exogenous factors and the effect of previous policy decisions can change the current rent maximizing decisions. By viewing a decision and policy within this context of a changing landscape of variables, a more complete picture can be created (Sterman, 2001).

System dynamics feedback mechanisms can provide an analysis of sensitivity and unintended consequences of decisions. An often cited example of unintended consequences is increasing the capacity of existing roads to alleviate traffic congestions (Sterman, 2001). Traffic and road capacity are not static decisions and require a dynamic perspective to examine their impact on a decision over time. In the short-term traffic congestion is mediated through an increase in capacity of new roads. Increases in road capacity leads to a change in incentives for people that are building housing along these new roads. As traffic congestion decreases, incentives to build housing that can utilize more road capacity is increased. Soon increases in housing stocks have eliminated the gains from more traffic capacity leaving the system back at its original condition of congested roads. The short-term benefit created the same situation in the long-term that the policy decision was intended to fix.
2.4.2 Feedback Cycles

A feedback cycle that perpetuates itself is referred to as a reinforcing or self-sustaining (Sterman, 2001). Reinforcing loops either continuously grow or decline until some outside force acts on it. Fig. 1 shows a graphical representation of the reinforcing loops. Any change in the system cause the loop to become unstable.

![Reinforcing Feedback Loop](image)

Fig. 1 Reinforcing Feedback Loop (Reproduced from (Sterman, 2000: 351)

A feedback cycle that limits its own growth is referred to as a balancing, self-correcting, virtuous, or goal-oriented cycle (Sterman, 2000, , 2001). The balancing loop can change its value while being acted on by a variable in the system. As the goal is reached the loop obtains an equilibrium position. Two common forms of the graphs are the s-shaped or logistic growth curve and the asymptotic growth or decay functions (Sterman, 2000). Fig. 2 shows a graphical representation of the balancing loop. Any movement changes the system while it is being acted on. Once the perturbation is removed from the system it returns to an equilibrium value. The location of the equilibrium position can change position through changes to the system. Any movement of an equilibrium position does not change the property of the balancing mechanism.
A balancing or reinforcing loop can be calculated mathematically. The first step is to trace the causal loop and indicate the direction of action for each variable, represented by the direction of the arrow. Each variable in the loop must be identified as well as the variables it has an effect on. See Fig. 3 for an example of a causal loop. The second step is to determine what impact a variable has on another. To determine this impact, two questions can be asked:

1. Does a change in variable $A$ reinforce the change in variable $B$?

   If question 1 is answered “yes”, the sign of the arrow is a positive (+).

2. Does a change in variable $A$ counteract the change in variable $B$?

   If question 2 is answered “yes”, the sign of the arrow is negative (-).

By completing the circuit of the causal loop, each sign is found.
To determine if a loop is balancing or reinforcing, equation (2.1) (Sterman, 2000: 145) is used. SGN indicates the sign of the variable obtained from the questions above. For the example in Fig. 3, the output of variable A, $X^O_A$, becomes the input for variable B, $X^I_B$. If the partial first derivative of A with respect to B, $\left( \frac{\partial X^O_A}{\partial X^I_B} \right)$, is positive the sign for this input/output pair is (+). If the partial first derivative of A with respect to B, $\left( \frac{\partial X^O_A}{\partial X^I_B} \right)$, is negative the sign for this input/output pair is negative. The general form of the polarity calculation is given in Equation 2.1. For the causal loop example, Equation 2.2 the polarity of the loop can be determined. The polarity sign of a reinforcing loop is designated as a positive (+). The polarity sign of a balancing loop is designated as a negative (-).
Polarity: \( \text{SGN} \left( \frac{\partial x^O}{\partial x_1} \right) = \text{SGN} \left( \frac{\partial x^O}{\partial x_n} \right) \times \text{SGN} \left( \frac{\partial x_2}{\partial x_{n-1}} \right) \times \text{SGN} \left( \frac{\partial x_3}{\partial x_{n-2}} \right) \times \ldots \times \text{SGN} \left( \frac{\partial x_2}{\partial x_1} \right) \) (2.1)

(Sterman, 2000: 146)

The polarity computation for the causal loop in Fig. 3 is then,

Polarity: \( \text{SGN} \left( \frac{\partial x^O_A}{\partial x_A^n} \right) = \text{SGN} \left( \frac{\partial x^O_A}{\partial x_B^n} \right) \times \text{SGN} \left( \frac{\partial x_B^n}{\partial x_C^n} \right) \times \text{SGN} \left( \frac{\partial x_C^n}{\partial x_D^n} \right) \times \text{SGN} \left( \frac{\partial x_D^n}{\partial x_A^n} \right) \) (2.2)

2.4.3 Stocks and Flows

Stocks represent an accumulation of some measureable resource belonging to a firm or to a supply chain network. Stocks are not limited to physical resources and can represent intangible resources such as the knowledge embedded in a product or process. Movement of resources from one stock to another stock is represented through flows which allow for the transfer of stocks within a system, accumulation of stocks from outside a system, and declines of stocks. All flows between stocks and out of stocks are controlled by variables and policy decisions within the model. The flows are important to the model because changes in the level of the stocks must always be accounted for (Sterman, 2000).

For example, the product stock of a firm is created through the transformation of slack resources in the innovation process. The decline in the product stock can be caused by market turbulence, technological turbulence, unfunded incremental products, and abandoned products. The change in level of product stock at any given period is the difference between the stock created through innovation and lost through turbulence or during in the innovation process. There is no direct flow between the product stock and
knowledge stock, but the embedded knowledge in each product is an indicator of the level of knowledge stocks in the system.

2.4.4 Time Delays

Not all increases or decreases to a stock are available to a firm or to a supply chain network as soon as the resources are invested. Time delays are an important aspect of system dynamics because they allow for a temporal element to be added to the development process. Typically, innovations and product developments are not instantaneously available and take time to develop and commercialize.
CHAPTER III

THE MODEL

The systems dynamic model that represents a dyadic supply chain relationship consists of three regions, as represented in Fig. 4: a focal firm’s sole focus area, a supplier firm’s sole focus area, and an overlapping joint area of interest. The focal and supplier firms control the resources and product stocks within their sole focus areas. The joint area of interest is the overlap of their boundaries. The focal and supplier firms’ sole focus areas consist of a radical product stock, incremental product stock, knowledge stock, slack resources, and flows that represent the radical and incremental innovation. The joint area of interest consists of a radical product stock, incremental product stock, product knowledge stock, radical process stock, incremental process stock, process knowledge stock, and flows that represent radical and incremental innovation. The sole focus areas and the joint area of interest have flows and resources across these boundaries as shown in Fig. 5. Fig. C.1 – C.4 show the schematic details of the three regions. As a note, in
Fig. 5 and Fig. C.1-C.4, the supplier firm’s sole focus area is not shown because it has the same properties as the focal firm’s sole focus area.

![Diagram of Focal and Supplier Firms and Joint Area of Interest](image)

Fig. 4  Focal and Supplier Firms and Joint Area of Interest

The joint area of interest is not directly controlled by either firm, but each firm contributes resources to it in a collaborative effort to create knowledge. Through investments in joint area process innovation, the knowledge stock that is generated in the joint area of interest is available for transfer to the focal and supplier firms’ sole focus areas.
Fig. 5 Stock and Flow Diagram for Sole Focus Area and Joint Area of Interest
3.1 Focal Firm, Supplier Firm, and Joint Area Product Stocks (Fig. C.1 & C.2: Section A)

In general, the accumulation rate of knowledge in knowledge stocks is a function of the embedded knowledge within each radical and incremental product. The embedded knowledge generation differs between radical and incremental products, so these two product stocks are defined separately in the model. The incremental product and process stocks are segmented into four categories based on the time since the launch: less than one year (<1yr), one to five years (1-5yr), six to ten years (6-10yr), and more than ten years (>10yr) based on the study by Garcia et al., (2003). The radical product and process stocks are segmented into two categories based on the time since the launch: less than one year (<1yr) and one to five years (1-5yr). Any radical product or process that is older than 5 years is assumed to no longer be radical and thus becomes an incremental product or process. As the product ages, its ability to add to the knowledge stock is reduced. Furthermore, reductions in product stocks take place through market turbulence (MT) and through technological turbulence (TT). The products that are being replaced by their improved versions are also removed from the stocks. Thus at time t, the total number of radical products in the stock is equal to the number of radical products in the stock at time t-1, plus the difference between the number of new radical product launches and the number of products terminated due to MT, TT, and new version introductions.

For radical products launched <1yr, \( \text{Rad}_\text{Prod}_{it,<1yr} \) the following formula can be used to calculate the number of radical products left in the stock at time t. Thus,

\[
\text{Rad}_\text{Prod}_{it,<1yr} = \text{Rad}_\text{Prod}_{it-1,<1yr} + P_{\text{launch}}_{it} - \left( MT_{it,<1yr} - TT_{it,<1yr} - \text{Rad}_{it,<1yr} - P_{it,1-5yr} \right)
\]

where \( P_{\text{launch}}_{it} \) is the number of products launched based on radical innovation for
firm $i$,

$MT_{it,<1yr}$ is the number of products terminated due to market turbulence for firm $i$,

$TT_{it,<1yr}$ is the number of products terminated due to technological turbulence for firm $i$,

$Rad_{it,<1yr}$ is the number of products entering the incremental innovation cycle for firm $i$, and

$P_{it,1-5yr}$ is the number of products transferred from $Rad_{Prod_{it,<1yr}}$ stock to $Rad_{Prod_{it,1-5yr}}$ stock for firm $i$.

This equation can be used for the stocks in the sole focus area of the focal firm and supplier firm, as well as the stocks of the joint area. That is,

$i \in \{focal \ firm, \ joint \ area, \ supplier \ firm\}$.

The products entering the radical and incremental product stocks are launched from their respective innovation cycles. One year after its launch, if not terminated, a product in the $Rad_{Prod_{it,<1yr}}$ stock flows to the $Rad_{Prod_{it,1-5yr}}$ stock. After 5 years, any product that used to be classified as radical, goes into the incremental product stock and is classified as incremental. Thus,

$$Rad_{Prod_{it,1-5yr}} = Rad_{Prod_{it,1-5yr}} + P_{it,1-5yr} - P_{Inc_{it,6-10yr}} - MT_{it,1-5yr} - TT_{it,3-5yr} - Rad_{it,3-5yr}$$

where $P_{Inc_{it,6-10yr}}$ is the number of radical products transferred from $Rad_{Prod_{it,1-5yr}}$ stock to $Inc_{Prod_{it,6-10yr}}$ stock for firm $i$ and

$i \in \{focal \ firm, \ joint \ area, \ supplier \ firm\}$.
In order to observe changes that take place within a year of launch, the time increments should be a fraction of a year. Let \( \alpha \) be the fraction of a year that \( t \) is incremented by. Thus,

\[
t = \alpha (\text{yr})
\]

\[
\alpha \in (0,1)
\]

The dynamics of how incremental product stocks accumulate is the same as the radical stocks. Thus,

\[
\text{Inc}\_\text{Prod}_{it,c,1\text{yr}} = \text{Inc}\_\text{Prod}_{i,t-1,c,1\text{yr}} + P\_\text{launch}_i - MT_{it,c,1\text{yr}} - TT_{it,c,1\text{yr}} - \text{Inc}_{it,c,1\text{yr}} - P_{it,1-5\text{yr}}
\]

\[
\text{Inc}\_\text{Prod}_{it,1-5\text{yr}} = \text{Inc}\_\text{Prod}_{i,t-1,1-5\text{yr}} + P_{it,1-5\text{yr}} - MT_{it,1-5\text{yr}} - TT_{it,1-5\text{yr}} - \text{Inc}_{it,1-5\text{yr}} - P_{it,6-10\text{yr}}
\]

\[
\text{Inc}\_\text{Prod}_{it,6-10\text{yr}} = \text{Inc}\_\text{Prod}_{i,t-1,6-10\text{yr}} + P_{it,6-10\text{yr}} + P\_\text{Inc}_{it,6-10\text{yr}} - MT_{it,6-10\text{yr}} - TT_{it,6-10\text{yr}} - \text{Inc}_{it,6-10\text{yr}} - P_{it,>10\text{yr}}
\]

\[
\text{Inc}\_\text{Prod}_{it,>10\text{yr}} = \text{Inc}\_\text{Prod}_{i,t-1,>10\text{yr}} + P_{it,>10\text{yr}} - MT_{it,>10\text{yr}} - TT_{it,>10\text{yr}} - \text{Inc}_{it,>10\text{yr}}
\]

where \( P\_\text{Inc}_{it,6-10\text{yr}} \) is the number of radical products transferred from \( \text{Rad}\_\text{Prod}_{it,1-5\text{yr}} \) stock to \( \text{Inc}\_\text{Prod}_{it,6-10\text{yr}} \) stock for firm \( i \) and

\[
i \in \{\text{focal firm, joint area, supplier firm}\}
\]

3.1.1 Focal Firm, Supplier Firm, and Joint Area Product Knowledge Stocks (Fig. C.1 & C.2: Section B)

Knowledge stocks are a function of the number of products in the system, the age of the product \( k \), and the source of the innovation: radical or incremental. Let \( c\_\text{rad}_k \) be the embedded knowledge contained in each radical product for product age \( k \), and \( c\_\text{inc}_k \)
be the embedded knowledge contained in each incremental products for product age $k$.

The newer products have higher knowledge content due to less depreciation of the knowledge embedded in each product. Forgotten knowledge reduces the knowledge of the products by a percentage. Let $\text{forget}_{ik}$ be the percentage of knowledge forgotten for firm $i$ for product of age $k$. At time $t$, each firm’s product knowledge stock, $\text{KS}_{it}$, is equal to the accumulated knowledge from the products for all products at age $k$ less the outflow of knowledge due to forgetting. Thus,

$$\text{KS}_{it} = \text{KS}_{\text{Transfer}_{it}} + \sum_{k} \left( (c_{\text{rad}_k} \times \text{Rad}_{it} + c_{\text{inc}_k} \times \text{Inc}_{it}) \times (1 - \text{forget}_{ik}) \right)$$

where $\text{KS}_{\text{Transfer}_{it}}$ is the knowledge transferred from the joint area product knowledge stock for firm $i$,

$$i \in \{ \text{focal firm, supplier firm} \}, \text{ and}$$

$$k \in \{ <1\text{yr}, 1\text{--}5\text{yr}, 6\text{--}10\text{yr}, >10\text{yr} \}.$$

The knowledge stock in the joint area differs from that of the focal and supplier firms’ because it does not have an inflow of transferred knowledge from the joint area. Thus,

$$\text{KS}_{\text{joint},t} = \sum_{k} \left[ (c_{\text{rad}_k} \times \text{Rad}_{\text{joint},it} + c_{\text{inc}_k} \times \text{Inc}_{\text{joint},it}) \times (1 - \text{forget}_k) \right]$$

where $k \in \{ <1\text{yr}, 1\text{--}5\text{yr}, 6\text{--}10\text{yr}, >10\text{yr} \}$

3.1.2 Joint Area Process Stocks (Fig. C.3)

Process stocks are the results of the accumulation of processes developed through process innovation. The focal and supplier firms have two choices for increasing their
knowledge stocks. They can either invest resources in their sole focus area innovation or invest in the capability to transfer knowledge from the joint area product knowledge stock to the knowledge stocks of their sole focus area. For example, focal and supplier firms’ investments in collaborative process innovation can result in methods, protocols, software, etc. that facilitate the transfer of knowledge from the joint area of interest to each firm. Neither firm has sole discretion over these processes, but each can collaboratively invest in the innovation of radical and incremental processes. The processes have the same attributes of product stocks by being subject to MT, TT, forgetting, and depreciation of their knowledge contribution as the processes age.

Due to the collaborative effort of process innovation, process stocks are only contained within the joint area. The dynamics of how the process stocks accumulate are the same as the way product stocks accumulate. Thus,

\[ \text{Rad}_t \text{Process}_{t, <1yr} = \text{Rad}_t \text{Process}_{t-1, <1yr} + P_{\text{launch}} - \]
\[ MT_{t, <1yr} - TT_{t, <1yr} - \text{Rad}_t \text{Process}_{t, <1yr} - P_{t, 1-5yr} \]

\[ \text{Rad}_t \text{Process}_{t, 1-5yr} = \text{Rad}_t \text{Process}_{t-1, 1-5yr} + P_{t, 1-5yr} - P_{\text{Inc}}_{t, 6-10yr} - \]
\[ MT_{t, 1-5yr} - TT_{t, 1-5yr} - \text{Rad}_t \text{Process}_{t, 1-5yr} \]

where \( P_{\text{launch}} \) is the number of processes launched from radical innovation,
\( P_{\text{Inc}}_{t, 6-10yr} \) is the number of radical processes transferred from \( \text{Rad}_t \text{Process}_{t, 1-5yr} \) stock to the \( \text{Inc}_t \text{Process}_{t, 6-10yr} \) stock

\( MT_{tk} \) is the number of processes terminated for market turbulence,
\( TT_{tk} \) is the number of processes terminated for technological turbulence,
\( Rad_{tk} \) is the number of processes entering the incremental innovation cycle,
\( P_{tk} \) is the number of processes transferred to \( \text{Rad}_t \text{Process}_{t,k+1} \).
The dynamics of how incremental process stocks accumulate is the same as the radical process stocks. Thus,

\[ \text{Inc\_Process}_{t, <1yr} = \text{Inc\_Process}_{t-1, <1yr} + \text{P\_launch}_t - \]
\[ MT_{t, <1yr} - TT_{t, <1yr} - \text{Inc\_Process}_{t-1, <1yr} - P_{t, 1-5yr} \]

\[ \text{Inc\_Process}_{t, 1-5yr} = \text{Inc\_Process}_{t-1, 1-5yr} + P_{t, 1-5yr} - \]
\[ MT_{t, 1-5yr} - TT_{t, 1-5yr} - \text{Inc\_Process}_{t-1, 1-5yr} - P_{t, 6-10yr} \]

\[ \text{Inc\_Process}_{t, 6-10yr} = \text{Inc\_Process}_{t-1, 6-10yr} + P_{t, 6-10yr} + P_{t, 6-10yr} - \]
\[ MT_{t, 6-10yr} - TT_{t, 6-10yr} - \text{Inc\_Process}_{t-1, 6-10yr} - P_{t, >10yr} \]

\[ \text{Inc\_Process}_{t, >10yr} = \text{Inc\_Process}_{t-1, >10yr} + P_{t, >10yr} - \]
\[ MT_{t, >10yr} - TT_{t, >10yr} - \text{Inc\_Process}_{t-1, >10yr} \]

where \( P_{\text{Inc}_{t, 6-10yr}} \) is the number of radical processes transferred from \( \text{Rad\_Process}_{t, 1-5yr} \) stock to the \( \text{Inc\_Process}_{t, 6-10yr} \) stock.

3.1.3 Process Knowledge Stocks in the Joint Area (Fig. C.3 Section B)

Similar to product knowledge stocks, the process knowledge stock is a function of the number of processes. Let \( c_{\text{rad}}'_k \) be the embedded knowledge contained in each radical process for process age \( k \), and \( c_{\text{inc}}'_k \) be the embedded knowledge contained within each incremental process for process age \( k \). At time \( t \), the total process knowledge, \( KS\_Process_t \) is then,

\[ KS\_Process_t = \sum_k \left( c_{\text{rad}}'_k \text{ Rad\_Process}_{\theta_k} + c_{\text{inc}}'_k \text{ Inc\_Process}_{\theta_k} \right) \times (1 - \text{forget}_k) \]

where \( \text{forget}_k \) is the percent reduction of knowledge content at time \( t \), and

\( k \in \{<1yr, 1-5yr, 6-10yr, >10yr\} \)
3.2 Profits Generated from Products Developed in the Sole Focus Areas (Fig. C.4)

The focal firm’s and the supplier firm’s product stocks generate profits that are the source of slack resource availability which can be used for future investments. The profit, $\Pi_{it}$, is a function of the number of products in the radical and incremental stocks and the time since the product’s launch for firm $i$. Let $\pi_{rad_{ik}}$ be the profit each firm earns from their radical products and $\pi_{inc_{ik}}$ be the profits earned from their incremental products for firm $i$ for product age $k$. Thus, at time $t$,

$$\Pi_{it} = \sum \text{Rad Prod}_{ik} \times \pi_{rad_{ik}} + \sum \text{Inc Prod}_{ik} \times \pi_{inc_{ik}}$$

where $i \in \{\text{focal firm, supplier firm}\}$, and

$$k \in \{<1\text{yr}, 1-5\text{yr}, 6-10\text{yr}, >10\text{yr}\}.$$

3.2.1 Resource Investment in Sole Focus Product Innovation

Each firm sets a profit goal that indicates its breakeven point for its investments in product stocks. In our model we assume that the minimum investment cost is the profit goal. Let $G_i$ be the focal and supplier firms’ profit goal. At time $t$, the focal and supplier firms compare their profits generated, $\Pi_{it}$ against their profit goal, $G_i$. At time $t$, the profit gap, $Gap_{it}$ is equal to the difference between the profit generated and the profit goal. Thus,

$$Gap_{it} = \Pi_{it} - G_i$$

In the literature, slack resources are defined as the pool of resources that exceeds the minimum investment cost (Nohria & Gulati, 1996). Thus, for firm $i$ at time $t$, the amount of slack resources available, $SR_{it}$ for investment is,
\[ SR_i = \max \{ Gap_i, 0 \} \]

where \( i \in \{ \text{focal firm, supplier firm} \} \).

Note, that if the profit gap is negative for any period \( t \), then the firm does not have any slack resources to invest in that period.

The profit gap is an important feedback mechanism in measuring a firm’s innovation performance. A positive value for \( Gap_i \) indicates that the firm is exceeding its profit goal. This typically decreases the firm’s interest in taking additional risks. Thus, the firm directs more of its slack resources to investments in incremental innovation. On the other hand, a negative \( Gap_i \) indicates that the firm is not meeting its profit goals and forces the firm to invest in higher, but riskier returns, i.e. radical innovation. The size of the gap indicates the firm’s inclination towards developing more or less radical or incremental products. Let \( frac_i \) be the proportion of resources invested in incremental innovation for firm \( i \). Then, \( 1 - frac_i \) would indicate the proportion of resources invested in radical innovation for firm \( i \). Based on the study by Garcia et al (2003), at time \( t \), \( frac_i \) can be formulated as:

\[ frac_i = \frac{1}{1 + \exp(-g \cdot Gap_i)} \]

where \( g \) is a fractional growth rate as defined in Sterman (2000) and

\[ i \in \{ \text{focal firm, supplier firm} \} . \]

Note that when \( Gap_i = 0 \), the investment fraction is balanced indicating that an equal amount of resources are devoted to both radical and incremental innovation.

Each firm can allocate its resources for product innovation in the sole focus area with \( frac_i \). The resources that will be invested in radical and incremental innovation for
firm $i$ at time $t+1$ would be a combination of slack resources generated at time $t$, $SR_\text{it}$ plus a budgeted amount for firm $i$, $\text{budgeted}_\text{it}$. Thus,

$$IR_{\text{Inc}, i, t+1} = \frac{\text{frac}_\text{it}}{} \left( SR_\text{it} + \text{budgeted}_\text{it} \right)$$

$$IR_{\text{Rad}, i, t+1} = (1 - \frac{\text{frac}_\text{it}}{}) \left( SR_\text{it} + \text{budgeted}_\text{it} \right)$$

where $IR_{\text{Inc}, i, t+1}$ is the invested resources in incremental innovation for firm $i$ and $IR_{\text{Rad}, i, t+1}$ is the invested resources in radical innovation for firm $i$.

3.2.2 Focal and Supplier Firms’ Resource Investment in Joint Area Product Innovation

The focal and supplier firm also invest resources in the radical and incremental product innovation to increase the product knowledge stocks in the joint area. The investment from the focal and supplier firms is necessary because the joint area products do not generate their own slack resources. For this model, it is assumed that the focal and supplier firms do not have the capability to transfer these products back to the product stocks in their sole focus areas. To benefit from the joint area product stocks, the focal and supplier firm can transfer “knowledge” from the product knowledge stock in the joint area to the knowledge stocks in their sole focus area. To transfer the product knowledge stock, each firm can invest in radical and incremental process innovation in the joint area.

Each firm sets a goal which indicates the minimum desired level of knowledge stocks to be maintained in its sole focus areas. Let $G_\text{KS}_i$ be the knowledge stock goal for firm $i$. At time $t$, the focal and supplier firms compare their current knowledge stocks available, $KS_\text{it}$, against their knowledge stock goals, to determine the size of the gap. Thus,
The knowledge stock gap is another important feedback mechanism in measuring the accumulation of the firm’s knowledge stock. Similar to \( \text{Gap}_{it} \), a positive value for \( \text{Gap}_{KS_{it}} \) indicates that the firm is exceeding its knowledge stock goal. This typically decreases the firm’s interest in taking additional risks in its joint area product innovation investment. Thus, the firm directs more resources to incremental innovation. On the other hand, a negative value for \( \text{Gap}_{KS_{it}} \) indicates that the firm is not creating enough knowledge and this forces the firm to direct more resource investments to radical innovation that takes place in the joint area product stocks. Let \( \text{frac}_{KS_{it}} \) be the proportion of resources invested in incremental product innovation in the joint area for firm \( i \). Then, \( 1 - \text{frac}_{KS_{it}} \) would indicate the proportion of resources invested in radical innovation for firm \( i \). Thus, at time \( t \),

\[
\text{frac}_{KS_{it}} = \frac{1}{1 + \exp(-g_{KS} \times \text{Gap}_{KS_{it}})}
\]

where \( g_{KS} \) is a fractional growth rate and

\[ i \in \{ \text{focal firm}, \text{supplier firm} \}. \]

Note that when \( \text{Gap}_{KS_{it}} = 0 \), the investment fraction is balanced indicating an equal amount of resources can be devoted to radical and incremental innovation.

Each firm can allocate its resources for product innovation in the joint area with \( \text{frac}_{KS_{it}} \). The resources that will be invested in radical and incremental innovation in the joint area products, at time \( t+1 \), would be a combination of slack resources generated for firm \( i \) at time \( t \), \( \text{SR}_{it} \), and a budgeted amount, \( \text{budgeted}_{JointProd_{it}} \). Thus,
\[ \text{JointProd}_i^{IR\_Inc}_{t+1} = \text{frac}_i \cdot \text{KS}_{i_t} \cdot \text{SR}_{i_t} + \text{budgeted}_i \cdot \text{JointProd}_i \]

\[ \text{JointProd}_i^{IR\_Rad}_{t+1} = (1 - \text{frac}_i) \cdot \text{SR}_{i_t} + \text{budgeted}_i \cdot \text{JointProd}_i \]

where \( \text{JointProd}_i^{IR\_Inc}_{t+1} \) is the resources invested in incremental product innovation in the joint area for firm \( i \),

\( \text{JointProd}_i^{IR\_Rad}_{t+1} \) is the invested resources in radical product innovation in the joint area for firm \( i \), and

\( i \in \{\text{focal firm, supplier firm}\} \).

3.2.3 Focal and Supplier Firm’s Resource Investment in Joint Area Product Innovation

In addition to measuring \( \text{Gap}_K_i \), each firm also monitors the performance of the process knowledge stocks against a goal. Let the focal and supplier firms’ process knowledge stock goal be \( \text{G}_K_i \). At time \( t \), a firm compares the process knowledge stock to its goal. The process knowledge stock performance gap, \( \text{Gap}_K_i \), is equal to the difference between the joint process knowledge stock and the goal. Thus,

\[ \text{Gap}_K_i = \text{KS}_i - \text{G}_K_i \]

where \( \text{KS}_i \) is the process knowledge stock available, and

\( i \in \{\text{focal firm, supplier firm}\} \).

This process knowledge stock gap is another important feedback mechanism. Similar to \( \text{Gap}_it \) and \( \text{Gap}_KS_i \), a positive gap for \( \text{Gap}_KS_i \) indicates that the process knowledge stock is exceeding its goal. This typically decreases a firm’s willingness to take additional risk in its investments in processes, directing more
resources to incremental innovation. On the other hand, a negative value for $\text{Gap}_{KS\_Process_{it}}$ indicates that the performance of the process knowledge stocks is underperforming, requiring the firm to direct a larger proportion of resources to radical process innovation. Let $\text{frac}_{KS\_Process_{it}}$ be the proportion of resources invested in incremental innovation. Then, let $1-\text{frac}_{KS\_Process_{it}}$ be the proportion of resources invested in radical innovation. Thus, for firm $i$ at time $t$,

$$\frac{\text{frac}_{KS\_Process_{it}}}{1 + \exp(-g_{KS\_Process} \times \text{Gap}_{KS\_Process_{it}})}$$

where $g_{KS\_Process}$ is a fractional growth rate, and

$$i \in \{\text{focal firm, supplier firm}\}.$$

Note that when $\text{Gap}_{KS\_Process_{it}}=0$, the investment fraction is balanced between radical and incremental innovation.

Each firm can allocate its resources for process innovation in the joint area with $\text{frac}_{KS\_Process_{it}}$. The resources that will be invested in radical and incremental process innovation would be a combination of the slack resources generated at time $t$, $\text{SR}_{it}$ plus the budgeted amount, $\text{budgeted\_Process}_{it}$. Thus, at time $t+1$,

$$\text{JointProcess\_IR\_Inc}_{i,t+1} = \text{frac}_{KS\_Process_{it}} \times (\text{SR}_{it} + \text{budgeted\_Process}_{it})$$

$$\text{JointProcess\_IR\_Rad}_{i,t+1} = (1 - \text{frac}_{KS\_Process_{it}}) \times (\text{SR}_{it} + \text{budgeted\_Process}_{it})$$

where $\text{JointProcess\_IR\_Inc}_{i,t+1}$ is the invested resources in incremental process innovation in the joint area for firm $i$,

$\text{JointProcess\_IR\_Rad}_{i,t+1}$ is the invested resources in radical process innovation in the joint area for firm $i$, and
In our model we assume the amount of accumulated knowledge stock of these processes determines the capability of the knowledge transfer. Two factors contribute to a firm’s capability of knowledge transfer: the proportion of the process knowledge stock goal being achieved and the difficulty of assimilating that knowledge. Let $KT_{i,t+1}$ be the knowledge transfer capability for firm $i$ at time $t+1$ and let $\Theta$ indicate the level of knowledge assimilation (Lee et al., 2003). Knowledge stocks that are more difficult to transfer have a lower $\Theta$, reducing the efficiency of the knowledge transfer. Thus,

$$KT_{i,t+1} = \frac{1}{1 + \exp \left( -g_{KT} \cdot \frac{KS_{Process_i}}{G_{KS_{Process_i}}} \right)} \cdot \Theta$$

where $KS_{Process_i}$ is the process knowledge stock available at time $t$,

$$G_{KS_{Process_i}}$$

is the process knowledge stock goal for firm $i$, and

$g_{KT}$ is the fractional growth rate.

The amount of knowledge transferred from the product knowledge stock is a function of both the level of knowledge available in the product stock of the joint area, $KS_{joint,t}$, and the knowledge transfer capability. The amount of knowledge that is transferred for firm $i$ at time $t+1$, $KS_{Transfer_{i,t+1}}$ is:

$$KS_{Transfer_{i,t+1}} = KT_{i,t+1} \cdot KS_{joint,t}$$

where $i \in \{focal \ firm, supplier \ firm\}$.
3.3 Incremental and Radical Product and Process Innovation Cycles

3.3.1 Focal Firm, Supplier Firm, and Joint Area Incremental Product Innovation Cycle (Fig. C.1 & C.2: Section C)

The first phase of incremental innovation is the removal of products from the current radical and incremental product stocks. The removed products are marked as available stock for incremental innovation, $\text{Inc Prod Available}_{i,t+1}$. Thus, at time $t+1$,

$$\text{Inc Prod Available}_{i,t+1} = \sum_k \text{Inc}_{ik} + \sum_k \text{Rad}_{ik}$$

where $\text{Inc}_{ik}$ is the number of products removed from the incremental product stocks for firm $i$ for products at age $k$,

$\text{Rad}_{ik}$ is the number of products removed from the radical product stocks for firm $i$ for products at age $k$,

$i \in \{\text{focal firm, joint area, supplier firm}\}$, and

$k \in \{<1\text{yr}, 1-5\text{yr}, 6-10\text{yr}, >10\text{yr}\}$.

For a product entering the incremental innovation cycle, the possibility of it being selected for further development depends on the amount of invested resources for incremental innovation and the level of the knowledge stock available. Let $\phi_{\text{inc}}$ be the resource requirement for an incremental product to be chosen and let $\kappa_{\text{inc}}$ be the knowledge requirement for that product. The maximum number of products funded, $\text{Inc Prod Funded}_{i,t}$, for firm $i$ will be determined either by the product’s resource usage or by the product’s knowledge requirement. Thus, at time $t$,

$$\text{Inc Prod Funded}_{i,t} = \min \left\{ \frac{\text{Inc}_{i,t}}{\phi_{\text{inc}}}, \frac{\text{KS}_{i,t}}{\kappa_{\text{inc}}} \right\}$$
where $IR_{Inc_{it}}$ is the invested resources firm $i$,

$KS_{it}$ is the knowledge stock available firm $i$,

$i \in \{ \text{focal firm, supplier firm} \}$.

The incremental product funding for the joint area differs from the focal and supplier firms because the invested resources are not generated within the joint area. The invested resources are the combination of the focal firm’s plus the supplier firm’s invested resources. Thus,

$$
Inc_{Prod\_Funded\_joint,t} = \min\left\{ \frac{JointProd\_IR\_Inc_{focal,t} + JointProd\_IR\_Inc_{supplier,t}}{\varphi_{inc}}, \frac{KS_{joint,t}}{\kappa_{inc}} \right\}
$$

where $Inc_{Prod\_Funded\_joint,t}$ is the number of incremental products available for funding,

$JointProd\_IR\_Inc_{focal,t}$ is the amount of invested resources from the focal firm,

$JointProd\_IR\_Inc_{supplier,t}$ is the amount of invested resources from the supplier firm, and

$KS_{joint,t}$ is the knowledge stock available in the joint area.

Given the pool of products available for incremental innovation, $Inc_{Prod\_Available_{it}}$, and the funding being allocated, the number of incremental products to be developed, $Inc_{Prod\_Development_{it}}$, can be determined. When the number of incremental products available, $Inc_{Prod\_Available_{it}}$, exceeds the number of products funded, $Inc_{Prod\_Funded_{it}}$, then the unfunded products flow to the dormant product stock. Thus, at time $t$,

When $Inc_{Prod\_Available_{it}} \geq Inc_{Prod\_Funded_{it}}$
\[ \text{Inc\_Prod\_Development}_{it} = \text{Inc\_Prod\_Funded}_{it} \]

where \( i \in \{\text{focal firm, joint area, supplier firm}\} \).

On the other hand, if the number of products funded for incremental innovation is greater than the number of products available, the excess resources can be used to recover dormant products, \( \text{Recovered\_Prod}_{it} \). Thus, at time \( t \),

\[ \text{Inc\_Prod\_Development}_{it} = \text{Inc\_Prod\_Available}_{it} + \text{Recovered\_Prod}_{it} \]

Once a product has begun development, it has a success rate of \( s_{inc} \) when launched into the market and an \( 1-s_{inc} \) rate of failure for becoming a dormant product. Dormant products can re-enter the incremental innovation cycle at a later time. Successful products are subject to the time delay, \( \delta_{inc} \) before their launch, for the time required to incrementally innovate the product. Let, \( \delta_{inc} \) be the incremental time delay. Thus,

\[ P_{\text{launch},t+\delta_{inc}} = \text{Inc\_Prod\_Development}_{it} \times s_{inc} \]

where \( P_{\text{launch},t+\delta_{inc}} \) is the number of incremental products launched for firm \( i \) at time \( t + \delta_{inc} \) and

\[ i \in \{\text{focal firm, joint area, supplier firm}\} \]

3.3.2 Focal Firm, Supplier Firm, and Joint Area Radical Product Innovation Cycle
(Fig. C.1 & C.2: Section D)

Radical product innovation differs from the incremental product innovation in that it is based on existing products. The number of radical products started in the innovation cycle is limited by either the amount of invested resources for radical innovation or by
the level of the knowledge stock available. Let $\varphi_{rad}$ be the resource requirement for a radical product and let $\kappa_{rad}$ be the knowledge requirement for that product. Thus, at time $t$,

$$Rad_{Prod\_Development} = \min \left\{ \frac{IR_{Rad,i}}{\varphi_{rad}}, \frac{KS_{i}}{\kappa_{rad}} \right\}$$

where $Rad_{Prod\_Development}$ is the number of radical products being developed for firm $i$, $IR_{Rad,i}$ is the amount of invested resources for firm $i$, $KS_{i}$ is the product knowledge stock available for firm $i$, and $i \in \{ \text{focal firm, supplier firm} \}$

The radical products of the joint area entering into the innovation cycle differs from the focal and supplier firms because the invested resources are not generated within the joint area. The invested resources are the combination of the focal firm’s $JointProd\_IR_{Rad\_focal,t}$ plus the supplier firm’s $JointProd\_IR_{Rad\_supplier,t}$. Thus, at time $t$,

$$Rad_{Prod\_Development} = \min \left\{ \frac{JointProd\_IR_{Rad\_focal,t} + JointProd\_IR_{Rad\_supplier,t}}{\varphi_{rad}} \right\}$$

where $Rad_{Prod\_Development}$ is the number of products available for radical development and $KS_{joint,t}$ is the joint area product knowledge stock available.

The commercialization aspect of the radical product innovation is similar to that of incremental product innovation. After the development is completed, a product has a success rate, $s_{rad}$ when launched into the market, again indicating that a product has an
1 - s_rad rate of failure for becoming a dormant product. Successful products are subject to the time delay, δ_rad before the launch for the time required to radically innovate the product. Let δ_rad be the radical time delay. Thus, at time t,

\[ P_{\text{launch}_{i,t+\delta_{rad}}} = \text{Rad}_i \cdot \text{Prod}_i \cdot s_{rad} \]

where \( P_{\text{launch}_{i,t+\delta_{rad}}} \) is the number of incremental products launched for firm \( i \) at time \( t + \delta_{rad} \),

\( \text{Rad}_i \cdot \text{Prod}_i \) is the number of products available for radical development for firm \( i \), and

\( i \in \{ \text{focal firm, joint area, supplier firm} \} \).

3.3.3 Dormant Products (Fig. C.1 & C.2: Section C)

Dormant products contain embedded knowledge which may be used at a later time. The products can be reintroduced to the incremental innovation cycle in the event that there is excess resource availability. The total number of dormant products is the sum of all unsuccessful product developments coming from the radical and incremental innovation cycle. The dormant product stock is reduced through reintroduced incremental innovation products and aged products.

3.3.4 Incremental Process Innovation Cycle in the Joint Area (Fig. C.3: Section C)

The first phase of incremental process innovation is the removal of processes from the current radical and incremental process stocks. The removed processes are marked as available stock for incremental innovation, \( \text{Inc}_i \cdot \text{Process}_i \). Thus, at time \( t+1 \),
\[ Inc\_Process\_Available_{t+1} = \sum_{k} Inc_{kt} + \sum_{k} Rad_{kt} \]

where \( Inc_{kt} \) is the number of processes removed from the incremental process stocks at age \( k \) at time \( t \),

\( Rad_{kt} \) is the number of processes removed from the radical process stocks at age \( k \) at time \( t \), and

\[ k \in \{<1\,yr, 1-5\,yr, 6-10\,yr, >10\,yr\} . \]

For a process entering the incremental innovation cycle, the possibility of it being selected for further development depends on the amount of invested resources for incremental innovation and the level of the process knowledge stock available. Let \( \phi_{inc} \) be the resource requirement for an incremental process to be chosen and let \( \kappa_{inc} \) be the knowledge requirement for that process. Given the limited resources, the maximum number of processes funded, \( Inc\_Process\_Funded \), will be determined either by the process’ resource usage or by the process’ resource requirement. Thus,

\[ Inc\_Process\_Funded = \min \left\{ \frac{JointProcess\_IR_{Inc, focal, t} + JointProcess\_IR_{Inc, supplier, t}}{Process\_KS_t}, \frac{\phi_{inc}}{\kappa_{inc}} \right\} \]

where \( JointProcess\_IR_{Inc, focal, t} \) is the amount of invested resources from the focal firm,

\( JointProcess\_IR_{Inc, supplier, t} \) is the amount of invested resources from the supplier firm,

\( Process\_KS_t \) is the process knowledge stock available,

Given the pool of processes available for incremental innovation and the funding being allocated, the number of processes to be developed can be determined. When the
number of incremental processes available exceeds the number of processes funded, then
the unfunded processes flow to the dormant process stock. Thus, at time \( t \),
when \( \text{Inc Processes Available}_{t} \geq \text{Inc Processes Funded}_{t} \)

\[
\text{Inc Process Development}_{t} = \text{Inc Process Funded}_{t}
\]

On the other hand, if the number of processes funded for incremental innovation
is greater than the number of processes available, the excess resources can be used to
recover dormant processes, \( \text{Recovered Processes}_{t} \). Thus, at time \( t \),
When \( \text{Inc Processes Available}_{t} + \text{Recovered Processes}_{t} \geq \text{Inc Processes Funded}_{t} \)

\[
\text{Inc Process Development}_{t} = \text{Inc Process Available}_{t} + \text{Recovered Process}_{t}
\]

A process has a success rate of \( s_{inc}' \) when launched into the market and an
\( 1-s_{inc}' \) rate of failure for becoming a dormant process. Successful processes are subject
to time delay, \( \delta_{inc} \) before the launch for the time required to incrementally innovate the
process. Let \( \delta_{inc} \) be the incremental time delay. Thus,

\[
P_{\text{launched}_{t+\delta_{inc}}} = \text{Inc Process Development}_{t} \times s_{inc}'
\]

where \( P_{\text{launch}_{t+\delta_{inc}}} \) is the number of incremental processes launched at time
\( t+\delta_{inc} \).

3.3.5 Joint Area Radical Process Innovation Cycle (Fig. C.3: Section D)

The resources investment in radical process innovation is similar to the resources
investment in radical product innovation in the joint area. The invested resources are a
combination of the focal firm’s \( \text{JointProcess IR Rad}_{\text{focal,}t} \) and supplier firm’s
JointProcess IR Rad\textsubscript{supplier, t}. Let $\phi_{\text{rad}}'$ be the resource requirement for a radical process and let $\kappa_{\text{rad}}'$ be the knowledge requirement for that process. Thus, at time $t$,

$$
\text{Rad\textsubscript{Process\_Development}}_t = \min\left\{ \frac{\text{Joint\_Process\_IR\_Rad\textsubscript{fixed}, t} + \text{Joint\_Process\_IR\_Rad\textsubscript{supplier}, t}}{\text{KS\_Process, } \kappa_{\text{inc}'}} \right\}
$$

where $\text{Rad\textsubscript{Process\_Development}}_t$ is the number of radical processes funded,

The commercialization aspect of the radical process innovation is similar to that of the incremental process innovation. After the development is completed, a process has a success rate of $s_{\text{rad}}'$ when launched into the market, indicating that a process has an $1 - s_{\text{rad}}'$ rate of failure for becoming a dormant process. Successful processes are subject to the time delay, $\delta_{\text{rad}}$ before the launch for the time required to incrementally innovate the process. Let $\delta_{\text{rad}}$ be the radical time delay. Thus,

$$
P_{\text{launch}_{t+\delta_{\text{rad}}}} = \text{Rad\textsubscript{Process\_Development}}_t * s_{\text{rad}}'
$$

where $P_{\text{launch}_{t+\delta_{\text{rad}}}}$ is the number of radical processes launched at time $t + \delta_{\text{rad}}$.

3.3.6 Dormant Processes (Fig. C.3: Section C)

Similar to dormant products, dormant processes contain embedded knowledge which may be used at a later time. The processes can be reintroduced into the incremental innovation cycle in the event that there is excess resource capability. The total number of dormant processes is the sum of all unsuccessful process developments coming from the radical and incremental innovation cycle. The dormant process stock is reduced from reintroduced incremental innovation processes and aged processes.
4.1 Propositions for Resource Investment in Radical and Incremental Innovation

The intent of the model is to study the interactions of the focal and supplier firms’ investment decisions for radical and incremental innovation. The following propositions are designed to test how the focal and supplier firms respond to changes in endogenous and exogenous variables, stocks, and goals.

4.1.1 Radical and Incremental Innovation that Takes Place in the Sole Focus Area

Each firm generates a profit from the products that are within its sole focus area product stocks. In order to generate profits, the firms need to invest resources in the radical and incremental innovation cycle. The number of funded products is dependent on both the amount of invested resources and the level of sole focus area knowledge stocks. Firms can use their sole focus area knowledge stocks and they can also transfer knowledge from the joint area knowledge stock. As the focal and supplier firms produce
more knowledge stocks within their sole focus areas, their need for knowledge creation in the joint area will be reduced.

**Proposition 1:** As the focal firm’s sole focus area knowledge stock increases, the proportion of resources invested in incremental product innovation in the joint area increases.

Also, as the product knowledge stocks of the joint area are increasing, the focal and supplier firms’ need to invest resources in radical product innovation in their sole focus areas to maintain their product knowledge stocks is reduced.

**Proposition 2:** When the product knowledge stock of the joint area increases, the focal and supplier firm will invest a higher proportion of resources in incremental product innovation in their sole focus areas.

By having the capability to transfer knowledge through higher levels of process knowledge stock, each firm should require fewer investments in riskier, radical innovation to maintain the knowledge stocks in its sole focus area.

**Proposition 3:** As the process knowledge stocks of the joint area increase, the focal and supplier firms will invest a higher proportion of their resources in incremental product innovation in their sole focus areas.

4.1.2 Exogenous and Endogenous Factors

The sole focus area and joint area product and process stocks are reduced through the exogenous effects of both MT and TT. As these turbulences remove products from the stocks, the focal and supplier firms should invest more resources in radical innovation to replenish these stocks through the innovation cycle (Garcia et al., 2003; Hanvanich et
al., 2006; Hult et al., 2007; March, 1991). In the model, MT and TT have the same effect and are combined in the following propositions.

**Proposition 4a:** When product stocks in the sole focus area are reduced by MT and TT, the focal and supplier firms will invest a higher proportion of resources in radical product innovation in their sole focus areas.

**Proposition 4b:** When product stocks in the joint area are reduced by MT and TT, the focal and supplier firms will invest a higher proportion of resources in radical product innovation in the joint area.

**Proposition 4c:** When process stocks in the joint area are reduced by MT and TT, the focal and supplier firms will invest a higher proportion of resources in radical product innovation in their sole focus areas.

The product and process knowledge stocks are reduced through the endogenous variable forgetting. As forgetting removes knowledge from the stocks, the focal and supplier firms should invest a higher proportion of resources in radical product and process innovation to increase the product and process stocks and therefore increase the knowledge stocks (Garcia et al., 2003).

**Proposition 5a:** As the rate at which the product knowledge stock of the sole focus area becomes obsolete increases, the focal and supplier firms will invest a higher proportion of resources in radical product innovation in their sole focus areas.
Proposition 5b: As the rate at which the product knowledge stock of the joint area becomes obsolete increases, the focal and supplier firms will invest a higher proportion of resources in radical product innovation in the joint area.

Proposition 5c: As the rate at which the process knowledge stock of the joint area becomes obsolete increases, the focal and supplier firms will invest a higher proportion of resources in radical process innovation in the joint area.

Two additional endogenous variables are the resources and knowledge stock required per product. As these variables become larger, the number of funded products decrease. To generate profits and knowledge stock with fewer products, the focal and supplier firms should invest a higher proportion of their resources in radical innovation (Garcia et al., 2003).

Proposition 6a: As the resource requirement per product increases, the focal and supplier firms will invest a higher proportion of resources in radical product innovation in their sole focus areas.

Proposition 6b: As the knowledge stock investment per product increases, the focal and supplier firms will invest a higher proportion of resources in radical product innovation in their sole focus areas.

4.1.3 Effects of Performance Goals

Three of the feedback loops in the model are related to the performance of: profits, product knowledge stocks in the sole focus area, and process knowledge stocks in the joint area. The goals for the focal and supplier firms can either be balanced or one can be larger. If the focal firm has a larger profit goal, relative to the supplier firm, it
should invest a higher proportion of its resources in radical product innovation within its sole focus area to generate higher profits (He & Wong, 2004; March, 1991).

**Proposition 7:** A focal firm’s larger profit goal, relative to the supplier, results in a higher proportion of invested resources in radical product innovation in its sole focus area.

Similarly, if the focal firm’s knowledge stock goal is larger than the supplier firm’s goal, it should invest a higher proportion of its resources in radical product innovation in the joint area to increase its sole focus area knowledge stocks through knowledge transfer.

**Proposition 8:** A larger knowledge stock goal of the focal firm, relative to the supplier, results in a higher proportion of invested resources in radical product innovation in the joint area.

Like the knowledge stock goal, if the focal firm has a larger process knowledge stock goal, relative to the supplier firm’s goal, it should invest a higher proportion of its resources in radical process innovation to increase that knowledge stock.

**Proposition 9:** A larger process knowledge stock goal of the focal firm, relative to the supplier, results in a higher proportion of invested resources in radical process innovation in the joint area.

4.1.4 Investments in Process Innovation for Knowledge Transfer

To benefit from the product knowledge stocks in the joint area, the focal and supplier firms require the capability to transfer this knowledge to their sole focus areas. A decrease in the process knowledge stocks can reduce the ability of the focal and
supplier firm to transfer knowledge, requiring each firm to invest a higher proportion of their resources in radical innovation.

**Proposition 10:** As a firm’s knowledge transfer capability decreases, the focal and supplier firm will invest a higher proportion of resources in radical product innovation in their sole focus areas.

The level of knowledge assimilation affects the transfer of knowledge from the joint area to the sole focus areas. As the knowledge assimilation difficulty increases, each firm should invest a larger proportion of their resources in radical product innovation in its sole focus area to increase their knowledge stocks. To overcome the lack of knowledge transferred, the firms can increase their internal knowledge creation through radical innovation.

**Proposition 11:** As the level of knowledge assimilation decreases, the focal and supplier firms will invest a higher proportion of slack resources in radical product innovation in their sole focus areas.

### 4.2 Establishing a Computational Structure

Only a limited study of this model is suggested by Garcia et al. (2003). It has been assumed that the variables that were tested were linear and independent with respect to the outputs of the model, although this assumption needs to be tested. To determine the linearity of the variables, a central composite design (CCD), $3^k$ design is recommended (Kleijnen, Sanchez, Lucas, & Cioppa, 2005; Montgomery, 1997).

The independent variables proposed for the factorial analysis are the endogenous and exogenous factors: MT/TT; forgetting rate, $\text{forget}_k$; resource investment per product,
knowledge stock investment per product, $\kappa$; and the level of knowledge assimilation, $\Theta$. These variables were selected because they represent the key inputs in the model.

The dependent variable for the initial estimation analysis should be the focal firm’s profit value for all of the CCD and factorial analysis. The final performance goal of each firm is to increase its profits from being part of the supply chain relationship.

4.2.1 Central Composite Design and $3^k$ Factorial

The CCD design has a balanced number of values above and below a middle point. The $3^k$ design has three values, so the combination of the two methods has a midpoint, labeled 0, a low point, labeled -1, and a high point, labeled 1. Having three points per variable allows for the assumption of a linear or quadratic effect to be tested.

In addition to the quadratic effect, some of the variables chosen may have interactions with each other in the model. By using a full factorial design, all effects can be tested. To test for all interactions with five independent variables in a full factorial, $3^k$ design yields 243 runs for each replication. By not testing for an interaction, the number of runs can be reduced, but the understanding that the variables do not have any interactions before hand (Montgomery, 1997). While this number seems large, the benefit of a computer simulation is that each run does not require a great deal of effort or expense. To test for any potential issues with the problem, the factorial methodology should be used.

4.2.1.1 Replications for CCD and Monte Carlo Simulation

With the proposed model, all replications would yield the same results without the introduction of randomness to the variables. The randomness can be added to the five
independent variables previously discussed. But, doing that complicates the testing of the quadratic effect of each of these variables by adding within variance to the ANOVA tests (Kleijnen et al., 2005). To reduce variance, the alternative is to utilize another variable in the model: the success rate for product launches.

The number of replications to be used is dependent upon the degrees of freedom of the error term in the statistical analysis. The full-factorial model is fully specified and has zero degrees of freedom with one replication. The degrees of freedom of the model is \( n-1 \), where \( n \) is the number of replications. This value should be a minimum of 12 replications, but it may be higher depending upon the variation of the model. The exact number of replications will be determined during the model validation.

To produce replications, a Monte Carlo simulation can be used to vary the success rate along a normal distribution. A method to reduce the variation from a random number is to employ a common random number (CRN) (Law, 2007). Each replication of the simulation has a random number seed that remains constant. For example, the success rate is set and will remain the same throughout the replication, but then changes at the beginning of the next replication.

4.2.1.2 Steady-State Data Collection During Simulations

During the running of the simulation, the data values should have a higher variation at the beginning while the system is reaching a steady state. Law (2007) provide two techniques for analyzing a small, initial set of data and utilizing a moving average to determine when the steady state has been reached. The time to reach steady state can be used to remove the transient data points from the remaining runs. The
second method is to plot the output simulations and visually determine if the dependent variable has reached a steady-state condition.

4.2.2 Propositions Tested with CCD

During the testing of the CCD, Propositions 4, 5, 6, and 11 can be verified. Each of these propositions is measured on the proportion of invested resources for sole focus area product innovation. These propositions will be tested using an ANOVA analysis with the runs from the -1 and 1 values for each of the five variables.

If an independent variable has a quadratic effect, there is the possibility that the -1 and 1 values will yield a non-significant conclusion. If an effect is found to be quadratic, the proposition can be tested using OLS with a squared value, $\beta_i X_i^2$.

4.2.3 Testing Propositions 1, 2, 3, and 10

After completing the CCD testing and establishing the effects of the independent variables, the testing of the model can be completed. Depending on the results of the CCD test, each of the five independent variables will be set to their center point values. These variables are then constants for the remainder of the proposition testing. All initial conditions with regards to the focal and supplier firms’ and the joint area of interest will be the same for the CCD and testing of these propositions.

Propositions 1, 2, and 3 are investigating the effects of changes in the differing knowledge stocks and the impacts on the proportion of investments in radical innovation. Proposition 10 is similar to testing for Propositions 1, 2, and 3 except the knowledge transfer capability is used in place of the knowledge stocks. To test these propositions,
the same Monte Carlo simulation from the CCD test will be used for each of the runs. To test the propositions, linear regression analysis will be used to test the slope of the line.

4.2.4 Scenario Testing of the Model for Propositions 7, 8, and 9

After completing the CCD testing and establishing the effects of the independent variables, the testing of the model can be completed. Propositions 7, 8, and 9 are based on initial conditions of the model. Each of these propositions has the relative value of a goal: larger for the focal firm relative to the supplier. To test these propositions, two sets of runs need to be completed. The first set of runs will set the goals of the focal and supplier firms equal to one another to establish a baseline with the success rate varied through a Monte Carlo simulation. The relative value for the goals will be offset and using the same success rate variations, the same number of runs will be completed.

Using the same steady state conditions from the CCD replications, the dependent variable, the proportion of radical innovation, will be collected. To test the propositions, an ANOVA test will be used.

4.3 CCD and Factorial Analysis

We tested our model with 5 key variables that impact the firms, the joint area, and how each firm responds to the changes brought about by the interaction of the variables. The independent variables used for the CCD and factorial analysis are the endogenous and exogenous factors: turbulence rate, $MTi$; forgetting rate, $forgetk$; resource investment per product, $\varphi$; knowledge stock investment per product, $\kappa$; and the knowledge assimilation level, $\Theta$. Each of these variables has three different levels in which it is run:
a low value coded -1, a mid value, coded 0, and a high value, coded 1. See Table II for the values used for the CCD analysis and Appendix D for the replications used.

Table II  CCD and $3^k$ Factorial Values

<table>
<thead>
<tr>
<th>Variable</th>
<th>Low Value (Coded -1)</th>
<th>Mid Value (Coded 0)</th>
<th>High Value (Coded 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulence Rate, $MT_i$</td>
<td>0.01</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>Forgetting Rate, $forget_k$</td>
<td>0.02</td>
<td>0.11</td>
<td>0.20</td>
</tr>
<tr>
<td>Theta, $\theta$</td>
<td>0.10</td>
<td>0.55</td>
<td>1</td>
</tr>
<tr>
<td>Knowledge per Incremental Product, $\kappa_{inc}$</td>
<td>30</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Resources per Incremental Product, $\varphi_{inc}$</td>
<td>30</td>
<td>40</td>
<td>50</td>
</tr>
</tbody>
</table>

These values are tested in a variety of combinations from the points on the CCD cube face and axial points. We conducted 13 runs using a series of incremental product success rates that start at 0.40 and increase by 0.025 each run, with the final run having a success rate of 0.7.

Each run consists of 54 iterations with the order and pairing of the values created using Minitab’s built-in Design of Experiments (DOE) response surface function. As a note, Minitab’s CCD generator creates a series of replication points that repeat the center points, or all 5 variables repeated at their 0 coded values. This feature is designed to test systems or models that have variation across runs with the same settings. Our model does not have random variation between runs or iterations, however these points were not removed from the CCD analysis because the cost of running the additional iterations is essentially zero and the analysis is not affected by keeping them.
4.3.1 Steady-State Condition

All of the iterations for the CCD runs were plotted in Excel to visually determine the steady state condition of the focal firm’s profit value. The typical iteration reached a steady-state condition by period 60 with the latest steady-state condition being reached by period 70.

4.3.2 Response Surface Plots

Each of the pairs of variables used in the CCD analysis were used to generate a response surface plot that shows how the two variables vary the focal firm’s profits for all three values of each variable, showing the interactions of the variables. As a note, the supplier firm is modeled the same as the focal firm and thus yields the same results. The following figures illustrate graphically the interactions of the variables on the focal firm’s profit value across the 13 runs. Only two variables are changed for each graph with the other variables are being held at their 0 coded value.

The focal firm’s profits are averaged across the last 20 time periods because there are small oscillations in the profits as the focal firm reacts to its goals. We also standardized the profit on a scale from 0 to 100 to make comparison across all of the graphs more consistent due to large variations in profits across the values of the variables used.

Some of the variable pairs show little interaction and have expected affects on the focal firm’s profits and show relatively flat graphs, as in fig. 6, 7, & 9. On the other hand, many of the variables show interactions for the three levels of the variables in our CCD analysis, as in fig. 8, & 10 - 15. These graphs will be described in more detail below.
Fig. 6  Surface Plot of Focal Firm’s Profit Value for Knowledge per Incremental Product and Forget Rate

Fig. 7  Surface Plot of Focal Firm’s Profit Value for Turbulence Rate and Forget Rate
As shown in fig. 8, low rates of theta, or a low level of knowledge assimilation, and high rates of turbulence cause very low profits for the focal firm. However, as theta increases, the focal firm is able to generate higher profits, showing that theta decreases the effect of higher rates of turbulence. A similar decrease in the effect at lower turbulence rates is also evident, indicating that the ability to transfer knowledge from the joint area increases the focal firm’s profits for all turbulence rates by allowing the focal firm to develop enough innovations to replenish a portion of the product stocks.

Fig. 8  Surface Plot of Focal Firm’s Profit Value for Turbulence and Theta
Similarly, fig. 10 shows that the effect of theta increasing the amount of knowledge the focal firm transfers from the joint area, reduces the effect of forgetting, which increases the focal firm’s profits. Across the three forgetting rates, the amount of knowledge transferred reduces the effects of forgetting on the focal firm’s profits.
As shown in fig. 11, the resources per incremental product has a convex impact on the focal firm’s profits. While not a large effect, the value of 40 resources per incremental product actually has a lower profit level than the value of 30 or 50. This result is partially due to the difference the focal firm’s investments in incremental and radical innovation. Under higher levels of resources per incremental innovation, the focal firm may not be able to develop the same number of products causing it to invest more resources in radical innovation.
Fig. 11 Surface Plot of Focal Firm’s Profit Value for Knowledge per Incremental Product and Resources per Incremental Product

Similar to theta’s ability to mitigate the effects of turbulence and forgetting, it also has the effect of increasing the focal firm’s profits, (see fig. 12). As theta increases the amount of knowledge that is transferred from the joint area, the focal firm is able to offset some of the effect of needing more knowledge to develop an incremental product.
Again, as illustrated in fig. 13, theta is able to decrease the effect of needing more resources to develop an incremental product. This increase in profits is partially due to the focal firm having adequate levels of knowledge stock to maintain its number of innovation developments. The increase in impact of the higher resources required for each incremental innovation is lessen because the unused resources can be used to recover dormant products.
Similar to the effect shown in fig. 11, the resource per incremental products have a similar convex interaction with turbulence, (see fig. 14). Again, the mid-point value has the lowest level of profits for all turbulence rates, which is partially caused by the focal firm’s radical innovation investments.
Fig. 14  Surface Plot of Focal Firm’s Profit Value for Turbulence and Resources per Incremental Product

Fig. 15 illustrates the dual effect of increasing turbulence and higher knowledge per incremental product innovation resulting in very low profits when both are at their high values. The focal firm is able to develop few innovations under both of these conditions.
4.3.3 Results for CCD Analysis

The previous graphs show that the five variables chosen for our model have an effect and interactions when measured against the focal firm’s profits. The $R^2$ adjusted is 76.7%, indicating that our variable selection accounts for a large portion of the explained variance in the focal firm’s profits. These results though are not only due to the changes in the variables alone, but are also due in part to the changes in the joint area and the supplier firm’s responses to the changes in its performance. Consequently, these variables and levels chosen are shown to have an effect on the performance of the focal firm and supplier firm, though the supplier firm is not shown in this analysis.

Another component of the CCD analysis is to run a regression analysis based on the 13 runs that also generated the response surfaces. The regression analysis tests the
quadratic effect of the individual variables (see Table III). Two of the variables, theta and turbulence, have quadratic effects that are significant at the p=0.01 level and knowledge per incremental product and resources per incremental product are significant at the p=0.10 level. The quadratic effects show that these variables have different impacts on the model at either their low or high values, as compared to their mid-point value. This result is important to better understand the resource investment decisions of the focal and supplier firm, as a quadratic effect may result in a different decision at a low/high value of a variable as compared to its mid-value. For instance, in fig. 11, the resources per incremental product results in a lower focal firm profit when it is at its mid-value as compared to its low and high-values.

Table III  CCD Analysis Output for Testing Quadratic Effect of Variables

<table>
<thead>
<tr>
<th>Variables</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulence*Turbulence</td>
<td>0.006</td>
</tr>
<tr>
<td>KS per Inc Prod*KS per Inc Prod</td>
<td>0.075</td>
</tr>
<tr>
<td>Res per Inc Prod*Res per Inc Prod</td>
<td>0.065</td>
</tr>
<tr>
<td>Forget Rate*Forget Rate</td>
<td>0.805</td>
</tr>
<tr>
<td>Theta*Theta</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

4.4 Results for Full Factorial Analysis

The CCD analysis is limited in the higher order interactions that it can test for due to its lower number of iterations, which does not provide enough degrees of freedom. A full-factorial $3^k$ was also run using the same variables and success rate iterations as the
CCD analysis to allow for all interactions to be tested. The increased degrees of freedom for the error term in the full-factorial are 2916 as compared to the 657 degrees of freedom for the error term in the CCD analysis. With the increase in degrees of freedom, all of the individual variable terms are now significant at the $p=0.001$ level.

Appendix E shows the results of all of the interactions, which indicate that there are higher order interactions in the model. These higher level interactions indicate that our model has many different variables are interacting to affect the focal firm’s profits. These higher order interactions were expected due to the feedback mechanisms in SD modeling. The are two 4\textsuperscript{th} order interactions that are significant at the $p=0.05$ level: Turbulence*KS per Inc Prod*Res per Inc Prod*Theta and Turbulence*KS per Inc Prod*Forget Rate*Theta. Both of these interactions directly impact, in different manners, the number of radical and incremental innovations that the firms and the joint area can develop.
CHAPTER V

COMPUTATIONAL SCENARIOS AND RESULTS

One of the uses of system dynamic modeling is to create and test a learning environment. To accomplish this goal, a series of scenarios are developed, providing insights into how the focal and supplier firms react, individually and as a supply chain, to changes in both their individual firms and in the joint area. The scenarios are based, in general, on different conditions that can affect the firms and the joint area.

In order to learn more from each scenario, all of the changes to the scenario are not made at once, but serially which we denote as runs. By using runs, we can investigate how the firms and the joint area respond to these serial changes in the scenario. For example, in one scenario, to investigate risk averse firms and how supply chains differ from those that respond to goals, we set the investment decisions for the firms, $frac_{it}, frac_{KS_{it}}$ and $frac_{KS\_Process_{it}}$ equal to one. This scenario is then divided into three runs: 1) a baseline run with no changes to the initial conditions, 2) a run in which only the focal firm is subject to the change, 3) a run in which both the focal and supplier firms, or the supply chain, are subject to the change.
In order to provide differing results for each of the runs, we divide them into iterations. To generate different results for each of the iterations, we use a Monte Carlo simulation along a normal distribution. The variable that we selected for all iterations is the incremental product success rate, \( s_{\text{inc}} \), with a mean of 0.6 and a standard deviation of 0.05. To provide a range of values for analysis, each run consists of 1000 iterations. The purpose of the Monte Carlo simulation is to introduce variation within the runs, although between run variations might occur within the scenario. We reduce the between run variation through a CRN seed which allows each run to use the same set of random numbers as every other run. Table IV contains a listing of the terminology used in our model.

We define three sets of scenarios for our analysis. One set of scenarios focuses on changes made to the initial conditions, levels of stocks, and other factors affecting the interaction of the firms and the joint area that are in effect for all time periods of the iteration. All of these changes are made to the model, depending on the scenario, before the scenario is started. Thus, the changes to the model impact the firms and the joint area at the beginning of the simulation and we monitor how the firms respond. These scenarios provide insight into the investment decisions of the firms, the impact of knowledge assimilation, profit seeking priorities, and different stages of relationships between the firms. See Appendix F for a detailed listing of the scenarios.

A second set of scenarios is created by making changes to the model after the focal and supplier firms and the joint area have reached a steady state condition. This set of scenarios permits us to explore how a firm in steady state responds to both changes
from exogenous and endogenous conditions. Thus, each firm and the joint area have
stable product and knowledge stocks to utilize in their response to the changes.

The last set of scenarios explores how different industries, e.g. pharmaceuticals
and high technology, respond to changes within their firms and their supply chain. We
modify the model to change the focal and supplier firm relationship to a market based
one, which differs from the previous set that rely on collaborative relationship through
the joint area. In the market-based supply chain, the focal firm and supplier firm do not
share a joint area in which both firms invest resources and transfer knowledge. The focal
firm instead uses its resources to purchase innovations at different stages of development
and introduces the purchases into its product development cycle.

For the CCD analysis, we selected and tested five endogenous and exogenous
variables, which we use as the key group of variables for the scenarios. For any scenario
that does not explicitly change one of these variables, we use the values shown in Table
V. These values were determined through exploratory analysis of the model and by
analyzing the outputs from the CCD and $3^k$ full-factorial analyses. This range of values
also provides significant interaction effects that can be used to investigate the feedback
mechanisms in the firms and the joint area.
Table IV  Computational Results Terminology

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>The Vensim structure consisting of a focal firm, a supplier firm, and a joint area</td>
</tr>
<tr>
<td>Scenario</td>
<td>A specific set of changes to the model based on changes to the initial conditions, exogenous conditions, or the structure of the model itself</td>
</tr>
<tr>
<td>Runs</td>
<td>A partial modification to a scenario to explore specific changes</td>
</tr>
<tr>
<td>Iterations</td>
<td>Individual simulations of a run/scenario using the Monte Carlo random number generation</td>
</tr>
<tr>
<td>Simulation</td>
<td>A set of calculations of the model for all available time periods based on a given scenario and run</td>
</tr>
</tbody>
</table>

Table V  Endogenous and Exogenous Variable Values for Scenarios

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulence</td>
<td>0.02</td>
</tr>
<tr>
<td>Forgetting Rate, ( forget_k )</td>
<td>0.11</td>
</tr>
<tr>
<td>Theta, ( \theta )</td>
<td>0.55</td>
</tr>
<tr>
<td>Knowledge per Incremental Product, ( \kappa_{inc} )</td>
<td>40</td>
</tr>
<tr>
<td>Resources per Incremental Product, ( \varphi_{inc} )</td>
<td>40</td>
</tr>
</tbody>
</table>
5.1 Focal and Supplier Firms’ Reactions to Investment Decisions

Both the focal and supplier firms can react to the changes in the system by adjusting the proportion of their invested resources that are allocated to radical and incremental innovation within their firms and product and process innovation of the joint area. Neither firm directly monitors the performance of the other firm, however they monitor the knowledge stocks of the joint area. The performance of these knowledge stocks is dependent on the investments in the joint area of each firm, creating a feedback loop, affecting each firm’s future innovation investments in the joint area. For instance, as the profits increase (decrease) in a firm, it has more (fewer) resources to invest in innovation both within its own firm and the joint area, creating a feedback loop through with the other firm reacts to these investments. The reactions of the firms are dictated by their performance gaps, $\text{Gap}_{KS}$ and $\text{Gap}_{KS\text{ Process}}$. To reduce the performance gaps, each firm allocates its invested resources to radical and incremental innovation in the joint area to reach its knowledge stock goal, $G_{KS}$ and process knowledge stock goal, $G_{\text{Process}}$. These investments affect the levels of the joint area stocks, which in turn affects the amount of knowledge that can be transferred. For example, if Firm A reduces its investments in the joint area, the product and process knowledge stocks of the joint area decline, reducing the amount of knowledge that is available for Firm B can transfer. If this decrease in knowledge transfer causes Firm B to become knowledge constrained in its product innovation, and it develops fewer products than it would have if Firm A had maintained its joint area investments, Firm B’s profits may decline. Thus, Firm A’s investments, through the joint area, can affect Firm B.

In our model, we examine how changes to exogenous and endogenous factors, investment decisions by either firm, and the structure of the relationship between the
focal and supplier firm, i.e. new relationship, new firms, etc., impact the focal and supplier firm and the joint area. Because each firm is connected by a variety of feedback loops through the joint area, changes to, or by, one firm affect the other. By exploring these responses, through the lens of feedback loops, we can develop a better understanding of how each firm and the joint area reacts to both the direct, i.e. the firm’s investments in the joint area and indirect changes, i.e. changing turbulence rates and knowledge stock retention issues.

5.2 Initial Condition Scenarios

For the initial condition scenarios, we make changes to the endogenous variables and the investment fractions, respective goals for both the focal and supplier firms, and the initial product and process stocks. All of these changes for each scenario and run are made before the simulations are begun. Thus, the firms are reacting to the changes from the start of each iteration. On the other hand, the baseline runs have no changes made to the model.

5.2.1 Scenario 1: All Incremental Innovation Investment

The focal and supplier firms invest a proportion of their resources in radical and incremental innovation based how their product and joint product and process stocks perform to their corresponding goals, $G_i$, $G_{KS_i}$, and $G_{Process_i}$. As a firm or the supply chain becomes risk averse, more resources can be invested in incremental innovation. In this scenario, we change the proportion of invested resources to be fully invested in incremental innovation. This scenario consists of three runs: 1) a baseline run in which both firms react to their goals and change their investment decisions at each time t, 2) a
run in which only the focal firm is risk averse and the supplier firm still reacts to its
goals, and 3) a run in which both the focal and supplier firms are risk averse. By dividing
the scenario into three runs, we can investigate the difference between a single firm and
the supply chain being risk averse.

5.2.1.1 Computational Results for Scenario 1: Focal Firm Only Run

The results of this run show that when only the focal firm follows a risk averse
investment decision and directs all invested resources to incremental innovation, we
observed its profits to decrease by 95% compared to the baseline run. As shown in Fig.
16, at time 12 the focal firm’s profits for the baseline run start to increase while profits in
the risk averse run declines. In the baseline run, the focal firm reacts to its goals and
invests its resources in a combination of radical and incremental innovations. However,
when the focal firm invests all of its resources in incremental innovation it cannot
maintain its profits.

When the focal firm becomes risk averse, the supplier firm responds to its goals
and maintains a profit similar to the baseline run (see fig. 17). One reason the supplier
firm maintains its profit is the level of product knowledge stock of the joint area that is
transferred allowing the supplier firm to maintain its level of product developments. The
other reason is the supplier firm responds to the decrease in product knowledge stocks of
the joint area (see fig. 18), and adjusts its investments in the product innovation in the
joint area (see fig. 19). At around period 35, the supplier firm increases its investment in
radical innovation, which yield larger increases in the knowledge stocks. Radical
innovation has a higher probability of failure, however in this run, the increase in
knowledge stocks compensate for the increased risk.
5.2.1.2 Computational Results for Scenario 1: Supply Chain Run

When both the focal and supplier firms are risk averse and we force all investments to incremental innovation, neither firm is able to maintain its profits as compared to the baseline run (see fig. 16 & 17). The risk averse investment strategy is not able to maintain the knowledge stock levels in the focal firm, the supplier firm, nor the joint area, (see fig. 19). These reductions in knowledge stocks are due in part to the lower amount of embedded knowledge per incremental product, \( c_{\text{inc}} \), as compared to radical products. It is also due to the number of incremental products in development (see fig. 20). In the baseline run, as the profits are decreasing and forming a negative profit gap, the focal and supplier firms react by increasing their investments in radical innovation. However, with all incremental innovation investments, a reinforcing feedback loop is created and as a result neither firm is able to increase its profits.

The reinforcing loop continues to reduce the number of products that are being developed because the focal and supplier firms cannot generate enough profits to continue to fund incremental innovation. This lack of funding further reduces both the knowledge stocks and the slack resources available for product development. Each firm is funding incremental innovation with a budgeted amount that is added to the invested resources. However, without the additional invested resources from profits, the budgeted amount is not enough to maintain product developments. Thus, both firms solely relying on incremental innovation do not produce enough profits or knowledge stocks to maintain their product development.
5.2.1.3 Implications and Conclusions for the Supply Chain: Scenario 1

The risk aversion scenario and its runs show that at least one firm in the supply chain needs to continue to invest in radical innovation to sustain an adequate level of knowledge stocks and profits to continue to develop products. Therefore, each firm in the supply chain must be aware of not only its own investment decisions, but also those of the other members of the supply chain. Knowing the strategy of the other supply chain members, the supplier firm can align its internal and joint investment decisions to maintain its profitability.

![Fig. 16 Focal Firm’s Profit Value for Scenario 1](image_url)
Fig. 17  Supplier Firm’s Profit Value for Scenario 1

Fig. 18  Product Knowledge Stock of the Joint Area Level for Scenario 1
Fig. 19 Supplier Firm’s Joint Product Frac for Scenario 1

Fig. 20 Supplier Firm’s Number of Incremental Products in Development for Scenario 1
5.2.2 Scenario 2: All Radical Innovation Investment

The focal and supplier firms can change their goal oriented investment decisions to seek risk, allocating all of their invested resources to radical innovation. This strategy may be undertaken if a firm has a competitor that is consistently developing radical products that are displacing the firm’s products. Therefore, to stay ahead of the competition the firm devotes all of its resource investments to radical innovation. In this scenario, we force all resources to be invested in radical innovation by setting $\frac{K_{it}}{K_{S_{it}}}$, $\frac{K_{S_{it}}}{K_{S_{Processit}}}$, and $\frac{K_{S_{Processit}}}{K_{S_{Processit}}}$ equal to 0. This scenario is subdivided into three runs: 1) a baseline run in which both firms react to their goals and change their investment decisions at each time t, 2) a run in which only the focal firm is risk seeking and the supplier firm still reacts to its goals, and 3) a run in which both the focal and supplier firms, or the supply chain, are risk seeking.

5.2.2.1 Computational Results for Scenario 2: Focal Firm Only Run

For this run, we force the focal firm to invest all of its resources in radical innovation, which results in its profits to decline by 66% by period 100 (see fig. 21). The supplier firm responds to its goals and maintains a profit similar to the baseline run (see fig. 22). The focal firm’s investments in radical innovation do not enable it to generate enough knowledge to maintain its product developments and the higher failure rate of radical innovations contributes to its reduction in profits. On the other hand, the supplier firm is able to continue its level of profitability because its resource investments in product knowledge stock of the joint area help it to transfer enough knowledge to maintain its number of innovations (see fig. 23). The supplier firm reacts to the reduction
in the product knowledge stock of the joint area by decreasing its $frac_{it}$ and allocating more invested resources to radical innovation (see fig. 24), allowing it to maintain its level of transferred knowledge.

Another reason for the decrease to the focal firm’s profits is due to the lack of improvements to its existing products. The investment in only radical innovations does not allow the allocation of any resources to the incremental product development cycle. Therefore, as products are removed from the stocks for improvement and re-enter the incremental product development cycle, there are not sufficient resources available to fund these innovations. Thus, the products are permanently removed from the focal firm’s product stocks. In addition, the incremental product development cycle is further affected because there is no funding for the recovery of dormant products in the incremental innovation cycle. The joint area is also affected in the same manner because only the supplier firm is investing in incremental product and process innovation in the joint area.

5.2.2.2 Computational Results for Scenario 2: Supply Chain Run

For this run, we force both firms to invest all resources in radical innovation, and we observe a 90% decrease in their profits by period 100 (see fig. 21 & 22). The reduced profits also decrease the product knowledge stock of the joint area because each firm has fewer resources to invest in innovation (see fig. 23). In the previous run, the supplier firm’s radical and incremental innovation investments in the joint area helped to maintain the joint area’s knowledge stocks, allowing the focal firm to transfer more knowledge. However, in this run, the focal firm cannot transfer the same amount of knowledge, causing it to be able to develop fewer product innovations.
A reason for the reduction in profits is that the supply chain relies solely on radical products to generate profits. While having a higher profit per product, $\pi_{\text{rad}}$, the success rate for radical products is lower than that of incremental products. The higher profit per product is not enough to overcome the lower success rate, so both the focal and supplier firm are not able to maintain their profits, which further decreases the number of products being funded. In addition, the supply chain is not able to take advantage of the dormant products in the incremental innovation cycles, further reducing the products available for innovation (see fig. 25).

5.2.2.3 Implications and Conclusions for the Supply Chain: Scenario 2

The results of this scenario shows supply chain members need to communicate and coordinate their strategies so that at least one firm invests in incremental innovation to sustain an adequate level of knowledge stocks and profits to continue to develop products, especially if there is a risk seeking firm in the supply chain. Without the incremental innovations, the dormant products and products that require improvements are lost. Thus, knowing the strategy of the other supply chain members allows the supplier firm to align its internal and joint investment decisions to maintain its profitability.
Fig. 21  Focal Firm’s Profit Value for Scenario 2

Fig. 22  Supplier Firm’s Profit Value for Scenario 2
Fig. 23  Product Knowledge Stock of the Joint Area Level for Scenario 2

Fig. 24  Supplier Firm’s Joint Product Frac Value for Scenario 2
Fig. 25  Focal Firm’s Number of Dormant Products for Scenario 2
5.2.3 Scenario 3: Equal Investments in Radical and Incremental Innovation

The focal and supplier firms invest their resources in radical and incremental innovation based how their profits and how the joint product and process knowledge stocks perform to their corresponding goals, $G_i$, $G\_KS_i$, and $G\_Process_i$. In this scenario, we change the proportion of invested resources to be equally divided between radical and incremental innovation by setting $frac_it$, $frac\_KS_it$, and $frac\_KS\_Process_it$ equal to 0.5. This scenario is divided into three runs: 1) a baseline run in which both firms invest their resources based on their goals, 2) a run in which the focal firm invests equally in radical and incremental innovation, and 3) a run in which both the focal and supplier firms, or the supply chain, invest equally in radical and incremental innovation.

5.2.3.1 Computational Results for Scenario 3: Focal Firm Only Run

In this run, we force the focal firm to have equal investments in radical and incremental innovation by setting all $fracs = 0.5$, and we observe an increase in its profits by 16% as compared to the baseline run by period 100 (see fig. 26). During the baseline run, the focal firm’s $frac_it$ was 0.75 at period 100; or 75% of its resources were invested in incremental innovation. Our forced equal resource investments causes the focal firm’s investments in radical innovation to increase by 25 percentage points (see fig. 27), resulting in higher profits for the focal firm. On the other hand, the additional resources that are invested in the joint area, due to the focal firm’s increased profits, do not result in increases to the product knowledge stock of the joint area (see fig. 28). The joint area is knowledge constrained; therefore, the additional investments by the focal firm do not result in additional product or process innovations.
The supplier firm’s profits were the same as the baseline run (see fig. 29), because the supplier firm is resource constrained and cannot undertake additional product innovations without additional resources. Even if the joint area was not knowledge constrained, the supplier firm could not utilize the increased knowledge transfer to undertake more product innovations. Therefore, the supplier firm does not notice the focal firm’s additional profits because there is no change in the joint area knowledge stocks. Thus, there is no change in the supplier firm’s decision and it keeps the same proportion of radical and incremental investments in the focal only run as it did in the baseline run (see fig. 30).

5.2.3.2 Computational Results for Scenario 3: Supply Chain Run

In this run, we force both the focal and supplier firms to equally invest in radical and incremental innovation, resulting in the supplier firm’s profits increasing by 16% (see fig. 29). The increased profits allow the supplier firm to invest more resources in innovation and utilize its knowledge stocks to undertake additional products. Nevertheless, the focal and supplier firm are still resource constrained in this run and could undertake more product innovations with more resources.

5.2.3.3 Implications and Conclusions for the Supply Chain: Scenario 3

The focal firm is able to increase its profits when equally investing in radical and incremental innovation. This increase in profits illustrates the need of the focal and supplier firms to monitor their goals to maintain optimal profits. In addition, the firms need to assess the knowledge and/or resource constraints of their firms and of the joint area because the joint area requires more knowledge, not resources, to undertake more product and process innovations.
In this scenario, the supplier firm is not able to detect the focal firm’s increase in profits because the product and process knowledge stocks of the joint area do not change. Therefore, the monitoring mechanisms of the supplier firm are not adequate to measure the performance of its supply chain partners. This issue, coupled with the focal firm’s investments in a knowledge constrained joint area, highlights the need for proper measurement and analysis of constraints and communication in a supply chain relationship. If the supplier firm has information about the focal firm’s increased profits and investments in the joint area, it could request that the focal firm redirect its investments from the joint area to the supplier firm. Though not directly benefiting the focal firm, this redirection in investments would increase the profitability of the supply chain as a whole.

Fig. 26  Focal Firm’s Profit Value for Scenario 3
Fig. 27  Focal Firm’s Frac Value for Scenario 3

Fig. 28  Product Knowledge Stock of the Joint Area Level for Scenario 3
Fig. 29 Supplier Firm’s Profit Value for Scenario 3

Fig. 30 Supplier Firm’s Frac Value for Scenario 3
5.2.4 Scenario 4: Low, Medium, and High Knowledge Assimilation for the Supply Chain

This scenario explores how the difficulty of assimilating knowledge, $\Theta$, impacts the investment decision of the focal and supplier firms. The knowledge stocks of the focal and supplier firm are one of the limiting factors on the number of product developments. The ability of the focal and supplier firms to assimilate knowledge from the product knowledge stock of the joint area affects their abilities to develop incremental and radical products.

Knowledge assimilation differs from knowledge transfer. The firms can have the ability to transfer the knowledge based on their investments in joint area process innovations, but if the firms cannot assimilate the knowledge and utilize it for their own product developments, the knowledge does not benefit the firm’s product development. For example, if Firm A has 100 units of knowledge transferred in a period and has a knowledge assimilation of 10%, they can use 10 units of knowledge for their product development. On the other hand, if Firm B has only 50 units of knowledge transferred in a period yet has a knowledge assimilation of 50%, they can use 25 units of knowledge for their product development. Thus, the quantity of knowledge transferred alone is not an indication of a firm’s ability to gain from the knowledge and use it for innovations.

We initialize the value of $\Theta$ for both the focal and supplier firms. The scenario is divided into three runs: 1) a low knowledge assimilation, or $\Theta = 0.1$ for both the focal and supplier firms and 2) a medium knowledge assimilation, or $\Theta = 0.55$ for both the focal and supplier firms, and 3) a high knowledge assimilation, or $\Theta = 1$ for both the focal and supplier firms. These runs allow the firms to transfer 10%, 55%, and 100% of the knowledge that is available for transfer respectively. Runs 2 and 3 will be discussed
in the same section because they have similar affects on the profitability of the focal and supplier firms.

5.2.4.1 Computational Results for Scenario 4: Low Knowledge Assimilation Run

The results of this run indicate that the ability to assimilate 10% of the knowledge resulting in a decrease of 62% in the focal and supplier firms’ profits by period 100 (see fig. 31 & 32). At time 12, the focal and supplier firms’ profits reach their highest level and decrease gradually for the remainder of the simulation. This is due to their inability to transfer knowledge to the firms’ knowledge stocks, which decreases the number of innovations they can develop (see fig. 32). Responding to the lower profits, as compared to their profit goal, the focal and supplier firms invest a lower proportion of $\text{frac}_{it}$, or more of their resources in radical innovation (see fig. 33).

The decrease in profits causes a further decrease in the knowledge stock due to fewer resources that can be invested in future innovations. In addition, the assimilation of 10% of the knowledge that is available for transfer from the joint area contributes to the lower knowledge stock levels in general. Both of these factors create a feedback loop in which both firms continue to invest a higher proportion of resources into radical innovation to try and achieve their profit goals (see fig. 33). However, the investment in radical innovation, while having higher profit and knowledge gains from a successful innovation, also has a lower probability of success. The firms’ increasing investments in radical innovations cause the feedback loop to become reinforcing, i.e., causing the firms to continually invest in radical innovation as their profits and knowledge stocks continue to decline.
Another factor reducing the number of innovations that can be developed is the knowledge stock investment per radical product. In our model, we assume that the knowledge required to innovate a radical product is 150% greater than an incremental product. Thus, the firms are investing more resources into products that require higher levels of knowledge per product, while lowering knowledge stock levels. This reinforcing feedback loop does not allow an increase in profits.

5.2.4.2 Computational Results for Scenario 4: Medium and High Knowledge Assimilation Runs

The results for the medium and high knowledge assimilation runs are very similar in their final values. Starting at time 12, the profits for the high assimilation run exceed those of the medium knowledge assimilation run, but by period 85 they converge (see fig. 31). The reason for the differences in profits in the beginning periods is that the medium knowledge assimilation run has lower knowledge stock levels, compared to the high knowledge assimilation run (see fig. 33), allowing fewer innovations to be developed. The lower profits, relative to the goal, cause the focal and supplier firms to invest more resources in radical innovation which causes their profits to match that of the high knowledge assimilation run (see fig. 33).

The reason these two runs achieve the same profit level by the end of the simulation is that the knowledge stocks are not the only limiting factor in the number of products that can be developed. Although not visible in the figures, at period 53, resources start becoming the limiting factor for the medium knowledge assimilation run and the high knowledge assimilation run becomes resource constrained at period 26. In these two periods, the additional knowledge that is generated from product innovation,
both in the firms and the transferred knowledge, does not result in an increase in product innovations.

5.4.2.3 Implications and Conclusions for the Supply Chain: Scenario 4

Firms that have low knowledge assimilation in their supply chain relationships need to be observant of the knowledge that is required for their innovation. Developing products that have relatively high knowledge stock requirements will limit the number of products that can be developed. If these types of products are needed in the market, then the firms need to have access to another supply chain member that can both provide the knowledge and can assist in the assimilation of the knowledge. If current investments in the joint area are yielding low returns on the knowledge that can be assimilated for innovations, the firms should seek ways to increase their knowledge assimilation via investing in technology. Increasing their knowledge assimilation could increase the amount of knowledge transferred more so than just increasing the investments in the joint area.

Another implication for the supply chains is the role of knowledge requirements for innovation and the profit goals of the firms. As illustrated in the low knowledge assimilation run, the focal and supplier firms have lower knowledge stock levels and when coupled with the higher knowledge stock investment per radical innovation further decrease the number of radical innovations they can develop. With the reinforcing feedback loop, the higher investments in radical innovation led to lower profits and neither firm was able to achieve their profit goals.

Finally, an important implication of this scenario is the identification of the constraints on innovation. As shown in the medium and high knowledge assimilation
runs, there is a point when additional knowledge from the joint area has no marginal benefit to the firms. At these points, the firms are resource constrained; therefore additional resource investments in increasing the knowledge assimilation or improving the knowledge transfer from the joint area do not result in more innovations. However, investing resources into their own product innovation could increase the profits of the firms.

Fig. 31  Focal and Supplier Firms’ Profit Value for Scenario 4
Fig. 32  Focal and Supplier Firms’ Level of Knowledge Stock for Scenario 4

Fig. 33  Focal and Supplier Firms’ Frac Value for Scenario 4
Fig. 34  Focal and Supplier Firms’ Level of Knowledge Transfer for Scenario 4
5.2.5 Scenario 5: High Focal and Low Supplier Knowledge Assimilation

Firms can have different levels of knowledge assimilation or absorptive capacity (Cohen & Levinthal, 1990), which affect their ability to commercialize knowledge. In this scenario, a focal and supplier firm have different capabilities of understanding and the usage of the transferred knowledge from the joint area for innovations. An example of low knowledge assimilation is a supplier firm investing resources in the joint area, but the knowledge generated and transferred to the supplier firm has little relevance to its own product innovations. On the other hand, if the focal firm has higher knowledge assimilation level, it has the capability to more easily understand and use the transferred knowledge from the joint area to increase the number of innovations that it can undertake. In general, the supplier firm’s investments in the joint area benefit the supply chain members with higher knowledge assimilation, even though the supplier firm itself does not.

For this scenario, we set different levels of knowledge assimilation for the focal and supplier firms. We initialize the knowledge assimilation level of the focal firm to be, \( \theta = 1 \), and the supplier firm’s knowledge assimilation level to be, \( \theta = 0.1 \). Thus, the focal firm is able to transfer 100% of the available knowledge from the product knowledge stock of the joint area and the supplier firm is only able to transfer 10%.

5.2.5.1 Computational Results for Scenario 5

The first influence of the different knowledge assimilations is on the amount of knowledge that is transferred from the product knowledge stock of the joint area to each of the firms (see fig. 35). Beginning at period 8, the focal firm’s knowledge stock
steadily increases while the supplier firm has a consistently lower level of knowledge stock (see fig. 36). The larger knowledge stock enables the focal firm to generate profits 61% higher than the supplier firm by period 100 (see fig. 37). The supplier firm’s lower knowledge stock reduces the number of product innovations it can undertake, creating a reinforcing feedback loop. As the supplier firm responds to the lower profits by decreasing its $\frac{1}{T}$ (see fig. 38), it decreases the number of innovations it can undertake because radical innovations require more knowledge stock.

The supplier firm responds to the lower amount of knowledge transferred by matching the focal firm’s investment in radical process innovation in the joint area (see fig. 39). However, the knowledge assimilation difficulty has a larger influence on the amount of knowledge transferred than the supplier firm’s investments in joint process innovation. Thus, its investments in the joint area do not increase its knowledge transfer (see fig. 35).

5.2.5.2 Implications and Conclusions for the Supply Chain: Scenario 5

As shown in this scenario, the supplier firm’s investments in the joint area did not improve its ability to innovate products and generate profits. The investments in the joint area would be more productive if directed to improving the supplier firm’s knowledge assimilation capability, allowing it to transfer more knowledge. The other option available to the supplier firm is to enter a supply chain relationship that enables it to have a higher knowledge assimilation level. Either way, without knowledge transfer from the joint area, the supplier firm cannot increase its profits.

Another interesting aspect of this scenario is the selection of supply chain members. The focal firm could be affected by the supplier firm’s low level of knowledge
assimilation due to the supplier firm’s lower level of resource investments in the joint area. The lower investments decrease the product knowledge stock of the joint area which decreases the amount of knowledge the focal firm can transfer, which could reduce the number of innovations it can develop. Thus, each firm has a vested interest in insuring the other supply chain members are able to assimilate the knowledge from the joint area and successfully innovate products with that knowledge. One member having difficulties in the supply chain can cause a cascading effect that results in many other firms being able to innovate fewer products.

Fig. 35  Focal and Supplier Firms’ Level of Knowledge Transfer for Scenario 5
Fig. 36  Focal and Supplier Firms’ Knowledge Stock Level for Scenario 5

Fig. 37  Focal and Supplier Firms’ Profit Value for Scenario 5
Fig. 38 Focal and Supplier Firms’ Frac for Scenario 5

Fig. 39 Focal and Supplier Firms’ Process Frac Value for Scenario 5
5.2.6 Scenario 6: Doubling of the Focal Firm’s Profit Goal

Focal and supplier firms can have different goals for their profits, resulting in different investment decisions for radical and incremental innovation. As the profits and stocks diverge from their respective goals, the firms respond by changing the proportion of resources that are invested in radical and incremental innovation. For instance, profits that exceed their goal result in a positive profit gap, $\text{Gap}_{it}$, which signals to the firm that more resources should be invested in incremental innovation and fewer in radical innovation. To explore the affects of differing goals between the focal and supplier firms, we subdivide the scenario into two runs: 1) a baseline run and 2) a run in which the focal firm’s profit goal is double the supplier firm’s profit goal.

The change to the focal firm’s goals can have an impact on the supplier firm’s profitability, even though the supplier’s profit goal is unchanged. For example, if the focal firm’s profits decrease while trying to meet its higher goal, it has fewer resources to invest in the joint area. Because the supplier firm relies on the product and process knowledge stocks of the joint area for its product development, a change in the focal firm’s ability to invest in the joint area creates a feedback loop between the two firms.

5.2.6.1 Computational Results for Scenario 6

The results for this scenario show that when we change the focal firm’s profit goal, then its profits decrease by 58% by period 100, while the supplier’s profits achieve the baseline run’s profit value by period 75 (see fig. 40). At time 12, both firms have similar profits values, but they respond in different ways. The focal firm’s doubled profit goal results in it having a larger negative profit gap, in comparison to the supplier firm.
To meet its profit goal, the focal firm invests a larger proportion of its resources in radical innovation, by decreasing $\text{frac}_{it}$, while the supplier firm begins to invest more resources in incremental innovation (see fig. 41).

The focal firm’s profit goal and its corresponding gap establish a reinforcing feedback loop. The focal firm needs to increase its profits, but the magnitude of the gap forces it to invest too many resources in radical innovation for it to achieve its goal. While radical innovation provides higher profits and gains to the knowledge stock in the long run, it also has a higher risk of failure during innovation. The failure rate exceeds the rewards from profits and knowledge stock, prohibiting the focal firm from exiting this feedback loop. As a result, it continues its investment in radical innovation, decreasing $\text{frac}_{it}$ to under 0.1 (see fig. 41), or over 90% of the focal firm’s investments in radical innovation and decreasing the focal firm’s knowledge stock level (see fig. 42).

The focal firm’s investment in the joint area affects the supplier firm because its lower profits decrease its investments in the joint area, which decreases both the product and process knowledge stocks in the joint area. This in turn decreases the amount of knowledge that is transferred to the supplier firm (see fig. 43). The supplier firm responds by modifying its investment decision and invests more resources in radical innovation, as compared to the baseline run. Thus, the focal firm’s reduced investments cause the supplier firm to change its own product innovation investments to make-up for the reduction in transferred knowledge.

5.2.6.2 Implications and Conclusions for the Supply Chain: Scenario 6

This scenario provides a unique look at how a firm’s ‘greed’ or emphasis on generating profits beyond its ability affecting not only its profits, but also decreases the
supplier firm’s profits as well. The supplier firm responds by increasing its investments in radical innovation, which overcomes the decrease in the knowledge transfer from the joint area. If the supplier firm was not successful in increasing its knowledge stocks on its own, it could have been affected by the same reinforcing feedback loop.

In this scenario, the supplier firm was able to make changes to its innovation investments when the focal firm’s investments in the joint area decreased. However, the loss of knowledge from the joint area could have caused its profits to be dramatically affected. Thus, the focal firm needs to inform its supply chain partners when changing its profit goals so that the supply chain can properly assess the changes and plan alternative sources of knowledge or change its investment decisions.

![Fig. 40  Focal and Supplier Firms’ Profit Value for Scenario 6](image)
Fig. 41  Focal and Supplier Firms’ Frac Value for Scenario 6

Fig. 42  Focal and Supplier Firms’ Level of Knowledge Stocks for Scenario 6
Fig. 43  Focal and Supplier Firms’ Level of Knowledge Transfer for Scenario 6
5.2.7 Scenario 7: Established Focal Firm, New Supplier, and New Supply Chain Relationship

This scenario investigates the investment responses of an established focal firm and a new supplier firm forming a new supply chain relationship. During the development of a new relationship, both the focal and supplier firms invest resources in product and process innovations in the joint area. The benefits of these investments are not immediately available because the products and processes take time to progress through the radical and incremental development cycles. However, the firms need knowledge to undertake their innovations, so the focal firm relies on its knowledge stocks for investments in radical and incremental product innovations. On the other hand, because the supplier is a new firm, it has limited initial product stocks. Therefore, its ability to innovate products relies heavily on knowledge transfer from the joint area during the early periods of the scenario.

In the computational analysis, we initialize the supplier firm and joint area with a positive product and process stock level. Because the supplier firm is new and is just beginning to develop product innovations, we initialize its radical product development stock with 1 product and the incremental product development stock with 2 products. Likewise, we initialize the radical products and processes development stocks of the joint area with 2 products and 2 processes and the incremental products and processes development stocks of the joint area with 5 products and 5 processes. These products and processes of the joint area represent the focal firm’s experience and knowledge from previous supply chain relationships.
To explore how new firms invest their resources under different goals, we divide this scenario into two runs that will be discussed together: 1) a run in which the supplier’s goals are equal to the focal firm’s and 2) a run in which the supplier’s goals for profit, $G_i$, joint area knowledge stock, $G_{KS_i}$, and joint area process knowledge stock, $G_{Process_i}$, are reduced by one-half. Both of these runs are also compared at three levels of knowledge assimilation for the supplier firm: a) $\Theta=10\%$, b) $\Theta=55\%$, and c) $\Theta=100\%$. The different levels of knowledge assimilation allow us to investigate the affect of knowledge transfer from the joint area on the development of the supplier firm and the supply chain relationship.

5.2.7.1 Computational Results for Scenario 7

Throughout this scenario, the focal firm’s profits remain the same, regardless of the supplier firm’s goals or knowledge assimilation level (see fig. 44). The profits are unchanged because the focal firm is knowledge constrained in the number of innovations it can undertake. One way the focal firm can increase its knowledge stocks is through knowledge transfer from the joint area. However, the joint area is also knowledge constrained and only varies slightly for all runs (see fig. 45). Therefore, any resource investments that exceed the maximum number of products that can be developed based on the knowledge stocks are wasted.

When we reduce the supplier’s goals by one-half, its profits increase for all knowledge assimilation levels (see fig. 46). In the first run, as the supplier attempts to meet the same goals as the focal firm, it invests more resources in radical innovation to obtain higher levels of profits and knowledge stocks (see fig. 47). The higher levels of radical innovation also affect the supplier firm’s knowledge stocks because radical
innovations require more knowledge stock investment per innovation, $\kappa_{rad}$. This investment level, coupled with the lower knowledge stock level, further limits the number of products that can be developed.

Like the focal firm, the supplier firm is also knowledge constrained during both runs. However, when we change its knowledge assimilation level it can transfer more knowledge from the joint area, decreasing the impact of the being knowledge constrained. As the knowledge stock increases through knowledge transfer, the supplier firm can innovate more products, increase its profits, and enter a balancing loop (see fig. 46). The balancing loop is illustrated in fig. 47 during the reduced goals run at knowledge assimilation levels of 55% and 100%, the supplier firm approaches its profit goal and invests more resources in incremental innovation.

5.2.7.2 Implications and Conclusions for the Supply Chain: Scenario 7

This scenario shows that both firms need to assess their constraints on innovations and the constraints on the joint area. A portion of the focal firm’s investments in both its firm and the joint area are not effective because of the knowledge constraints. If the focal firm’s investments focused on increasing its knowledge stocks it could also increase the number of innovations it could undertake and increase its profits. The goals established by a firm also affect its profitability. For instance, when the supplier firm is new its knowledge stocks are limited and its investments need to focus on increasing the number of innovations that can be developed. When it sets goals that require high levels of radical innovation, the knowledge stock per innovation for radical innovation limits the number of innovations. The changing of its goals to allow more incremental innovation
would increase the number of product innovations it can undertake, resulting in a more rapid increase in its knowledge stocks.

This scenario leads to two important insights on innovations within a supply chain. The first is that firms need to assess when they are knowledge or resource constrained to determine where investments should be focused: on innovation investments or on increasing their knowledge stocks. As shown in this scenario, without additional knowledge, more investments in innovation, without a corresponding increase in knowledge stocks, do not increase profits. The second is that firms need to assess their goals when determining their resource investments. Radical innovation appears to be a better choice when a firm is trying to build its knowledge stocks; however, too much reliance on this riskier investment can lead to lower profits. Reducing the goals, and subsequently increasing the investments in incremental innovation, leads to an increase in knowledge stocks and profits.

![Fig. 44  Focal Firm’s Profit Value for Scenario 7](image-url)
Fig. 45  Product Knowledge Stock of the Joint Area Level for Scenario 7

Fig. 46  Supplier Firm’s Profit Value for Scenario 7
Fig. 47  Supplier Firm’s Frac Value for Scenario 7
5.2.8 Scenario 8: New Focal and Supplier Firms and New Supply Chain Relationship

This scenario investigates the responses of new focal and supplier firms forming a new supply chain relationship. During the development of a new relationship, both the focal and supplier firms are investing in product and process innovations in the joint area as well as developing their own product stocks. However, the profits and knowledge generated by these investments are not immediately available because the products and processes take several periods to progress through the radical and incremental development cycles. The firms have limited knowledge stocks of their own during the beginning periods of the scenario. Therefore, the rate of knowledge stock growth can have a strong influence on the growth rate of the firms and the joint area.

In addition, the firms also need to wait as the supply chain relationship develops and the joint area product and process stocks generate knowledge that both firms can use for their product innovations. Transferring knowledge from the joint area can reduce some of the demand for internal knowledge stock development. One factor affecting the knowledge transfer from the joint area is the focal and supplier firm’s ability to assimilate the knowledge required for innovations. Higher levels of knowledge assimilation allow the firms to use more of the product knowledge stocks of the joint area for product innovations.

In the computational analysis, we initialize the focal and supplier firm and joint area with a positive product and process stock level. Without loss of generality, we start each firm with 1 radical and 2 incremental products in development. Each firm has no previous experience with their supply chain, so we initialize the joint area with 1 radical product and 1 radical process and 2 incremental products and 2 incremental processes in
development. In addition, the focal and supplier firm do not generate any profits until these initial products are launched into the product stocks, so the budgeted investments are the sole funding source during the beginning periods of the simulation.

To explore how new firms entering a new supply chain relationship respond to a different set of goals, we reduce the focal firm’s goals by one-half, while the supplier firm’s goals remain at the original values. We divided this scenario into three runs: 1) a run in which the focal and supplier firms have a low knowledge assimilation level, with $\Theta = 0.1$, 2) a run in which the focal and supplier firms have medium knowledge assimilation level, with $\Theta = 0.5$, and 3) a run in which the focal and supplier firms have high knowledge assimilation level, with $\Theta = 1$.

5.2.8.1 Computational Results for Scenario 8

Each firm starts with a limited product stock; therefore, their ability to generate their own knowledge is limited. Thus, the ability to transfer knowledge from the joint area has a large impact on the profitability of the firms (see fig. 48). Due to the low initial profits, as compared to their profit goal, each firm focuses their invested resources into radical innovation, with a low level of $\frac{t}{\text{frac}}$ (see fig. 49). Beginning at period 6, the firms begin to invest more resources in incremental innovations as the initial products launch and begin to produce profits. This trend continues for the remainder of time periods for all of levels of knowledge assimilation.

Under a high knowledge assimilation level, the focal firm transfers more knowledge from the joint area, which allows it to undertake more innovations in the early periods, as compared to a low knowledge assimilation level (see fig. 50). These innovations, once successfully launched create a reinforcing feedback loop, by leading to
higher knowledge stocks within the firms, which allow more product innovations (see fig. 51). This feedback loop continues until the firms begin to reach their goals, after period 100 in this scenario, at which point a balancing feedback loop is established as the firms maintain their profits and knowledge stocks through a balance of radical and incremental innovation.

The knowledge assimilation is the key factor in determining the success of new focal and supplier firms. The ability to assimilate the knowledge is important because the joint area is knowledge constrained for all time periods (see fig. 52). Therefore, the focal and supplier firm can only increase their own knowledge stocks, and subsequently the number of additional innovations they undertake, through their ability to transfer additional knowledge with higher levels of assimilation.

5.2.8.2 Implications and Conclusions for the Supply Chain: Scenario 8

New firms have limited knowledge within their firms or the joint area; therefore, their ability to increase the knowledge stocks quickly is a key to profitability. Consequently, new firms that are involved in industries that require knowledge intensive product innovations need to establish supply chain relationships with high knowledge assimilation levels to accomplish this. In addition, without the ability to assimilate the knowledge, the firms cannot utilize it for product innovations. Thus, new firms need not only to find partners that can create a supply chain that can transfer knowledge, but also knowledge that can be assimilated.

In this scenario, it is interesting to note the importance of quickly building the knowledge stocks of the joint area. As the firms begin their own product innovations, they are dependent on knowledge stocks to undertake more innovations. The joint area
proves to be an important source of knowledge, depending on the knowledge assimilation level, that can assist the new firms in building their product stocks. If the joint area is knowledge constrained, knowledge transfer is limited due to fewer innovations being developed. Therefore, the supply chain needs to not only invest resources in the joint area, but also focus on building its knowledge stocks to increase the amount of knowledge that can be transferred.

Fig. 48  Focal and Supplier Firms’ Profit Values for Scenario 8
Fig. 49  Focal and Supplier Firms’ Frac Value for Scenario 8

Fig. 50  Focal and Supplier Firms’ Level of Knowledge Transfer for Scenario 8
Fig. 51  Focal and Supplier Firms’ Level of Knowledge Stocks for Scenario 8

Fig. 52  Product Knowledge Stock of the Joint Area Level for Scenario 8
5.2.9 Scenario 9: Established Focal and Supplier Firms with a New Supply Chain Relationship

This scenario investigates the responses of established focal and supplier firms forming a new supply chain relationship. During the development of a new relationship, both the focal and supplier firms invest in product and process innovations in the joint area. However, with a new supply chain relationship the benefits of these investments are not immediately available because the products and processes take several periods to progress through the radical and incremental development cycles. Therefore, as the relationship develops, the firms solely rely on their own knowledge stocks for innovations until they are able to transfer knowledge from the joint area.

In the beginning stages of the relationship, the product and process stocks of the joint area are much lower than an established relationship; this in turn affects how the firms invest their resources in the joint area. If a firm sets its goals for the product and process knowledge stocks of the joint area the same as the goals for an established relationship, it could invest too many resources in radical innovation in an attempt to build these stocks rapidly. Relying too heavily on radical innovation may lead to a reinforcing feedback loop that limits the development of the joint area due to the higher risk of failure.

We divide this scenario into three runs: 1) a baseline run, 2) a run in which the focal and supplier firms establish a relationship in the joint area and invest according to their original goals, and 3) a run in which the focal and supplier firm establish a relationship in the joint area with the focal firm setting new goals. In the third run, we reduce the focal firm’s goals for profit, $G_i$, joint area knowledge stock, $G_{KS_i}$, and joint
area process knowledge stock, $G_{Process}$, by one-half to observe the affect of changing the firm’s investments in radical and incremental innovation investments on the new supply chain relationship. Without loss of generality, we initialize runs 2 and 3 with 5 incremental and 2 radical products and 2 processes in the respective development available stocks of the joint area.

5.2.9.1 Computational Results for Scenario 9: Original Goals Run

For this run, the product knowledge stock of the joint area remains at a level much below the baseline run through period 100 (see fig. 53). One reason is that the focal and supplier firms invest their resources in the joint area based on their expectations of an established relationship. Their goals for the product and process knowledge stocks are much higher than they should be for a developing supply chain relationship, resulting in levels of radical innovation investments that are too high (see fig. 54). The increased investments in radical innovation are detrimental to the joint area because the amount of knowledge stock investment per radical innovation, coupled with the lower knowledge stock levels, reduces the number of innovations the joint area undertakes.

The focal firm starts with the same knowledge stock level, as it did in the baseline run; however, after period 1, with a lower level of knowledge transfer due to the lower level of the product knowledge stock of the joint area, its knowledge stock quickly decreases (see fig. 55). The drop in knowledge stocks decreases the number of innovations the focal firm can undertake, which reduces its profits (see fig. 56). The focal firm’s profit goal result in it investing too many resources in radical innovation (see fig. 57), causing it to enter a reinforcing feedback loop that it does not exit by period 100.
5.9.2.2 Computational Results for Scenario 9: New Focal Firm Goals

For this run, we reduce the focal firm’s goals by one-half and its profits increase by 71%, compared to its original goals (see fig. 56). The reduced profit goal shifts more of the focal firm’s investments to incremental innovation in its own firm (see fig. 57) and the joint area (see fig. 54). Although incremental innovations yield lower profits and knowledge stocks, as compared to radical innovations, in this scenario the higher success rate overcomes these issues. When the focal firm shifts more of its resource investments to incremental innovation, the joint area undertakes more innovations, increasing the product knowledge stock of the joint area (see fig. 53).

On the other hand, the supplier firm’s profits increase only slightly from the focal firm’s shift to more incremental innovation in the joint area (see fig. 58). The increase in the product knowledge stock of the joint area increases the knowledge transfer to the supplier firm, increasing the number of innovations it undertakes. However, under its original goals the supplier firms relies heavily on radical innovations (see fig. 59), which creates a reinforcing feedback loop that the supplier firm cannot exit, without also changing its goals.

5.2.9.3 Implications and Conclusions for the Supply Chain: Scenario 9

For new supply chain relationships, the focal and supplier firms need to assess their goals to ensure that they are not investing too many resources in radical innovation. As illustrated in this scenario, reliance on radical innovation to build the firms’ and joint area’s knowledge stocks while the relationship develops, causes a reinforcing feedback loop that steadily decrease the profits. As an interesting observation of this scenario, only when the focal firm’s goal is to generate less profit, it is able to increase its profits by
investing more resources in incremental innovation. On the other hand, the supplier firm only increases its profits when the focal firm changes its goals and increases the knowledge stocks of the joint area.

In addition, if the firms are reliant on knowledge transfers from the joint area, they need to start with enough products and processes to ensure the joint area is not knowledge constrained. Even when we changed the focal firm’s goals and it invested more resources for incremental innovation, the joint area still remains knowledge constrained. Transferring knowledge stocks to the joint area would have been a more effective investment. By understanding when a resource or knowledge constraint is the limiting factor in the number of innovations that can be developed, the resource investments can be allocated to relax the constraint.

Fig. 53  Product Knowledge Stock of the Joint Area Level for Scenario 9
Fig. 54  Focal Firm’s Joint Product Frac Value for Scenario 9

Fig. 55  Focal Firm’s Level of Knowledge Stock for Scenario 9
Fig. 56  Focal Firm’s Profit Value for Scenario 9

Fig. 57  Focal Firm’s Frac Value for Scenario 9
Fig. 58  Supplier Firm’s Profit Value for Scenario 9

Fig. 59  Supplier Firm’s Frac Value for Scenario 9
5.2.10 Scenario 10: Supplier Freeloader

An issue in supply chain relationships is opportunistic knowledge transfer (Hamel, 1991) which occurs when one firm does not invest any resources in the joint area but still transfers knowledge. In this scenario, we eliminate the supplier firm’s investments in joint area product and process innovation. Thus, the supplier firm becomes a ‘freeloader’ when it benefits from the focal firm’s investments in the joint area. We also reallocate all of the supplier firm’s investments from the joint area to its own radical and incremental product innovations. In our model, the focal firm cannot directly monitor the supplier firm’s investment changes; however, it might detect the changes to the knowledge stocks of the joint area or its profits and adjust its resource investments accordingly. In the event the focal firm detects the supplier firm is a freeloader, it can remove the supplier firm from the supply chain relationship and eliminate the supplier firm’s ability to transfer knowledge from the joint area.

We divide this scenario into three runs: 1) a baseline run, 2) a run in which the supplier allocates all of its invested resources to its own firm, and 3) a run in which the supplier allocates all of its invested resources to its own firm and the focal firm does not allow knowledge transfer from the joint area to the supplier firm.

5.2.10.1 Computational Results for Scenario 10: Joint Area Knowledge Transfer

The focal firm’s first indication of the supplier firm not investing in the joint area is a 3% decrease in its profits (see fig. 60). In addition, the level of the product knowledge stock of the joint area decreases by 41% due to the supplier firm’s lack of resource investments (see fig. 61). As a result of the decrease, the focal firm transfers less
knowledge from the joint area (see fig. 62) and its knowledge stock decreases by 19% (see fig. 63). The lower knowledge stock then slightly decreases the number of radical and incremental innovations that the focal firm undertakes, which is the reason for the focal firm’s decrease in profits. In response, the focal firm increases its resource investments in radical innovation, which helps to maintain adequate knowledge stock levels to continue its innovations (see fig. 64).

The most interesting aspect of this scenario is the profits generated by the supplier firm when we allocate all of its joint area innovation investments to its own product innovations. The supplier firm triples its innovation investments and yet its profits only increase by 13% (see fig. 65). The supplier firm’s redirecting of its extra resources to innovation investment is not proportional to its increase in profits because it quickly becomes knowledge constrained. This is evident in the supplier firm’s knowledge stock levels, which is the same as the baseline run by period 80 (see fig. 66). As the supplier firm’s profits increase, it invests more resources in incremental innovation, which do not generate enough additional knowledge stock to allow the supplier firm to undertake more innovations (see fig. 67).

5.2.10.2 Computational Results for Scenario 10: No Knowledge Transfer from the Joint Area

As the focal firm monitors the changes to the joint area, we change our model and remove the supplier firm from the supply chain. Once the supplier firm is removed, it loses its ability to transfer knowledge from the joint area and solely relies on its own knowledge stock for innovation. As in the previous run, the supplier firm is still knowledge constrained, which is made worse when it can no longer transfer knowledge
from the joint area. In response to the loss of knowledge transfer, the supplier firm increases its investment in radical innovation (see fig. 67) to increase both its profits and its knowledge stock levels (see fig. 66). However, the shift to more radical innovation investments is not enough to offset the loss of transferred knowledge, which reduced its profits by 19% (see fig. 65).

5.2.10.3 Implications and Conclusions for Supply Chain: Scenario 10

This scenario yields an interesting insight into the benefits and consequences of one firm taking advantage of the joint area and other supply chain members. The supplier firm runs a significant chance of being identified as a freeloader because the focal firm can detect the changes in the joint area. As a freeloader, the supplier firm’s overall profits increase; however, the additional invested resources needed to generate these extra profits are not proportional to the amount invested. The resources would be better invested to gain knowledge stocks from other supply chain members, purchase the knowledge, or improve its knowledge assimilation.

As shown in this scenario, the risk the supplier takes is not worth the benefit of the additional resources that it invests in its own firm. The supplier firm is knowledge constrained; therefore, the loss of knowledge transfer outweighs the benefits of investing the additional resources. In the event that the supplier firm would suffer a decrease in its knowledge stocks, due to an endogenous or exogenous factor, it would not have the knowledge stocks of the joint area to act as a buffer to replenish its own knowledge stocks. The supplier firm is better served in investing a portion of its resources in increasing its knowledge assimilation to transfer more knowledge from the joint area.
Fig. 60  Focal Firm’s Profit Value for Scenario 10

Fig. 61  Product Knowledge Stock of the Joint Area Level for Scenario 10
Fig. 62  Focal and Supplier Firms’ Level of Knowledge Transfer for Scenario 10

Fig. 63  Focal Firm’s Level of Knowledge Stock for Scenario 10
Fig. 64  Focal Firm’s Joint Product Frac Value for Scenario 10

Fig. 65  Supplier Firm’s Profit Value for Scenario 10
Fig. 66 Supplier Firm’s Level of Knowledge Stock for Scenario 10

Fig. 67 Supplier Firm’s Frac Value for Scenario 10
5.3 After Steady State Scenarios

In this set of scenarios we make changes to the system after it has reached a steady-state condition. In the previous set of scenarios, the firms are both responding to any changes in the model and to their goals for profits and knowledge stocks. The impact of certain changes may be hidden by other changes or the firms responding to their goals. By making the changes as the firms approach a steady-state condition, the reasons for the change can be more clearly identified and isolated.

These scenarios include single changes to the model at a specific time and changes that are repeated several times throughout the simulation. The single change scenarios investigate the role of turbulence in the firms, the supply chain, and the joint area by either increasing or decreasing the turbulence rate for the remainder of the simulation. The scenarios that have multiple changes help to investigate the repeated affect of product and process stock reductions and the affect of lower knowledge retention rates.

A turbulence rate can increase when a new competitor enters into a market. For example, Apple Computer® announced the introduction of their iPad® into the e-book reader market. Several companies, such as Amazon® with their Kindle® e-book reader are already in the market and the entrance of a new competitor will force them to increase the rate of change in their existing products. An effect of this new competitor is the existing products have a higher turbulence rate and will become obsolete more quickly. The opposite effect may occur when a competitor exits the market and the remaining companies no longer have to maintain their current rate of product innovations, resulting
in a lower turbulence rate. Another potential outcome of a competitor’s radical product launch is to cause all current products on the market to become obsolete. These changes in the market can cause the focal and supplier firms to change their innovation investments.

5.3.1 Scenario 11: Reduction of Product and Process Stocks at T Period Intervals

Firms and supply chains are periodically affected by the introduction of new technologies, new competitors, or changes to their markets that can cause all or most of their products to become obsolete. In this scenario, we explore the impact of repeated losses of product stocks to a single firm, to the supply chain, and to the supply chain and the joint area, which occur at T period intervals throughout the simulation. Without loss of generality, we set T to 25. We do not eliminate the products and processes that are currently in the radical and incremental development cycles because the firms and the joint area have the ability to alter the innovations to react to the changes that can obsolesce their product and process stocks.

We divide this scenario into four runs: 1) a baseline run with no reduction in product stocks, 2) a run in which only the focal firm’s product stocks are reduced, 3) a run in which only the focal and supplier firms’, or the supply chains’, product stocks are reduced, and 4) a run in which the supply chain’s product stocks and the joint area’s product and process stocks are reduced.

The simulations for this scenario are extended to 200 time periods to allow for multiple stock reductions and recoveries. The focal and supplier firms’ product stocks generate their profits and knowledge stock; therefore, when the product stocks are reduced, the firms temporarily lose their ability to generate profits and knowledge. To
provide the firms with profits and the resources for innovation investment, we have a budgeted value of 100 units of resources that is available in each period.

5.3.1.1 Computational Results for Scenario 11: Focal Firm Only

In this run, we reduce the focal firm’s radical and incremental product stocks beginning at period 50 and we repeat this reduction every 25th period. The reduction decreases the focal firm’s profits by 31% by period 200, as compared to the baseline run (see fig. 68). The affect on the focal firm’s knowledge stock is large immediately after the reduction (see fig. 69). To help replenish its knowledge stocks, the focal firm transfers knowledge from the product knowledge stock of the joint area and increases its resource investments in radical innovation (see fig. 70). In addition, as products progress through the radical and incremental product development cycle and are successfully launched, these products enter the product stocks and generate knowledge. The focal firm’s reactions are effective in helping to replenish its knowledge stock (see fig. 71) and allow it to increase its profits after every reduction (see fig. 68). A contributing factor in the focal firm’s profit recovery is the supplier firm’s continued investment in the joint area, which help to maintain the product knowledge stock of the joint area at a particular level. In the absence of the knowledge transferred from the joint area, the focal firm would not be able to sustain its innovations and its profits would not recover.

The supplier firm does not directly monitor the performance of the focal firm; however, it can detect changes to the joint area as the focal firm decreases its investments in the joint area. For instance, the focal firm, after the first reduction, invests enough resources in the joint area that the product knowledge stock of the joint area does not change (see fig. 71). However, the focal firm’s second product stock reduction, at period
75, decreases its profits, which causes a decrease in its resource investments in the joint area. Finally, after period 100, the supplier firm notices the reduction in the product knowledge stock of the joint area (see fig. 71) and its own knowledge stock (see fig. 72) due to a decrease in knowledge transfer from the joint area. However, the supplier firm’s knowledge stock reduction is not large enough to affect the number of innovations it undertakes; therefore, the supplier firm’s profits remain the same as the baseline run (see fig. 73).

5.3.1.2 Computational Results for Scenario 11: Supply Chain Run

In this run, we reduce both the focal and supplier firms’ product stocks beginning at period 50 and repeat this reduction every 25th period, which decreases the focal and supplier firms’ profits by 68% (see fig. 68 & 73). After each reduction, the focal and supplier firms return to approximately the same profit levels as the previous reduction. At this level of profitability, both the focal and supplier firms’ resource investments in their own firms and the joint area are just enough to sustain the number of innovations developed. In response to the decreased profits, both the focal and supplier firms invest more resources in radical innovation (see fig. 70 & 74). They gradually decrease this investment as their profits increase before the next reduction takes place and increase it immediately following the product stock decrease. This investment cycle continues for the remaining product stock reductions for the rest of the simulation.

5.3.1.3 Computational Results for Scenario 11: All Products and Processes Stocks Run

In this run, we reduce both the supply chain’s product stocks and the product and process stocks of the joint area beginning at period 50 and repeat this reduction every 25th period. Reducing the product and process stocks of the entire model causes the focal and
supplier firms’ profits to decrease by 99% (see fig. 68 & 73). In the previous runs, the focal and supplier firm replenished a portion of their knowledge stocks by transferring knowledge from the joint area. However, when we reduce the joint area product and process stocks as well, neither firm transfers enough knowledge to maintain their innovations. The reductions, along with the decrease in knowledge transfer creates a reinforcing feedback loop in which neither firm nor the joint area are able to exit. Even with the budgeted resources in each period, without the necessary knowledge stocks, few innovations are developed.

5.3.1.4 Implications and Conclusion for the Supply Chain: Scenario 11

Overall, this scenario stresses the importance of the ability to transfer knowledge from the joint area in order to replenish knowledge stocks. This is critical in helping a firm recover from a loss of its product stocks. Therefore, if a firm is in a market or develops products that are subject to obsolescence, it needs to develop supply chain relationships with firms that are not subject to these same reductions. As illustrated in our second run, through the resource investments of the supplier firm in the joint area, the focal firm is able to transfer enough knowledge from the joint area to begin investing in innovations that rebuild its product stocks. The third and fourth run illustrate that if either the supplier firm and/or the joint area is also affected by the product stock reductions, the focal or supplier firms cannot regain their baseline level of profitability.

Therefore, once a reduction takes place, especially to more than one firm or to the joint area, access to knowledge stocks is critical. The supply chain can gain access to knowledge stocks through another supply chain partner, the acquisition of a firm, or
purchasing knowledge stocks from the market. If the focal firm cannot find access to these knowledge stocks, it has no means to innovate products or to regain its profitability.
Fig. 70  Focal Firm’s Frac Value for Scenario 11

Fig. 71  Product Knowledge Stock of the Joint Area Level for Scenario 11
Fig. 72  Supplier Firm’s Level of Knowledge Stocks for Scenario 11

Baseline Run  Focal Firm Only Run  Supply Chain Run  All Products and Processes Run

Fig. 73  Supplier Firm’s Profit Value for Scenario 11

Baseline Run  Focal Firm Only Run  Supply Chain Run  All Products and Processes Run
Fig. 74  Supplier Firm’s Frac Value for Scenario 11
5.3.2 Scenario 12: Knowledge Retention Issues in Supply Chains

This scenario is an investigation of the effects of knowledge retention capabilities of the focal firm, the supply chain, and the joint area. As knowledge retention becomes an issue within firms and supply chains, the rate at which knowledge stocks decrease may accelerate. As firms’ knowledge stocks decrease the number of innovations they can undertake may potentially decrease as the knowledge is less viable for future innovations. A method of replenishing the knowledge stocks is by transferring it from the joint area, although knowledge transfer is dependent on the firm’s knowledge assimilation ability.

We initialize the knowledge loss rate at 11% per period and increase it by a factor of 2 at every 100 time periods. The scenario consists of three runs: 1) a run in which only the focal firm’s knowledge stock is subject to increased knowledge loss, 2) a run in which the focal and supplier firms’, or the supply chain’s, knowledge stock is subject to increased knowledge loss, and 3) a run in which the supply chain’s knowledge stocks and the joint area’s product and process knowledge stocks are subject to increased knowledge loss. In each of these runs, we set three different knowledge assimilation levels for the firms: a low level with Θ=10%; a medium level with Θ = 55%; and a high level with Θ=100%. We extend the number of time periods to 500 for this scenario to allow the firms an opportunity to adjust to changes in their rate of knowledge loss and potentially return to a steady state condition before the next increase.

5.3.3.1 Computational Results for Scenario 12: Focal Firm Only Run

The results for this run show that a firm with a low knowledge assimilation level has decreased profits before the first increase in the knowledge loss (see fig. 75). The
focal firm, with low knowledge assimilation level, is not able to replenish its knowledge stocks through innovation and knowledge transfer from the joint area faster than it is lost. The decreasing knowledge stock then limits the number of innovations developed, further reducing the focal firm’s profits and knowledge stocks, and resulting in a reinforcing feedback loop. On the other hand, at higher levels of knowledge assimilation, the focal firm is able to maintain its profits through period 300, with the knowledge loss rate at six times the initial levels. However, the focal firm’s profits, with a medium knowledge assimilation level, begin a rapid decrease at this rate of knowledge loss (see fig. 75). With a high knowledge assimilation level, the focal firm’s profits gradually decrease until period 400. After this period, the decreases in the knowledge stock (see fig. 76) limit the number of innovations and all knowledge assimilation levels cease earning profits (see fig. 75).

Similar to the focal firm, the supplier firm, with a low knowledge assimilation level, has a gradual decrease in profits. On the other hand, the supplier firm maintains its profitability until period 400 with a high knowledge assimilation level, and has a slight decrease in profits with a medium knowledge assimilation level (see fig. 77). One difference between the focal and supplier firms is the period at which the profits begin to decline. The supplier firm’s profits begin to decline 100 periods after the focal firm’s, because the supplier firm is not subject to a direct increase in its rate of knowledge stock loss. As the focal firm’s profits decrease, it invests fewer resources in joint area innovations, which decreases the product knowledge stocks of the joint area and the amount of knowledge the supplier firm can transfer (see fig. 78).
5.3.2.2 Computational Results for Scenario 12: Supply Chain Run

In this run, both the focal and supplier firms’ profits are the same and begin to decline at period 300 (see fig. 79), which corresponds with the decrease in the firms’ knowledge stocks (see fig. 80). As in the previous run, both the focal and supplier firms’ level of knowledge assimilation acts to delay the affect of the increasing knowledge stock loss rate. For example, at period 200, the focal firm’s knowledge stock level, with high knowledge assimilation, is approximately the same as the level with medium knowledge assimilation at period 199 (see fig. 80). Thus, a firm with high knowledge assimilation and four times the initial rate of knowledge stock loss has the same knowledge stock level as a firm with medium knowledge assimilation at two times the initial rate of knowledge stock loss. Therefore, a firm with high level of knowledge assimilation can delay the decrease in its knowledge stock more so than a firm with a lower level of knowledge assimilation.

5.3.2.3 Computational Results for Scenario 12: All Knowledge Stocks

In this run, the focal and supplier firms have the same profits, which begin declining after period 200 (see fig. 81). In the previous two runs, the focal and supplier firms relied on the joint area to lessen the impact of their knowledge stock losses. However, when the joint area also experiences the same increases in knowledge stock loss rates, its knowledge stocks also decrease (see fig. 82), which, in turn, decreases the amount of knowledge transferred to the firms. The affect that higher knowledge assimilation had in delaying the profit declines in the previous runs is no longer effective in this run because there is less knowledge to transfer from the joint area.
5.3.2.4 Implications and Conclusions for the Supply Chain

This scenario differs from some of the other scenarios in the benefit to the focal and supplier firms being in a supply chain relationship. Without the supply chain and a supplier firm that is not subject to the same knowledge stock losses, the focal firm would not be able to delay the effect of its knowledge stock losses by transferring knowledge from the joint area. The supplier firm also benefits from the supply chain relationship when it is also subject to an increased losses in its knowledge stocks. Through their investments in the joint area, the firms use the product knowledge stock of the joint area as a buffer to their losses in knowledge stock by transferring knowledge. However, this knowledge buffer is only effective when the firms can assimilate the knowledge transfers and when the joint area is not subject to increased losses in its own knowledge stock. In an environment that is subject to increased rates of knowledge stock losses, the firms not only need to develop supply chain relationships that are not affected by the same losses, but they also must be able to assimilate the knowledge that is available for transfer.
Fig. 75 Focal Firm’s Profit Value for Scenario 12: Focal Firm Only Run

Fig. 76 Focal Firm’s Level of Knowledge Stocks for Scenario 12: Focal Firm Only Run
Fig. 77  Supplier Firm’s Profit Value for Scenario 12: Focal Firm Only Run

Fig. 78  Joint Area Product Knowledge Stock Level for Scenario 12: Focal Firm Only
Fig. 79  Focal and Supplier Firms’ Profit Value for Scenario 12: Supply Chain Run

Fig. 80  Focal and Supplier Firms’ Level of Knowledge Stocks for Scenario 12: Supply Chain Run
Fig. 81  Focal and Supplier Firms’ Profit Value for Scenario 12: All Knowledge Stocks Run

Fig. 82  Product Knowledge Stock of the Joint Area Level for Scenario 12: All Knowledge Stocks Run
5.3.3 Scenario 13: From High to Low Turbulence Rate at Period T

Individual firms and supply chains are subject to periods of turbulence in the markets. For example, if a competitor exits the market, or the supply chain develops a product line that is difficult for the competition to imitate, the rate at which products obsolesce might be reduced. The reduction in the turbulence rate reduces the number of products and processes that are removed from the stocks, thus increasing the profits and knowledge that firms can generate. Therefore, the firms and the joint area may invest in less risky innovations to generate the same level of profits and knowledge, compared to a higher turbulence market.

For this scenario, we initialize the turbulence rate at 7% per period and reduce it to 2% per period at period T: without loss of generality, we set T to 25. As a note, the turbulence rate of 2% is the baseline rate for all scenarios. We divide this scenario into 4 runs: 1) a baseline run, 2) a run in which only the focal firm is subject to a change in its turbulence rate, 3) a run in which the focal and supplier firms, or supply chain, are subject to a change in their turbulence rate, and 4) a run in which both the supply chain and the joint area are subject to a change in their turbulence rate.

5.3.3.1 Computational Results for Scenario 13: Focal Firm Only Run

In this run, we initialize the focal firm’s turbulence rate at 7% per period and reduce it to 2% per period at time 25. The initially high turbulence rates leads to a 31% decrease in the focal firm’s profits at period 100, as compared to the baseline run (see fig. 83). The reason for this is the focal firm’s knowledge stock decreases to such a level, by period 25, that it cannot regain its baseline run’s level by period 100 (see fig. 84). After
the turbulence rate is reduced, the knowledge stock replenishes through successful innovations and knowledge transfer from the joint area.

The supplier firm is not subject to the initial increase in the turbulence rate, during the first 25 time periods, and has the same profits as compared to the baseline run (see fig. 85). The focal firm’s knowledge stock recovery is assisted by the supplier firm’s profits and investments in the joint area. However, the supplier firm’s resource investments are not enough to fully off-set the focal firm’s decrease in investments due to its lower profits, and the knowledge stock has a small decrease starting at period 40, compared to the baseline run (see fig 86).

5.3.3.2 Computational Results for Scenario 13: Supply Chain Run

In this run, we initialize the focal and supplier firms’ turbulence rate at 7% per period and reduce it to 2% per period at time 25. The supplier firm’s profits decrease by 39%, (see fig. 85), caused by its product stock decrease and the subsequent decrease to its knowledge stocks (see fig. 87). The reduced knowledge stocks decrease the supplier firm’s ability to replenish its product stocks because it can undertake fewer innovations each period. The decrease in profits also affects the joint area, because the supplier firm has fewer resources to invest in the joint area decreasing its product knowledge stock (see fig. 86). This decrease also affects the supplier firm because it needs to replenish its own knowledge stocks, but the joint area has less knowledge to transfer. The decrease in the product knowledge stock of the joint area also decreases the focal firm’s profits slightly, compared to run 2 (see fig. 83).
5.3.3.3 Computational Results for Scenario 13: All Products and Processes

In this run, we initialize the turbulence rate at 7% per period for all products and process stocks and reduce it to 2% per period at time 25. The focal and supplier firms’ profits decrease by 74%, compared to the baseline run (see fig. 83 & 85). The profit decreases of the firms and the initial increase in the turbulence rate in the joint area further reduces the number of innovations developed in the joint area and its product knowledge stock (see fig. 86). Without the same level of knowledge transfer as the previous runs to offset the effects of the increase in the turbulence rate, neither firm can undertake as many innovations. If this run is extended to 250 periods, the focal and supplier firm finally return to their baseline profitability and knowledge stock levels. Thus, the initial 25 periods of an increased turbulence rate decreases the knowledge stocks to such a level that it requires an additional 225 periods to recover.

5.3.3.4 Implications and Conclusions for the Supply Chain

As this scenario illustrates, a short duration of an increased turbulence rate can have long-term effects on the profitability of a firm and a supply chain. In the event that a single firm is subject to an increased turbulence rate, it needs to have supply chain partners and a joint area that are not affected by the same turbulence rates. Therefore, when selecting supply partners, a firm must take this issue into account, especially if it is in a market that has a high probability of turbulence.

If both firms and the joint area are affected by increased turbulence rates, they need to find access to additional knowledge stocks to replenish their own and the joint area’s knowledge stocks. Relying solely on their own innovations and knowledge transfers from the joint area limits the recovery rate of their profits and knowledge stocks.
Another important factor is the timing of when the knowledge is added to the stocks because the sooner the firms can increase the number of innovations developed, the more rapidly their knowledge stocks will recover.

Fig. 83 Focal Firm’s Profit Value for Scenario 13
Fig. 84  Focal Firm’s Level of Knowledge Stock for Scenario 13

Fig. 85  Supplier Firm’s Profit Value for Scenario 13
Fig. 86  Product Knowledge Stock of the Joint Area Level for Scenario 13

Fig. 87  Supplier Firm’s Level of Knowledge Stock for Scenario 13
5.3.4 Scenario 14: From Low to High Turbulence Rate at Period T

Firms and supply chains are subject to periods of turbulence, in which the rate of products and processes being removed from the stocks can increase. For example, when a new competitor enters the market, the turbulence rate of products can increase, causing products to obsolesce more quickly. The removal of a product from a firm’s product stocks decreases a firm’s profits and knowledge stocks, which may require a change in the level of resource investment in radical and incremental innovation.

For this scenario, we set the initial turbulence rate to 2% per period and increase it to 7% per period. Without loss of generality, we set T to 25. The scenario is divided into 4 runs: 1) a baseline run, 2) a run in which only the focal firm’s product turbulence rates increase, 3) a run in which the supply chain’s product turbulence rates increase and, 4) a run in which all product and process turbulence rates increase.

5.3.4.1 Computational Results for Scenario 14: Focal Firm Only Run

In this run, we increase the focal firm’s turbulence for its radical and incremental product stocks from 2% to 7% in period 25. After doing this, we observed that its profits decreased by 71% (see fig. 88). In addition, the decrease in the product stocks affects the knowledge stock beginning in period 26 (see fig. 89). In response to the decrease in profits and knowledge stock, the focal firm increases \( \frac{frac_{ri}}{n} \) and invests more resources in radical innovation (see fig. 90). The replenishment of the knowledge stock is accomplished by transferring knowledge from the joint area. However, the focal firm’s decrease in profits allow it to invest fewer resources in the joint area which decreases the number of innovations to be developed in the joint area and results in a decrease in the
product knowledge stock of the joint area after period 25 (see fig. 91). Due to the continued investments by the supplier firm, the decrease in this knowledge stock is small (see fig. 92), which allows it to slightly increase its profits after period 80 (see fig. 88).

The decrease in profits by the focal firm affects the investment decisions of the supplier firm, even though the supplier firm’s turbulence rate does not change. The decrease in the product knowledge stock of the joint area decreases the knowledge the supplier firm is able to transfer. With less knowledge transfer, the supplier firm’s knowledge stock decreases slightly (see fig. 93), which lowers the number of innovations it undertakes and decreases its profits following the increase in turbulence (see fig. 94). It responds by decreasing $frac_{it}$, and increasing its resource investments in radical innovation (see fig. 95) allowing it to return to its baseline profitability by period 60.

5.3.4.2 Computational Results for Scenario 14: Supply Chain Run

In this run, we increase the focal and supplier firms’, or the supply chain’s, turbulence from 2% to 7% per period at time 25. The focal firm undertakes fewer innovations, which results in its profits decreasing, compared to the previous run (see fig. 88). The supplier firm’s increase in turbulence decreases its profits by 75%, as compared to the baseline run (see fig. 94), which decreases its resource investments in the joint area. As a result, the product knowledge stock of the joint area decreases (see fig. 91), affecting the focal firm by decreasing the amount of knowledge transferred (see fig. 92). In response to these changes in turbulence, the focal and supplier firms increase their resource investments in radical innovation (see fig. 90 & 95). However, the decreased knowledge stocks do not allow enough innovations to be developed for either firm to exit the reinforcing feedback loop that is created with the increased turbulence rate.
5.3.4.3 Computational Results for Scenario 14: All Products and Processes Run

In this run, we increase the turbulence for the focal and supplier firms’ products and the products and processes of the joint area from 2% to 7% per period at time 25. The increase in turbulence results in both firms and the joint area having lower levels of knowledge stocks (see fig 89, 91, & 93), which leads to a 92% decrease in the focal and supplier firms’ profits, compared to the baseline run (see fig. 88 & 94). The decrease in profits results in fewer resource investments in innovation, which creates a reinforcing feedback loop for the focal and supplier firms.

Both firms attempt to exit the reinforcing feedback loop by increasing their investments in radical innovations (see fig. 90 & 95). In the previous runs, each firm utilizes the joint area knowledge stock as a cushion to absorb the loss of their own knowledge stocks. However, when the product knowledge stock of the joint area is also affected, neither firm can transfer enough knowledge to maintain their radical innovations.

5.3.4.4 Implications and Conclusions for the Supply Chain: Scenario 14

If either the focal or supplier firm, or both, experience increased turbulence in their product stocks, access to the joint area helps them to recover a portion their profitability and knowledge stocks, as compared to the baseline run. On the other hand, when the joint area is also subject to increased turbulence, neither firm is able to maintain its profitability. Therefore, if a firm is in a market that is subject to increases in turbulence, it should select supply chain members that are not subject to the same turbulences. The transferred knowledge alone is not sufficient for the firms to recover because it does not allow them to regain their profitability by the end of the simulation.
Nevertheless, the firms can begin to replenish both their product and knowledge stocks through the transfer of knowledge from the joint area and begin to return to their previous profit levels.

In a supply chain relationship, the focal and supplier firms need to establish a joint area that is not susceptible to the same turbulences. As shown in this scenario, if the focal and supplier firms experience turbulence and the joint area can maintain its product knowledge stocks, each firm can slowly regain its profitability. In contrast, if the joint area is also subject to turbulence, neither firm regains its profitability. In the event that both firms and the joint area are subject to the increased turbulence, the firms need to change their strategy and should invest their resources into radical or incremental products that are not subject to the turbulence. This change can also be accomplished through the acquisition of technologies from other firms or introducing a firm to the supply chain relationship that provides product stocks, and subsequently knowledge stocks that are not subject to the increased turbulence.
Fig. 88  Focal Firm’s Profit Value for Scenario 14

Fig. 89  Focal Firm’s Level of Knowledge Stock for Scenario 14
Fig. 90  Focal Firm’s Frac Value for Scenario 14

Fig. 91  Product Knowledge Stock of the Joint Area Level for Scenario 14
Fig. 92  Focal Firm’s Level of Knowledge Transfer for Scenario 14

Fig. 93  Supplier Firm’s Level of Knowledge Stock for Scenario 14
Fig. 94  Supplier Firm’s Profit Value for Scenario 14

Fig. 95  Supplier Firm’s Frac Value for Scenario 14
5.4 Industry Scenarios

We use two different industries, high technology and pharmaceutical drug development, to investigate how they respond to innovations and supply chain relationships. In these scenarios, we employed two modified supply chain strategies. In the high technology scenario, we use a model similar to the previous scenarios with the addition of the ability of the focal firm to utilize any non-allocated resources to purchase radical innovations from the market. In the pharmaceutical scenario, the focal firm relies solely on the market based interactions to purchase drugs at different stages of development. By changing how the focal firm interacts with relationships outside of its boundaries, relationships that are not purely collaborative can be investigated.

5.4.1 Scenario 15: High Technology Industry

In this scenario, we model the change to the Samsung Electronics Corporation as it shifted its focus from a provider of commodity consumer products to being a key competitor in product innovation in the electronics industry (Forhoomand, 2009). Samsung Electronics originally focused on the manufacture of consumer products for its supply chain partners and on incremental product development. However, it soon realized that this segment of the market is highly cost competitive, so it shifted its focus on product development to more radical products that had less price competition in the market (Forhoomand, 2009). Samsung Electronics not only changed its internal operations, but also the operations and structure of its supply chain relationships to focus less on individual products and more on a portfolio of products. In doing so, Samsung Electronics invests only a portion of its resources in the development of supply chain
relationships in order to gain knowledge from foreign markets and it focuses much of its efforts on the development of its own innovation capability (Forhoomand, 2009).

5.4.1.1 Model Set-up: Scenario 15

This scenario uses the same base model as Scenarios 1-14 with some modifications to the focal firm and the addition of the ability of the focal firm to purchase radical innovations. As a note, we did not include this ability in the previous scenarios because the focus of those runs was to investigate the collaborative aspects of supply chain relationships. However, in the high technology market place, internal innovation alone may not be enough to allow supply chains to succeed due to the faster pace of obsolescence and the emphasis on radical innovations to generate profits and knowledge. Therefore, to stay competitive, firms and supply chains have more incentive to look beyond their relationships to purchase promising innovations from other firms in the market.

One change to the model is the profits and knowledge generated for radical and incremental products, which we changed to reflect the high technology industry’s shorter product life cycles and larger reliance on radical products. The knowledge stock and profits per incremental product are reduced by 20% from the previous scenarios and the values for the radical products are increased by 20% to reflect the importance of radical innovations for the supply chain. We also increased the amount of profit and knowledge generated by each radical product to reward the radical innovations over incremental innovations. In addition, the product and process stocks have new time categories that also reflect the shorter product life cycles: <1 mo, 1-3 mo, 4-6 mo, and >6 mo. Table VI shows the modified values for profit and knowledge stock generated for a given time
category, which are applied to the focal and supplier firm and the joint area. (See Appendix G for the modified Vensim model)

Another change to the focal firm is the amount of resources that are allocated in the firm and in the joint area. In the original model, the focal firm invests equal proportions of its resources in the firm, product innovation in the joint area, and process innovation in the joint area. These original values are designed to be an exploratory to analyze the relative difference of the values. The values for this scenario are also exploratory and are changed to reflect the high technology industry’s higher reliance on internal investments and purchases of innovations. We change the focal firm’s allocation to 50% of its resources in its own firm, and 25% each in product and process innovation in the joint area. We also increase the focal firm’s profit goals from 450 to 1300, which results in lowering the focal firm’s $frac_{it}$, placing more emphasis on radical innovation within its firm. We also introduce a uniform random factor between [0.90, 1.10] that is multiplied by the Rad Prod Success Rate to vary the focal and supplier firms’ value between 90% and 110% each period.
Table VI  New Values for Profit and Knowledge per Radical and Incremental Product for Scenario 15

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<th>Time Category</th>
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<td></td>
<td>Profit, $\pi_{rad}$</td>
<td>Knowledge, $\kappa_{rad}$</td>
</tr>
<tr>
<td>&lt;1 mo</td>
<td>36</td>
<td>14</td>
</tr>
<tr>
<td>1-3 mo</td>
<td>24</td>
<td>10</td>
</tr>
<tr>
<td>4-6 mo</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>&gt;6 mo</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

(Note: All radical product that are older than 3 months are transferred to the incremental product stock of 4-6 months)

The final change to the model is the ability of the focal firm to purchase radical innovations from the market by utilizing its non-allocated innovation resources. Because the purchased products are already developed and ready to be added to the focal firm’s launched radical product stock, we assume that the firm pays a price that is twice the cost of developing its own products. These products are eventually launched to the focal firm’s <1 mo product stock where they progresses through the firm the same as an internally developed product.

5.4.1.2 Computational Results for Scenario 15

Purchasing radical products from the market changes the focal firm’s growth in profits at later periods of the simulation, as compared to the previous scenarios. In the previous scenarios, the firms are typically knowledge constrained in their ability to innovate products. As the focal firm purchases radical products, it can increase its
knowledge stock level at a faster rate than through innovation and knowledge transfer from the joint area alone (see fig. 96). Using its non-allocated resources, the focal firm typically purchases between 1 and 2 radical products per period, with a mean value of 1.57 (see fig. 97). Over the course of the simulation, these products are slowly enabling the knowledge stock level of the focal firm to increase and the knowledge constraint to decrease.

At approximately period 50, in the iterations with higher success rates, these additional knowledge stocks alleviate the focal firm’s knowledge constraint, allowing it to increase the number of innovations it can develop within its firm. These additional innovations further increase the focal firm’s knowledge stock level, allowing it to continue to increase the number of innovations developed internally, resulting in an increase in its profits (see fig. 98). However, by period 150, the focal firm is knowledge constrained again because the increase in its level of profits again allow it to fund more innovations than the knowledge stock levels allow. The purchased innovations are not able to overcome the knowledge constraint again by the end of the simulation and the profits remain steady (see fig. 98).
Fig. 96  Focal Firm’s Knowledge Stock Level for Scenario 15

Fig. 97  Number of Radical Products Purchased per Period for Scenario 15
5.4.1.3 Implications and Conclusions for the Supply Chain

In this scenario, the high technology firm is able to utilize both its supply chain relationship and the purchase of innovations from the market to build its level of knowledge stock level. Without access to the market based sources of innovation and the knowledge that these innovations provide to the firm, the number of internal innovations the firm can develop is limited. By alleviating its knowledge constraint more quickly than waiting on knowledge transfers and internal innovations alone, the firm is able to increase the number of innovations it can develop by 33% internally, in addition to the purchased innovations. The firm’s profits increase by 63% after the purchased innovations are able to overcome the initial knowledge constraint.

This scenario also illustrates that firms that have very short life cycle products need to look outside of its firm and supply chain in order to increase their knowledge stock levels. Even by paying twice the internal development cost for an innovation, the
focal firm is able to have a sizable return on these investments by increasing their profits and the number of innovations it can internally develop. On average, the focal firm invests a total of 31,400 units of resources in the purchase of radical innovations over the course of 200 periods. These investments help to increase the focal firm’s profits between periods 100 and 200 by an average of 370 units. The increased profit levels generates an additional 37,000 units of resources in profits, resulting in a net gain from the radical innovation purchases of 5,600 units of resources.

The emphasis on radical innovation in the high technology industry requires the firms and supply chains to seek additional knowledge from outside its relationships. However, these purchased innovations only help the focal firm for a short period of time before the firm becomes knowledge constrained again. The firms and supply chains need to continuously monitor its knowledge stock because it has a large impact on the profit growth of the firms and the supply chain. As our scenario shows, purchasing radical innovations, even at twice the internal development cost, can increase profits when the knowledge stock they provide alleviates a firm’s knowledge constraint.

5.4.2 Scenario 16: Pharmaceutical Firm

In this scenario we model a pharmaceutical company that is involved in the development and marketing of drugs. A company has many options in how it brings these drugs to the market, including collaborative relationships with their supply chain, joint ventures, and purchasing the drugs in development from the market-based relationships. This scenario differs from the first two sets in that the pharmaceutical company that we model uses market based relationships to purchase drugs at different stages of development. Therefore, company’s external relationships are based on more
than a focal or supplier firm investing resources in a joint area and receiving knowledge for future product innovations. This type of relationship is common in the pharmaceutical industry where the current cost of bringing a drug to the market, in 2006, was $1.3 billion, with over 2900 compounds in development, and an average time to develop a drug being between 10 to 15 years (PHARMA, 2009). The company cannot solely depend on its own internal development, but needs to scan the market for promising drugs to purchase. The company has an opportunity to purchase a drug(s), at various stages of development, for the accumulated costs of the drug’s development, that have not received Food and Drug Administration (FDA) approval. This drug then enters the company’s current drug development cycle in the anticipation that the purchased drug will be successfully launched into the market. (See Appendix H for the Vensim model)

5.4.2.1 Scenario 16: Pharmaceutical Company’s Drug Development Cycle

The company has the opportunity to internally develop two types of drugs: a new chemical entity (NCE) and a life cycle management (LCM) drug (Mathieu, 2003). NCEs are drugs that do not have a direct competitor currently in the market. LCMs are drugs that are approaching their patent expiration and have been modified and resubmitted for a new patent or an NCE that is being resubmitted for a new patent to develop the drug for a different effect. An example of an LCM drug is Viagra® which had a side effect noticed during its original NCE development as a drug to treat angina, or heart pain, and was subsequently resubmitted for a patent as an LCM drug (Langreth, 1998).

There are five stages to the development for both LCM and NCE drugs after an Investigational New Drug (IND) patent has been filed: Preclinical, Phase I, Phase II, Phase III, and NDA Review (Mathieu, 2003). In our model, we combine all pre-patent
development stages and aggregate the time and costs into the Preclinical stage. In the Preclinical stage, the drug is tested on animals for safety and metabolism. If successful the drug moves to the next stage of development, Phase I, where the drug is tested on a small group of healthy people. Again, if successful, the drug then moves on to next stage of development, Phase II, where it tested on a small sample of people for safety and efficacy. A successful drug then moves to the development stage, Phase III, where the sample of people is expanded and the drug is tested on a larger group of people. It then moves to the final development stage, where the New Drug Application (NDA) Review is submitted to the FDA, and if successfully reviewed, the drug enters the market (Girotra, Terwiesch, & Ulrich, 2007; Mathieu, 2003). We assume that any drug that is unsuccessful at any stage of development is placed in the Dormant Drugs stock.

As a note, the costs are based on the time a drug spends in a particular development stage and include the development of both successful and unsuccessful drugs. Tables VII & VIII show the development time, costs, and success rates for the NCE and LCM development cycles.
Pharmaceutical companies employ several methods of introducing new drugs into their development cycle. One method is to internally undertake R&D from the beginning stages of research and development of the drug through to its launch in the market. As shown in Tables VII and VIII the overall success rate of a drug after its patent filing is very low, therefore a large number of drugs need to be developed in order for a single
drug to be successfully launched. According to Mathieu (2003: 55) the ten largest pharmaceutical companies, in terms of revenues, need an average of 11.8 IND patent filings per year to achieve 1 NCE launch per year. Therefore, we introduce 11.8 new NCE drugs into the Preclinical stage in our model.

The pharmaceutical companies can also form joint ventures and other structured agreements with biotechnology and other pharmaceutical companies to co-develop drugs. Pharmaceutical companies can also outsource the development of promising LCMs and NCEs to Contract Research Organizations (CRO). The CROs are utilized for their expertise in a certain area or to outsource the development of the NCE or LCM if the pharmaceutical company does not have the resources or time to continue the development themselves. Both of these options are collaborative in nature because of the joint involvement of each company throughout the development stages (Ohba & Figueiredo, 2007).

Another method of developing drugs is through the purchase of an NCE at various stages of development from the market. In our model, we use this market-based strategy to investigate a relationship that does not rely exclusively on collaborative development through the joint area. In this model, if the company chooses to purchase an NCE drug in a given period, it uses a percentage of its profits to acquire the drug. We assume the company’s purchase price for an NCE is the cumulative cost of the drug up to that point in its development, which is the same cost as if it were developed internally (see Table VII). The NCE then enters the company’s own drug development cycle at the stage from which it is purchased and proceeds through the development cycle, where it
incurs all costs and is subject to the same success rates as all other NCEs currently in development.

5.4.2.2 Pharmaceutical Market

After a drug is successfully reviewed by the FDA, it enters the market and we form four time categories for the drugs progression through its life cycle: _New, 1-3 yrs, 4-6 yrs, and 7-12 yrs_. These time categories were selected based on the annual revenues generated by a typical drug (Grabowski, Vernon, & DiMasi, 2002) (see fig. 99 & Table IX). During its progression through the time categories, a drug may be taken off of the market due to efficacy, safety, or economic reasons (Mathieu, 2003). Without loss of generality, we move these types of drugs to the _Dormant Drug_ stock at a rate of 3% per year. If a drug is not removed to the Dormant Drug stock and has been on the market for 12 years, we move the drug to the _Off-patent_ stock. Once a drug has been on the market for 20 years, we classify it as expired and remove it from the Off-patent stock.

After the launch of a new NCE, there is the chance that the drug might have a competing _Follow-on_ drug launched into the market. The Follow-on drugs may be a competitor drug that launches after the NCE or a drug that was brought into development by a competing company after the IND filing (Ganuza, Llobet, & Dominguez, 2009). Once a Follow-on drug is launched into the market, the current drug is moved from the NCE stock to the corresponding Follow-on stock of the same time category. NCE drugs that become Follow-on drugs have been on the market for more than 1 year, therefore Follow-on’s first time category is _1-3 yrs_. We assume that the drugs are moved from the NCE to Follow-on stocks at the following rate: 1-3 years at 5% per period; 4-6 years at 10% per period; and 7-12 years at 15% per period.
Grabowski et al. (2002) determined the revenue values of a typical NCE drug (see fig. 99 for a copy of their graph) and we interpolate the values from the graph and averaged them for our given time categories (see Table IX). An LCM drug has 50% of the revenues of an NCE drug (Mathieu, 2003). We assume that the revenues of all Follow-on drugs will be the same as a typical LCM for a given time category due to competitive pricing. We also assume that all off-patent drugs receive the same revenue.

Table IX Annual Revenues for NCE, Follow-on, and LCM Drugs (in MM$) for Scenario 16

<table>
<thead>
<tr>
<th></th>
<th>New</th>
<th>1-3 yrs</th>
<th>4-6 yrs</th>
<th>7-12 yrs</th>
<th>Off-patent</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCE</td>
<td>75</td>
<td>108.33</td>
<td>250</td>
<td>545.83</td>
<td>200</td>
</tr>
<tr>
<td>Follow-on</td>
<td>NA</td>
<td>54.17</td>
<td>125</td>
<td>277.92</td>
<td>200</td>
</tr>
<tr>
<td>LCM</td>
<td>37.5</td>
<td>54.17</td>
<td>125</td>
<td>277.92</td>
<td>200</td>
</tr>
</tbody>
</table>

(Grabowski et al., 2002) & (Mathieu, 2003)
Using the development cost values from Table VII and the revenues from Table IX, the annual revenues for all NCE, Follow-on, and LCM drugs, based on their time category can be calculated. In addition, the development costs for the LCMs and NCEs can be calculated for each period and for each stage of development. Let $AR_{LCM_t}$ be the annual revenues for the LCM drug stocks at time $t$ and $AR_{NCE_t}$ be the annual revenues for the NCE drug stocks at time $t$. Also, let $AR_{Follow-on_t}$ be the annual revenues for the Follow-on drug stocks for at time $t$. Thus,

$$AR_{LCM_t} = \sum_k LCM_{kt} \times LCM_{Rev_k}$$

$$AR_{NCE_t} = \sum_k NCE_{kt} \times NCE_{Rev_k}$$
Where $LCM_k$ is the number of LCM drugs in time category $k$, 

$LCM_{Rev}^k$ is the revenue of an LCM drug in time category $k$, 

$NCE_k$ is the number of NCE drugs in time category $k$, 

$NCE_{Rev}^k$ is the revenue of an NCE drug in time category $k$, and 

$k \in \{New, 1-3 \text{ yrs}, 4-6 \text{ yrs}, 7-12 \text{ yrs}, Off\text{-}patent\}$

$$AR_{\text{Follow-on}_t} = \sum_m \text{Follow-on}^*_m \times \text{Follow-on}_{Rev}^m$$

Where $\text{Follow-on}^*_m$ is the number of Follow-on drugs in time category $m$, 

$\text{Follow-on}_{Rev}^m$ is the revenue of a Follow-on drug in time category $m$, and 

$m \in \{1-3 \text{ yrs}, 4-6 \text{ yrs}, 7-12 \text{ yrs}, Off\text{-}patent\}$

The company also incurs costs for the development of LCM and NCE drugs at the various stages of development. Let $DC_{\text{LCM}_t}$ be the development cost for all LCM drug developments at time $t$ and let $DC_{\text{NCE}_t}$ be the development cost for all NCE drug developments at time $t$. Thus,

$$DC_{\text{LCM}_t} = \sum_n LCM_{\text{Dev}^n} \times LCM_{C^n}$$

$$DC_{\text{NCE}_t} = \sum_n NCE_{\text{Dev}^n} \times NCE_{C^n}$$

Where $LCM_{Dev}^n$ is the number of LCM drugs in development stage $n$, 

$LCM_{C^n}$ is the development cost of an LCM drug at development stage $n$, 

$NCE_{Dev}^n$ is the number of NCE drugs in development stage $n$, 

$NCE_{C^n}$ is the development cost of an NCE drug at development stage $n$, and 

$n \in \{Preclinical, Phase I, Phase II, Phase III, NDA Review\}$
These annual revenues and development costs are combined to determine the *Profits* for each period $t$. Thus,

$$\text{Profits}_t = (AR_{-LCM} + AR_{-NCE} + AR_{-Follow-on}) - (DC_{-LCM} + DC_{-NCE})$$

5.4.2.3 Purchasing of Developmental NCEs

The typical pharmaceutical firm spends 13% of their total revenues on R&D (Grabowski et al., 2002). Thus, we assume a portion of the expenditures is spent on the company’s current NCE and LCM developments. Therefore, the portion of the revenues less the development costs, which we calculate as the profits, is the remaining portion of the company’s revenues that are not allocated and available to be used to purchase NCE drugs. Let $R&D_{-NCE} \_ P_t$ be the amount of profits that the firm can use to purchase an NCE drug at time $t$. Thus,

$$R \& D_{-NCE} \_ P_t = \text{Profits}_{t-1} \times 0.13$$

5.4.2.4 Computational Set-up for Scenario 16

The model is simulated for 100 time periods, with each period representing 1 year. Each development stage for an NCE drug is initialized with the number of drugs that would be available without any purchases from the market. For example, the company introduces 11.8 INDs per year and the Preclinical stage’s success rate is 39%, therefore the Phase I has an initial value of 4.6 drugs. Without loss of generality, we also initialize each time category in the NCE, Follow-on, and LCM stocks with 1 product per year a typical drug spends in the stock. For example, a typical drug is in the *New* stock.
for 1 year, therefore it is initialized with a value of 1 drug, and the 7-12 years stock is initialized with a value of 6 drugs.

To analyze the effects of changing success rates on this model, we run 200 iterations and vary the success rate for the NCE and LCM developments at each stage. To do so, a uniform random number between [0.90, 1.10] is generated at the beginning of each iteration and multiplied by the given NCE and LCM success rates for each stage of development. This variation results in a range of success rates between 90% and 110% of those given in the literature.

To determine at which stage of development an NCE drug is purchased, we assume that the number of drugs in any given development stage within the company is proportional to the probability of the company purchasing an NCE drug in that stage. At each period, a uniform random number between [1,100] is generated to determine the stage of development for the NCE drug purchase, based on the cumulative percent of development stages in Table X. Let $P_{NCE nt}$ be the number of NCE drugs purchased at stage $n$ of development at time $t$. Thus,

$$P_{NCE nt} = \text{Integer} \left( \frac{R \& D_{NCE P_t}}{CC_n} \right)$$

Where $CC_n$ is the cumulative cost of development of an NCE drug (from Table VII)

$$n \in \{ \text{Preclinical, Phase I, Phase II, Phase III, NDA Review} \}$$

Any non-allocated portion of $R\&D_{NCE P_t}$ is added to the next period $t+1$. Once an NCE is added to a development stage, it is treated the same as all other drugs in that stage and is subject to the same success rates throughout its remaining development.
Table X  Probability of Purchasing NCE from the Market

<table>
<thead>
<tr>
<th></th>
<th>Preclinical</th>
<th>Phase I</th>
<th>Phase II</th>
<th>Phase III</th>
<th>NDA Review</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average # of NCEs in phase</td>
<td>11.8</td>
<td>4.6</td>
<td>3.3</td>
<td>1.7</td>
<td>1.1</td>
</tr>
<tr>
<td>% of Total NCEs</td>
<td>52</td>
<td>20</td>
<td>15</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Cumulative % of Total NCEs</td>
<td>52</td>
<td>72</td>
<td>87</td>
<td>95</td>
<td>100</td>
</tr>
</tbody>
</table>

(Mathieu, 2003)

5.4.2.5 Computational Results for Scenario 16

The analysis shows that the profits of the company has a high degree of variation, with respect to the success rates of the NCE development cycle (see fig. 100). Fig. 100 is divided into confidence intervals (CI) based on the values of profit for 50%, 75%, 95%, and 100% of the iterations and the line near the middle of the CI represents the mean value of all of the iterations. The mean annual profit value for all iterations is $3,095 million, the maximum value is $5,181 million, and the minimum value is $715 million. Thus, a 10% increase in the success rates results in an profit increase of 67% and a 10% decrease in the success rate results in an profit decrease of 77%.

A similar affect is illustrated in the number of NCE launches that are entering into the market (see fig. 101). At higher values of the success rate, the number of successful launches increases by 106%, while at lower values of the success rate, the number of successful launches decreases by 69%. Therefore, at the higher values of the success rate, the company has additional revenues available to invest in purchasing more NCE
developments. The increase in profit, however, does not create a reinforcing feedback
loop in which the profits continuously grow because of the high cumulative failure rate of
NCEs purchased in the early stages of development.

The number of LCM launches has much less variation, as compared to the NCE
launches (see fig. 102). The LCM development cycle does not have any purchases being
introduced; therefore, the change in success rate only changes the probability of an LCM
successfully advancing to the next phase. Without NCE purchases, the graph for the
number of NCE launches would look very similar.

In our model, the development stage in which an NCE is purchased and added to
the development cycle has a large influence on the company’s profits. For example, for
every 11.8 INDs added to the Preclinical stage only 1 drug successfully makes it to the
market. Therefore, including the success rate of NDA Review development stage, 10.7
purchases at the Preclinical development stage is equivalent to a single purchase at the
NDA Review development stage. However, the probability of an NCE being purchased
at the Preclinical development stage is 52% and the probability of an NCE being
purchase at the NDA Review development stage is 5%, assuming the company has
sufficient funds to purchase the drugs. Thus, a single purchase of a NDA Review NCE
has a much larger potential to increase the profits than 10.7 NCEs purchased at the
Preclinical Phase (see Table XI).
Fig. 100 Profits for Scenario 16 (in $MM)

Fig. 101 NCE Launches for Scenario 16
5.4.2.6 Implications and Conclusions: Scenario 16

As shown in the collaborative supply chain relationships in the previous scenarios, one firm’s success can have a strong influence on another firm through their
interaction in the joint area. In this scenario, even though the pharmaceutical company only has market-based relationships through the purchase of NCEs, it still has an influence on its relationships. Though not explicitly modeled, the company still has an influence on its relationships through the successful launch of a drug and the generation of additional profit to purchase more NCEs.

As illustrated in this scenario, the development stage in which an NCE is purchased is more significant than the quantity that is purchased. Based on this result, there are two possible strategies that the company can follow for the development of NCEs. The first is to develop partnerships or joint ventures with companies that have NCEs that are in the later stages of development. This strategy increases the probability of purchasing a drug that is successfully approved by the FDA; however, this strategy also increases the purchasing cost, making an unsuccessful review more costly for the supply chain. One advantage to this strategy is that it frees resources that would be used in the development of the drug to other drugs already in development. The second strategy is to partner with another pharmaceutical or biotechnology company that has a large number of drugs that are entering the Preclinical stage. If a strong pipeline of drugs can be developed, the company can overcome the high failure rates and have enough drugs in development to produce an adequate number of successful drugs with high enough revenues to continue funding the development process. The high quantity of developments places a larger burden on the development resources on the company, which can be mitigated through the use of CROs to help manage the process. If the company can successfully use these strategies to increase its success rates by 10% it can
increase its profit by 67% and the number of drugs launched into the market by 106%, as shown in this scenario.

The structure of the company’s relationships can take on many forms depending on its strategy. Recently, the pharmaceutical company Pfizer has taken the strategy of growth through acquisition of entire companies, with their purchase of Wyeth Pharmaceuticals, to gain access to that company’s drug developments. The reason for the purchase is that Pfizer is uncertain about its ability to develop the next blockbuster drug. Therefore, it is seeking to save on development costs of existing drugs by removing duplicate and overlapping developments of the two companies (Rockoff, 2010), essentially removing Follow-on drugs from development. Likewise, the pharmaceutical company GlaxoSmithKline is also changing its development strategy in both its development and purchasing of drugs to focus less on riskier investments, such as anti-depressants and pain management drugs. Instead, they are focusing on their development and purchase of drugs that have a more definitive success benchmarks, such as drugs to treat Alzheimer’s and Parkinson’s (Whalen, 2010).

5.5 Model Propositions

The following section discusses validity of the propositions offered earlier for our model, supporting or denying the propositions based the results from the computational scenarios and runs. The propositions are evaluated using the graphical representations of the simulation runs.
5.5.1 Proposition 1

**Proposition 1**: As the focal firm’s sole focus area knowledge stock increases, the proportion of resources invested in incremental product innovation in the joint area increases.

Fig. 103 indicates that as the focal and supplier firms increase their knowledge stocks they invest more resources in incremental innovation in the joint area by increasing its \( \text{frac}_\text{KS}_{it} \), supporting Proposition 1.

Fig. 103  Focal Knowledge Stock and Joint Product Frac for Proposition 1a
5.5.2 Proposition 2

**Proposition 2:** When the product knowledge stock of the joint area increases, the focal and supplier firm will invest a higher proportion of resources in incremental product innovation in their sole focus areas.

Fig. 104 indicates, that as the product knowledge stock of the joint area increases, the focal and supplier firm invest more resources in incremental innovation in their firms, by increasing their $frac_{it}$, supporting Proposition 2.

Fig. 104  Joint Product Knowledge Stock and Focal and Supplier Firm’s Frac for Proposition 2
5.5.3 Proposition 3

Proposition 3: As the process knowledge stocks of the joint area increase, the focal and supplier firms will invest a higher proportion of their resources in incremental product innovation in their sole focus areas.

Fig. 105 indicates, that as the process knowledge stock of the joint area increases, the focal and supplier firm invest more resources in incremental innovation in their firms by increasing their \( \text{frac}_{it} \), supporting Proposition 3.

![Graph showing Joint Process Knowledge Stock and Focal and Supplier Firm’s Frac for Proposition 3](image)

Fig. 105 Joint Process Knowledge Stock and Focal and Supplier Firm’s Frac for Proposition 3
5.5.4 Proposition 4

**Proposition 4a:** When product stocks in the sole focus area are reduced by MT and TT, the focal and supplier firms will invest a higher proportion of resources in radical product innovation in their sole focus areas.

**Proposition 4b:** When product stocks in the joint area are reduced by MT and TT, the focal and supplier firms will invest a higher proportion of resources in radical product innovation in the joint area.

**Proposition 4c:** When process stocks in the joint area are reduced by MT and TT, the focal and supplier firms will invest a higher proportion of resources in radical product innovation in their sole focus areas.

In Scenario 14, we reduce the focal and supplier firms’ product stocks and the joint product and process stocks. The results from that scenario indicate that as the turbulence rate decreases the focal and supplier firms’ product stock and the product and process stocks of the joint area, the focal and supplier firms increase their investments in radical innovation (see fig 106), supporting Proposition 4a, 4b, and 4c.
5.5.5 Proposition 5

**Proposition 5a:** As the rate at which the product knowledge stock of the sole focus area becomes obsolete increases, the focal and supplier firms will invest a higher proportion of resources in radical product innovation in their sole focus areas.

**Proposition 5b** As the rate at which the product knowledge stock of the joint area becomes obsolete increases, the focal and supplier firms will invest a higher proportion of resources in radical product innovation in the joint area.

**Proposition 5c:** As the rate at which the process knowledge stock of the joint area becomes obsolete increases, the focal and supplier firms will invest a higher proportion of resources in radical process innovation in the joint area.
In scenario 12, we increase the rate at which the focal and supplier firm and the joint product and process knowledge stocks become obsolete. The results from that scenario indicate that as the different knowledge stocks in the firms and the joint area experience an increase in the rate at which the knowledge becomes obsolete, the focal and supplier firms increase their investments in radical innovations (see fig 107), supporting Proposition 5a, 5b, and 5c.

Fig 107  Focal Firm’s Frac, Joint Product Frac and Joint Process Frac for Proposition 5

5.5.6 Proposition 6

Proposition 6a: As the resource requirement per product increases, the focal and supplier firms will invest a higher proportion of resources in radical product innovation in their sole focus areas.
**Proposition 6b:** As the knowledge stock investment per product increases, the focal and supplier firms will invest a higher proportion of resources in radical product innovation in their sole focus areas.

To provide evidence for this proposition, two runs were conducted: one in which the knowledge investment per incremental innovation was set equal to the knowledge investment per radical innovation and another in which the resources per incremental innovation was set equal to the resources per radical innovation. Both of these runs are compared to a baseline run and in each case, the focal and supplier firm increase their resource investments in radical innovation, by decreasing $\text{frac}_{it}$. These results indicate that both Proposition 6a & 6b are supported (see fig. 108 & 109).

![Graph showing Frac for Higher Knowledge Investment per Incremental Product](image)

**Fig. 108** Focal Firm’s Frac for Higher Knowledge Investment per Incremental Product for Proposition 6
Fig. 108  Focal Firm’s Frac for Higher Resource Investment per Incremental Product for Proposition 6

5.5.7 Proposition 7

**Proposition 7:** A focal firm’s larger profit goal, relative to the supplier, results in a higher proportion of invested resources in radical product innovation in its sole focus area.

In Scenario 6, we double the focal firm’s profit goal, relative to the supplier firm. The results from this scenario indicate that when the focal firm’s profit goal is double that of the supplier firm, it invests more resources in radical innovation, by decreasing \( \text{frac}_{it} \) (see fig. 110), providing support for Proposition 7.
5.5.8 Proposition 8

**Proposition 8:** A larger knowledge stock goal of the focal firm, relative to the supplier, results in a higher proportion of invested resources in radical product innovation in the joint area.

The analysis of higher knowledge stock goal was not included in the previous analysis of Scenario 6; however, when the focal firm’s knowledge is double that of the supplier firm, it invests a higher proportion of its resources in radical process innovation in the joint area, by decreasing $frac_{KS_{it}}$. (see fig. 111), providing support for Proposition 8.
Fig. 111 Focal Firm’s Joint Product Frac Value for Double Focal Firm Goals for Proposition 8

5.5.9 Proposition 9

**Proposition 9:** A larger process knowledge stock goal of the focal firm, relative to the supplier, results in a higher proportion of invested resources in radical process innovation in the joint area.

The analysis of higher process knowledge stock goal was not included in the previous analysis of Scenario 6; however, when the focal firm’s process knowledge is double that of the supplier firm, it invests a higher proportion of its resources in radical process innovation in the joint area, by decreasing $frac_{KS_{Process_i}}$, (see fig. 112), providing support for Proposition 9.
5.5.10 Proposition 10

**Proposition 10:** As a firm’s knowledge transfer capability decreases, the focal and supplier firm will invest a higher proportion of resources in radical product innovation in their sole focus areas.

In Scenario 11 we reduce the process knowledge stock of the joint area. The results from this scenario indicate that as the knowledge retention rate of the process knowledge stock of the joint area decreases, the focal and supplier firms invest more resources in radical innovation, by decreasing their $frac_{it}$, in an effort to increase the knowledge stocks in their own firms (see fig. 113), providing support for Proposition 10.
Fig. 113  Product Frac Value for Focal and Supplier Firms for Proposition 10

5.5.11 Proposition 11

**Proposition 11:** As the knowledge assimilation level decreases, the focal and supplier firms will invest a higher proportion of slack resources in radical product innovation in their sole focus areas.

In Scenario 4, we have three different runs with three levels of knowledge assimilation: high, medium, and low. Under high levels of knowledge assimilation, or high theta, the focal and supplier firms decrease their resource investments in radical innovation, or increase their $frac_{it}$. Likewise, under low levels of knowledge assimilation, or low theta, the focal and supplier firms increase their resource investments in radical innovation (see fig. 114), providing support for Proposition 11.
In summary, we conducted an extensive number of simulation scenarios and runs to test these propositions. The propositions are tested in the regions of the radical and incremental innovation are in a balancing loop. The conclusions cannot be generalized to conclude that in all circumstances, an increase in radical innovation investment will lead to higher profits. When the increase in radical innovation investment causes a firm or the supply chain to enter a reinforcing feedback loop, profits do not necessarily increase.
CHAPTER VI
DISCUSSION OF RESULTS

The shift in competitive paradigms is altering how firms respond to changes that not only affect their firms but also their supply chains. Market conditions are constantly forcing firms and supply chains to adapt and change their investments in radical and incremental product innovation to increase their profits. These changes are not limited to the exogenous events outside of the firms’ and the supply chain’s boundaries. The firms’ and supply chain’s performance, relative to their goals, is also affecting their responses to these internal changes. The responses firms make by changing their innovation investments are not made in isolation and impact future decisions based on the feedback received from the firms and supply chain. Our model incorporates many of these factors, decision variables, and feedback mechanisms. The modeling of knowledge transfer and its impact on radical and incremental innovation expands on the current state of supply chain modeling by exploring and investigating how both the focal and supplier firms
respond to these changes, both as individual firms and as a supply chain. In addition, we also investigate how firms can extend their relationships beyond the collaborative supply chain relationships and utilize market-based purchases of innovations to improve their profitability.

As our model demonstrates, a single firm benefits when it collaboratively invests in innovations with another firm through a joint area. However, the formation of a collaborative relationship alone is not sufficient for either firm in the supply chain to be profitable due to both endogenous and exogenous factors. We tested a variety of scenarios where the conditions affecting the firms and supply chain change both before and after they have reached a steady state. We demonstrated how firms and supply chains chose different relationship characteristics that lead to higher profits. We also extended our model to different industries to illustrate how market-based relationships can help to improve collaborative supply chain relationships. The results of all these scenarios are documented and interpreted to both firms and supply chains to help improve their profitability.

6.1 System Dynamics and Supply Chain Management

Firms and supply chains are not static systems in which the effects of investment decisions of one firm can be isolated from the rest of the supply chain. While cross-sectional research helps to describe the landscape in which firms and supply chains operate, the isolation of the constructs into a single time frame limits the understanding of how supply chains interact. Also, the cross-sectional analysis of the supply chain is often limited to the sample population being studied and the results often cannot be generalized or applied to different situations. By using SD, we create a more robust model to analyze
a variety of different supply chain features and situations. This more robust supply chain model also expands the understanding of not only how firms and supply chains react, but allows us the ability to generalize our model and results to a variety of situations and industries. The reactions of the firms also lead to the analysis of potential feedback loops that can be created as the firms respond by changing their innovation investments.

6.1.1 Balance of Radical and Incremental Innovation

It is important for the focal and supplier firm and the supply chain to find a balance between radical and incremental innovation. This balance is on a continuum and changes depending on the endogenous and exogenous factors impacting a firm and its supply chain. For instance, a firm may decide to ‘play it safe’ and eliminate its investments in radical innovation because they are seen as being too risky; however, as illustrated in Scenario 1, not investing in radical innovation is risky in and of itself. The focal firm’s focus on all incremental innovation, results in its profits being decreased by 95%. Fortunately, the supplier firm is able to modify its investments to avoid the same profit decrease and prevents the focal firm from having a larger decrease in its profits. However, when both firms pursue this innovation investment strategy, the supply chain becomes unprofitable. Therefore, when a single firm pursues this strategy, it only harms itself, but when the supply chain avoids risk in its innovation investments both firms have a large decrease in their profits.

At the other end of the continuum, a firm may have such high expectations of either its profit or knowledge generated, that it relies exclusively on radical innovation, as demonstrated in Scenario 2. Similar to an all incremental innovation strategy, when the focal firm invests too heavily in radical innovation, its profits are decreased by 66%
because the reliance on radical innovation cannot maintain its knowledge stock.

Similarly, the supplier firm is able to avoid a decrease of its profits by maintaining its innovation investment balance, but when it also joins the focal firm in the same strategy, both firms’ profits decrease by 90%.

These results show that if a firm still desires to invest solely in either radical or incremental innovation it needs to choose supply chain members that do not have the same investment strategy. The supplier firm’s continued investments in the joint area and the resulting knowledge transfer from the joint area help to mitigate some of the drop in the focal firm’s profits. In both of these innovation investment examples, the supplier firm and joint area act to maintain the focal firm’s knowledge stocks, and hence its ability to develop innovations. On the other hand, while the supplier firm and joint area help to mitigate a larger decrease in profits, the knowledge stock of the joint area is not large enough to allow the focal firm to recover fully its profit level within the given time periods. The supply chain is an aid in the focal firm’s recovery, but is not the answer to deficient innovation investment strategies.

These scenarios illustrate the decrease in profits from following a singular investment strategy and point to the need for firms to select and monitor the investment strategies of their supply chain members. In addition, as discussed in the next section, once a supply chain partner invests too heavily in one innovation strategy, changing this strategy can be difficult due to the feedback loops that can be created.

6.1.1.1 Reinforcing Feedback Loops

The ability of a firm to exit a reinforcing feedback loop can be difficult, as shown in several of our scenarios. Therefore, a firm needs to understand what endogenous and
exogenous factors lead to the creation of feedback loops, to avoid entering one in the future. Another important issue for the firms is the understanding of what actions can be taken to exit a loop. For example, in Scenario 9, when the focal and supplier firms are establishing a new supply chain relationship and are responding to their original goals, they are in a reinforcing feedback loop and their continued increase in radical innovation investments do not increase their profits. When investing according to these goals, the radical innovation investments do not allow the firms to generate enough knowledge stock to exit their reinforcing feedback loop. However, the focal firm is able to exit the loop when we reduce its goals by one-half. This scenario demonstrates that once a firm or supply chain enters a reinforcing feedback loop, simply trying more of the same action that created the loop is not sufficient to exit it. When the focal firm’s investment in incremental innovation increases, through the reduction of its goals, it is able to exit the reinforcing loop and begin to regain its profitability.

6.1.1.2 Balancing Loops

Balancing feedback loops are desirable in the short-term for firms because they allow for consistent profitability once the firms reach their profit goal. However, while reinforcing feedback loops can be easier to identify because of the continued deterioration in profits, a balancing loop can be more difficult to change. Firms can become complacent in balancing loops because they have little risk of decreasing their profits if they continue with their current investments. The balancing loops give the firms less incentive to change their innovation investments to try to increase their profits due to the stability of their profits. An example of this risk is in Scenario 6, when the focal firm tries to double its profits, it exits a balancing feedback loop and enters a
reinforcing feedback loop that decreases its profits. However, in Scenario 3, both the focal and supplier firms are in a balancing loop and when we change their investment strategy to one that is balanced between radical and incremental innovation, both firms exit their current balancing loop and enter another one in which their profits are 16% higher. These scenarios show the risk and reward of exiting a balancing loop and illustrate that firms need to understand the effect of changing their innovation investments have on their profits.

6.2 Factors and Situations Affecting the Supply Chain

Our model provides insight into the factors and situations that affect both the performance of a single firm and a supply chain. By analyzing a variety of different factors and situations and modeling specific industries, we develop a set of guidelines based on our scenarios for firms and supply chains. Our analysis investigates establishing a firm, entering into new supply chain relationships, and selecting supply chain partners in knowledge intensive industries that require high levels of knowledge assimilation.

6.2.1 New Firms and New Supply Chain Relationships

Many factors influence the speed and success of both new firms and established firms that are beginning new supply chain relationships. As new firms work on building their product and knowledge stocks to become established firms in the market, they need to consider not only their supply chain partners, but also their profit and knowledge stock expectations of their own firm and the joint area. During the early stages of the firms, their ability to increase their knowledge stocks is critical in determining their success, as
we demonstrate in Scenario 7, 8, & 9. Likewise, even established firms need to focus their supply chain partner selection efforts on the ability to build relationships with other firms that can invest in the joint area and on the firm’s ability to assimilate knowledge from the joint area. Both of these criteria are important in ensuring the rapid growth of the knowledge stock of the firms, supply chain, and joint area.

6.2.1.1 New Firms

As shown in Scenario 7, if the firms’ performance expectations for their new firm are too high, then they will invest too many resources in radical innovation leading them into a reinforcing feedback loop in which the reliance on radical innovations continuously decreases their profits and knowledge stocks. In this situation, taking less risk can be more profitable and a means to build knowledge stocks. When we reduce the focal firm’s goals by one-half, it invests more resources in incremental innovation, resulting in its profits increasing by 80%, with a low knowledge assimilation level; and 18%, with a high knowledge assimilation level. This scenario demonstrates both the new firm’s need to establish realistic goals and to establish supply chains that enable it to have a high level of knowledge assimilation.

6.2.1.2 New Supply Chain Relationship

Established firms differ from new firms because they are not trying to build their internal knowledge stocks at the same time as beginning a new supply chain relationship. This may lead to firms being more complacent in their new relationships and thus not dedicating adequate resources to the joint area during the early phases, as illustrated in Scenario 8. This issue is especially important in knowledge intensive industries, where the firms are relying heavily on the knowledge transfer from the joint area to increase the
number of innovations they can develop. The initial decisions, by both the focal and supplier firm, of how many initial products and processes to start in the joint area can have a long-term effect on both firms and the joint area. For instance, if both firms provide too few products and processes initially to the joint area, the knowledge stocks of the joint area can take many periods to build to a level that is beneficial to the firms. Without the initial product and process stocks, simply increasing the amount of resource investments by either firm cannot remedy the situation.

Another resolution to an initially low level of investment in product and process stocks is to increase the amount of resources invested in incremental innovation. In Scenario 9, both firms and the joint area are in a reinforcing feedback loop and when we reduce the focal firm’s goals, it shifts more investments to incremental innovation. The incremental innovations help the focal firm and joint area to exit their reinforcing feedback loop and their knowledge stocks begin to increase. The focal firm’s profits increase by 71% and the supplier firm’s profits increase slightly; however, these profit values are still well below the baseline run’s levels. Therefore, changing the focal firm’s goals is beneficial to its profits, but the better solution is to ensure a sufficient level of products and processes to start with in the joint area, to ensure its success.

6.2.2 Knowledge Assimilation

During times of change, a firm’s ability to retain its knowledge stock can decrease because of turbulence in its product stocks or knowledge retention issues. As shown in several scenarios, a firm can maintain and replenish its knowledge stock through knowledge transfer from the joint area, which is strongly influenced by the firm’s knowledge assimilation level. In scenario 4, we modeled three different supply chains
that only differed based on their knowledge assimilation level, which had dramatic impacts on the profits of the firms. A supply chain, in which both firms have low levels of knowledge assimilation, shows a 62% decrease in its profits when compared to supply chains with medium and high levels of knowledge assimilation. A similar result is shown in Scenario 7, where a new supplier firm is able to increase its profits by 89% if it has a high level of knowledge assimilation. These two examples illustrate the need of firms to both select supply chains in which they can have the potential for higher levels of knowledge assimilation and to invest resources in developing and maintaining this ability. These investments can be made in information-communication technologies (ICTs) that assist firms and supply chains to more easily store, retrieve, and transfer knowledge (Carlsson, 2003). This ability is especially important in knowledge intensive industries where the amount of knowledge that a firm transfers can dictate the number of innovations it can develop.

6.2.3 Knowledge and Resource Constraints

As shown in several scenarios and illustrated in the high technology scenario, understanding what is the most productive investment of resources has a key impact on the growth of a firm’s profits and knowledge. For example, when knowledge constrained, firms should redirect some of their resource investments away from funding additional innovations to the acquisition of knowledge through purchased innovations. The second option, as discussed previously, is to invest resources in improving the firm’s knowledge assimilation level to be able to transfer more knowledge from the joint area.

Scenario 15, with the Samsung Electronics Corporation, is an example of how a firm can overcome its knowledge constraint and increase its profits by purchasing
innovations. The firm is knowledge constrained through the first half of the scenario until its purchasing of radical product innovations increases its knowledge stock to a level in which it can develop more product innovations. This scenario shows that when knowledge constrained and paying a price twice the internal development cost, purchased innovations can be a profitable investment.

Though not explicitly modeled in our scenarios, the firms and the supply chain also have an option of not developing the products themselves, but licensing the knowledge if they are resource constrained. For example, in the pharmaceutical industry, companies use CROs to manage the development and testing of drugs in various stages of development (Ohba & Figueiredo, 2007). This way the pharmaceutical company is redirecting its knowledge to another company with the strategic purpose of conserving its resources and investing them to where it can receive a higher return.

6.2.4 Industry Scenarios

Supply chains are not always purely collaborative in nature and can purchase innovations from sources outside the boundaries of the supply chain. The robust nature of our model provides us an opportunity to investigate several types of industries that differ in both how they manage their supply chain and the effects of purchasing innovations. These scenarios illustrate what factors are limiting firms from achieving higher profits and what innovation purchasing strategies can increase their profits.

6.2.4.1 High Technology

As previously discussed in Scenario 15 with the Samsung Electronics Corporation, in knowledge constrained firms, the ability to redirect resources to
purchasing radical innovations from the market can play a key role in increasing a firm’s profits. This scenario illustrates that even when the focal firm is investing twice the amount of resources than its internal innovations it is able to increase its profits. The focal firm has not abandoned the supply chain to purchase innovations from the market because it still needs the knowledge transferred from the joint area. However, if the focal firm relies solely on the supply chain for the increases in its knowledge stocks, the focal firm cannot alleviate its knowledge constraint. Only through the purchases of innovations can it break the constraint and improve its profits.

While this type of relationship with the supply chain is not purely collaborative in nature, the supply chain as a whole benefits from the innovation purchases. This scenario helps to illustrate an important supply chain concept of improving the supply chain’s global optima instead of each firm’s local optima (Chen & Paulraj, 2004a). The supply chain is forgoing some revenue that would be generated if the focal firm purchases the innovations from the supply chain. However, if purchasing the innovation from the supply chain, it might not be purchasing the best innovation possible and the resulting increase to the focal firm’s knowledge stock might still leave it knowledge constrained. Thus, in the short-term, the supply chain’s revenues are not as high, but the long-term benefits to the focal firm and the supply chain outweigh this issue.

6.2.4.2 Pharmaceutical Drug Development

Another type of relationship is one that does not have a collaborative supply chain relationship and only relies on the market for the purchase of innovations. In Scenario 16, we show how a pharmaceutical drug company can use purely market-based relationships to purchase drug innovations. Even without a supply chain relationship, the
pharmaceutical company is able to increase its profits through both the internal
development of drugs and by purchasing drugs under development, from the market. On
the other hand, without a collaborative relationship with a supply chain, the
pharmaceutical company might be subject to increased prices or other relational issues in
the market place, making the market-based relationship potentially more risky.

The results from this scenario show another potential risk to the pharmaceutical
company because its profits are sensitive to the success rate of the drugs it develops
internally and it purchases: a 10% increase in the success rate during the drug
development cycle can increase the company’s profits by 67% and the number of NCE
launches by 106%. On the other hand, a decrease in the success rate during the drug
development cycle can decrease the company’s profits by 77% and the number of NCE
launches by 69%. These results indicate that a pharmaceutical company needs to pay
close attention to its purchases because it does not have a collaborative relationship with
the market and needs to be extra diligent.

6.3 Supply Chain Benefit

6.3.1 Innovation

The success of the firms and the supply chain is based partly on their ability to
provide new and improved products that the market is willing to buy. Each firm may be
capable of generating enough knowledge by themselves to be profitable, but by
combining and sharing knowledge through the joint area, they can increase their profits.
Additionally, the joint area provides knowledge that can be transferred to help a firm
recover its profitability when affected by an endogenous or exogenous event. Without
the transfer of knowledge from the joint area to begin the recovery process, a firm has a
very difficult task of replenishing its knowledge stocks on its own. Even if the firm does finally recover, the time and effort of doing so by themselves will be much longer than with the assistance of its supply chain.

6.3.1.1 Joint Area as a Knowledge Stock Buffer

There are many types of events that can affect a firm’s knowledge stocks causing it to decrease: a new product entering the market that obsolesces the firm’s product stocks, new competition that increases the firm’s turbulence rates, or a decrease in the firm’s ability to maintain and retain its knowledge stocks. Whatever the cause, the transfer of knowledge from the joint area provides a critical opportunity for the firm to begin to replenish its knowledge stocks. Because firms need knowledge to develop their innovations, the transferred knowledge assists the firm in regaining its ability to develop innovations and return to profitability.

Scenario 11 illustrates the ability of knowledge transfer from the joint area to help buffer the firm from the obsolescence of its product stock and the resulting impact on its knowledge stock. When the focal firm’s product stocks are repeatedly obsolesced every 25 periods, its profits decrease by 31% by period 200. While this is a substantial decrease in profits, the knowledge transfer from the joint area keeps the decrease from being much larger. For instance, when the supplier firm is also impacted by the same loss of product stocks, the focal firm’s profits decrease by 68% and when the joint area is also affected, the focal firm’s profits decrease by 99%. Thus, the knowledge transfer from the joint area acts as a buffer to the focal firm’s knowledge loss.
6.3.1.2 Knowledge Stock Retention

When firms are subject to increased losses in their knowledge stocks through the introduction of new technologies or products in the market, their ability to develop future product innovations is decreased. By forming supply chain relationships that are not subject to the same knowledge stock retention issues, the firm can lessen the impact through knowledge transfer. On the other hand, the availability of knowledge in the supply chain is not as beneficial, or is useless, without the firm’s ability to assimilate the knowledge. These points are demonstrated in Scenario 12; when the focal firm has a medium or high knowledge assimilation level it can maintain its profits even when the rate of knowledge loss is 6 times its normal rate.

Two potential options to replenish the knowledge stocks are the purchase of innovations from the market and establishing new supply chain relationships. Purchasing innovations can be costly if other firms are also pursuing these innovations to replenish their own knowledge stocks, escalating its price. On the other hand, as shown in Scenario 9, the development of new relationships can take a long period of time and if not properly managed can lead to inadequate knowledge transfers. Therefore, firms need to remain aware of the market and if there is a high probability of potential knowledge stock issues, they should pursue the purchase of innovations and develop new supply chain relationships before they are needed.

In addition, during the replenishment of its knowledge stocks, the knowledge assimilation capability of the firm can play a large role in determining how fast it can recover. The time to build this capability though can be long, so firms must be proactively developing and maintaining their capabilities. This investment may not have a positive return while the firm is in a steady-state condition, but the investment can
quickly provide a return when knowledge transfer is needed to replenish a firm’s knowledge stock.

Another method firms can use to improve their ability to retain knowledge is the mechanisms through which they store their knowledge. Tukel et al. (2010) describe a knowledge bank format in which companies can store knowledge in external sources for later use. The knowledge banks both assist firms in transferring knowledge to external sources and potentially increasing it or licensing it to others that can use the knowledge to develop innovations.

6.3.1.3 Turbulence

While knowledge stock retention issues can decrease the number of innovations that a firm can develop in the future, increases in turbulence have an immediate impact on the profits. As illustrated in Scenario 13 & 14, due to this immediate impact, the firm and the supply chain have a small window of opportunity in which to respond. Because turbulence can quickly deplete knowledge stocks any delay in rebuilding them can lead to being deeply entrenched in a reinforcing feedback loop. The other supply chain members have a vested interest in their partner succeeding, especially if they need the firm’s investments in the joint area for their own knowledge transfer. In addition, if the supply chain is also impacted by the increase in turbulence, the speed of their reactions is even more important because the joint area knowledge stock is quickly depleted due to a lack of resource investment by both firms. Once this knowledge stock is too small to help the firms with their own innovations, neither firm can return to their previous level of profitability.
6.3.1.4 Investments of Supply Chain Members

During an increase in knowledge retention issues and/or turbulence, the continued profitability of the supply chain members can allow the individual firms to begin to recover the knowledge stocks that have been lost. While the transferred knowledge from the joint area is critical to help a firm to recover, without the investments of the other firm in the relationship, there would be no knowledge to transfer. During the steady-state operations of the firms, the investments in the joint area may not appear to be worth the investments, but as soon as an issue arises, those investments quickly pay-off. Therefore, firms need to consider the performance of their firms, and especially the supply chain and joint area, not just in terms of the benefit this period or the next, but also as part of an insurance policy.

6.3.1.5 Increased Profits Due to Knowledge Investment and Transfer

As illustrated in many of our scenarios, the knowledge transfer from the joint area is a determining factor in the profits generated by the firms and the supply chains. In knowledge intensive industries that can become knowledge constrained or enter a reinforcing feedback loops as a result of low knowledge stocks, knowledge transfer from the joint area is critical to ensuring the firms’ profitability. Choosing a supply chain that has a high level of knowledge assimilation ensures that the firms can transfer enough knowledge to increase the number of innovations they can develop.

6.3.1.6 Purchasing of Innovations

Many times the knowledge that is generated within the firms and the joint area is not adequate to allow the firms to develop the number of innovations that they have the resources available to fund. In these instances, as we demonstrated in Scenario 15 & 16,
a firm can purchase innovations from the market and provide a benefit to the supply chain as well. Thus, extending investments beyond the supply chain should be viewed as positive, which increases the global optima of the supply chain instead of just increasing a single firm’s local optima.

6.3.1.7 Freeloader Issue

The issue of the freeloading of a supply chain member is a serious issue for a firm because its investments in the supply chain are not reciprocated, as demonstrated in Scenario 10. The supplier firm takes a large risk in the focal firm detecting its freeloading for an increase in its profits of 13%. Because the supplier firm is knowledge constrained, its gamble of not being detected by the focal firm is a dangerous one. If the focal firm determines its 3% decrease in profits is due to the supplier firm’s freeloading and it stops knowledge transfer to the supplier firm, the supplier firm’s profits decrease by 19%. In supply chains that are knowledge intensive and require knowledge transfers from the joint area to maintain the number of innovations they develop, freeloading is not worth the risk.

6.4 Summary and Conclusions

As the supply chain becomes the focus of competitive advantage (Kanter, 1994), firms must understand how their selection of supply chain partners can impact their ability to compete in the market. The supply chain is not a set of firms that are statically investing their resources, but instead is a set of firms that are constantly adjusting their investments in radical and incremental innovation. The model developed in this study is an initial effort to analyze the innovation investments and knowledge transfer in a
dynamic supply chain relationship and provides support for Tushman and O’Reilly’s 
(1996) ambidexterity theory regarding the need for balance between radical and 
incremental innovation. Firms need to invest a portion of their resources in radical and 
incremental innovations to not only sustain their knowledge stocks, but also to avoid 
entering a reinforcing feedback loop.

The 16 scenarios and 40 unique runs highlight the importance of creating the right 
supply chain partnerships that can enable both firms to have higher profits. This study 
shows that when the focal firm is impacted by product stock reductions or has difficulties 
in retaining its knowledge stock, then the supplier firm’s investments and the joint area’s 
knowledge stock can help to mitigate some of the negative effects. In addition, the 
supplier firm’s investments and the joint area’s knowledge stock can also lessen the loss 
of focal firm’s profits when the focal firm undertakes an all incremental or all radical 
innovation strategy. In these situations, the innovation investments by the supplier firm 
and the knowledge stocks of the joint area allow the focal firm to replenish its knowledge 
stocks. Without this knowledge from the joint area, the focal firm would not return to its 
previous level of profitability as quickly.

The modeling of dynamic supply chain relationships contributes to the literature 
by providing both guidelines and a learning environment to simulate the reaction and 
interactions of the supply chain partners. Including both the feedback mechanisms and 
the responses of the supply chain partners in the model shows how one firm’s investment 
strategies can be beneficial or detrimental to the other firm’s profits. The inclusion of 
feedback mechanisms and feedback loops in the model is an important contribution to the 
supply chain literature. As the results show, when a firm is not aware of being in a
reinforcing feedback loop, it may continue to follow the current strategy and make the supply chain’s performance worse. As shown in several of the scenarios, continuing on the same investment strategy only leads to lower profits. Knowing when to change the investment strategy or when to purchase innovations from the market, firms can make timely adjustments in order to exit the feedback loop.
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Capabilities for Continuous Innovation. *Supply Chain Management: An


APPENDICES
## APPENDIX A

### Variables Used

<table>
<thead>
<tr>
<th>Variables Used</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rad_Prod_{it,k}</strong></td>
<td>Radical product stock for firm <em>i</em> for product age <em>k</em></td>
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<td><strong>Inc_Prod_{it,k}</strong></td>
<td>Incremental product for firm <em>i</em> for product age <em>k</em></td>
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APPENDIX B

Glossary of Terms

Absorptive capacity – the ability of a firm to recognize the value of new, external information, assimilate it, and apply it to commercial ends (Cohen & Levinthal, 1990).

Ambidexterity – maintaining a balance between radical and incremental innovation (Tushman & O'Reilly, 1996).

Idiosyncratic resources – combining resources in a manner that is difficult for the competition to imitate. These resources allow a firm to generate a rent when compared to the competition (Dierickx & Cool, 1989).

Rent – Profits that exceed the opportunity or investment costs for a firm. For example, zero rent would occur when a firm’s profits are equal to the expected profits for any firm in the market.

Relational rent – Rents that are generated from the collaboration of two or more firms (Dyer & Singh, 1998).

Slack resources – Resources generated from rents that are available to be invested in future innovation (Nohria & Gulati, 1996).
Fig. C.1  Focal or Supplier Product Stock, Knowledge Stock, and Innovation Cycle
Fig. C.2  Product Stock, Knowledge Stock, and Innovation Cycle of the Joint Area
Fig. C.3  Process Stock, Knowledge Stock, and Innovation Cycle of the Joint Area
Fig. C.4 Focal and Supplier Firm Profit Stocks
APPENDIX D

CCD Replications

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### APPENDIX E

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<td>&lt; 0.001</td>
</tr>
<tr>
<td>Turbulence<em>Res per Inc Prod</em>Forget Rate*Theta</td>
<td>0.994</td>
</tr>
<tr>
<td>KS per Inc Prod<em>Res per Inc Prod</em>Forget Rate*Theta</td>
<td>1</td>
</tr>
<tr>
<td>Turbulence<em>KS per Inc Prod</em>Res per Inc Prod<em>Forget Rate</em>Theta</td>
<td>0.779</td>
</tr>
</tbody>
</table>
APPENDIX G

Vensim Model for High Technology Focal Firm: Scenario 15

Fig. G.1  Focal Firm for Scenario 15: High Technology
APPENDIX H

VENSIM Model for Scenario 16: Pharmaceutical Supply Chain

Fig. H.1  Development Cycle for Scenario 16: Pharmaceutical Scenario
Fig. H.2  Market for Scenario 16: Pharmaceutical Scenario
Fig. H.3  Revenues, Development Costs, and Profits for Scenario 16: Pharmaceutical Scenario
APPENDIX I

VENSIM PROGRAM CODE

Aged Dormant Products =
   Focal Dormant Products * Aged Product Rate

Aged Product Rate = 0.2

"Budgeted (focal)" = 100

"Budgeted (supplier)" = 100

"Budgeted Joint Process (F)" = 100

"Budgeted Joint Process (S)" = 100

"Budgeted Joint Prod (F)" = 100

"Budgeted Joint Prod (S)" = 100

"F, KS Forget (1-5 yr)" =
   "Focal KS (1-5 yr)" * "Forget Rate (1-5 yr)"

"F, KS Forget (6-10 yr)" =
   "Focal KS (6-10 yr)" * "Forget Rate (6-10 yr)"

"F, KS Forget (<1 yr)" =
   "Focal KS (<1 yr)" * "Forget Rate (<1 yr)"

"F, KS Forget (>10 yr)" =
   "Focal KS (>10 yr)" * "Forget Rate (>10 yr)"

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Focal Dormant Products= INTEG (
    "To F, Inc Prod (Unsuccessful)"+"To F, Rad Prod (Unsuccessful)"+Unfunded
Focal Prod-Aged Dormant Products-Recovered Focal Product, 0)

Focal Funded Products=
    MIN("To Inc Prod, (F)"/Resource per Inc Prod,Focal KS/Knowledge per Inc
    Prod)

Focal Goal KS=250

"Focal IR, Joint Process"= INTEG (
    "To Focal IR, Joint Process"+"Budgeted Joint Process (F)"-"To J, Inc Process
    (F)"-"To J, Rad Process (F)", 0)

"Focal IR, Joint Prod"= INTEG (  
    "To Focal IR, Joint Prod"+"Budgeted Joint Prod (F)"-"To J, Inc Prod (F)"-"To J,
    Rad Prod (F)", 0)

"Focal IR, Prod"= INTEG (  
    "To Focal IR, Prod"+"Budgeted (focal)"-"To Inc Prod, (F)"-"To Rad Prod, (F)",0)

Focal KS= ACTIVE INITIAL (  
    Focal Transferred KS+"To Focal KS (1-5 yr)"+"To Focal KS (6-10 yr)"+"To
    Focal KS (<1 yr)"+"To Focal KS (>10 yr)", 100)

"Focal KS (1-5 yr)"= INTEG (  
    "Focal, Rad Prod (1-5 yr)"*"KS per Rad Prod (1-5 yr)+"Focal, Inc Prod (1-5
    yr)"*"KS per Inc Prod (1-5 yr)"."F, KS Forget (1-5 yr)"-"To Focal KS (1-5 yr)", 0)

"Focal KS (6-10 yr)"= INTEG (  

"Focal, Inc Prod (6-10 yr)*""KS per Inc Prod (6-10 yr)"-"F, KS Forget (6-10 yr)"
-"To Focal KS (6-10 yr)", 0)

"Focal KS (<1 yr)"= INTEG ( 
 "Focal, Rad Prod (<1 yr)*""KS per Rad Prod (< 1yr)"+"Focal, Inc Prod (<1 yr)*""KS per Inc Prod (<1 yr)"-"F, KS Forget (<1 yr)"-"To Focal KS (<1 yr)", 0)

"Focal KS (>10 yr)"= INTEG ( 
 "Focal, Inc Prod (>10 yr)*""KS per Inc Prod (>10 yr)"-"F, KS Forget (>10 yr)"
 -"To Focal KS (>10 yr)", 0)

Focal KS Transfer= INTEG ( 
 Joint Product KS*Focal KT-Focal Transferred KS, 0)

Focal KT=
1/(1+exp(-0.03*(Joint Process KS-Focal Process KS Goal)/Focal Process KS Goal))*Theta

Focal Process KS Goal= 225

Focal Product Frac=
1/(1+exp(-0.01*(Focal Slack Resources-Focal Profit Goal)))

Focal Profit Goal=250

Focal Profits= INTEG ( 
 "Focal, Inc Prod (<1 yr)*""Inc Profit (<1 yr)"+"Focal, Inc Prod (1-5 yr)*""Inc Profit (1-5 yr)"+"Focal, Inc Prod (6-10 yr)*""Inc Profit (6-10 yr)"+"Focal, Inc Prod (>10 yr)*""Inc Profit (>10 yr)"+"Focal, Rad Prod (<1 yr)*""Rad Profit (<1 yr)"+"Focal, Rad Prod (1-5 yr)*""Rad Profit (1-5 yr)"-To Focal Slack Resources, 0)
Focal Slack Resources= INTEG (  
To Focal Slack Resources-"To Focal IR, Joint Process"-"To Focal IR, Joint Prod"-"To Focal IR, Prod", 0)

Focal to Joint Process Frac=
\[ \frac{1}{1+\exp(-0.01\text{(Joint Process KS-Focal Process KS Goal)})} \]

Focal to Joint Product Frac=
\[ \frac{1}{1+\exp(-0.003\text{(Focal KS-Focal Goal KS)})} \]

Focal Transferred KS= Focal KS Transfer

"Focal, Inc Prod (1-5 yr)"= INTEG (  
"P (1-5 yr)"-"MT, F Inc Prod (1-5 yr)"-"To F, Inc Prod (6-10 yr)"-"To F, Inc Prod Dev (1-5 yr)"-"TT, F Inc Prod (1-5 yr)", 8)

"Focal, Inc Prod (6-10 yr)"= INTEG (  
"To F, Inc Prod (6-10 yr)"+"To F, Rad to Inc Prod"-"MT, F Inc Prod (6-10 yr)"-"To F, Inc Prod (>10 yr)"-"To F, Inc Prod Dev (6-10 yr)"-"TT, F Inc Prod (6-10 yr)", 6)

"Focal, Inc Prod (<1 yr)"= INTEG (  
"To F, Inc Prod (<1 yr)"-"MT, F Inc Prod (<1 yr)"-"P (1-5 yr)"-"Inc (<1 yr)"-"TT, F Inc Prod (<1 yr)", 10)

"Focal, Inc Prod (>10 yr)"= INTEG (  
"To F, Inc Prod (>10 yr)"-"MT, F Inc Prod (>10 yr)"-"To F, Inc Prod Dev (>10 yr)"-"TT, F Inc Prod (>10 yr)", 4)

"Focal, Inc Prod (Development)"= INTEG (  
"To F, Inc Prod (Development)"-"To F, Inc Prod (Successful)"-"To F, Inc Prod (Unsuccessful)", 0)
"Focal, Inc Prod (Successful)" = INTEG (  
  "To F, Inc Prod (Successful)" - "To F, Inc Prod (Launch)", 0)

"Focal, Inc Prod Development (Available)" = INTEG (  
  Recovered Focal Product + "To F, Inc Prod Dev (1-5 yr)" + "To F, Inc Prod Dev (6-10 yr)" + "Inc (<1 yr)" + "To F, Inc Prod Dev (>10 yr)" + "To F, Rad Prod Dev (1-5 yr)" + "To F, Rad Prod Dev (<1 yr)" - "To F, Inc Prod (Development)" - Unfunded Focal Prod, 0)

"Focal, Rad Prod (1-5 yr)" = INTEG (  
  "To F, Rad Prod (1-5 yr)" - "MT, F Rad Prod (1-5 yr)" - "To F, Rad Prod Dev (1-5 yr)" - "To F, Rad to Inc Prod" - "TT, F Rad Prod (1-5 yr)", 2)

"Focal, Rad Prod (<1 yr)" = INTEG (  
  "To, F Rad Prod (<1 yr)" - "MT, F Rad Prod (<1 yr)" - "To F, Rad Prod (1-5 yr)" - "To F, Rad Prod Dev (<1 yr)" - "TT, F Rad Prod (<1 yr)", 5)

"Focal, Rad Prod (Development)" = INTEG (  
  "To F, Rad Prod (Development)" - "To F, Rad Prod (Successful)" - "To F, Rad Prod (Unsuccessful)" , 0)

"Focal, Rad Prod (Launched)" = INTEG (  
  "To F, Rad Prod (Successful)" - "To, F Rad Prod (<1 yr)", 0)  

"Focal, Rad Prod Development (Available)" = INTEG (  
  MIN( "To Rad Prod, (F)" / Resources per Radical Product , Focal KS/Knowledge per Radical Product) - "To F, Rad Prod (Development)", 0)

"Forget Rate (1-5 yr)" = 0.02
"Forget Rate (6-10 yr)" = 0.025

"Forget Rate (<1 yr)" = 0.015

"Forget Rate (>10 yr)" = 0.03

"Inc (<1 yr)" =

   "Focal, Inc Prod (<1 yr)" ** "Inc Prod Rate (<1 yr)"

Inc Process Success Rate = 0.6

"Inc Prod Rate (1-5 yr)" = 0.05

"Inc Prod Rate (6-10 yr)" = 0.04

"Inc Prod Rate (<1 yr)" = 0.03

"Inc Prod Rate (>10 yr)" = 0.05

Inc Product Success Rate = 0.6

"Inc Profit (1-5 yr)" = 10

"Inc Profit (6-10 yr)" = 6

"Inc Profit (<1 yr)" = 10

"Inc Profit (>10 yr)" = 4

Incremental Delay = 2
"J, KS Forget (1-5 yr)"=
  "Joint KS (1-5 yr)"*"Forget Rate (1-5 yr)"

"J, KS Forget (6-10 yr)"=
  "Joint KS (6-10 yr)"*"Forget Rate (6-10 yr)"

"J, KS Forget (<1 yr)"=
  "Joint KS (<1 yr)"*"Forget Rate (<1 yr)"

"J, KS Forget (>10 yr)"=
  "Joint KS (>10 yr)"*"Forget Rate (>10 yr)"

"J, KS Process Forget (1-5 yr)"=
  "Joint Process KS (1-5 yr)"*"Forget Rate (1-5 yr)"

"J, KS Process Forget (6-10 yr)"=
  "Joint Process KS (6-10 yr)"*"Forget Rate (6-10 yr)"

"J, KS Process Forget (<1 yr)"=
  "Joint Process KS (<1 yr)"*"Forget Rate (<1 yr)"

"J, KS Process Forget (>10 yr)"=
  "Joint Process KS (>10 yr)"*"Forget Rate (>10 yr)"

Joint Aged Processes=
  Aged Product Rate*Joint Dormant Processes

Joint Aged Products=
  Joint Dormant Products*Aged Product Rate
Joint Dormant Processes = INTEG ( "To J, Rad Process (Unsuccessful)" + "To J, Inc Process (Unsuccessful)" + Unfunded Processes - Joint Aged Processes - Recovered Joint Processes, 0)

Joint Dormant Products = INTEG ( "To J, Inc Prod (Unsuccessful)" + "To J, Rad Prod (Unsuccessful)" + Unfunded Joint Prod - Joint Aged Products - Recovered Joint Product, 0)

Joint Funded Processes = MIN("To J, Inc Process (F)" / Resource per Inc Process, Joint Process KS/Knowledge per Inc Process)

Joint Funded Products = MIN("To J, Inc Prod (F) / Resource per Inc Prod, Joint Process KS/Knowledge per Inc Prod)

"Joint KS (1-5 yr)" = INTEG ( "Joint, Inc Prod (1-5 yr)" * "KS per Inc Prod (1-5 yr)" + "Joint, Rad Prod (1-5 yr)" * "KS per Rad Prod (1-5 yr)" - "J, KS Forget (1-5 yr)" - "To Joint KS (1-5 yr)", 50)

"Joint KS (6-10 yr)" = INTEG ( "Joint, Inc Prod (6-10 yr)" * "KS per Inc Prod (6-10 yr)" - "J, KS Forget (6-10 yr)" - "To Joint KS (6-10 yr)", 20)

"Joint KS (<1 yr)" = INTEG ( "Joint, Inc Prod (<1 yr)" * "KS per Inc Prod (<1 yr)" + "Joint, Rad Prod (<1 yr)" * "KS per Rad Prod (<1yr)" - "J, KS Forget (<1 yr)" - "To Joint KS (<1 yr)", 50)

"Joint KS (>10 yr)" = INTEG ( "Joint, Inc Prod (>10 yr)" * "KS per Inc Prod (>10 yr)" - "J, KS Forget (>10 yr)" - "To Joint KS (>10 yr)", 20)
Joint Process KS = ACTIVE INITIAL ( 
   "To Joint Process KS (1-5 yr)"+"To Joint Process KS (>10 yr)"+"To Joint Process KS (6-10 yr)"+"To Joint Process KS (<1 yr)" , 100)

"Joint Process KS (1-5 yr)" = INTEG ( 
   "Joint, Inc Process (1-5 yr)"*"KS per Inc Prod (1-5 yr)"+"Joint, Rad Process (1-5 yr)"*"KS per Rad Prod (1-5 yr)"-"J, KS Process Forget (1-5 yr)"-"To Joint Process KS (1-5 yr)" , 10)

"Joint Process KS (6-10 yr)" = INTEG ( 
   "Joint, Inc Process (6-10 yr)"*"KS per Inc Prod (6-10 yr)"-"J, KS Process Forget (6-10 yr)"-"To Joint Process KS (6-10 yr)" , 10)

"Joint Process KS (<1 yr)" = INTEG ( 
   "Joint, Inc Process (<1 yr)"*"KS per Inc Prod (<1 yr)"+"Joint, Rad Process (<1 yr)"*"KS per Rad Prod (<1yr)"-"J, KS Process Forget (<1 yr)"-"To Joint Process KS (<1 yr)" , 10)

"Joint Process KS (>10 yr)" = INTEG ( 
   "Joint, Inc Process (>10 yr)"*"KS per Inc Prod (>10 yr)"-"J, KS Process Forget (>10 yr)" -"To Joint Process KS (>10 yr)" , 8)

Joint Product KS = ACTIVE INITIAL ( 
   "To Joint KS (1-5 yr)"+"To Joint KS (>10 yr)"+"To Joint KS (6-10 yr)"+"To Joint KS (<1 yr)" , 50)

"Joint, Inc Process (1-5 yr)" = INTEG ( 
   "To J, Inc Process (1-5 yr)"-"MT, J Inc Process (1-5 yr)"-"To J, Inc Process (6-10 yr)"-"To J, Inc Process Dev (1-5 yr)"-"TT, J Inc Process (1-5 yr)" , 10)
"Joint, Inc Process (6-10 yr)" = INTEG ( 
"To J, Inc Process (6-10 yr)" +"To J, Rad to Inc Process" -"MT, J Inc Process (6-10 yr)" -"To J, Inc Process (>10 yr)" -"To J, Inc Process Dev (6-10 yr)" -"TT, J Inc Process (6-10 yr)", 8)

"Joint, Inc Process (<1 yr)" = INTEG ( 
"To J, Inc Process (<1 yr)" -"MT, J Inc Process (<1 yr)" -"To J, Inc Process (1-5 yr)" -"To J, Inc Process Dev (<1 yr)" -"TT, J Inc Process (<1 yr)", 10)

"Joint, Inc Process (>10 yr)" = INTEG ( 
"To J, Inc Process (>10 yr)" -"MT, J Inc Process (>10 yr)" -"To J, Inc Process Dev (>10 yr)" -"TT, J Inc Process (>10 yr)", 8)

"Joint, Inc Process (Development)" = INTEG ( 
"To J, Inc Process (Development)" -"To J, Inc Process (Successful)" -"To J, Inc Process (Unsuccessful)", 0)

"Joint, Inc Process (Launched)" = INTEG ( 
"To J, Inc Process (Launch)" -"To J, Inc Process (<1 yr)", 0)

"Joint, Inc Process (Successful)" = INTEG ( 
"To J, Inc Process (Successful)" -"To J, Inc Process (Launch)", 0)

"Joint, Inc Process Development (Available)" = INTEG ( 
Recovered Joint Processes +"To J, Inc Process Dev (1-5 yr)" +"To J, Inc Process Dev (6-10 yr)" +"To J, Inc Process Dev (<1 yr)" +"To J, Inc Process Dev (>10 yr)" +"To J, Rad Process Dev (1-5 yr)" +"To J, Rad Process Dev (<1 yr)" -"To J, Inc Process (Development)" -Unfunded Processes, 0)

"Joint, Inc Prod (1-5 yr)" = INTEG ( 

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"To J, Inc Prod (1-5 yr)"-"MT, J Inc Prod (1-5 yr)"-"To J, Inc Prod (6-10 yr)"-"To J, Inc Prod Dev (1-5 yr)"-"TT, J Inc Prod (1-5 yr)", 8

"Joint, Inc Prod (6-10 yr)"= INTEG ( "To J, Inc Prod (6-10 yr)"+"To J, Rad to Inc Prod"-"MT, J Inc Prod (6-10 yr)"-"To J, Inc Prod (>10 yr)"-"To J, Inc Prod Dev (6-10 yr)"-"TT, J Inc Prod (6-10 yr)", 4)

"Joint, Inc Prod (<1 yr)"= INTEG ( "To J, Inc Prod (<1 yr)"-"MT, J Inc Prod (<1 yr)"-"To J, Inc Prod (1-5 yr)"-"To J, Inc Prod Dev (<1 yr)"-"TT, J Inc Prod (<1 yr)", 10)

"Joint, Inc Prod (>10 yr)"= INTEG ( "To J, Inc Prod (>10 yr)"-"MT, J Inc Prod (>10 yr)"-"To J, Inc Prod Dev (>10 yr)"-"TT, J Inc Prod (>10 yr)", 2)

"Joint, Inc Prod (Development)"= INTEG ( "To J, Inc Prod (Development)"-"To J, Inc Prod (Successful)"-"To J, Inc Prod (Unsuccessful)", 2)

"Joint, Inc Prod (Launched)"= INTEG ( "To J, Inc Prod (Launch)"-"To J, Inc Prod (<1 yr)", 0)

"Joint, Inc Prod (Successful)"= INTEG ( "To J, Inc Prod (Successful)"-"To J, Inc Prod (Launch)", 0)

"Joint, Inc Prod Development (Available)"= INTEG ( Recovered Joint Product+"To J, Inc Prod Dev (1-5 yr)"+"To J, Inc Prod Dev (6-10 yr)+"To J, Inc Prod Dev (<1 yr)"+"To J, Inc Prod Dev (>10 yr)+"To J, Rad Prod Dev (1-5 yr)+"To J, Rad Prod Dev (<1 yr)"-"To J, Inc Prod (Development)-Unfunded Joint Prod, 0)
"Joint, Rad Process (1-5 yr)" = INTEG (  
"To J, Rad Process (1-5 yr)"-"To J, Rad Process Dev (1-5 yr)"-"To J, Rad to Inc Process"-"TT, J Rad Process (1-5 yr)"-"MT, J Rad Process (1-5 yr)", 6)  

"Joint, Rad Process (<1 yr)" = INTEG (  
"To, J Rad Process (<1 yr)"-"TT, J Rad Process (<1 yr)"-"To J, Rad Process (1-5 yr)"-"To J, Rad Process Dev (<1 yr)"-"MT, J Rad Process (<1 yr)", 8)  

"Joint, Rad Process (Development)" = INTEG (  
"To J, Rad Process (Development)"-"To J, Rad Process (Successful)"-"To J, Rad Process (Unsuccessful)", 1)  

"Joint, Rad Process (Launched)" = INTEG (  
"To J, Rad Process (Successful)"-"To J, Rad Process (<1 yr)", 0)  

"Joint, Rad Process Development (Available)" = INTEG (  
MIN(("To J, Rad Process (F)"+"To J, Rad Process (S) ")/Resource per Radical Process, Joint Process KS/Knowledge per Radical Process)-"To J, Rad Process (Development)", 0)  

"Joint, Rad Prod (1-5 yr)" = INTEG (  
+"To J, Rad Prod (1-5 yr)"-"To J, Rad Prod Dev (1-5 yr)"-"To J, Rad to Inc Prod"-"TT, J Rad Prod (1-5 yr)"-"MT, J Rad Prod (1-5 yr)", 2)  

"Joint, Rad Prod (<1 yr)" = INTEG (  
"To, J Rad Prod (<1 yr)"-"TT, J Rad Prod (<1 yr)"-"To J, Rad Prod (1-5 yr)"-"To J, Rad Prod Dev (<1 yr)"-"MT, J Rad Prod (<1 yr)", 4)  

"Joint, Rad Prod (Development)" = INTEG (  
"To J, Rad Prod (Undertaken)"-"To J, Rad Prod (Successful)"-"To J, Rad Prod (Unsuccessful)", 0)
"Joint, Rad Prod (Launched)" = INTEG ( 
    "To J, Rad Prod (Successful)" - "To J Rad Prod (<1 yr)", 0)

"Joint, Rad Prod Development (Available)" = INTEG ( 
    MIN(("To J, Rad Prod (F)" + "To J, Rad Prod (S)")/Resources per Radical Product, 
    Joint Product KS/Knowledge per Radical Product) - "To J, Rad Prod (Undertaken)", 0)

Knowledge per Inc Process = 10

Knowledge per Inc Prod = 10

Knowledge per Radical Process = 15

Knowledge per Radical Product = 15

"KS per Inc Prod (1-5 yr)" = 3

"KS per Inc Prod (6-10 yr)" = 2

"KS per Inc Prod (<1 yr)" = 4

"KS per Inc Prod (>10 yr)" = 1

"KS per Rad Prod (1-5 yr)" = 4

"KS per Rad Prod (< 1yr)" = 5

"MT (1-5 yr)" = 0.015

"MT (6-10 yr)" = 0.02
"MT (<1 yr)" = 0.0125

"MT (>10 yr)" = 0.025

"MT, F Inc Prod (1-5 yr)" =
   "Focal, Inc Prod (1-5 yr)" * "MT (1-5 yr)"

"MT, F Inc Prod (6-10 yr)" =
   "Focal, Inc Prod (6-10 yr)" * "MT (6-10 yr)"

"MT, F Inc Prod (<1 yr)" =
   "Focal, Inc Prod (<1 yr)" * "MT (<1 yr)"

"MT, F Inc Prod (>10 yr)" =
   "Focal, Inc Prod (>10 yr)" * "MT (>10 yr)"

"MT, F Rad Prod (1-5 yr)" =
   "Focal, Rad Prod (1-5 yr)" * "MT (1-5 yr)"

"MT, F Rad Prod (<1 yr)" =
   "Focal, Rad Prod (<1 yr)" * "MT (<1 yr)"

"MT, J Inc Process (1-5 yr)" =
   "Joint, Inc Process (1-5 yr)" * "MT (1-5 yr)"

"MT, J Inc Process (6-10 yr)" =
   "Joint, Inc Process (6-10 yr)" * "MT (6-10 yr)"

"MT, J Inc Process (<1 yr)" =
   "Joint, Inc Process (<1 yr)" * "MT (<1 yr)"
"MT, J Inc Process (>10 yr)" =
"Joint, Inc Process (>10 yr)" * "MT (>10 yr)"

"MT, J Inc Prod (1-5 yr)" =
"Joint, Inc Prod (1-5 yr)" * "MT (1-5 yr)"

"MT, J Inc Prod (6-10 yr)" =
"Joint, Inc Prod (6-10 yr)" * "MT (6-10 yr)"

"MT, J Inc Prod (<1 yr)" =
"Joint, Inc Prod (<1 yr)" * "MT (<1 yr)"

"MT, J Inc Prod (>10 yr)" =
"Joint, Inc Prod (>10 yr)" * "MT (>10 yr)"

"MT, J Rad Process (1-5 yr)" =
"Joint, Rad Process (1-5 yr)" * "MT (1-5 yr)"

"MT, J Rad Process (<1 yr)" =
"Joint, Rad Process (<1 yr)" * "MT (<1 yr)"

"MT, J Rad Prod (1-5 yr)" =
"Joint, Rad Prod (1-5 yr)" * "MT (1-5 yr)"

"MT, J Rad Prod (<1 yr)" =
"Joint, Rad Prod (<1 yr)" * "MT (<1 yr)"

"MT, S Inc Prod (1-5 yr)" =
"Supplier, Inc Prod (1-5 yr)" * "MT (1-5 yr)"
"MT, S Inc Prod (6-10 yr)"=
   "Supplier, Inc Prod (6-10 yr)"*"MT (6-10 yr)"

"MT, S Inc Prod (<1 yr)"=
   "Supplier, Inc Prod (<1 yr)"*"MT (<1 yr)"

"MT, S Inc Prod (>10 yr)"=
   "Supplier, Inc Prod (>10 yr)"*"MT (>10 yr)"

"MT, S Rad Prod (1-5 yr)"=
   "Supplier, Rad Prod (1-5 yr)"*"MT (1-5 yr)"

"MT, S Rad Prod (<1 yr)"=
   "Supplier, Rad Prod (<1 yr)"*"MT (<1 yr)"

"P (1-5 yr)"=
   "Focal, Inc Prod (<1 yr)"/4

P launch= INTEG ( 
   "To F, Inc Prod (Launch)"-"To F, Inc Prod (<1 yr)", 0)

Rad Process Success Rate=0.4

"Rad Prod Rate (1-5 yr)"=0.04

"Rad Prod Rate (<1 yr)"=0.03

Rad Product Success Rate=0.4

"Rad Profit (1-5 yr)"=12
"Rad Profit (<1 yr)"=12

Radical Delay=4

Recovered Focal Product=
   IF THEN ELSE(Focal Funded Products>"Focal, Inc Prod Development (Available)", MIN(Focal Funded Products-"Focal, Inc Prod Development (Available)" , Focal Dormant Products), 0)

Recovered Joint Processes=
   IF THEN ELSE( Joint Funded Processes>"Joint, Inc Process Development (Available)", MIN(Joint Funded Processes -"Joint, Inc Process Development (Available)" ,Joint Dormant Processes), 0)

Recovered Joint Product=
   max(IF THEN ELSE(Joint Funded Products-"Joint, Inc Prod Development (Available)" >0, MIN(Joint Funded Products-"Joint, Inc Prod Development (Available)" ,Joint Dormant Products),0), 0)

Recovered Supplier Product=
   IF THEN ELSE( Supplier Funded Products>"Supplier, Inc Prod Development (Available)", MIN(Supplier Funded Products-"Supplier, Inc Prod Development (Available)" ,Supplier Dormant Products), 0)

Resource per Inc Process=10

Resource per Inc Prod=20

Resource per Radical Process=15

Resources per Radical Product=50
"S, KS Forget (1-5 yr)" =
"Supplier KS (1-5 yr)"**"Forget Rate (1-5 yr)"

"S, KS Forget (6-10 yr)" =
"Supplier KS (6-10 yr)"**"Forget Rate (6-10 yr)"

"S, KS Forget (<1 yr)" =
"Supplier KS (<1 yr)"**"Forget Rate (<1 yr)"

"S, KS Forget (>10 yr)" =
"Supplier KS (>10 yr)"**"Forget Rate (>10 yr)"

Supplier Aged Products =
Supplier Dormant Products * Aged Product Rate

Supplier Dormant Products = INEG (
"To S, Inc Prod (Unsuccessful)" + "To S, Rad Prod (Unsuccessful)"+ Unfunded
Supplier Prod-Recovered Supplier Product-Supplier Aged Products, 0)

Supplier Funded Products =
MIN("To Inc Prod, (S)"/Resource per Inc Prod, Supplier KS/Knowledge per Inc Prod)

"Supplier IR, Joint Process" = INEG (
"To Supplier IR, Joint Process" + "Budgeted Joint Process (S)" - "To J, Inc Process (S)" - "To J, Rad Process (S)", 0)

"Supplier IR, Joint Prod" = INEG (
"To Supplier IR, Joint Prod" + "Budgeted Joint Prod (S)" - "To J, Inc Prod (S)" - "To J, Rad Prod (S)", 0)
"Supplier IR, Prod" = INTEG (To Supplier IR + "Budgeted (supplier)" - "To Inc Prod, (S)" - "To Rad Prod, (S)", 0)

Supplier KS = ACTIVE INITIAL ("To Supplier KS (1-5 yr)" + "To Supplier KS (6-10 yr)" + "To Supplier KS (<1 yr)" + "To Supplier KS (>10 yr)" + Supplier Transferred KS, 100)

"Supplier KS (1-5 yr)" = INTEG ("Supplier, Inc Prod (1-5 yr)" * "KS per Inc Prod (1-5 yr)" + "Supplier, Rad Prod (1-5 yr)" * "KS per Rad Prod (1-5 yr)" - "S, KS Forget (1-5 yr)" - "To Supplier KS (1-5 yr)", 0)

"Supplier KS (6-10 yr)" = INTEG ("Supplier, Inc Prod (6-10 yr)" * "KS per Inc Prod (6-10 yr)" - "S, KS Forget (6-10 yr)" - "To Supplier KS (6-10 yr)", 0)

"Supplier KS (<1 yr)" = INTEG ("Supplier, Inc Prod (<1 yr)" * "KS per Inc Prod (<1 yr)" + "Supplier, Rad Prod (<1 yr)" * "KS per Rad Prod (<1 yr)" - "S, KS Forget (<1 yr)" - "To Supplier KS (<1 yr)", 0)

"Supplier KS (>10 yr)" = INTEG ("Supplier, Inc Prod (>10 yr)" * "KS per Inc Prod (>10 yr)" - "S, KS Forget (>10 yr)" - "To Supplier KS (>10 yr)", 0)

Supplier KS Goal = 250

Supplier KS Transfer = INTEG (Joint Product KS * Supplier KT - Supplier Transferred KS, 0)

Supplier KT =
\[
\frac{1}{1+\exp(-0.03*\text{Joint Process KS-Supplier Process KS goal})/\text{Supplier Process KS goal}} \times \Theta \\
\]

Supplier Process KS goal = 225

Supplier Product Frac =
\[
\frac{1}{1+\exp(-0.01*\text{Supplier Slack Resources-Supplier Profit Goal})} \\
\]

Supplier Profit Goal = 250

Supplier Profits = INTEG ("
"Supplier, Inc Prod (<1 yr)"*"Inc Profit (<1 yr)" + "Supplier, Inc Prod (1-5 yr)"*"Inc Profit (1-5 yr)" + "Supplier, Inc Prod (6-10 yr)"*"Inc Profit (6-10 yr)" + "Supplier, Inc Prod (>10 yr)"*"Inc Profit (>10 yr)" + "Supplier, Rad Prod (<1 yr)"*"Rad Profit (<1 yr)" + "Supplier, Rad Prod (1-5 yr)"*"Rad Profit (1-5 yr)" - To Supplier Slack Resources, 0)

Supplier Slack Resources = INTEG ("
To Supplier Slack Resources - To Supplier IR - "To Supplier IR, Joint Process" - "To Supplier IR, Joint Prod", 0)

Supplier to Joint Process Frac =
\[
\frac{1}{1+\exp(-0.01*\text{Joint Process KS-Supplier Process KS goal})} \\
\]

Supplier to Joint Product Frac =
\[
\frac{1}{1+\exp(-0.003*\text{Supplier KS-Supplier KS Goal})} \\
\]

Supplier Transferred KS =
Supplier KS Transfer

"Supplier, Inc Prod (1-5 yr)" = INTEG (}
"To S, Inc Prod (1-5 yr)" - "MT, S Inc Prod (1-5 yr)" - "To S, Inc Prod (6-10 yr)" - "To S, Inc Prod Dev (1-5 yr)" - "TT, S Inc Prod (1-5 yr)", 8

"Supplier, Inc Prod (6-10 yr)" = INTEG ( 
"To S, Inc Prod (6-10 yr)" + "To S, Rad to Inc Prod" - "MT, S Inc Prod (6-10 yr)" - "To S, Inc Prod (>10 yr)" - "To S, Inc Prod Dev (6-10 yr)" - "TT, S Inc Prod (6-10 yr)", 6

"Supplier, Inc Prod (<1 yr)" = INTEG ( 
"To S, Inc Prod (<1 yr)" - "MT, S Inc Prod (<1 yr)" - "To S, Inc Prod (1-5 yr)" - "To S, Inc Prod Dev (<1 yr)" - "TT, S Inc Prod (<1 yr)", 10

"Supplier, Inc Prod (>10 yr)" = INTEG ( 
"To S, Inc Prod (>10 yr)" - "MT, S Inc Prod (>10 yr)" - "To S, Inc Prod Dev (>10 yr)" - "TT, S Inc Prod (>10 yr)", 4

"Supplier, Inc Prod (Development)" = INTEG ( 
"To S, Inc Prod (Development)" - "To S, Inc Prod (Successful)" - "To S, Inc Prod (Unsuccessful)", 0

"Supplier, Inc Prod (Launched)" = INTEG ( 
"To S, Inc Prod (Launch)" - "To S, Inc Prod (<1 yr)", 0

"Supplier, Inc Prod (Successful)" = INTEG ( 
"To S, Inc Prod (Successful)" - "To S, Inc Prod (Launch)", 0

"Supplier, Inc Prod Development (Available)" = INTEG ( 
Recovered Supplier Product + "To S, Inc Prod Dev (1-5 yr)" + "To S, Inc Prod Dev (6-10 yr)" + "To S, Inc Prod Dev (<1 yr)" + "To S, Inc Prod Dev (>10 yr)" + "To S, Rad Prod Dev (1-5 yr)" + "To S, Rad Prod Dev (<1 yr)" - Unfunded Supplier Prod - "To S, Inc Prod (Development)", 0

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"Supplier, Rad Prod (1-5 yr)" = INTEG (  
"To S, Rad Prod (1-5 yr)" - "MT, S Rad Prod (1-5 yr)" - "To S, Rad Prod Dev (1-5 yr)" - "To S, Rad to Inc Prod" - "TT, S Rad Prod (1-5 yr)", 2) 

"Supplier, Rad Prod (<1 yr)" = INTEG (  
"To, S Rad Prod (<1 yr)" - "MT, S Rad Prod (<1 yr)" - "To S, Rad Prod (1-5 yr)" - "TT, S Rad Prod (<1 yr)" - "To S, Rad Prod Dev (<1 yr)", 5) 

"Supplier, Rad Prod (Development)" = INTEG (  
"To S, Rad Prod (Development)" - "To S, Rad Prod (Successful)" - "To S, Rad Prod (Unsuccessful)", 0) 

"Supplier, Rad Prod (Launched)" = INTEG (  
"To S, Rad Prod (Successful)" - "To, S Rad Prod (<1 yr)", 0) 

"Supplier, Rad Prod Development (Available)" = INTEG (  
MIN("To Rad Prod, (S)"/Resources per Radical Product,Supplier KS/Knowledge per Radical Product) - "To S, Rad Prod (Development)", 0) 

Theta = 0.55 

"To F, Inc Prod (6-10 yr)" =  
"Focal, Inc Prod (1-5 yr)"/16 

"To F, Inc Prod (<1 yr)" =  
P launch 

"To F, Inc Prod (>10 yr)" =  
"Focal, Inc Prod (6-10 yr)"/20
"To F, Inc Prod (Development)" =
    MIN(Focal Funded Products,"Focal, Inc Prod Development (Available)"

"To F, Inc Prod (Launch)" =
    "Focal, Inc Prod (Successful)"

"To F, Inc Prod (Successful)" =
    DELAY FIXED("To F, Inc Prod (Development)*Inc Product Success Rate , Incremental Delay, 0"

"To F, Inc Prod (Unsuccessful)" =
    DELAY FIXED("To F, Inc Prod (Development)*(1-Inc Product Success Rate) , Incremental Delay, 0"

"To F, Inc Prod Dev (1-5 yr)" =
    "Focal, Inc Prod (1-5 yr)"*"Inc Prod Rate (1-5 yr)"

"To F, Inc Prod Dev (6-10 yr)" =
    "Focal, Inc Prod (6-10 yr)"*"Inc Prod Rate (6-10 yr)"

"To F, Inc Prod Dev (>10 yr)" =
    "Focal, Inc Prod (>10 yr)"*"Inc Prod Rate (>10 yr)"

"To F, Rad Prod (1-5 yr)" =
    "Focal, Rad Prod (<1 yr)"/4

"To F, Rad Prod (Development)" =
    "Focal, Rad Prod Development (Available)"

"To F, Rad Prod (Successful)" = DELAY FIXED ( 
    "To F, Rad Prod (Development)"*Rad Product Success Rate, Radical Delay , 0)
"To F, Rad Prod (Unsuccessful)"=
DELAY FIXED("To F, Rad Prod (Development)"*(1-Rad Product Success Rate),
Radical Delay, 0 )

"To F, Rad Prod Dev (1-5 yr)"=
"Focal, Rad Prod (1-5 yr)"*"Rad Prod Rate (1-5 yr)"

"To F, Rad Prod Dev (<1 yr)"=
"Focal, Rad Prod (<1 yr)"*"Rad Prod Rate (<1 yr)"

"To F, Rad to Inc Prod"=
"Focal, Rad Prod (1-5 yr)"/16

"To Focal IR, Joint Process"=
Focal Slack Resources/3

"To Focal IR, Joint Prod"=
Focal Slack Resources/3

"To Focal IR, Prod"=
Focal Slack Resources/3

"To Focal KS (1-5 yr)"=
"Focal KS (1-5 yr)"-"F, KS Forget (1-5 yr)"

"To Focal KS (6-10 yr)"=
"Focal KS (6-10 yr)"-"F, KS Forget (6-10 yr)"

"To Focal KS (<1 yr)"=
"Focal KS (<1 yr)"-"F, KS Forget (<1 yr)"
"To Focal KS (>10 yr)"=
   "Focal KS (>10 yr)"-"F, KS Forget (>10 yr)"

To Focal Slack Resources=
   Focal Profits

"To Inc Prod, (F)"=
   Focal Product Frac*"Focal IR, Prod"

"To Inc Prod, (S)"=
   Supplier Product Frac*"Supplier IR, Prod"

"To J, Inc Process (1-5 yr)"=
   "Joint, Inc Process (<1 yr)"/4

"To J, Inc Process (6-10 yr)"=
   "Joint, Inc Process (1-5 yr)"/16

"To J, Inc Process (<1 yr)"=
   "Joint, Inc Process (Launched)"

"To J, Inc Process (>10 yr)"=
   "Joint, Inc Process (6-10 yr)"/20

"To J, Inc Process (Development)"=
   MIN(Joint Funded Processes, "Joint, Inc Process Development (Available)"

"To J, Inc Process (F)"=
   Focal to Joint Process Frac*"Focal IR, Joint Process"
"To J, Inc Process (Launch)"=
    "Joint, Inc Process (Successful)"

"To J, Inc Process (S)"=
    Supplier to Joint Process Frac*"Supplier IR, Joint Process"

"To J, Inc Process (Successful)"=
    DELAY FIXED( "To J, Inc Process (Development)"*Inc Process Success Rate ,
    Incremental Delay , 0)

"To J, Inc Process (Unsuccessful)"= DELAY FIXED ( 
    "To J, Inc Process (Development)"*(1-Inc Process Success Rate),Incremental 
    Delay , 0)

"To J, Inc Process Dev (1-5 yr)"=
    "Joint, Inc Process (1-5 yr)"**"Inc Prod Rate (1-5 yr)"

"To J, Inc Process Dev (6-10 yr)"=
    "Joint, Inc Process (6-10 yr)"**"Inc Prod Rate (6-10 yr)"

"To J, Inc Process Dev (<1 yr)"=
    "Joint, Inc Process (<1 yr)"**"Inc Prod Rate (<1 yr)"

"To J, Inc Process Dev (>10 yr)"=
    "Joint, Inc Process (>10 yr)"**"Inc Prod Rate (>10 yr)"

"To J, Inc Prod (1-5 yr)"=
    "Joint, Inc Prod (<1 yr)"/4

"To J, Inc Prod (6-10 yr)"=
    "Joint, Inc Prod (1-5 yr)"/16
"To J, Inc Prod (<1 yr)" =
   "Joint, Inc Prod (Launched)"

"To J, Inc Prod (>10 yr)" =
   "Joint, Inc Prod (6-10 yr)"/20

"To J, Inc Prod (Development)" =
   MIN(Joint Funded Products, "Joint, Inc Prod Development (Available)")

"To J, Inc Prod (F)" =
   Focal to Joint Product Frac**"Focal IR, Joint Prod"

"To J, Inc Prod (Launch)" =
   "Joint, Inc Prod (Successful)"

"To J, Inc Prod (S)" =
   Supplier to Joint Product Frac**"Supplier IR, Joint Prod"

"To J, Inc Prod (Successful)" =
   DELAY FIXED("To J, Inc Prod (Development)"*Inc Product Success Rate,
   Incremental Delay, 0 )

"To J, Inc Prod (Unsuccessful)" =
   DELAY FIXED("To J, Inc Prod (Development)"*(1-Inc Product Success Rate),
   Incremental Delay, 0 )

"To J, Inc Prod Dev (1-5 yr)" =
   "Joint, Inc Prod (1-5 yr)"**"Inc Prod Rate (1-5 yr)"/4

"To J, Inc Prod Dev (6-10 yr)" =
"Joint, Inc Prod (6-10 yr)"**"Inc Prod Rate (6-10 yr)"/4

"To J, Inc Prod Dev (<1 yr)"=
"Joint, Inc Prod (<1 yr)"**"Inc Prod Rate (<1 yr)"/4

"To J, Inc Prod Dev (>10 yr)"=
"Joint, Inc Prod (>10 yr)"**"Inc Prod Rate (>10 yr)"/4

"To J, Rad Process (1-5 yr)"=
"Joint, Rad Process (<1 yr)"/4

"To J, Rad Process (Development)"=
"Joint, Rad Process Development (Available)"

"To J, Rad Process (F)"=
(1-Focal to Joint Process Frac)"Focal IR, Joint Process"

"To J, Rad Process (S)"=
(1-Supplier to Joint Process Frac)"Supplier IR, Joint Process"

"To J, Rad Process (Successful)"=
DELAY FIXED("To J, Rad Process (Development)"*Rad Process Success Rate, Radical Delay, 0)

"To J, Rad Process (Unsuccessful)"=
DELAY FIXED("To J, Rad Process (Development)"*(1-Rad Process Success Rate), Radical Delay, 0)

"To J, Rad Process Dev (1-5 yr)"=
"Joint, Rad Process (1-5 yr)"**"Rad Prod Rate (1-5 yr)"
"To J, Rad Process Dev (<1 yr)"=
   "Joint, Rad Process (<1 yr)"*"Rad Prod Rate (<1 yr)"

"To J, Rad Prod (1-5 yr)"=
   "Joint, Rad Prod (<1 yr)"/4

"To J, Rad Prod (F)"=
   (1-Focal to Joint Product Frac)*"Focal IR, Joint Prod"

"To J, Rad Prod (S)"=
   (1-Supplier to Joint Product Frac)*"Supplier IR, Joint Prod"

"To J, Rad Prod (Successful)"=
   DELAY FIXED("To J, Rad Prod (Undertaken)"*Rad Product Success Rate, Radical Delay, 0)

"To J, Rad Prod (Undertaken)"=
   "Joint, Rad Prod Development (Available)"

"To J, Rad Prod (Unsuccessful)"=
   DELAY FIXED("To J, Rad Prod (Undertaken)"*(1-Rad Product Success Rate), Radical Delay, 0)

"To J, Rad Prod Dev (1-5 yr)"=
   "Joint, Rad Prod (1-5 yr)"*"Rad Prod Rate (1-5 yr)"/4

"To J, Rad Prod Dev (<1 yr)"=
   "Joint, Rad Prod (<1 yr)"*"Rad Prod Rate (<1 yr)"/4

"To J, Rad to Inc Process"=
   "Joint, Rad Process (1-5 yr)"/16
"To J, Rad to Inc Prod"=
  "Joint, Rad Prod (1-5 yr)"/16

"To Joint KS (1-5 yr)"=
  "Joint KS (1-5 yr)"-"J, KS Forget (1-5 yr)"

"To Joint KS (6-10 yr)"=
  "Joint KS (6-10 yr)"-"J, KS Forget (6-10 yr)"

"To Joint KS (<1 yr)"=
  "Joint KS (<1 yr)"-"J, KS Forget (<1 yr)"

"To Joint KS (>10 yr)"=
  "Joint KS (>10 yr)"-"J, KS Forget (>10 yr)"

"To Joint Process KS (1-5 yr)"=
  "Joint Process KS (1-5 yr)"-"J, KS Process Forget (1-5 yr)"

"To Joint Process KS (6-10 yr)"=
  "Joint Process KS (6-10 yr)"-"J, KS Process Forget (6-10 yr)"

"To Joint Process KS (<1 yr)"=
  "Joint Process KS (<1 yr)"-"J, KS Process Forget (<1 yr)"

"To Joint Process KS (>10 yr)"=
  "Joint Process KS (>10 yr)"-"J, KS Process Forget (>10 yr)"

"To Rad Prod, (F)"=
  (1-Focal Product Frac)*"Focal IR, Prod"
"To Rad Prod, (S)" = 
(1-Supplier Product Frac)*"Supplier IR, Prod"

"To S, Inc Prod (1-5 yr)" = 
"Supplier, Inc Prod (<1 yr)/4

"To S, Inc Prod (6-10 yr)" = 
"Supplier, Inc Prod (1-5 yr)/16

"To S, Inc Prod (<1 yr)" = 
"Supplier, Inc Prod (Launched)"

"To S, Inc Prod (>10 yr)" = 
"Supplier, Inc Prod (6-10 yr)/20

"To S, Inc Prod (Development)" = 
MIN(Supplier Funded Products,"Supplier, Inc Prod Development (Available)"

"To S, Inc Prod (Launch)" = 
"Supplier, Inc Prod (Successful)"

"To S, Inc Prod (Successful) " = 
DELAY FIXED("To S, Inc Prod (Development)"*Inc Product Success Rate, Incremental Delay, 0)

"To S, Inc Prod (Unsuccessful)" = 
DELAY FIXED("To S, Inc Prod (Development)"*(1-Inc Product Success Rate), Incremental Delay, 0)

"To S, Inc Prod Dev (1-5 yr)" = 
"Supplier, Inc Prod (1-5 yr)"*"Inc Prod Rate (1-5 yr)"
"To S, Inc Prod Dev (6-10 yr)" =
"Supplier, Inc Prod (6-10 yr)" * "Inc Prod Rate (6-10 yr)"

"To S, Inc Prod Dev (<1 yr)" =
"Supplier, Inc Prod (<1 yr)" * "Inc Prod Rate (<1 yr)"

"To S, Inc Prod Dev (>10 yr)" =
"Supplier, Inc Prod (>10 yr)" * "Inc Prod Rate (>10 yr)"

"To S, Rad Prod (1-5 yr)" =
"Supplier, Rad Prod (<1 yr)" / 4

"To S, Rad Prod (Development)" =
"Supplier, Rad Prod Development (Available)"

"To S, Rad Prod (Successful)" =
DELAY FIXED("To S, Rad Prod (Development)" * Rad Product Success Rate, Radical Delay, 0)

"To S, Rad Prod (Unsuccessful)" =
DELAY FIXED("To S, Rad Prod (Development)" * (1 - Rad Product Success Rate), Radical Delay, 0)

"To S, Rad Prod Dev (1-5 yr)" =
"Supplier, Rad Prod (1-5 yr)" * "Rad Prod Rate (1-5 yr)"

"To S, Rad Prod Dev (<1 yr)" =
"Supplier, Rad Prod (<1 yr)" * "Rad Prod Rate (<1 yr)"

"To S, Rad to Inc Prod" =
"Supplier, Rad Prod (1-5 yr)"/16

To Supplier IR=
Supplier Slack Resources/3

"To Supplier IR, Joint Process"=
Supplier Slack Resources/3

"To Supplier IR, Joint Prod"=
Supplier Slack Resources/3

"To Supplier KS (1-5 yr)"=
"Supplier KS (1-5 yr)"-"S, KS Forget (1-5 yr)"

"To Supplier KS (6-10 yr)"=
"Supplier KS (6-10 yr)"-"S, KS Forget (6-10 yr)"

"To Supplier KS (<1 yr)"=
"Supplier KS (<1 yr)"-"S, KS Forget (<1 yr)"

"To Supplier KS (>10 yr)"=
"Supplier KS (>10 yr)"-"S, KS Forget (>10 yr)"

To Supplier Slack Resouces=
Supplier Profits

"To, F Rad Prod (<1 yr)"=
"Focal, Rad Prod (Launched)"

"To, J Rad Process (<1 yr)"=
"Joint, Rad Process (Launched)"
"To, J Rad Prod (<1 yr)"=
   "Joint, Rad Prod (Launched)"

"To, S Rad Prod (<1 yr)"=
   "Supplier, Rad Prod (Launched)"

"TT (1-5 yr)"=0

"TT (6-10 yr)"=0

"TT (<1 yr)"=0

"TT (>10 yr)"=0

"TT, F Inc Prod (1-5 yr)"=
   "Focal, Inc Prod (1-5 yr)"*"TT (1-5 yr)"

"TT, F Inc Prod (6-10 yr)"=
   "Focal, Inc Prod (6-10 yr)"*"TT (6-10 yr)"

"TT, F Inc Prod (<1 yr)"=
   "Focal, Inc Prod (<1 yr)"*"TT (<1 yr)"

"TT, F Inc Prod (>10 yr)"=
   "Focal, Inc Prod (>10 yr)"*"TT (>10 yr)"

"TT, F Rad Prod (1-5 yr)"=
   "Focal, Rad Prod (1-5 yr)"*"TT (1-5 yr)"

"TT, F Rad Prod (<1 yr)"=
"Focal, Rad Prod (<1 yr)" * "TT (<1 yr)"

"TT, J Inc Process (1-5 yr)" =
"Joint, Inc Process (1-5 yr)" * "TT (1-5 yr)"

"TT, J Inc Process (6-10 yr)" =
"Joint, Inc Process (6-10 yr)" * "TT (6-10 yr)"

"TT, J Inc Process (<1 yr)" =
"Joint, Inc Process (<1 yr)" * "TT (<1 yr)"

"TT, J Inc Process (>10 yr)" =
"Joint, Inc Process (>10 yr)" * "TT (>10 yr)"

"TT, J Inc Prod (1-5 yr)" =
"Joint, Inc Prod (1-5 yr)" * "TT (1-5 yr)"

"TT, J Inc Prod (6-10 yr)" =
"Joint, Inc Prod (6-10 yr)" * "TT (6-10 yr)"

"TT, J Inc Prod (<1 yr)" =
"Joint, Inc Prod (<1 yr)" * "TT (<1 yr)"

"TT, J Inc Prod (>10 yr)" =
"Joint, Inc Prod (>10 yr)" * "TT (>10 yr)"

"TT, J Rad Process (1-5 yr)" =
"Joint, Rad Process (1-5 yr)" * "TT (1-5 yr)"

"TT, J Rad Process (<1 yr)" =
"Joint, Rad Process (<1 yr)" * "TT (<1 yr)"

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"TT, J Rad Prod (1-5 yr)"=
"Joint, Rad Prod (1-5 yr)"*"TT (1-5 yr)"

"TT, J Rad Prod (<1 yr)"=
"Joint, Rad Prod (<1 yr)"*"TT (<1 yr)"

"TT, S Inc Prod (1-5 yr)"=
"Supplier, Inc Prod (1-5 yr)"*"TT (1-5 yr)"

"TT, S Inc Prod (6-10 yr)"=
"Supplier, Inc Prod (6-10 yr)"*"TT (6-10 yr)"

"TT, S Inc Prod (<1 yr)"=
"Supplier, Inc Prod (<1 yr)"*"TT (<1 yr)"

"TT, S Inc Prod (>10 yr)"=
"Supplier, Inc Prod (>10 yr)"*"TT (>10 yr)"

"TT, S Rad Prod (1-5 yr)"=
"Supplier, Rad Prod (1-5 yr)"*"TT (1-5 yr)"

"TT, S Rad Prod (<1 yr)"=
"Supplier, Rad Prod (<1 yr)"*"TT (<1 yr)"

Unfunded Focal Prod=
IF THEN ELSE("Focal, Inc Prod Development (Available)">Focal Funded Products, "Focal, Inc Prod Development (Available)"-Focal Funded Products, 0)

Unfunded Joint Prod
IF THEN ELSE( "Joint, Inc Prod Development (Available)"-Joint Funded Products>0 , "Joint, Inc Prod Development (Available)"-Joint Funded Products, 0)

Unfunded Processes=

Unfunded Supplier Prod=
IF THEN ELSE("Supplier, Inc Prod Development (Available)"->Supplier Funded Products, "Supplier, Inc Prod Development (Available)"-Supplier Funded Products , 0 )

********************************************************
Control
********************************************************
Simulation Control Parameters
FINAL TIME  = 100
Quarter
The final time for the simulation.

INITIAL TIME  = 0
Quarter
The initial time for the simulation.

SAVEPER =
TIME STEP
Quarter [0,?]
The frequency with which output is stored.

TIME STEP  = 1
Quarter [0,?]
The time step for the simulation.