Sustainable Supply Chain Excellence: A Biomimetic Perspective

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The paper studies sustainable supply chain management from the perspective of protein biosynthesis, which is one of the most fundamental supply chains present in every organism. After providing a review of literature, the study explains the protein biosynthesis process. The paper then analyzes sustainable supply chains using a biomimetic perspective of protein biosynthesis. Finally, lessons of excellence for supply chain sustainability based on unique characteristics present in the protein biosynthesis process have been delineated.

Introduction

Today's competitive economy fuelled by services sector has created increasingly sophisticated and capable customers. Manufacturers can no longer assume that they can innovate and manufacture products exclusively at their own pace and quality levels. They have recognized the need to quickly react to or even anticipate changing market demands. The result has been the adoption of agile manufacturing and flexible supply chain systems with the focus being completely on the customer. Further, with increase in environmental concerns, a consensus is growing that environmental issues accompanying industrial development should be addressed together with supply chain management, thereby contributing to green supply chain management (Hsu and Hu, 2007).

The current wave of corporate environmentalism, forced by resources depletion and the threat of global climate change, has led to a new role for companies. Corporates are being forced to move beyond compliance with regulations to a leadership stance in the green, energy efficient economy of the future. Emulating the patterns and designs and strategies in nature, including those of plants, animals and ecosystems, is an effective way for corporations to become cleaner, leaner and more consistently innovative (Bernstein, 2006). In fact, 'nature is the best teacher' (Baba, 2000, p. 250).

Biomimetics

Biomimetics is the method of imitating the processes and techniques used by nature to achieve efficiency, effectiveness and sustainability (Benyus, 1997). It is the application of

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methods and systems found in nature to the study and design of engineering systems and modern technology. The transfer of technology between life forms and synthetic constructs is desirable because evolutionary pressure typically forces natural systems to become highly optimized and efficient.

There were several successful applications of biomimetics in industry (Benyus, 1997; and Neinhuis and Barthlott, 1997):

- Ceramic tiles were manufactured by emulating the self-assembly of abalone shells.
- Adhesive tapes were produced patterned after geckos' (a type of lizard) feet.
- Computer chips were designed to assemble themselves through crystallization, just as microscopic algae called diatoms assemble their shells.
- Genetic algorithms were designed based on the natural selection process to optimize code for designs.
- Freshwater production systems were developed based on the reverse osmosis processes employed by the mangrove forests, a salt-water plant that grows along the coastlines of tropical areas.
- Self-cleaning facade paint was produced based on the water- and dust-repellent properties of the lotus leaf.
- Hulls of boats were created imitating the thick skin of dolphins.
- Sonar, radar and medical ultrasound imaging have imitated the echolocation of bats.
- Cybernetics, artificial neurons, artificial neural networks and swarm intelligence were created in the field of computer science based on laws of nature.

The present paper is an endeavor to develop a biomimetic framework based on the protein biosynthesis process for sustainable supply chain management. After a review of related literature, the paper discusses the protein biosynthesis process. The paper then analyzes sustainable supply chain management from the perspective of the protein biosynthesis process. The paper, finally, provides biomimetic lessons in supply chain sustainability excellence.

Literature Review

With the rapid changes taking place in the global market, it has become clear that enterprises need to integrate agile manufacturing with their systems (Onuh *et al.*, 2007). Therefore several advances through research in supply chain management have been brought about to facilitate agile manufacturing. Saravanan and Haq (2008) studied the scheduling problem of manufacturing cells, in which parts may need to visit different cells during the manufacturing process. Piranfar (2006) showed that adaptive organizations develop supply chains which can manage environment change effectively. Agile systems can withstand dynamic and uncertain factors in the supply chain (Miao *et al.*, 2008) and can manage risks proactively (Dani and Ranganathan, 2008). Hachicha *et al.* (2008) developed an axiomatic design for cellular manufacturing systems and combined it with design experiments to show its effectiveness. Minicell-based manufacturing systems can improve efficiency in mass customization conditions (Thuramalla and Badurdeen, 2008).

Research has focused on understanding supply chain management from a sustainable perspective. Carter and Rogers (2008) defined sustainable supply chain management as the strategic, transparent integration and achievement of an organization's social, environmental and economic goals through the systematic coordination of key inter-organizational business processes to improve the long-term economic performance of the individual company and its value network. Accenture (2008) stated that sustainable supply chain management requires handling ecological, social, economic and integration challenges. Business for Social Responsibility (2007) defined sustainable supply chain management as a system of aligned business activities throughout the lifecycle of products that creates value for all stakeholders, ensures ongoing commercial success and improves the wellbeing of people and the environment. Fitzgerald *et al.* (2007) stated that a network of companies that exchange resources—including materials, services and information—in a way that is sustainable is a sustainable supply chain. These definitions show that sustainable supply chain management systems have the goal of integrating environmental, social and economic concerns into supply chain design and practices.

Sustainable supply chain management has attracted the attention of several researchers due to its growing importance. Ratan *et al.* (2010) stressed that there is a compelling business issue for companies to work with suppliers to jointly develop products and services which are commercially viable, preserve environmental resources and look after workforce and communities. The advantages of sustainable supply chain management systems include increased efficiencies (Croom *et al.*, 2009), better customer and supplier relationships (Business for Social Responsibility, 2007) and improved risk management (Househam, n.d.). Scholars have focused on various corporate sustainable supply chain management practices which include recyclable content usage in various products (NZBCSD, 2003), green purchasing (Morali and Searcy, 2010), social purchasing and assembly (Berglund, 2005) and sustainable packaging initiatives (Urlaub, 2011). NZBCSD (2003) and Hsu and Hu (2007) discussed corporate initiatives in sustainable supply chain management.

Scholars have studied the protein biosynthesis process to understand the lesson it contains for agile manufacturing systems. Miller and Miller (1993) studied the protein synthesis process in a cell as a production process. They explained this process as the most fundamental of all production processes, which range from the cell level to ultimately the supra-national level. Simsek and Albayrak (2004) used the functions in a cell to describe production processes in a factory. Terming the process as the 'living factory' model the authors describe holonic manufacturing in terms of nucleus holons, endoplasmic reticulum holons, ribosome holons and Golgi holons named after different parts of the cell for more efficient manufacturing. Sundaresan and Sivakumar (2007) studied supply chain excellence using the protein biosynthesis process. The process has several lessons for improved supply chain management in terms of push pull balancing of the system, environmental efficiency, targeted distribution and inventory optimization. Demeester *et al.* (2003) researched on what the biological cell can teach about the future of manufacturing. In biological cells, all products and machines are built from a small set of common building blocks that circulate in local recycling loops. Based on this premise, the authors explain the cell metabolism as a manufacturing system and show its efficiency in the form of using pull-systems to avoid overproduction, minimizing work in process by using bottlenecks to control the release rate, using excess capacity to simplify control and managing quality at the source. The authors develop an 'organic production system' involving local production, standard components, templates and local closed recycling loops which enhance the efficiency of the production system. Sivakumar and Sundaresan (2008) showed that the protein biosynthesis process is much more than a supply chain. It is an integrated value system with a wide array of value-adding characteristics.

However, the understanding of the protein biosynthesis process from a sustainable supply chain perspective is yet to be attempted. The objective of this paper is to fill this research gap and develop a biomimetic framework for sustainable supply chain management.

The Protein Biosynthetic Process as a Supply Chain

Proteins are the chief actors within the cell, said to be carrying out the duties specified by the information encoded in genes. Proteins normally make up half the dry weight of a cell. The best-known role of proteins in the cell is their duty as enzymes, which catalyze chemical reactions. Enzymes are usually highly specific catalysts that accelerate only one or a few chemical reactions. About 4,000 reactions are known to be catalyzed by enzymes in a cell. Many proteins are involved in the process of cell signaling and signal transduction. Some proteins, such as insulin, are extracellular proteins that transmit a signal from the cell, in which they were synthesized into other cells in distant tissues. Others are membrane proteins that act as receptors whose main function is to bind a signaling molecule and induce a biochemical response in the cell. Antibodies are protein components of adaptive immune system whose main function is to bind antigens or foreign substances in the body, and target them for destruction. Many ligand transport proteins bind particular small biomolecules and transport them to other locations in the body. Membrane proteins contain internal channels that allow such molecules to enter and exit the cell. Structural proteins confer stiffness and rigidity to otherwise fluid biological components. Other proteins that serve structural functions are motor proteins such as myosin, kinesin and dynein, which are capable of generating mechanical forces. Proteins are thus vital products in the biological systems and the variety that exists is immense.

Because of their strategic importance in the cellular economy, protein biosynthesis is a regulated process. Protein biosynthesis is an extra-ordinarily complex process, in which genetic information encoded in the nucleic acids is translated into the primary structure of proteins. Protein biosynthesis is mediated by the coordinated interplay of more than a hundred macromolecules.

Proteins are biosynthesized based on a set process, as follows (Elliot and Elliot, 2001):

- The process of production of proteins is initiated by promoters. Promoters are signaling mechanisms in the cell which recognize the needs for proteins in the organism.
- The DNA in every cell chromosome transcripts and creates an mRNA (messenger RNA) using freely available nucleotide bases. 'Transcription' is copying the message coded in the nucleotides of the RNA into the amino acids that make up the protein.
- The mRNA moves to the ribosome in the cell, where it pairs with a tRNA (transfer RNA).
- The nucleotide bases on the mRNA and tRNA are recognized in triplets called as codons. The genetic code consists of 64 codons; 61 codons represent 20 different amino acids and three represent 'stop codons'.
- The codons representing amino acids get assembled one after another creating a chain. This process is called 'protein elongation'. This chain of amino acids represents a protein.
- Aminoacyl synthetases in the cell proofread the binding energy in the proteins for quality and reliability control. In case of wrong pairing, the tRNA diffuses away due to lack of energy and thus ensures quality.
- The synthesis of proteins stops with the signal from the 'stop codon'.
- The protein then moves to the Golgi complex, where it is sorted depending on its destination. The Golgi complex is to proteins what a mail sorting office is to a posted mail. The proteins are also packed to enhance their reliability.
- Nascent proteins contain signals that determine their ultimate destination. Structures called cisternae, pack the proteins into transport vesicles.
- Proteins are transported to their destinations in appropriately addressed transport vesicles.
- The vesicles are released into the cell's cytoplasm where they migrate to their destinations.
- Some proteins are stored in specified places till wanted. Secretory granules are used to store proteins till they are needed to be used.

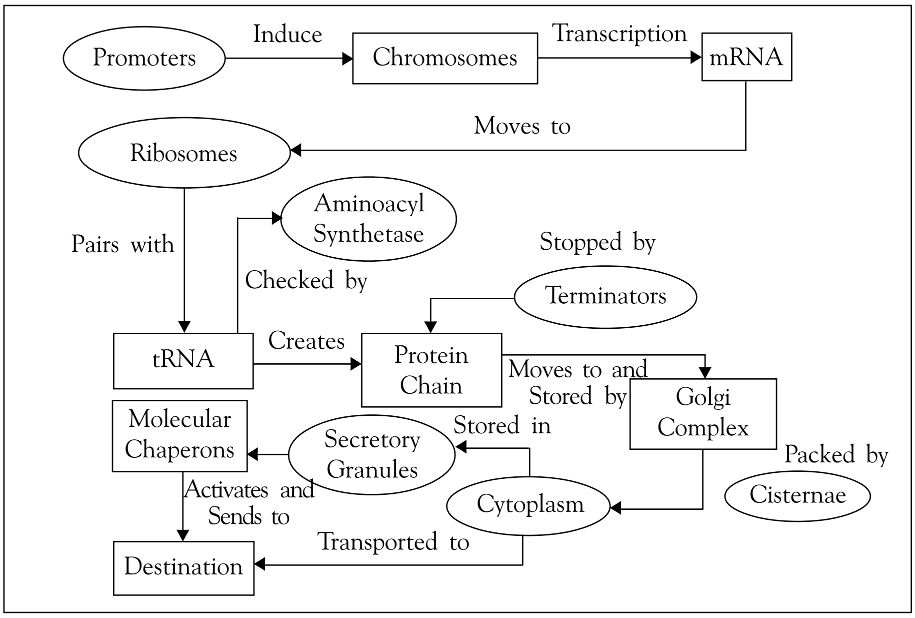
- Molecular chaperones convert proteins from their biologically inactive form to biologically active three-dimensional form prior to delivery. These are released when needed by neuronal or hormonal stimulus.

The protein biosynthesis process is supplemented with additional integrated aspects to achieve efficiency and higher value addition. These include:

- Using strong promoters to produce frequently needed proteins.
- Using ribosome modulation factors to deactivate ribosomes from manufacturing proteins during emergencies.
- Using mitochondria to outsource the production of proteins.

The above description of the protein biosynthesis shows that the process is a supply chain using amino acid raw materials to efficiently manufacture proteins which are stored and transported to the destination organs for end use. The protein biosynthesis supply chain is depicted in Figure 1.

Figure 1: The Protein Biosynthesis Supply Chain



Source: Sivakumar and Sundaresan (2008)

Sustainable Supply Chains: A Protein Biosynthesis-Based Biomimetic Perspective

Sustainable supply chains require the integration of several components of the supply chain in a sustainable manner. It involves the management of materials and information from suppliers to manufacturer to customer and back with the social and environmental impacts explicitly considered along with economic criteria (NZBCSD, 2003). Figure 2 depicts the sustainability issues across the supply chain.

Figure 2: Sustainability Issues Across the Supply Chain

Physical Supply Chain	Raw Materials	Manufacturing Plant	Warehouse	Transport	Distribution Center
Sustainability Issues/ Opportunities	Raw material waste Dependence of local economy on traditional agriculture Local jobs Fuel use Internal resources	Waste created Energy use Water pollution Emissions Safety Health impacts, e.g., reduce manual handling: noise levels Productivity	Energy use Reduce packaging waste Social impact of long/unsocial hours Repetitive handling Pay and conditions Inventory management	Fuel Usage Emissions Noise Impact on transport infrastructure Full loads in both directions where feasible Worklife balance Road accidents	Scheduling: Improve traffic flows Reusable tays and pallets Reverse logistics Unsocial hours-round the clock shifts Economies of scale from buying direct from supplier

Source: Adapted from NZBCSD (2003)

Figure 2 shows the sustainability in supply chains must start at procurement of raw materials and continue through production and distribution till consumption. The philosophy and culture of sustainability will have to be inculcated along the entire supply chain. The following subsections describe how the protein biosynthesis process promotes sustainability in its supply chain.

Raw Material, Procurement or Supplier Sustainability

At the procurement stage, sustainability can be inculcated by reducing raw material requirements and variety with the important aim of cutting down wastages. Further, dependence on existing resources improves sustainability. To improve social impact, the supply chain will have to rely on local raw materials created through local jobs. Sustainable supply chain design would require selecting suppliers based on their ethical and socially responsible behavior (Beamon, 2005).

Reduction in Raw Material Variety: The protein biosynthesis process reduces raw material variety and requirement through the process of ‘genetic buffering’. There are only 20 amino acids which make up proteins. However, there are 64 different combinations of bases which make up these amino acids. The genetic code ensures that different combinations of bases can lead to the same amino acid. This buffering ensures that protein requirements can be satisfied even with lesser raw material variety.

Promotion of Local Economy: The protein biosynthesis process depends upon and promotes the local economy. 'Raw materials' (the nucleotides that make up amino acids) and 'labor' (ribosome where the protein is synthesized) that are available locally from the immediate surroundings are used for the production process. The simplification of raw material requirement makes its free availability on a local scale possible. By sourcing locally, the process also ensures that every part of the body is strengthened to supply the necessary materials and labor on demand.

Usage of Internal Resources: The entire protein biosynthesis process depends upon internal resources. The DNA, RNA, enzymes, amino acids, antibodies, antigens and other chemicals are mostly internal resources. This makes the process of protein biosynthesis highly sustainable.

Resources Conservation: There are some vital proteins whose levels in the cell have to be constantly monitored. When the level goes up or, in other words, the need for these proteins reduces, the proteins are broken down to prevent resource wastage. The same holds good for those proteins which have already served their purpose and are non-essential presently. Thus resources conservation is inherent in the protein biosynthesis process.

Integrated Procurement Planning: Sustainability in the supply chain can be ensured through integrated planning for raw material requirements and their procurement. An organization may have several departments each having unique demands for parts, products or materials. However, such demands could be overlapping among departments. In a sustainable supply chain system, the needs of various departments are accumulated for proper planning. Protein biosynthesis framework shows a similar planning. The needs of proteins in different organs may be different. However, the basic amino acids which make up these proteins are common across various categories of proteins. Therefore, the genetic system plans for the supply of basic amino acids which are assembled into proteins in an integrated manner. Finally, these are made freely available as per requirement of different cells (Sivakumar and Sundaresan, 2008).

Manufacturing or Plant Sustainability

The next aspect of supply chain sustainability is at the manufacturing stage. The most important aspect of sustainability in manufacturing is productivity. If the efficiency of the production process is maintained at high levels, it automatically reduces raw material usage and wastage. However, sustainable supply chains, in the process of driving up efficiency also ensure that side impacts in the form of emissions and pollution, energy wastages and worker health and safety are not ignored (Penfield, 2009). Thus sustainable manufacturing accommodates economic, social and environmental criteria explicitly in a delicate balance.

Productivity and Efficiency: The protein biosynthesis process is one of the most efficient productive systems ever created. It has an extremely fast supply chain cycle. In a cell 100 proteins are produced per minute per translocase. There are approximately 500 translocases per cell leading to the production and distribution of around 50,000 proteins per minute. Such a high level of production and distribution leads to almost instant availability of proteins, leading to a highly efficient supply chain.

In the protein biosynthesis process, enzymes create sustainability using the bottleneck mechanism. The first enzyme is a bottleneck that limits the entry rate of production. The enzymes within the pathway can process products much faster than the entry rate, and as a result, no intermediate products accumulate. The cell has excess capacity for all but the first enzyme in its pathways to regulate production and thus ensures sustainability. Goldratt (1992) has highlighted the principle of using bottlenecks to control the release of jobs into a production line.

The protein biosynthesis process has a very efficient information system. All the information for synthesizing the proteins is encoded in the genetic material of the chromosomes. The first step in protein biosynthetic is synthesis of mRNA. The initiation of the synthesis of RNA is done using promoters regions in the DNA. Similarly there is a terminator region in the DNA, which stops the transcription process of an mRNA. Similarly in the ribosome where the proteins are actually synthesized there are initiators and terminators. Further, when a cell runs low on nutrients and energy, a ribosome modulation factor is used to deactivate ribosomes from manufacturing proteins. These mechanisms make protein biosynthesis a highly sustainable process.

Zero Wastage Through Perfect Quality Management: The protein biosynthesis process invests in defect prevention at various stages of its replication process, using 100% inspection processes, quality assurance procedures and fool-proofing techniques. This is called 'DNA proofreading'. DNA is a double helix of two intertwined DNA strands where the nucleotide adenine pairs with thymine, and cytosine with guanine. DNA is replicated in a semi-conservative way, where a new DNA strand is synthesized using one strand of the double helix as a negative. DNA polymerase is one of the enzymes responsible for the replication of DNA. DNA polymerase synthesizes the new strand by adding new nucleotides that are a complementary match of the nucleotide sequence of the matrix strand. Since DNA strands are anti-parallel and complementary, each strand can serve as a template for the reproduction of the opposite strand. The template strand is preserved as a whole piece and the new strand is assembled from nucleotide triphosphates. This process is called semi-conservative replication. In case of the incorporation of a wrong nucleotide, DNA polymerase possesses an exonuclease activity that removes the wrong nucleotide, thus ensuring a proper replication (Demeester *et al.*, 2003). Waste elimination is one of the important characteristics of protein biosynthesis sustainability.

Energy Use and Emission Controls: One of the important problems faced by modern supply chains is the indiscriminate use of energy in the production process and the resultant emissions thereof (Hervani *et al.*, 2005). This happens due to the need to manage variety and speed in production. Sustainability requires managing these through appropriate production regulation. There is no variety-volume tradeoff in the production of proteins in the cell that is often associated with man-made production systems. Though a huge variety of proteins exist, protein needs are immediately cognized and satisfied by the cell. Based on the need, only specific proteins are produced in cells at specific regions of the body. For example, the cells lining the stomach produce enzymes which are required in digestion predominantly and not structural proteins. However, in the unlikely event of other types of proteins being needed, these cells have all the information to produce the same in the DNA and can immediately satisfy the need.

In the protein biosynthesis process, the nucleotide bases are the raw materials used to build proteins. The process is designed in such a way that different end products often share a set of initial common steps. For example, in the biosynthesis of aromatic proteins, a number of common precursors are synthesized before the pathway splits up for different final products (Olsen and Saetre, 1997). Thus energy use is regulated.

Health Impacts: The immune system in the human body is responsible for the production of antibodies-proteins used to defend the body against invasions by antigens. The immune system has the ability to develop lifelong immunity to many common viral diseases after first initial exposure to a virus. The immune system is composed of millions of lymphocyte cells. Beginning early in lymphocyte development, many lymphocytes that would react against the antigenic determinants on self-macromolecules (i.e., those produced and used by the body) are eliminated or inactivated; as a result, the immune system normally reacts only to foreign antigens. The virgin cells in the human body are those which encounter the antigens for the first time. When this happens, they are stimulated to multiply and become activated cells. Other virgin cells are stimulated to multiply and mature into memory cells—cells that can be readily induced to become activated cells by a later exposure to the same antigen. It is interesting to note that the protein biosynthesis supply chain takes into long-term health impacts explicitly.

Safety: A sustainable supply chain takes into account the safety of the entire supply chain. This includes safety of material, human and information resources (Holme and Watts, 2000). The protein biosynthesis supply chain ensures safety by effectively adapting to mutations. Mutation can be regarded as the process of random changes followed by choosing and multiplying of the most favorable change. Though the change is random, a lot of intelligence is built in the analysis and dissemination of this change. The existence of species that have constantly evolved to cope with changes, both gradual and sudden, is proof that the adaptation process is self-sustaining and robust. The protein biosynthesis ensures sustainability by providing appropriate proteins so that the organism can safely adapt to mutations.

Warehouse and Inventory Sustainability

Sustainable warehousing practices involve efficient inventory management which eliminates all unnecessary inventories. It also deals with managing the problems related to repeated handling. It is also necessary to reduce packing wastages and focus on green practices in the warehouse (Vachon and Klassen, 2006).

Packaging Sustainability: Proteins are builtup in different tiers creating a robust packaging. Proteins have a primary structure which is constituted by a linear amino acid sequence. The secondary structure of proteins has hydrogen bonding interactions within contiguous stretches of polypeptide chains giving rise to α-helices or β-sheets. Proteins then are packed in a tertiary structure which is made by combinations of α-helices and β-sheets packed together to form compactly folded globular units called domains. Finally, the quaternary structure is formed by the binding of various domains via weak non-covalent interactions. To reduce packaging, waste proteins are packed and transported in a biologically inactive form and converted into biologically active form prior to delivery overseen by molecular chaperones, to their correct destination. Thus, robust and efficient packing creates sustainability.

Inventory Sustainability: The inventory in the protein biosynthesis process is amino acids (raw material) and manufactured proteins (finished goods). The amino acids are available in adequate quantity so that protein synthesis can be performed at any time. However, proteins are synthesized only on demand. Thus, an inventory of finished products which are unused at any point of time is almost eliminated. The protein biosynthesis process creates sustainability through speed and not inventory.

Economies of Scale: Economies of scale are achieved through large-scale handling and processing (Krugman, 1993). The protein biosynthesis process achieves economies of scale through large-scale handling of initial inventory. Initial inventory in terms of amino acids are handled in abundance, thus achieving scale economies.

Energy Use Sustainability: In the protein biosynthesis process, inventory of all forms of work in process and finished products are eliminated. This ensures that the space inside the cell is conservatively used. By reducing all forms of inventories, the protein biosynthesis process eliminates energy required for storing and later rehandling of these inventories. This leads to sustainability in energy usage.

Transportation Sustainability

One of the major sustainability issues in the supply chain deals with transportation (Sheu *et al.*, 2005). The sustainability issues in transport deals with fuel usage, emissions, safety and impact on transport infrastructure. The protein biosynthesis process has its own transportation network. RNA supplies amino acids which move to ribosome for manufacture of proteins using messenger RNA (mRNA), while the Golgi complex facilitates the transportation of the proteins to the necessary places. The Golgi complex sorts out the proteins based on their destinations. The Golgi complex consists of structures called cisternae, which packs the proteins into transport vesicles and releases them into the cell's cytoplasm, where the vesicles migrate to their destinations already coded into them.

Fuel Usage Reduction: The protein biosynthesis process reduces fuel consumption usage by reducing transportation to the minimum possible. Each cell has the common information store, based on which it assembles the required proteins in a localized fashion in the cell itself. Through this, the cell follows a concept of zero logistics and transport with regard to production and distribution of proteins.

Optimum Logistics: The protein biosynthesis optimizes logistics through integrated planning. For example, during an injury, the stimulus for the production of proteins can come simultaneously from several stimuli, yet the system understands the needs in an integrated manner. Also, the proteins are supplied at the correct destination where they are required at that moment, even if the stimulus to produce them came from another source. Optimum logistics enhances sustainability in the protein biosynthesis supply chain.

Distribution Center Sustainability

One of the drivers of sustainable supply chain management is the changing emphasis from the 'green consumer' to the 'responsible retailer' whereby the retailer/service provider and the brand owner assume responsibility for ensuring that consumers can buy products and services with confidence in their source and manufacture (NZBCSD, 2003). The sustainability issues related to the distribution center include scheduling and improved traffic flows, reverse logistics and attaining economies of scale.

Traffic Flow Sustainability: The protein biosynthesis process is an example of distribution excellence. Proteins are not distributed in a random manner. Instead they are targeted to specific locations using tailor-made encoded distribution systems and vehicles.

Reverse Logistics Sustainability: It is interesting to note that the protein biosynthesis has a sustainable reverse logistics process. Excess proteins, unused proteins, damaged and unstable proteins are all recycled. Various proteins and peptides generated by the cell are broken down into the constituent amino acids in the cell itself. The amino acid is the smallest functional unit of the protein. Any further breakdown into the nuclear bases and finally into the constituent elements will result in the loss of functionality of the component amino acids. Thus, by restricting the recycling only as far as the amino acid stage and no further, the cell ensures that the functional value added in the protein manufacture process is preserved.

Responsible Distributorship: The distribution center in the protein biosynthesis process is managed by specialized cells called molecular chaperones. These make sure that newly created proteins are folded correctly, which is critical to their proper functioning and saves folding time. The molecular chaperones help in ironing out the wrong folds and ensure that proteins achieve the correct secondary and tertiary structures. Thus as distribution centers they act in a responsible manner to achieve high levels of sustainability.

The above description of various aspects of supply chain sustainability as portrayed in the protein biosynthesis process shows that it has several lessons for sustainability excellence. These are discussed in the next subsection.

Lessons for Sustainable Supply Chain Excellence from the Protein Biosynthesis Process

Several important lessons can be learnt from the protein biosynthesis supply chain process, especially in terms of sustainability. These are elaborated below:

Sustainability Excellence Through Resource Reduction: The excellence feature of the protein biosynthesis process is that it works with minimal resources and inventories. For example, with only 20 varieties of amino acids more than 60 varieties of proteins are produced. Similarly, the process completely eliminates final product inventory. These are important in real business supply chains. Firms like Wal-Mart have done work to create variety through lesser inventory (Fernie *et al.*, 2000). Yet there is much more to learn from the protein biosynthesis process to achieve higher levels of excellence.

Sustainability Excellence Through Zero Wastage: Modern supply chains lose their sustainability edge due to excessive wastages at various stages. However, in the protein biosynthesis process wastage is totally eliminated. Through excellent quality control, production wastages are eliminated. Supply chains have been striving to reduce production wastages through TQM and six sigma practices for several years (Juran, 2010). However, the protein biosynthesis process achieves a quality level which acts as a model of excellence.

Sustainability Excellence Through Targeted Distribution: Huge amount of resources are wasted in supply chains due to targeting the wrong product to the wrong customer. However, using targeted distribution proteins are sent to their destinations perfectly avoiding situations of customer product mismatch. Firms like Unilever in India have been targeting appropriate products to customers, especially at the bottom of the pyramid (Prahalad, 2004).

Sustainability Excellence Through Recycling: Recycling is one of the three R's of waste management along with reduce and reuse (Burton *et al.*, 1999). The protein biosynthesis process recycles all products through a perfect reverse logistics system. All used proteins are recycled to their original components for reuse. Electronic gadget manufacturers like Nokia have increasingly started recycling procedures to conserve resources (Tanskanen and Butler, 2007). Business supply chains can learn much more from the protein biosynthesis process for excellence in recycling.

Sustainability Excellence Through Healthy Work Environments: One of the major problems in modern supply chains is its impact on the long-term health of all the participants in the supply chain. The protein biosynthesis process excellently manages the long-term health needs of the participants through an immunity system. Such models even though nonexistent in business supply chains, can be emulated to ensure that supply chains become truly sustainable.

Sustainability Excellence Through Operational Excellence: The protein biosynthesis supply chain has one of the most excellent operations system. Systems like bottle necks and instantaneous supply help in conserving resources. Dettmer (1997) has pointed out the real life applications of these systems. However, the protein biosynthesis process provides a far advanced model of achieving sustainability excellence through operations.

Sustainability Excellence Through Integrated Control: Close coordination between suppliers and other partners in the supply chain leads to benefits like cost reduction, eliminating excess inventory and increased customer responsiveness. Protein biosynthesis demonstrates excellence by creating integration through an auto-programmed system. All parts of the system work in close coordination excellently without any external coercion. The coordination is achieved through initiators, proofreaders, terminators, release factors, translocators and transporters all incorporated throughout the process (Sivakumar and Sundaresan, 2008). It is interesting to note that firms like Dell have been seriously attempting such integration in their supply chains (Hagel and Brown, 2001).

Sustainability Excellence Through Information Systems Excellence: Information systems form the backbone of sustainable supply chains. The protein biosynthesis process has highly excellent and reliable information systems. Dyckhoff *et al.* (2004) explained that firms can make their supply chains truly sustainable through integrated information systems. The protein biosynthesis process has much to offer in terms of integrating information systems to achieve maximum efficiency and sustainability.

Sustainability Excellence Through Meta-System Welfare: One of the major issues in sustainability is the lack of social awareness and a lack of concern for larger welfare. The developed economies of the west have impacted the environment through their individualistic concerns and motives in developing supply chains (de Geus, 2002). Similar patterns of growth and development are now being observed in emerging economies, which feel that they have right to exploit resources and the natural environment to their advantage for their growth (Wawryk, 2003). Yet, one of the most important lessons that can be learnt from the protein biosynthesis process is a meta-system welfare culture. The protein biosynthesis process exhibits this in several ways by ensuring that proteins that are most needed are produced in more abundance. Also, individual organ protein needs are sub served to the overall system protein needs. Each component of the protein biosynthesis process complements the other for overall welfare. This lesson in excellence is hard to be seen in business supply chains making the protein biosynthesis process a role model.

Sustainability Excellence Through Increased Concern: Sustainability can be ensured by understanding that every component in the supply chain must fare well and grow for the entire supply chain to be effective. The protein biosynthetic process is a great example of concern for each component. While each player serves others and the system, the entire system looks after the welfare of each component. Therefore 'giving' becomes more important than 'receiving' (Baba, 2000). Several firms have been trying to develop systems based on 'giving'. For example, Infosys Technologies, a major IT firm in India has been inculcating in its employees the 'spirit of giving' (Khandwalla, 2009). The protein biosynthesis process helps firms to learn the process of 'giving', in its fullest dimension to create sustainability.

Conclusion

The major aim of this paper was to describe the sustainability aspects in the supply chain, using a biomimetic framework of protein biosynthesis. The lessons that need to be learned for excellence in sustainable supply chain management were also delineated. When firms try to imbibe these lessons of excellence, they can create supply chains which will not only serve the limited needs of firms, but also the larger needs of the society and the environment. ⌘

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