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**Development of a Product Design and Supply Chain Fulfillment
System for Discontinuous Innovation**

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Development of a Product Design and Supply Chain Fulfillment System for Discontinuous Innovation

Abstract

Given the lengthy product development lifecycle process, high cost, and low success rate, many firms avoid considering discontinuous innovation strategies, in spite of their increase in frequency and importance in many markets. Even with advances in automation and technology, many of the techniques being utilized in product development are relatively unchanged, and the definition of discontinuous innovation itself lacks a structural component.

To address this problem, the authors developed a methodology for generative customization to implement discontinuous innovation. Using the emerging technologies of generative design and agent-based modeling, the authors developed a methodology to create *product inventions* and measure *product innovations* using a complex adaptive system (CAS) model. This appears to be the first model that represents a complex adaptive system environment to measure the success of discontinuous innovation in the development of a market equilibrium agent model (MEAM).

Keywords: generative customization, discontinuous innovation, product design

1. Introduction

Traditionally, a *discontinuous innovation* has been perceived as a function of a product invention, but for it to occur, dynamic forces from seemingly unrelated processes or industries often must converge upon the environment in order to develop a new consumer market. For instance, an Apple iPod is a discontinuous innovation, less as a function of its ability to store digital music files on a portable hard drive system, and more due to its ability to transform within processes and behaviors via supply chains and consumers, including related industries (such as the music industry). The

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SmartPhone was able to be adopted within consumer markets due to the size and functionality of the device, but the convergence of previously unrelated industries of mobile telephony, such as computer operating systems and applications was the critical element of the discontinuity of the innovation.

With less than 10% of new product designs being classified as discontinuous or radical innovation (Griffin, 1997), the question is whether a conventional NPD solely focused on product design is suitable for creation of products that must extend beyond its own physical functionality. Typically, a conventional method of product development, such as StageGate™, is a combination of linear, structured, processes linked as a closed system, which restricts creativity to a single body (such as a product developer within the OEM firm). One alternative to a linear, closed system process of product development that solely focuses on the product is Buffington’s (2010) concept of *generative customization* (Figure 1 represents its high level logical design) that is more of a framework than a process to develop discontinuous innovation. In this model, it is understood that design and fulfillment factors must extend beyond traditional definitions of new product development (NPD). In a study to understand consumer behavior and innovation, Buffington (2010) found generative customization to be a superior alternative to a traditional NPD design approach for discontinuous innovation.

Figure 1 - Generative Customization Supply Chain Logical Design

(Buffington, 2010)

The purpose of this study is to build upon this conceptual product design and supply chain fulfillment system of generative customization for discontinuous innovation. This paper will be structured as follows: next, a literature review will be presented discussing generative design and product design (front-end element), agent-based modeling and supply chain network (back-end system), and generative customization as a research concept. Following this literature review, using these concepts a conceptual system design structure will be developed.

2. Literature Review

2.1 Generative Design and Product Design

Chiva et al (2010) stated that a generative system implies being able to see beyond the situation and questioning operating norms within its environment. Buffington and McCubbrey (2011) expanded upon this point for discontinuous innovations, and found that generativity best serves discontinuous innovation, since it follows a process “on the edge of chaos”, which is a necessary condition for the creation of new functionality and markets, beyond the development of a product. Krishnamurti (1994) noted that generative learning requires an individual to focus on intuition and transcendence, which are typically not descriptors used in conventional product design and fulfillment systems; it describes more of a process than an end result. Weick (2007) described generativity as an evocative power or aptitude that is opposite of adaptation. McCormack et al (2004) described as generative design as the production of an artifact and experience, which is difficult to define.

Generative design processes enable complex relationships to form rather than undertaking a linear, reductionist approach and simplifying them for the sake of the supply chain system, or within the inter and intra organizational systems. McCormack et al (2004) found generative design to be defined in terms of dynamic processes and their outcomes. In the use of creative evolutionary systems (CES), entirely new designs can be generated from little or no knowledge guided by the process (Kicinger et al, 2005) rather than the designer. Avital and Te’eni (2009) defines these generative schemes as “simple recipes that allow anyone with basic skills to create or put together”, suggesting that “simple instructions will lead to infinite variations”. In research and practice, there is scant evidence of its ability to achieve creativity in an

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3 NPD process beyond a few industries, such as architecture, music and software
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5 development. Furthermore, generative design has been utilized solely to develop
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7 physical product designs, and to our understanding, has yet to consider definitions of
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9 critical processes and relationships to these product designs as well.
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13 The digitization of the design process has become a revolution, and has transformed
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15 into a unique field of endeavor, beginning to evolve its own unique methodologies, yet
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17 still largely unformulated (Oxman, 2006). While simple applications of Computer Aided
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19 Design (CAD) have been in existence as early as the 1960s (Sutherland's SKETCHPAD at
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21 MIT), its purpose has been focused almost entirely upon the digitization of form, rather
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23 than an improvement on design and market process possibilities. Szykman et al (2001)
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25 noted that "traditional CAD systems are limited to representations of geometric data
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27 and other types of information relating to geometry such as constraints, parametric
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29 information, features, and so on". Hanna and Turner (2006) noted that the focus of CAD
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31 is on the representation of the final form described geometrically. LaRocca et al (2002)
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33 noted the difference between traditional CAD and generative design being that the
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35 latter represents the engineering intent behind the geometric design. Liu et al (2005)
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37 acknowledged the progress made in CAD tools over the decades, but noted the large
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39 limitations associated with it being able to support human cognition and creativity.
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41 Pande and Kumar (2008) developed a generative planning process using computer aided
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43 process planning (CAPP) to become a link between CAD and computer aided
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45 manufacturing (CAM), further extending possibilities of CAD.
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Generative design is a method that has been implemented in various fields (art, architecture, communication design, product design) where the output is generated by a set of rules or an algorithm, and has a design schema, a means of creating variation and a means of selecting desirable outcomes (Wikipedia, 2010). Therefore, it is different from CAD because it must be based upon modeling knowledge that is created communally on an agreed set of standards (Krish, 2010), as opposed to part of a closed system. In this process, hundreds, or even thousands of design possibilities can be generated through the use of generative schemes and data, which allows a group of designers to change parameters in order to create an innovative design. Therefore, a new design schema is not simply a product of the parameters used to generate it, but rather also includes the conditions used by designers in this process. This is due to the design not being represented in *final form*, but rather as associative, with changes being enabled through computation (Hanna and Turner, 2006). These *communalities of form* may also be possible to be extended to *communalities of process*, to the authors of this paper.

The challenge of generative design is how to frame this human-computer interaction process, for a product-process combination. If generative design adheres to the rules set forth by Simon in his book *The Sciences of the Artificial* (1996) then the design is contingent upon the goals of the designer and the purposes for which the system is designed. Avital and Te'eni (2008) outlined this human-computer interaction process through the definition of *generative capacity* (a human's ability to reframe reality and produce something ingenious) and *generative fit* (an attribute of a system that is

conductive to evoking and enhancing that generative capacity in people). According to Avital and Te'eni (2008), a system has high *generative fit*, and can evoke *generative capacity* if it has the following attributes:

- *Visualization (to see an object from multiple perspectives)*
- *Simulation (to the underlying process or the object's behavior, capabilities, or response to stimuli in different context)*
- *Abstraction (the ability to move swiftly between levels of granularity to identify emergent patterns, commonalities, or anomalies)*
- *Integration (ability to merge views of various parallel subsystems or cross-cuts of objects)*
- *Communication (one's ability to talk and share information with other agents with no regard to institutionally imposed boundaries)*

The advancement of theory in generative design is beginning to establish characteristics in evolutionary science. Avital and Te'eni (2008) noted the difference between conventional computer assisted design and *generative evolutionary design* in being the former specified by predetermined parameters while the latter is focused on the generation or discovery of unique and unexpected solutions. Coblani (2009) developed the concept of Design DNA (DDNA) in the development of generative design.

Given its relative newness as a concept, generative design has significant limitations in research and practice. The discussion of this topic thus far in research has been primarily focused on concepts, or applications in niche industries, such as art and architecture. One concern from literature is that generative design solely addresses the domain of form, texture and color (Krish, 2010), but not functional parameters, or as we have proposed, process parameters as well. In consideration of a discontinuous innovation being defined by the consumer market and peripheral (and perhaps

perceived as insignificant) players as much as by the product design itself, generative design must be extended in the ex ante definition of future markets as well. This is a critical issue that must be addressed in future research.

2.1 Agent-Based Modeling in Supply Chain Fulfillment

Despite business environments changing dramatically over the past two decades (McCarthy, 2006), supply chain systems have been surprisingly static, and diagrammed in very unimaginable ways. In contrast, Koh et al (2006) prescribed that companies in the 21st century will face enormous complexity, and supply chains will need to become more agile and responsive as a prerequisite. Yet supply chain complexity cannot occur in isolation within a supply chain network; Jain et al (2009) found marketing, distribution, planning, manufacturing, and purchasing of organizations along the supply chain operating largely independent of one another, with the organizations having their own objectives and being in conflict with one another. Coordination between multi-agent systems (MASs) will stretch the limits of possibilities of how supply chain systems act and evolve, and will require a much greater interaction between the disciplines of supply chain and information technology than ever before.

Therefore, despite the efforts to manage supply chain systems within predictable and linear progressions, supply chains in the 21st century must present themselves as more dynamic and non-linear, leading to endogenous variability being created as companies seek to simplify in this manner. Beyond exogenous factors that are often perceived to be the greatest cause of uncertainty to supply chain systems, endogenous supply chain systems are gaining in complexity as well. Like biological systems, supply

chain systems possess both endogenous and exogenous forms of variability, and supply chain research hasn't progressed far in understanding how these forms of variability within and from agents in the supply chain impact the entire system. Prater (2005) found that while *supply chain uncertainty* is a major topic in supply chain literature, there is a tendency to lump various forms of supply chain complexity under a broad concept of *uncertainty* with few areas of differentiation. Kim's (2007) research validated this notion through stating that while supply chain research focused much attention on the 'bullwhip effect' (order variability impacting upstream systems), and its exogenous impact, less attention has focused on how endogenous variability could lead to exogenous variability. Furthermore, as is the case with discontinuous innovation, uncertainty is not always a factor that must be mitigated; instead, it should often be embraced, and developed.

Various methods for attempting to reduce *supply chain uncertainty* include improvements in modeling and forecasting different components of the supply chain (Ewing and Thompson, 2008). Moon and Phatak (2005) noted that simulations can often capture and describe the complex interactions within a particular manufacturing or supply chain system where traditional analytical methods fail. On the other hand, mathematical techniques can assist in the development of parameters in a modeling effort, how individual agent characteristics affect a system, and identification of agents to develop an agent-based modeling (ABM) effort (Surana, 2005). Instead of an *either or* decision, perhaps the most suitable approach is a combination of traditional mathematical techniques for the establishment of agents and a supply chain model, and

an integrated agent-based modeling tool, establishing less abstract modeling capabilities to understand and patterns issues of complexity and uncertainty. Surana (2005) found a useful amalgam of simulation and analytical techniques for the use of understanding and predicting supply chain systems.

However, there are limitations in the use of agent-based modeling in supply chain systems. One, simulations are developed offline and separate from enterprise software packages (Yoon and Shen, 2006), limiting observations to single event analysis. Moon (2005) found that traditional simulation models are usually not built for repetitive and continuous usage partially due to the laborious data collection process. Difficulty in automatic collection of data and continuous update of the data for the built simulation model discourages further usage of the initial model. In their study, Al-Zubaidi and Tyler (2004) noted a major requirement of the simulation model is that it should capture the dynamic and stochastic nature of consumer behavior at the retail store, which is not possible without easily accessible and usable operational data.

Similar to the use of generative design in product design processes, the use of ABM in the dynamic development of supply chain networks is in its infancy stages.

2.3 Generative Customization

Buffington and McCubbrey (2011) identified a major problem in the development of the generative customization concept being that while the front-end product design process could occur through the use of generative design processes and tools (Proposition P₃), there are no new product development (NPD) processes established for the fulfillment of this design in a mass market supply chain system. Given the

intuitive, creative, and largely unstructured approach of generative design, often avoiding the final form of the product design (Garud, et al, 2008), there are inherent problems in the identification of peripheral agents involved in a discontinuous innovation, future markets, and the fulfillment of the product as a result. In an expert-based approach to design that is represented in discontinuous innovation (Sanders, 2008), a collaborative process including the consumers and suppliers (some who are agents unknown) has not been found to be viable.

Numerous researchers, such as Danneels (2004) have found that consumers are almost never able to conceive a radical (or discontinuous) innovation, and their involvement in such a process is inefficient. Given this limitation, which is so critical in a dynamic supply chain system, the possibility of creating a *virtual consumer* and *supplier*, via generative design and agent-based modeling, has been proposed in generative customization as a compromise in the lack of a collaborative environment. For this purpose, the use of agent-based modeling techniques can be proven as useful in the establishment of how these products, processes and agents interface with one another in the creation of a discontinuous innovation.

In the development of a generative customization product design and supply chain fulfillment system, the inability to achieve collaboration as a function of the design of the product and process using generativity (creatively and separate from existing consumers and suppliers) poses an immense challenge for the achievement of discontinuous innovation. Danneels (2004) and Govindarajan and Kopalle (2006) both noted a firm's reluctance to pursue discontinuous innovation as a function of its inability

to more accurately predict its potential for success in a marketplace, ex ante. Outside of the use of structured (not necessarily linear) NPD processes and tools, we question how this research problem can be achieved, which leads to our model for generative customization as a set of NPD processes and tools for discontinuous innovation.

3. The Use of Generative Design and Agent-Based Modeling in Generative Customization

Through a definition of discontinuous innovation and the literature review of generative design, agent-based modeling, and generative customization, a three step process requirement will be established in this paper for the use of generative customization in the development of discontinuous innovation, as is shown below in Table 1. These steps in the process will be discussed through the product design process for generative customization, as will be discussed in this section.

Table 1 – Generative Customization Product Design and Fulfillment Methodology

Step	Definition	Explanaton
Product Variation (variate)	The modification of the digital representation of an existing product, or the creation of an entirely new invention (Generative Design).	Establishing a product design as a process (artifact and experience) rather than an invention in final form.
Non Product Variation (variate)	Starting with the base of a new product artifact, the use of generative design to develop non-product factors (agents and processes) for discontinuous innovation. These may be peripheral products or services.	If the product design is an artifact and experience (product variation), it will be extended in definition beyond the physical product to include other factors and markets.
Market Equilibrium Agent Model (MEAM) (interact)	Agent-based process that simulates the product and market variations in the achievement of new markets and peripheral agents (suppliers of products and services), enabling firms to conduct ex ante predictions.	Fusing generative designed product and non-product features in the development of generative customization. Both product design, and fulfillment parameters are created.

Schumpeter (1950) found a disruptive or discontinuous innovation process to commence from a market in a state of equilibrium, with a disruption (or multiple)

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3 converging upon the environment, creating a transformational change to the consumer,
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6 supplier, market and the product (not just to the design of the product). Since
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8 incumbents in a current market environment are generally comfortable with stability
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10 and equilibrium, the goal of the generative customization system will be to interject an
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12 element of disruption into the system to enable radical innovation.
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16 In the first step, the product designer will develop completely new product
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18 invention designs, or mutations of products from existing designs using generative
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20 design techniques. Through an *associative*, digital definition of the parameter form, the
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22 designer is able to make modifications to product parameters (represented in digital
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24 form), developing virtually an unlimited number of design permutations. Through this
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26 first step, a *product invention* has been achieved through the process, but not a product
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28 innovation, as these forms have been yet to be found as useful to a future consumer
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30 market. Given that discontinuous product designs (inventions) can often be a
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32 convergence of components from different products (such as a Smartphone being a
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34 convergence of a telephone, computer, and personal audio player, for example),
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36 generative design must transform the function as well as form parameters in design,
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38 which is relatively unproven in its history.
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46 Using this first stage (product variation), generative design techniques are used
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48 to create non-product parameters to enable the product invention. If the first stage is
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50 considered the traditional core product design, the non-product variation can be the
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52 development of peripheral products and services to support the core invention.
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54 Continuing to use the Smartphone as an example, a wireless headphone and car MP3
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3 player are examples of peripheral product developments, as is the case of mobile
4 applications, personal GPS, and Internet based delivery sites. The non-product
5 developments of a discontinuous innovation can become more prolific to a consumer
6 market potential than the core invention itself. Through the use of creative generative
7 design principles, these possibilities can be created as a function of the core product
8 development.

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11 As Schumpeter (1983) noted, there is a difference between a product invention
12 and innovation, with an innovation being a function of the market environment. From
13 Garcia (2007), the *market environment* for discontinuous innovation will be defined in
14 terms of two heterogeneous agents, as follows:
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- 1) *Future Consumer Adoption = f (individual preferences, consumer network effects, firm adoption, advertising)*
 - 2) *Future Firm and Supply Chain Adoption = f (innovativeness, firm network effects, consumer adoption)*

The development of a discontinuous innovation requires a combination of a new product invention, a new consumer market, and/or a new firm and supply chain. As an example, the development of a digital audio player is not useful without the development of a compressed audio file format, the development of online sources as a delivery mechanism, and other factors unrelated to the development of a portable audio player with a computer hard drive. As such, the development of the electronic component and these peripherals operate as an open innovation system (Chesbrough, 2003), with all consumers and suppliers are modeled in a market equilibrium agent model (MEAM), as opposed discrete and linear consumer and supplier agents solely

involved in an existing supply chain system. The MEAM process will define the third step of generative customization, to model both the product invention and the development of the market into one discontinuous innovation process.

As is shown in Figure 2, the third step will establish a product design and supply chain fulfillment model, created as a *market equilibrium agent model (MEAM)*, to dynamically interface the product and non-product clusters to establish the discontinuous innovation.

Figure 2 – Market Equilibrium Agent Model (MEAM)

The variation processes provides the definitions of the product and non-product parameters to be established via *associative* definitions, not defined in final form. The ability to *variate* both the product and non-product components/parameters do not appear to have a precedent in extant research, and needs to be explored in future research. While Krish (2010) discussed the variation of a limited range of products

through the use of generative design, we believe that there is potential for many products, but also the inclusion of non-product parameters as well.

After the *variate* stage has occurred, the final stage is the interaction between the *product innovation* and the existing market equilibrium (or MEAM) is the introduction of the interact phase of generative customization, as is noted in Table 1. This process is defined through agent based modeling (ABM), based upon Garcia’s (2005) conceptual map, is illustrated in Figure 3.

Figure 3 – Discontinuous Innovation Diffusion Model

The goal of this agent based model is to simulate an amended *diffusion of innovation* process, based upon Rogers (1962) model, but existing of a complex adaptive system (holistic) view of diffusion, not just related to the consumer. A fallacious assumption in discontinuous innovation is that only the consumer needs to adopt and change in this process, but in reality, diffusion needs to occur in various, and unstructured ways within

the stakeholders in the process, often newly created and involved. In this case, market equilibrium exists in a heterogeneous agent mode (Figure 2), that includes not just consumers and suppliers for the existing product, but including suppliers and consumers within the market, not necessarily involved in the current environment, but influencing, as is suggested in complex adaptive systems and open system (Chesbrough, 2003) theory. It is critical in an establishment of the MEAM, as shown in Figure 2, to represent the *entire possible market*, not just the *existing supply chain*, given that discontinuous innovation is the disruption of an existing market to the creation of new consumers, suppliers and market conditions; given the difficult of ex ante predictions, this is a difficult, unstructured step. As a result of this process, a supply chain system emerges and *self-organizes*, based upon the definition of the product design. As a result, a radical invention is transformed into a discontinuous innovation through the result of the efficient fulfillment of the product design.

The simulation of the *variated* product into the MEAM is the introduction of an invention into this market equilibrium to understand the *nature of the disruption*, as shown in the below mathematical problem:

$$DI_x = f(PI_x, NP_x, C_x, S_x)$$

Where,

DI_x = A definition of discontinuous innovation solutions, as a result of the interaction between the variables (to define an ex ante consumer market and peripheral agents).

PI_x = An introduction of a discontinuous product invention

NP_x = An introduction of a discontinuous non-product invention

C_x = A definition of the consumer response, as noted by Garcia (2007)

S_x = A definition of supplier's response, as noted by Garcia (2007)

Therefore, the product designer must establish numerous simulations of this process, because the difference between an *invention* and an *innovation* is the relationship that the product has with its environment, as noted in the following proposition:

Proposition_{DI}: The development of a discontinuous innovation via generative customization occurs through the dynamic interaction between product and non-product parameters, which have been developed and interacted through a generative and agent-based modeling simulation process.

From this process, an ex ante prediction process can occur to measure the potential of a discontinuous innovation, a process that is not possible today (Danneels, 2004). This dynamic environment will model the nature of a discontinuous innovation itself, and provide the firm with an improved structural framework to make new product development decisions.

4. Conclusions

The cruel irony facing firms when considering the development and implementation of discontinuous innovation is while there appears to be a greater frequency and severity of its occurrences of late (Birkinshaw et al, 2006), the process and risk associated with doing it remains greater than ever. When faced with the consideration of a radical innovation strategy through the use of conventionally linear and finite tools (even including CAD systems), the cliché *going to a gunfight with a knife* can often come to mind by firms, leading them to *play it safe* through incremental innovations, or staying safely (at least for the time being) within the comfortable confines of the market equilibrium.

The problem posed in this research paper, and in Buffington's (2010) definition of generative customization, is how to utilize the capabilities of computer technology and creative human cognition to improve the capabilities of seeking and achieving discontinuous innovation in product design. After a review of extant literature, a system design has been developed that achieves this purpose, at least in concept. This was accomplished through using the emerging technologies of generative design and agent-based modeling to create discontinuous innovation both in the form of a product design, supply chain process, the identification of future markets, and of new agents involved in the process.

Through the development of a three step generative customization methodological process, as is shown in Table 1, the fusion of generative design and agent based modeling was accomplished in the steps of *product variation*, *non-product variation*, and *interaction* is fashioned for the achievement of *generative fit*, as noted in Avital and Te'eni (2008). Therefore, the goal of this generative customization methodology is not in the achievement of a discontinuous design of a product, per se, but rather in the development of all parameters necessary for the development of a future consumer market. From this, Proposition_{DI} is introduced that defines discontinuous innovation as a function of a dynamic interfacing between these product and non-product parameters to improve the predictive nature of it. We believe that this is an original and significant finding in the measurement and development discontinuous innovation that is only possible through these emerging tools (and not possible through the use of linear tools, such as differential equations).

5. Future Research

To our knowledge, this is the first study that seeks to integrate the use of generative design and agent based modeling in the understanding, development and measurement of discontinuous innovation. While there has been some research related to agent based modeling and supply chain systems, and scarce, but some in relation to generative design and NPD, there needs to be a further examination of these factors, both separately and in conjunction with one another. Future studies can be individual case studies, surveys within an industry related to NPD practices, and modeling and simulations of this concept.

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