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Innovation Science

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Abstract

The term innovation resonates broadly in the cyberspace, books, and journals. A careful analysis of the literature indicates that the knowledge of the underlying science of innovation is limited. Innovation in any domain can be enhanced by principles and insights from different disciplines. However, the process of identifying the linkages between the diverse disciplines and the target domain is not well understood. The innovation process and conditions triggering innovation set the stage for economic progress. The ideas outlined in the paper provide a roadmap for future discovery of innovation science.

1. Introduction

A product, process, service, or a business can be described with various metrics, e.g., cost, quality, reliability. The emerging metric of particular interest is innovation. Innovation is often described in the literature as the activity of people and organizations leading to a change. The latter implies breaking a routine way of thinking and using new approaches. The scope of innovation varies from product and process to organization or even a society. The nature of innovation is user dependent, e.g., a product innovation for a designer can be a process innovation for a manufacturer.

The 21th century customers are better informed than ever before. The interaction time between a customer and a product has reduced. Companies are forced to analyze customer needs and behaviors impacting the product success in the marketplace.

The study of innovation – the development of new knowledge and artifacts – is of interest to engineering, business, social and behavioral sciences, and spans sociology, history, philosophy, economics, psychology, and political science. Innovations transform economies (e.g., California's agricultural economy transformed into the knowledge-based Silicon Valley economy). Innovations alter global relations (e.g., the impact of nuclear technologies on international treaties), and produce new structures of social control (e.g., the creation of international regulatory agencies to oversee pharmaceutical industries). Innovations change the day-to-day lives of individuals (e.g., the development and introduction of new biopharmaceutical discoveries that affect quality of life).

Innovations in any domain can be enhanced by principles and insights from other disciplines. However, the process of identifying the linkages between different domains and the need for innovation science is apparent. Innovation of products and processes is of particular interest to manufacturing and service applications.

1.1. Why innovation science?

There is a growing consensus among industry and academia that innovation should be studied. There are several new initiatives that address innovation. Two of the more prominent ones include: (1) the report *Innovate America*, published by the Council on Competitiveness [1], and (2) the Center for the Study of Innovation and Productivity launched by the San Francisco Federal Research Board (http://www.EconData.net) to study innovation, technology and productivity and their contributions to economic activity. Some of the facts that warrant accelerated development of innovation science include:

- Innovation is the engine of the global economy, accounting for some 50% of the economic growth (NIIR 2004).
- Innovation will mark the first economic revolution of the 21st century.
- Innovation involves almost all aspects of life, yet the innovation process is not well understood.

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- Innovation applies to the creation of methods used in industry, including the design of consumer goods, defense products, medical devices, medications, and services.
- The increasing complexity of technologies, their interdependencies, and the rapidly expanding volume of data call for a paradigm shift to be led by innovation.
- Educational revolution, in particular in engineering, is needed to create innovative workforce.

Innovation has been studied by psychologists and group process researchers at multiple levels, including the organizational level. Researchers have investigated how alternative leadership styles, varying degrees of worker autonomy, and organizational cultures (i.e., systems of values, norms, and beliefs) affect innovation in R&D teams (e.g., [2], [3]).

There are several areas where the study of innovation could initiate and potentially formalize the science of innovation. This includes the study of existing literature and patents, and innovators and creators (e.g., musicians, painters). Based on these studies one can conceptualize and model the innovation processes and its generalizations across engineering, arts, science, and social domains.

1.2. Basic typology of innovation

The industry has used three basic approaches to innovate: structured, creative, and dynamic, producing either a sustaining or disruptive product referred to as innovative [4]. Structured innovation spawned during the industrial era, was engineered to be highly efficient and replicable by innovating within set guidelines. It has been primarily used in large corporations, and it emphasizes internal leadership, strategic planning, effective execution of ideas, shareholder pressure, and financial resources more than other approaches, while placing less emphasis on a creative environment [5]. Creative innovation thrives more often in small organizations where focusing on "the big picture" can be accomplished more easily as these companies tend to consider the inspirational aspects of innovation versus the process [5]. The greatest advantage to the creative approach is the process itself [5]. Dynamic innovation is a blend of both the structure and creative innovation approaches. Businesses of all sizes from small to large have used the dynamic approach to produce successful innovation. Dynamic innovation has taken on the aspects of structured innovation that embody strategic thinking and planning, along with the need for execution of projects. Dynamic innovation incorporates cross-functional collaboration and makes the senior executive in charge of the innovation in the company. Even though 36% of participating companies have adopted this method, most of them would rank it as high risk [5].

Sustaining innovations are built off previous innovations [4], e.g., the palm PDA. The PDA has been an innovative and successful device; however, its predecessor the Apple Newton has failed. Sustaining innovations tend to be more successful then the disruptive innovations. The reason for this is that sustaining innovations are built based on a product or a process that is known to the market. The sustaining innovation is easier to develop and market, as it follows the incumbent.

Disruptive innovations are referred to as paradigm-shifters. They make current standards obsolete and anticipate future needs [4]. In the past, the heuristic rule was that a disruptive innovation occurred once every few decades, e.g., electricity, steam engines, assembly lines. Nowadays, innovations are brought to market more frequently, e.g., yearly. The example mentioned of a disruptive technology, Apple Newton, was large, bulky and not user friendly. Disruptive innovation is often not profitable, since it is expensive to develop and market. Some corporations do not invest in disruptive innovations due to the increased risk of losses.

2. Product Requirements and Innovation

The past two decades have seen the customer perspective reflected mostly in the product function and form. In the 1980th the interest has begun to shift from the requirements defined by experts (often design engineers) to the customer defined requirements. This customer focus has been driven by the necessity to increase customer satisfaction. The commonly used attributes used to measure customers' satisfaction often involved quality, reliability, and cost. The broadly accepted industrial initiatives such as concurrent engineering, integrated product and process design, and kaizen programs, have taken as serious look at the customer oriented attributes in the design of new products.

Product innovation I can be expressed as a function of requirements $\boldsymbol{x}$, $I = f(\boldsymbol{x})$. Understanding the requirements is key to the design of innovative products.

The more sophisticated and informed customer has imposed higher expectations on the product. A customer of today not only wants to get a product he/she perceives (product personalization), but is also impacted by additional attributes such as surprise (e.g., unexpected product function), pleasure (e.g., driving a car), fantasy, and so on. The list of these new requirements has not been completely defined; rather it evolves in time (see Fig. 1).

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One will likely see new product attributes (introduced by new requirements) emerging in time. They will be reflected in product designs and used in marketing to attract new customers. It will take multidisciplinary research to develop better understanding these attributes and matching them with the product development programs.

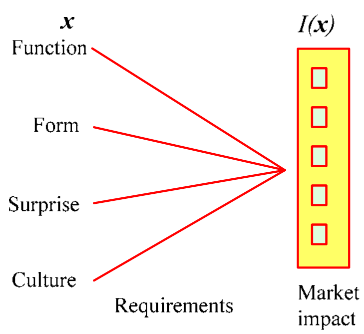

Figure 1. Expanded list of requirements.

An innovative design may emerge from the previous generations of the same product by considering new requirements. The innovation problem can be then reduced to the requirements formulation problem. An attempt should be made to capture the innovation-prone requirements as early as possible, ideally at the requirements formulation phase (Design phase 0 in Fig. 1) of the design process. One should also realize that additional requirements can be generated later in the design process (see Fig. 2). In fact any alteration of the existing and new requirements may take place along the product development life-cycle.

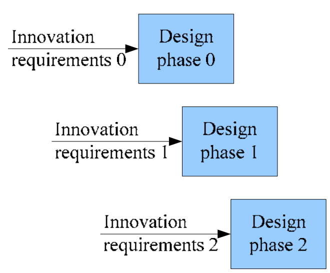

Figure 2. Context and time dependent innovation engine.

An open question that deserves separate investigation is how much of innovation happens outside of the requirements fostering innovation. The answer to this question is not easy as historical data and examples that could support or reject this hypothesis may not be easily available. One could argue, however, that even if the innovative aspect of the design has been conceived without a previously formulated requirement such a requirement could be generated when a serious attempt to create it would have been made.

Though many of the innovation issues included in this paper are discussed in the context of product design, they equally apply to the design and creation of processes and services. Using the proposed approach to generate hybrid solutions, e.g., a product, a process, and a service supporting the product could be the greatest asset.

A. Definition of Refined Requirements

There are numerous ways of eliciting detailed requirements:

- Traditional customer surveys and user-based input
- Data analysis, in particular data mining (e.g., [6].
- Evolutionary computation tools, in particular genetic programming discussed later in this paper.

Any approach producing requirements leading to product success is commendable. The focus of this research is to explore formal approaches to the generation of requirements, especially such requirements that are likely to produce innovative designs. Examples of two approaches that naturally fit here are data mining and evolutionary computation. They could be used independently or work in tandem.

Data-mining algorithms discover patterns in the data that may transform into requirements of interest. Since the width of data analyzed by the data-mining algorithms is practically unlimited, the patterns are likely to be unanticipated and interesting. The value delivered by these patterns is strictly related to the quality of data and textual databases used for mining. Besides the comprehensiveness of data processing, data mining brings yet another advantage – it may be used to support the needs of an individual customer.

3. Innovation Science Research

Scholars of technology have indicated that innovation lies at the intersection of science and technology (e.g., [7]). Within this perspective, "technology" is synonymous with "applied science" (i.e., the production of goods and services based on scientific research). One view proposes that innovation becomes possible through advances in basic science (e.g., the development of new ideas and theories) and is realized in concrete products within the context of applied science. Another view suggests that the development of innovative products through applied science generates new resources on which basic science draws to advance new ideas and theories. Barnes [8] proposed that science and technology are enjoined in a symbiotic relationship, drawing from and contributing to one another's cultures. The symbiosis, however, may not always involve facilitative relations. Interactions between basic and applied scientists are often characterized by conflict arising from different research methods and strategies, status tensions, and differences in occupational cultures (e.g., [9]).

As a new science, innovation is likely to borrow concepts from the existing sciences, e.g., data mining, evolutionary computation, cognitive sciences. Creativity and innovation are often considered as inseparable [10]. In fact, the breadth of the science base of innovation is likely to be larger than any of the known sciences.
The following five models of interest to innovation science are discussed next:

1. Hypothesis-based model.
2. Optimization-based model.
3. Evolutionary computation model.
4. Pattern discovery model.
5. Process model.

3.1. Hypothesis-based model

The innovation science should look at the role of hypothesis driven vs hypothesis discovery research. A framework for maintaining the proper balance between the two should be established. Hypotheses fostering innovation may have different ownership. In the product design context they can be generated by the customers, marketing departments, or the designers themselves. The growing volume of data collected along the product life-cycle and the information about the customers warrants a hypothesis-based discovery approach to be supported by data mining.

3.2. Optimization-based model

An optimization model of innovation involves objective function and constraints. For example, consider the innovation function in Fig. 3. Maximizing the innovation function $I = f(x)$ subject to a constraint $1 \leq x \leq 3$ would produce a local maximum, however, relaxing this constraint to $1 \leq x \leq 6$ could result in a global maximum. Modifying the same constraint to $4.5 \leq x \leq 5.5$ would be equivalent to a targeted innovation, where a reasonable effort (represented by the computation needed to determine the maximum of the function $I = f(x)$ (in Fig. 3) would maximize the innovation impact.

The optimization model of innovation is generalized by the evolutionary computation framework, in particular genetic programming discussed next.

3.3. Evolutionary computation model

Evolutionary computation deals with models based on natural evolution. A number of evolutionary computational algorithms have been developed, including genetic programming (e.g., [11], [12]), evolutionary algorithms (e.g., [13]), evolutionary strategies (e.g., [14]), and artificial life (e.g., [15]).

The applicability of evolutionary computation to innovation science is illustrated with genetic programming.

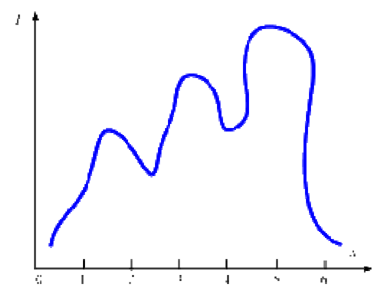

Figure 3. Innovation function *I = f(x)*.

What is genetic programming?

Genetic programming is an algorithm that can be used in a variety of ways to process data [11]. The proposed use of genetic programming in requirements-based innovation is to generate unexpected combinations of requirements, product functions, or product architectures. Besides functioning on its own, the genetic programming algorithm could be used in conjunction with data mining.

The main steps of a genetic programming algorithm include [11, 12]:

Creation of initial population of solutions

Functions and terminals are used to generate a random population of initial solutions. The set of functions may include arithmetic functions and conditional operators. The set of terminals include external inputs (such as the features) and random constants (such as 5.10 and 44.35). The randomly created initial solutions are typically of different sizes and shapes.

The main loop of genetic programming algorithm

The main loop of genetic programming includes fitness evaluation, selection, and genetic operations. The fitness of each individual solution in the population is evaluated. Solutions are then probabilistically selected from the population based on their fitness to participate in the various genetic operations, with reselection allowed. While a solution that is fit may have a better chance of being selected, unfit individuals compete. After numerous generations, an acceptable solution emerges.

Mutation operation

The mutation operation selects probabilistically a single parental solution from the population based on the fitness value. A mutation point is randomly chosen, the partial solution rooted at that point is deleted, and a new partial solution is grown according to the same random growth process that was used to generate the initial population.

Crossover operation

In the crossover, two parental solutions are probabilistically selected from the population based on the fitness value. The two parents participating in crossover are usually of different sizes and shapes. A crossover point is randomly chosen at the first parent and a crossover point is randomly chosen at the second parent. Then the partial solution at the crossover point of the first parent is deleted and replaced by the partial solution from the second parent. The crossover operator is dominant in genetic programming.

Reproduction operation

The reproduction operation copies a single individual solution, probabilistically selected based on fitness, into the next generation of the population.

Structure-altering operations

Rather than using a user-specified fixed structure for all solutions in the population, genetic programming allows for structure-altering operations to automatically determine solution structure that correspond to the natural gene transformations. These structure-altering operations produce population containing architecturally diverse solutions.

While most steps of the genetic algorithm appear to be feasible for implementation in innovation-driven product design, construction of the fitness function and its evaluation methods are not easy. For example, consider the design of modular products with a set of predefined components. Writing a computer program to evaluate the different part configurations appears to be difficult, especially in mechanical design. Representing an internal solution produced by the genetic algorithm with geometry would certainly ease this evaluation. For example, consider the visual evaluation of the fitness function illustrated in Fig. 4, where the genetic programming solution (GP) is expressed with geometry (a phenotypic expression). The quality of the geometry (design) is evaluated by a human user and the feedback is provided to the genetic programming algorithm.

3.4. Pattern discovery model

The role of patterns in innovation offers a great potential especially as large volumes of data become available. The data with potential impact on design is collected prior, during, and after the product has been designed. In essence, the design of a product is embedded in the data space containing knowledge pertaining to different aspects of the design, including innovation.

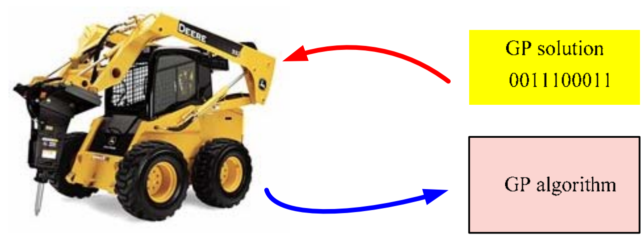

Figure 4. Phenotypic evaluation of the fitness function (The product design is courtesy of Deere & Company, Moline, IL).

The geometric evaluation of the fitness function is one of many possible ways of providing feedback to the GP algorithm.

The data-mining extracted patterns can be descriptive (e.g., formed with clustering algorithms) and predictive (e.g., extracted with decision-rule algorithms). Examples of the two types of patterns are discussed next. The forming of descriptive patterns is illustrated with the dependency structure matrix and clustering, while the predictive data mining is illustrated with decision rules.

Dependency structure matrix

In traditional design of products and product families, only limited interactions have been considered, mainly spatial interaction, energy, information, and material [16]. Physical proximity, alignment, and orientation were the underling reasons for defining these interactions. A frequent use of this interaction information would be modularity defined by the concept of the dependency structure matrix (DSM) ([17], [18], [19]). The traingularization algorithm (the matrix reorganization algorithm) discussed in [20] derives the interaction patters by transforming the dependency-structure matrix from an unstructured form to the form that most resembles the lower triangular matrix.

Clustering

Innovation calls for expanded definition of interactions, and determining a variety of patters. All patterns can be important, irrespectively of the type of interactions among them. Components that interact directly are candidates for modules (called here physical modules), while parts with no physical proximity and interactions form logical (virtual) modules. For example, if the same type and size tires and the steering wheels (a logical module) would be used across 95% of the in the designed vehicles, they would likely be assembled on the vehicle in the factory.

However, tires of 20 different types and 25 stirring wheels would be likely mounted at the car dealership. The information present in the patterns can be used in different ways. The close proximity information is likely to be utilized at the product design stage (physical module design). However, the logical modules can be implemented in a number of ways, e.g., as late product differentiators at the product assembly stage, or a sales outlet. Some of the component interactions discovered with data mining that may appear to be incidental could in fact be a source of innovation. For example, the vehicle could be steered with a mechanism different that the steering wheel.

Clustering algorithms form groups of objects that share common properties. The early cluster analysis algorithms are the *k*-means algorithm, ISODATA, and the quick partition algorithm [21]. Cluster analysis algorithms falls into the category of unsupervised classification tools. For review of most recent cluster analysis algorithms see [22] and [23].

The computational intelligence community has studied conceptual clustering [24] as well as other methodologies with a statistical flavor. The basic idea behind conceptual clustering is that instead of considering the similarity between objects, conceptual cohesiveness among the objects is considered as a criterion for classification. Conceptual clustering techniques are context based and arrange objects hierarchically [24]

Autoclass is a known Bayesian classifier that uses simplifying assumptions about the classification model. Rather than searching the entire hypothesis space and considering all states, they focused on a limited number of possible states thereby reducing the number of possibilities to be analyzed. In the case of real value attributes, the assumption is that data is distributed according to the normal probability distribution. A multinomial distribution is assumed for the discrete attributes. Autoclass uses the expectation maximization algorithm [25], to estimate the class parameters that maximize the posterior probability of the parameters for a given number of classes. The Autoclass algorithm can be downloaded from the NASA [26] website.

Decision rules

Decision-rule and decision-tree algorithms belong to a large class of supervised learning algorithms generating explicit knowledge (patterns). The two classes of algorithms have been implemented in numerous ways, for example:

- Decision-tree algorithms (e.g., C4.5 [27]
- Decision-rule algorithms (e.g., AQ15 [28], LERS [28], and numerous other algorithms based on the rough set theory [29])

Structured rules

The decision rules extracted in data mining may be used in “as-is” form or be structured. Rule structuring [30], is to enhance interpretability of the knowledge generated with machine learning algorithms. The need for knowledge structuring is supported by the notion of cognitive maps and mental models discussed in [31] and [32]. By structuring decision rules a human dimension will be incorporated into the knowledge extracted from data. The decision table structure and the decision differentiation methods are determined by factors such as:

- Type of the learning algorithm
- Rule selection criteria
- Constraints and objective functions imposed on a decision table structure

The structured decision tables offer potential for multiple applications. They can serve as a backbone of a visualization environment (e.g., virtual reality) and increase transparency of the decision making process.

3.5. Process models

Numerous methodologies have been developed for modeling processes. Although they vary in scope, representation, and theoretical foundations, each methodology provides insights from a particular perspective. Some of the existing process-modeling methodologies of interest to modeling innovation are listed next.

- *UML*: Unified Modeling Language is a visual and graphical modeling language to analyze and design object-oriented systems [33].
- *CIM-OSA*: Computer Integrated Manufacturing - Open Systems Architecture. Four enterprise views are provided: function, information, resource, and organization [34].
- *GRAI Method*: This method is built around a conceptual reference model that is based on the theory of complex systems, hierarchical systems, organization systems, and the discrete activity theory [35].
- *IDEF Methods*: A family of tools, including IDEF0 for functional modeling and IDEF3 for process modeling initiated by Air Force Program for Integrated Computer-Aided Manufacturing [36].
- *IEM*: A public domain methodology designed around the object-oriented paradigm.
- *SSADM*: A method of systems analysis with the focus on the information [37].

A product development model (intertwined with innovation activities) involves activities that are not known in advance and are not well predicted. The uncertainty associated with the innovation activates calls for innovation process management [38]. Data-mining algorithms may be used to determine the underlying patterns of success. Though these patterns are likely to be temporal, any use of structures is helpful in the execution of the innovation process [39].

To date numerous innovation models have been generated [39]. The early models viewed innovation as linear process with focus on either a technology-push or a demand-pull innovation process [40]. The prevailing view in the literature points to innovation models with complex interactions and cycles. The scope of innovation models has been widened to include suppliers, and business alliances, all serving customers demanding personalized products.

4. Innovation Enhancing Tools

Numerous tools have been developed in support of innovative design of products, including TRIZ [41], the creative problem solving (CPS) process [42], and the innovation technology (IvT) approach.

TRIZ was developed to foster innovation by analyzing the patterns of problems and solutions, rather than relying on the spontaneous creativity of individuals or groups. This is done by focusing on a problem in its basic form while simultaneously understanding that the problem considered is rarely the one to be solved. TRIZ handles three basic problems: the technical conflict and physical contradiction problem in which a solution creates another problem; the inventive problem where before a problem is solved, the solution of the conflict must be resolved; and the creation of the ideal machine/process in which something simplistic is constructed from a concept [43].

The CPS [42] is a problem solver for a generation of innovative solutions. During the solution generation process, combining convergent and divergent thinking is used to produce numerous potential solutions, while the user imagination is used freely to aid in the creation of innovative and working solutions.

Another approach used by engineers is the innovation technology, IvT, approach. It relies on various tools for problem-solving, e.g., modeling, simulation, virtual reality, data mining, artificial intelligence, rapid prototyping, high throughput chemistry, and high throughput screening. These technologies are becoming ubiquitous in the innovation process. The IvT approach has been used in the recent high profile projects, e.g., the design of the Millennium Bridge in London, reconstruction of the Leaning Tower of Pisa, the design, creation, and building of the Bilbao Guggenheim Museum, and solving London's roadway congestion problem [44]. Other innovation tolls include CREAX [45], Visual Mind [46], and Pull Thinking [47].

The above tools cover some aspects of the innovation space. Research is needed to identify gaps and explore other methodologies and tools enhancing innovation, e.g., creativity fostering tools. Yamamoto and Nakakoji [48] described an interactive tool that impacts user's cognitive processes.

5. Conclusion

Increasing innovation awareness by the discovery of the underlying science is critical to corporations' becoming progressive, competitive, and better prepared to handle future adversities. Innovation can fill the gap created by the shift in low-end manufacturing jobs and growing global market competitiveness. The paper outlined the need for the discovery of theories, processes, methodologies, and tools enhancing innovation. Some of the tools supporting innovation, e.g., genetic programming and data mining could be embedded in prototype software and integrated with the existing computational systems. Pattern discovery from data surrounding design, process, and service applications - and therefore data mining - and likely to become major solution approaches of the innovation cyber-infrastructure. The ramification and use of the existing theories (research is needed to formalize them), methodologies (e.g., group thinking, brainstorming), and innovation tools (e.g., TRIZ) needs be better understood, and new progressive models, methodologies, and tools should be developed.

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