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ASSESS NOVELTY OF AN INVENTION USING THE CENTRAL-EXTREME NOVELTY MATRIX: A CASE STUDY OF JUVO LABS'S FIBRE-OPTIC SENSOR MAT

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Abstract: Creativity studies have uncovered how novel combinations of prior technologies can influence the future value of resulting inventions. But such theoretical understandings have been seldom applied to analysing inventions and guiding real-world innovation practices. To fill this gap, we analysed a novel sleep-monitoring system that is commercialized by a start-up company in Singapore. Our case study demonstrates the novelty assessment method using the central-extreme novelty matrix, and reveals the challenges and opportunities that originate from the novel combinations of the underlying technologies but only appear at the later stages of product development and manufacturing in the innovation process. The findings provide implications for innovators to manage design novelty of the original invention, from the holistic perspective of the innovation process.

Keywords: *novelty assessment, technology combination, invention, product development and manufacturing, design practice, innovation*

1. Introduction

Novelty is an essential element of technology innovation (Lubart, 1994; Sternberg & Lubart, 1996). High novelty implies an increase in the variability that can result in both breakthrough and failure (Fleming, 2001). Much research work in design science and psychology has investigated the sources of design novelty at the stages of ideation, conceptualization, and functional prototyping, but seldom further studies the implication of design novelty at the later stages of the innovation process, e.g., product development, manufacturing, and commercialization in general (Luo, 2015). Thus, how to harvest the value of design novelty in practice remains unclear. To fill this gap between the studies on design novelty in early design process and later development and manufacturing stages, this paper focuses on unveiling how the design novelty of an invention influences the subsequent product development and manufacturing. Specifically, we conducted a case study on a new product (i.e., a novel sleep-monitoring system) being commercialized by a startup company in Singapore, based on patent analysis of the novelty of the invention itself and interviews with the inventor and the entrepreneur regarding the design, product development and manufacturing processes. Our findings contribute more nuanced understanding of challenges and opportunities of product development and manufacturing brought by design novelty of inventions, and propose guidance to innovators on more balanced strategies to harvest the economic value of novel inventions.

2. Related literature

2.1. Combination novelty and invention value

The prior literature has suggested that uncommon combinations give rise to novelty in invention. Simonton (1999) argued that the recombination of existing technologies leads to an invention and that unconventional combination of prior technologies results in the novelty of the invention. Arthur (2007) proposed that the source of an invention is the combination of existing technologies for recursive problem solving. Youn, Strumsky, Bettencourt, and Lobo (2015) found that the combination of existing technologies, rather than the introduction of new technologies, has been the major driver of modern inventions. Taura and Nagai (2012) revealed that in concept generation by concept blending, the highest novelty is obtained from the base concepts with high distance.

Combinations can be characterized with different novelty levels, leading to different outcomes. Uzzi, Mukherjee, Stringer, and Jones (2013) found that the scientific papers with both high conventionality and high novelty (i.e., grounded in a mass of exceptionally conventional combinations of prior work and a minor insertion of highly novel combinations) have the most potential to receive high citations. Kim, Cerigo, Jeong, and Youn (2016) found patents classified in both novel and conventional combinations of patent categories are most likely to become "hits." Fleming (2001, 2007) found that although US patents with novel combinations in their references became less useful on average, but exhibited a high chance for either breakthrough or failure due to the variability increased by high novelty.

In conclusion, the literature has suggested that novel combinations are fundamental for inventions and particularly crucial for breakthroughs, but excessively novel combinations may introduce challenges and lead to poor results. There might be a novelty "sweet spot" of prior technology combinations that give rise to the value of inventions.

2.2. Evaluation of design novelty

Design creativity researchers have suggested various definitions, metrics, and methods to evaluate novelty. Novelty generally indicates that an invention is new, original, unexpected, and surprising (Kaufman & Baer, 2004; Simonton, 2000; Sternberg & Lubart, 1999). The traditional method to evaluate novelty is collecting subjective opinions, based on intuitions or experiences from an expert group (Amabile, 1996). Then various techniques were introduced to assist expert groups and analyze their opinions. Sarkar and Chakrabarti (2007) proposed to use product characteristics to measure product novelty, introducing the Function-Behavior-Structure (FBS) model and the SAPPhIRE model. Brown (2015) presented a simple framework to compute design creativity by considering agent judging, the set of aspects, knowledge about the designer, etc. Grace, Maher, Fisher, and Brady (2015) developed an expectation typology that, when violated, produces surprise and contributes to novelty in creativity to some extent.

Evaluation relying on expert opinions is naturally subjective and limited due to the data sample size. Computational and data-driven evaluation of design novelty is increasingly demanded (Brown, 2015; He & Luo, 2017). For example, Shah, Smith, and Vargas-Hernandez (2003) proposed a posteriori approach to measure novelty of ideas by counting how many instances of a solution method exist in the entire idea collection, where the lower the count, the higher the novelty. Maher and Fisher (2012) illustrated an AI approach to evaluating novelty by building a description space of design attributes and measuring relative distances between designs. Recent studies also have developed methods to evaluate patented inventions by analysing patent documents. Fleming (2001) analysed historical frequencies of co-classification of a patent to indicate its novelty from a recombination perspective. He and Luo (2017) analysed historical frequencies of class pairs in a patent's references to assess the novelty of the patented invention. In this paper, we assess the novelty of a patent application by comparing it to the extensive patents in the USPTO (United States Patent and Trademark Office) patent database.

3. Methodology

In this study, we first assessed the novelty profile of a patent application using the patent data-driven novelty assessment method from our prior research (He & Luo, 2017). With the understanding of the invention's novelty profile, we then interviewed the inventor of the patent application and the CEO of a startup company developing new products to commercialize the invention. Finally, we integrated the results of the novelty assessment and the interviews to relate the invention's design novelty to the challenges and opportunities that became apparent in the later product development and manufacturing.

3.1. Data-driven novelty assessment for the invention with a patent application

The method developed from our prior research (He & Luo, 2017) is centred on using the historical patents in the USPTO database as a benchmark to assess the novelty of the technology combinations of a focal patented invention and thus its overall novelty profile. Specifically, each patent is assigned to one or more patent classes by USPTO examiners to indicate the types of technology it embodies. IPC4 (4-digit International Patent Classification) was used to mark 631 patent classes to approximate technology types. Each patent document also lists the references to prior patents. All pairs of the classes assigned to a patent's references approximate its recombination of existing technologies. Each class pair represents a combination of prior technologies and displays a degree of novelty, according to the frequency that it has occurred in the reference lists of all historical patents prior to the focal patent. Class pairs occurring more frequently would indicate less novelty. In this paper, we used about 5.2 million utility patents granted from 1976 to 2015 in the USPTO patent database as the overall sample for benchmarking the novelty of the combinations in the references of a focal patented invention. The case study focuses on the patent application "WO2011016778A1" entitled "A vital signs detecting device and a method for detecting vital signs".

On this basis, the novelty of a patented invention can be profiled by a distribution of novelty scores of the class pairs (the proxy of combinations of prior technologies) extracted from the patent's references. In the world of invention, both the general and the outlier are meaningful. The method focuses on the median and the highest score of the novelty distribution and measures them as central novelty and extreme novelty of the patented invention. He and Luo (2017) further used a 10-by-10 matrix to classify patents according to their 10-percentile central and extreme novelty levels (Figure 1), and found that the patents with a medium central novelty and high extreme novelty receive a relatively high number of future citations, which the literature has statistically correlated with high commercialization value of patents (Hall, Jaffe, & Trajtenberg, 2000; Harhoff, Narin, Scherer, & Vopel, 1999). Their results reveal that the upper centre region of the central-extreme novelty matrix is the "sweet spot" for invention value. Thus, the location of a patent in the central-extreme novelty matrix may provide implications to its future economic value. Compared with the existing novelty assessment methods, this method provides more nuanced novelty assessments of two aspects.

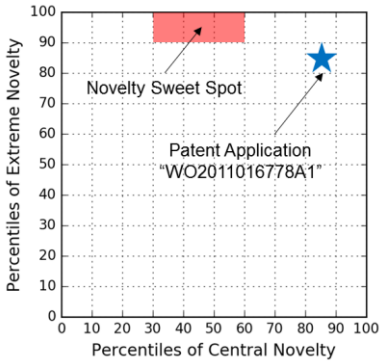

Figure 1. Central-extreme novelty matrix and the location of patent application "WO2011016778A1".

3.2. Interviews with the inventor and the entrepreneur

With the novelty assessment of the focal invention with a patent application, we interviewed the people involved in the innovation process from different points of view, to explore the details of the invention and the product realization process (product development and manufacturing). The interviewees include

- The patent inventor, who is familiar with the technologies combined in the original design.

- The entrepreneur, who has knowledge about the later processes of product development and manufacturing based on the invention.

The interviews were semi-structured. We first introduced the interviewees with the central-extreme novelty profile of the focal invention, then asked them for the details of the invention, the product design, and the product development and manufacturing experiences. The key questions in the interviews are listed in Table 1. The central-extreme novelty profile helped the interviewees explain their experiences and observations in their practices from the perspective of technology recombination, i.e., guided them to decompose the invention into technologies in different fields and reveal the product's challenges and opportunities caused by technology combination.

Table 1. Interview Questions

Interviewees	Interview Questions
Inventor	• What are the technologies related to the patent application's references? • What is the central part of the patented invention? What are the related prior technologies combined to realize this part? • What is the most novel part of the patented invention? What are the related prior technologies combined to realize this part? • How did you come up with the idea of this invention? • What were the opportunities and challenges you encounter or perceive in the technology development process? • What are the advantages and disadvantages of the invention facing competitors?
Entrepreneur	• What is the commercial product about? • How does the licenced patent contribute to the product? • How did you come up with the idea of the product? • What were the opportunities and challenges you met in the product development and manufacturing process? • What are your views on the novelty of technology recombination as an entrepreneur?

4. Results and discussion

Juvo is a sleep-monitoring system that tracks the vital signs and manages the environment from under the mattress to help people sleep better. It is developed, manufactured and marketed by Juvo Labs Pte. Ltd. in Singapore. Juvo Labs was founded in 2015 and focuses on Internet of Things products and platforms for healthcare. Juvo is the first product of Juvo Labs, developed based on a patent licenced from the Neural and Biomedical Technology Department of A*STAR (Agency for Science, Technology and Research, Singapore).

The design of Juvo comprises of a contactless sensor mat, a bedside monitor, and a mobile application (Figure 2). Juvo can monitor users' breathing, heartbeat, and movement to reveal the sleeping patterns. It can also monitor the environmental elements, i.e., the light, sound, and temperature, to see how they correlate to sleep patterns and quality. Integrating with other smart home devices, Juvo aims to create a more comfortable sleeping environment by switching lights, playing music, adjusting temperature, etc. Compared with other vital sign monitors, Juvo's advantage is that it requires no skin contact. Users just need to put the sensor mat under the mattress, without wearables.

Figure 2. Composition of Juvo: a contactless sensor mat, a bedside monitor, and a mobile application.

Juvo's skin noncontact feature benefits from the patented invention of fibre-optic sleep and vitals sensor (Chen et al., 2014; Lau et al., 2013). The sensing mechanism is shown in Figure 3. Unlike other sleep monitors that simply measure the movement using an accelerometer, Juvo uses the patented invention of a fibre-optic micro-bending sensor that picks up even the heartbeat from under the mattress. The main design principle is that heartbeat and breath generate vibration, change the pressure on the sensor, vary the micro bending of the optic fibre, and finally influence the intensity of the light propagating through the optic fibre. The sensor strip is ultra sensitive. By taking pressure measurements 100 times a second, it can sense the mechanical changes in pressure caused by the blood being pumped through the arteries as well as the air being pushed in and out of the lungs. The use of optic fibres as sensors of vital signs overcome many limitations for traditional electrical sensors, such as discomfort, fixation, radio wave emission, electro-magnetic interference, etc., and gives Juvo the product novelty and competitiveness in the market of bed monitoring products.

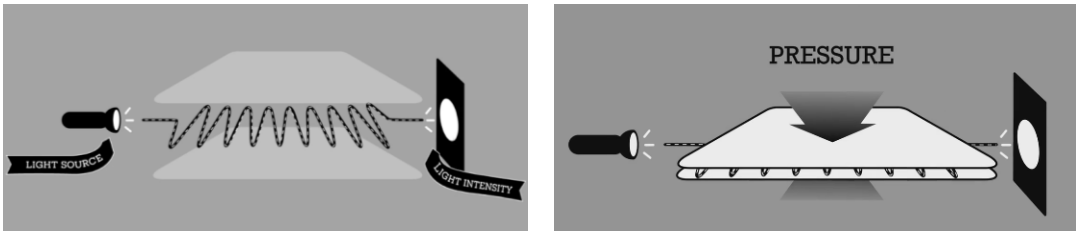

Figure 3. The sensing mechanism of the fibre-optic sensor in Juvo. (Source: https://www.indiegogo.com/projects/juvo-track-manage-sleep-from-under-your-bed#/)

4.1. Novelty of the invention behind Juvo

To assess the novelty of the invention behind Juvo, we analysed the references of the patent application it based upon, i.e., patent application "WO2011016778A1" entitled "A vital signs detecting device and a method for detecting vital signs". Table 2 lists the IPC4s assigned to the references of the patent application and the corresponding technologies. Figure 1 shows the invention was located at the top right corner of the central-extreme novelty matrix, i.e., with high central novelty and high extreme novelty, when Juvo was released in 2015. According to He and Luo (2017), the invention is close to, but outside the novelty sweet spot for invention value. Particularly, its central novelty is much higher than those in the "sweet spot". In contrast, the assessment of this patent application by the Patent Cooperation Treaty[1] only simply reports that the invention presents high novelty and high industrial applicability.

Table 2. Technologies combined in the invention (patent application "WO2011016778A1")

Reference IPC4	Technologies	Details
A61B	Medical Diagnostics	Detect heart and breath rates
G01B	Metering by Length	Optic fibre's length influences measurement sensitivity
G01D	Metering by Other Means	Measure by using optic fibres
G01H	Measuring Sound Waves	Measure the vibration
G01L	Measuring Force	Measure force with further signal processing
G01M	Testing of Machines	Not very related
G01P	Measuring Movement	Measure the vibration
G02B	Optical Systems	Use light source and optic fibre

The central novelty of the invention is determined by the combination of "G01D - Metering by Other Means" and "G01H - Measuring Sound Waves". This combination provides the invention's basic function—using an optic fibre to measure the vibration. Specifically, the device measures vital signs

[1] The document is available at https://register.epo.org/ipfwretrieve?apn=SG.2010000162.W&lng=en.

including the movement, the respiratory actions, and the heartbeat actions of a human body, by metering the micro bending of a multimode optic fibre, which is in a two-layer mesh-like mechanical structure receiving the pressure exerted by the human body. The combination of the special mechanical structure and an optic fibre sensor has never occurred in the prior arts. It forms the core of the invention and brings high central novelty by combining components that were irrelevant.
The extreme novelty is determined by the combination of "A61B - Medical Diagnostics" and "G01B - Optical Systems". This combination is about using an optic fibre to monitor vital signs. The rare combination of optic fibre sensing and vital sign monitoring gives the invention high extreme novelty, by applying an existing technology to a new application domain.
In general, the high-high central-extreme novelty of the invention contributes to not only opportunities but also challenges for the subsequent product development and manufacturing, which are revealed in our interview with the startup that has commercialized the invention.

4.2. Opportunities and challenges for Juvo

Our interviews show that the inventor and the entrepreneur hold different opinions on the benefits and challenges introduced by the novel combinations of technologies in the invention.
As analysed above, the combination of optic fibres and vibration detection determines the central novelty of the invention. According to the inventor, the key to detect vibration is the novel "sandwich"-like structure, made of an optic fibre sensor and two layers of mesh materials. All the components of the required meshes and optic fibres were available and affordable in the market. This situation made functional prototyping easy in the laboratory.
According to the entrepreneur, the fibre-optic vibration sensor is revolutionary and has never been used in a consumer product. This technology uses an unexpected effect of an optic fibre to provide motion sensing. It also uses a special packaging process, i.e. sandwiching the optic fibres within two mesh covers, which was not used in the industry. Therefore, it runs counter to the main research and development thrust in the fibre optics industry. The novel combination of the special mechanical structure and the optic fibre sensor makes it difficult for the invention to be developed, manufactured, and then commercialized as a high-quality product.
The entrepreneur shared that the high central novelty of the invention had brought a few challenges to commercialization. The first challenge is on talents. Highly novel combination means that the fibre optics industry does not naturally train engineers with the combined skill sets required by the "sandwich" design. The company cannot immediately find and recruit engineers with the synthesized knowledge and skills in both technical domains combined in the invention. The company as a startup does not have the resources and expertise to train the engineers from scratch, either. The second challenge is about suppliers. Highly novel combination means the mainstream suppliers are unfamiliar with all facets of the combination. It is difficult to immediately find the suppliers that have the synthesized experiences, technologies and equipment for integrating the mesh materials and the optic fibers for high-quality manufacturing. The startup ended up spending much time in searching for and engaging a large number of suppliers for small portions of the product. This situation increased the supply chain complexity and the management effort, which distracted them from the core task of marketing and selling.
Meanwhile, the entrepreneur also thinks the novelty challenges are easier to be dealt with for smaller product runs and fewer customers. These challenges arising from technology combination novelty may also build up a competitive barrier for future entrants to the market. It has taken the company enormous efforts to develop systematic and integrative product knowledge and manufacturing process, which are tacit and the potential competitors must go through as well.
As shown in our novelty analysis, the combination of optic fibre and vital sign monitoring appears the most novel in the combination space of the invention. The inventor believes that the invention can have a wide range of applications, including biomedical devices, since the optic fibre sensor is flexible and scalable. In fact, the patent has been licenced to multiple companies to develop different commercial products, for example:

- Juvo Labs Pte. Ltd.: real-time sleep and bed monitoring mats for home use and commercial use.
- Blue Amber Technology Pte. Ltd.: cable-less smart vital sign monitoring devices in hospitals.

- Darma Inc.: cushions that monitor users' posture, sitting habits, stress level, etc., and coach users to sit better.

The entrepreneur also believes that optic fibre technology and medical/health sensing together lead to novel applications. Juvo is the first of its kind. No other sleep-monitoring product goes under the mattress and is unobtrusive to use.

Taken together, the patent-based assessment of novel combinations in the invention and the startup company's experiences in later product development and manufacturing suggest:

- Highly novel combination of previously unrelated technologies may be feasible for prototyping in the lab (from the view of the inventor), but may bring challenges to later product development and manufacturing in the innovation process (from the view of the entrepreneur). Specifically, the high novelty of the technology combination implies few engineers and suppliers would be prepared with integrative knowledge and capabilities to synthesize technologies in product development and manufacturing.
- If one can successfully go through the process and establish the integrative capabilities to develop and manufacture the product embodying the highly novel combination of seemingly unrelated technologies, such capabilities will become sustainable advantages because they are rare and tacit and the later entrants to the market will have to go through the same learning process (from the view of the entrepreneur).

These findings connect design novelty of an invention to the later product development and manufacturing for the commercialization of the invention. In brief, the highly novel technology combinations give the invention high potentials to create products that are novel and useful, but also introduce challenges to its product realization and commercialization. These findings suggest the value to unite and integrate the creative engineering design process and entrepreneurship process in order to enhance innovation (Luo, 2015). Such understanding may better prepare inventors for the commercialization of their inventions.

4.3. Discussion

Note that the findings above are discovered in the context of a single startup company and a single product. It may not be the same case for a large established company. Compared with small startups, large companies may have more comprehensive and diverse talents and capabilities in house for product development and manufacturing, so they might be able to better ensure the commercial success of a highly novel invention through readily accessing and recombining the required resources and capabilities in house. Further research is expected to explore additional implications of technology design novelty on later product development and manufacturing in the innovation process, in different contexts.

In addition, although this case study is based on the understanding of a sweet spot of invention from the analysis of massive patents (He & Luo, 2017), the assessment method, in particular the central-extreme novelty matrix, should not be limited to patents. It concerns novelty in two dimensions (i.e., the central and extreme values from a novelty distribution of technology field combinations) rather than a single metric, and can be applied to assess inventions based on other types of design or invention data.

5. Conclusion

This paper has revealed some implications of technology design novelty to the later stages of the innovation process, including product development and manufacturing, by assessing the central-extreme novelty of an invention based on technology combinations and interviewing the inventor and the entrepreneur. First, a technology design from highly novel combinations of prior technologies is likely to be difficult to develop, integrate and manufacture into a high-quality product, because of the scarcity of versatile engineers and comprehensive suppliers with the required combinations of knowledge and capabilities. Second, a technology design from highly novel combinations may benefit from its high novelty in the market place, if a company can overcome the novelty challenges in product development and manufacturing. In this case, taking the perspective of a more holistic innovation process reveals these implications across the design, development, and manufacturing stages. Such understanding may

help with design decisions of inventors at an early stage, and may also better prepare product developers and manufacturers at a later stage for successful product realization and commercialization based on a highly novel technology design.

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