Innovation through ‘Meta-Engineering’
– Mining – Exploring – Converging – Implementing Process –

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Abstract—The authors propose the new creative concept of “Meta-Engineering” as a radical engineering approach that is critical for breakthrough innovation. Conventional engineering is defined to design a solution to a given issue optimally using technologies under given constraints. However, confronting increasingly diverse and complicated issues, the authors find limitations in this approach.

Meta-Engineering, a spiral process for innovation and for solutions to challenges confronting the world, includes “mining potential issues from a bird’s eye view (M),” “exploring and strengthening of the necessary science and technologies by thinking outside the box (E),” “converging these science and technologies to generate solutions (C),” and “implementing the solutions into challenges creating social added value (I).” This process is designated as a MECI cycle.

The authors studied Meta-Engineering in several cases of pursued innovation. The first was the on-demand bus (ODB) services. The authors describe that analysis of R&D and social implementation of ODB by the Meta-Engineering methodologies suggests further progress of ODB services. Meta-Engineering is evident in historical innovations such as blue LEDs and LED lamps, and the WALKMAN. Those observations suggest the importance of a Meta-Engineering approach in the pursuit of breakthrough innovation.

I. INTRODUCTION

Innovation has been expected to solve the problem of global economic stagnation. Globally, cloud computing, smart grids, and iPhone/iPad have arisen as innovations, but fewer innovations are coming from Japan these days, although Japan is said to be extremely good at engineering, to be capable of making excellent products, and to have many competent creative workers.

Innovation is realized by using engineering to resolve issues confronting society. Engineering, which has many definitions, is often described as “design under constraints [1]” by the US National Academy of Engineering, or “to provide an optimal solution within limited given conditions.” The authors question whether these definitions hold in discussion of innovation. Completely different answers might be obtained that might engender innovation by removing the constraints, instead of by narrowing them. The authors propose a new creative concept of “Meta-Engineering” as a radical engineering approach that is critical for breakthrough innovation.

Conventional engineering is defined to design a solution to a given issue optimally, with technologies under constraints. However, when confronting ever more diverse and complicated issues to tackle in the future, the authors find and expect limitations in pursuing this approach alone.

The authors propose a new concept as Meta-Engineering, a spiral process for innovation and further for solution to challenges that the world faces [2]. They discuss the importance of “Ba” in Japanese or the field of Meta-Engineering to accelerate spiral processes to create innovation.

After proposing Meta-Engineering, the authors studied Meta-Engineering that is emergent in several cases of pursuit of innovation. The first one was that of on-demand bus (ODB) services. The authors describe that analyzing R&D and social implementation of ODB using Meta-Engineering methodologies suggests further progress of ODB services. Meta-Engineering was confirmed to work well in historical innovations such as blue LEDs and LED lamps and the WALKMAN. Those evaluations support the importance of a Meta-Engineering approach in breakthrough innovation.

II. META-ENGINEERING CONCEPT

The limitations of conventional engineering are that the issues are visible ones, that many conditions should be considered, that only technologies are applied to solve the issues, and that no value is provided by solving the issues. This chapter presents the Meta-Engineering concept.

The authors designate the effort of mining potential issues and solving the issues by removing the limitations as “Meta-Engineering” (Fig. 1). The definition of Meta-Engineering is the following: First, we identify hidden issues in our society. Then we seek appropriate science and technology to solve the issue. In many cases, it is difficult to resolve an issue using a single scientific or technological principle. We must converge several science and technologies. Finally we implement this solution to the real world and provide new value to society.

Several references show that the term Meta-Engineering has been used in some areas [3], [4]. The authors selected this term for this new concept of engineering after considering other candidate names such as “holonic engineering,” “comprehensive engineering,” “ecological engineering,” “transformative engineering,” and “Japanese converging technology.” The authors chose Meta-Engineering because this name produces an image of metaphysical engineering as a level above current engineering. Meta-Engineering places a “why” question at the beginning of conception. For instance “why is innovation necessary in the energy field?” One answer might be “to conserve the global environment and natural resources for later generations.”
Always remaining mindful of the “why” above, Meta-Engineering circulates the four processes into a spiral. That spiral process includes “mining potential/latent issues from bird’s eye view (M),” “exploring and strengthening necessary science and technologies by thinking outside the box (E),” “converging these science and technologies to generate solutions (C),” and “implementing the solutions into challenges creating social added value (I).” This process is represented as MECI or an MECI cycle [5]. Another new issue emerges in this cycle. The image of the four processes turning round and round is important. One reason for returning to the process of mining a new issue is that innovation is meaningless unless it continues. Furthermore, the four processes repeat cyclically.

In that sense, it is a spiral rather than a cyclical feedback. It means that the world might change by introducing new things, but some other potential issues arise because of that new introduction.

This MECI process is cultivated in the Meta-Engineering field or as “Ba” in Japanese.

A. Importance of the “why” process

In conventional engineering, an issue is regarded as a problem to be solved. In other words, the “what” is given; an engineer figures out “how” to make something. In Meta-Engineering, it is suggested that an engineer first examine “what” and “why.” To realize Meta-Engineering, that “why” process is the most important one (Fig. 2).

B. Methodology

The outline of the methodology of Meta-Engineering is depicted in Fig. 3. When one applies Meta-Engineering to an issue to be studied, the first step to be followed is to state “why the issue is to be studied” based on the field on which “what is the issue to be studied.” Then it is necessary to extract the “what”. The process will become that portrayed in Fig. 4.

What can become "why"? Anything might be allowable if engineering alone is workable and ethically acceptable for the proposition. It is unsuitable if the motion is based on greed to take money by cheating socially vulnerable people, such as a retired handicapped person or a young child, even if it can be easily accomplished by application of modern ICT technologies.
After defining the potential issue, the process proceeds to the “Exploring” process. This process is presented in Fig. 5. It is necessary to develop the concrete parts, or constituents, which form “what.” In this process, an important consideration is to neglect conventional constraints by inquiring “why do these constraints exist?” It is then important to clarify the boundary condition of these issues: to specify the conditions so that each problem would be solvable, by exploring these issues without sticking in a single science and engineering domain.

Subsequently, the process to seek candidate solutions by combining the knowledge of related fields or by deepen a specific field is proceeded. Then the most adaptable solution is selected (sometimes plural solutions are selected), developed, designed, and implemented (Fig. 6). At the final stage, the business incentives are quite important. Not only the business model, but also social systems such as taxation and regulation (deregulation), must be innovated. This concept of Meta-Engineering is presented in terms of some actual projects in the following chapters.

III. APPLICATION TO ON-DEMAND BUS SYSTEM

In this chapter, the on-demand bus system application is analyzed using the Meta-Engineering methodology. First, ODB itself is explained. Next, ODB research and development progress made at a university laboratory is analyzed. Then its implementation results at a small Japanese rural town, named Tamaki Town, are studied. Finally, the future of ODB is examined.

A. What is an on-demand bus system?

People want to move. Those needs are fulfilled by various traffic systems. For example, a privately owned car, a taxi, streetcar, and a bus are some systems. The on-demand bus system is a type of regional public transportation system. A short comparison of ODB to the conventional bus on a regular route will be the following. A regular route bus is operated on a predetermined route and timetable. An ODB is operated upon a user request. It is a demand response transfer service.

If the ratio of people who own private car(s) increases, then public bus service profitability decreases. This engenders the withdrawal of private bus companies from business operations. Even then, some people must use public bus services. They are socially weak people who cannot own their cars for physical or economic reasons. Their transfer needs must be fulfilled socially. A straightforward solution is to use a taxi system. To provide supplemental taxi coupons might help these socially weak people. However, the cost which a local government bears is not small. It is worth study to ascertain whether ODB can work or not.

B. Academic research

In Japan, several organizations are tackling ODB systems development. Among them, the authors have noticed R&D
accomplished by Prof. Hiroyuki Yamato and Dr. Kota Tsubouchi of the Graduate School of Frontier Science at the University of Tokyo [6]. The strong features of the system which they have realized are the following.
* Precise operation times
* Flexibility of reservations
* Door-to-door service
* Reliable bus service control system
* Low server cost

We can produce the ODB R&D of the Yamato Laboratory by interpreting their establishment through meta-Engineering.

The need for ODB research was born in the newly developed University of Tokyo campus, Kashiwanoha Campus, where commuting facilities were vulnerable. Many students and staff commuted using the Tsukuba Express Train. The distance between the closest train station to the new campus was considerably far. Although bus services existed there, the blank spaces in their timetable were conspicuous. The ODB was planned at the Yamato Laboratory. The inconvenience of commuting was the "why" of the first step. No element of the system at this stage was sophisticated. The engineering level was no more than bachelor’s study item. A key factor was the fusion of Information Communication Technology (ICT) and Global Positioning System (GPS) technology. Bachelor student Kota Tsubouchi came up with the concept of the system.

The second step became research at the master’s thesis level. The Yamato Laboratory started receiving supporting requests from a few regional public bodies on building an ODB service. Through the development, knowledge related to using the internet, a bus operation algorithm, and an operation system were accumulated. In parallel with that, the social purpose of ODB—the “Why ODB?”—of permissible cost, obstacles caused by regulations, and other reasons were also examined. Many non-technical but unavoidable potential problems revealed themselves. These might not be engineering issues in a narrow meaning, but they are unavoidable hurdles that must be overcome to tackle ODB engineering and create social value.

Then the research advanced to the third stage, where the university laboratory and ODB business operation sides cooperated more closely to remove various obstacles as well as technical developments. Higher advancement of the operation algorithm and a more human-friendly terminal function were developed.

Many ODB systems remain at the second stage, or are slated to move on to the third stage. Here, we can describe the actual example of the third stage; that is the ODB system of the Tamaki town of central Japan [7].

C. Successful application

Tamaki, a small municipal town in Mie Prefecture with a population of about 15,000, is located near the Ise Shrine, one of the most famous shrines for Japan. The ratio of elderly people (population aged 65 and older) there is slightly higher than 20%.

In 1996, the town started a free public bus on a regular route service called the “Fukushi Bus (Welfare Bus)” after facing the wholesale withdrawal of a private company from the bus service business. Tamaki expected the bus to be used by elderly people who go to a hospital or who go shopping. However, the bus service could not cover the widely expansive residential area; the bus was called an “Air Bus”, which carried air instead of passengers. They recognized the existence of ODB. Still they were reluctant to introduce it because of the difficulty of operation management.

Then a turning point came. A leader of the Tamaki Social Welfare Council, which was an execution unit of the welfare administration of the town, found on-demand traffic research of The University of Tokyo. He, together with the person in charge of the town office, visited and inspected the laboratory. The mayor decided to support the experimental introduction. Here, the "why" was "offering the transportation mean as part of welfare administration", "what" was ODB and "how" was the enabling technology such as collaborative filtering, which The University of Tokyo had developed. The new bus was called the “Genki Bus (Healthy Bus)” and the fare was free, as was that of the "Air Bus."

The transition of the monthly number of users after ODB was introduced in October 2010, as shown in Fig. 7. The town has put various measures into practice to make a "Genki Bus" more convenient. Following the improvements, the user consciousness changed. According to the social surveys, the users at first used ODB because the bus stop was located near one’s home and convenient. Then they started thinking of using ODB to go to the welfare center of the town where various events such as gymastics, cooking, and literary lectures are regularly offered, to go to the hot spring facilities where shopping and dining are also available, and even to enjoy chats inside the bus. The bus now serves as a tool to promote the physical and mental health of the Tamaki people.

Tamaki has set its sights on other developments to increase the welfare of its people.

Then, what is the key factor for success for Tamaki. Are other towns and cities also successful? Let us consider this topic next.

D. Obstacles and future perspective

Tamaki town has implemented various efforts to increase convenience. However, these efforts might entail great costs without careful consideration. Therefore, it is necessary to elicit a greater effect with fewer buses, a smaller frequency of operation, and fewer staff members.

The “ride together” which is one feature of ODB is now observed. Because the ODB system which The University of Tokyo developed has been used in many cities and towns, a comparison among them is possible, and the ride together ratio (RTR) is selected as a measure. The RTR is the ratio representing the accumulation of bus operation times of two or more passengers divided by the total operation time. Fig. 8 shows the RTR of various ODB operations, where “O” is
Tamaki. The horizontal axis is the lapsed days from start until the RTR is surveyed. The vertical axis is RTR. It is interesting that RTRs are markedly lower than those of Tamaki at most towns and cities. It seems readily apparent that the technologies which are useful are common anywhere because the systems are built on the same technologies of one research laboratory. Regulations are also basically the same. Why does this difference in the data occur?

The authors think that the difference arises from the difference of adopted engineering in a wide meaning. ODB is not the final objective, but only a measure to transport people from some place to another. Tamaki mines continuously, which is the M of the MECI cycle, the objectives from the town people welfare perspective. They start thinking about the family of town dwellers who live outside the town and who are anxious about the elderly Tamaki family members. The ODB database can be useful to help judge the health condition of residents, although there must be careful consideration of privacy. The authors infer that this kind of mining process is quite important for ODB success.

Another important process is implementation, which is the I of the MECI cycle. Discovery of the permissible operation conditions under existing traffic regulations and control are extremely important at this stage, where the ride fare, whether it should be free or not, is related to regulation. Tamaki has been very flexible and aggressive in overcoming regulation problems.

Tamaki’s ODB is apparently transferable to any place if they commonly share the "why–what–how" thinking and follow the MECI cycle to make the transfer more successful.

IV. APPLICATION TO BLUE LEDS AND LED LAMPS AND THE WALKMAN

The authors have examined Meta-Engineering for analysis of several historical innovation cases, and have found that most progress of innovations has followed the MECI cycle, whether they realize it or not. The authors select two examples of historical innovation among them to show how they are evolved in accordance with the MECI cycle. They are the blue light emitting diode (LED) and LED lamp, and the WALKMAN.
A. Blue LEDs and LED lamps

1) Blue LEDs

The first blue LED fabricated on a GaN crystal was demonstrated by Shuji Nakamura of Nichia Corporation in 1994. Difficulty of the innovation of the blue LED existed in the Exploring and Converging processes of the MECI cycle. The technological breakthrough triggered the innovation in this case [8].

Mining: The need for a blue LED had become obvious by the 1970s. Red and green LEDs had been developed and had come to be widely applied to electrical signboards because of their long life and low energy consumption characteristics. Everybody eagerly hoped for the emergence of an inexpensive blue LED to realize a full color display. Consequently, the Mining process had finished by the 1970s, and competition in development of blue LEDs began heating up.

Exploring: A GaN single crystal of satisfactory quality was necessary to realize a blue LED. However, the development of this GaN single crystal was extremely difficult. Although many researchers had sought to grow satisfactory quality GaN crystal on a sapphire substrate in the 1970s, most of them failed and gave up. Many researchers strove to develop the blue LED on a ZnSe substrate, an alternative to GaN. Some of them subsequently developed blue LEDs. However, they only proved that problems of poor reliability were insurmountable and that ZnSe was useless.

In 1985, Isamu Akasaki and Hiroshi Amano of Nagoya University first developed a GaN single crystal of satisfactory quality on a sapphire substrate. This was the first step of the Exploration process of the development of blue LEDs.

Converging: While the high-quality GaN crystal was developed, two more breakthroughs were necessary to realize production of a high-quality blue LED: p-type GaN and InGaN mixed crystal. Magnesium doping technology to realize p-type GaN was developed in 1989 by Akasaki and Amano at Nagoya University also. The growth process of InGaN mixed crystal was developed by Takashi Matsuoka of NTT in 1989. However, their crystal quality was not yet sufficient to fabricate a highly efficient blue LED. In 1990, Nakamura of Nichia Corp. invented an ingenious process by which he succeeded in obtaining excellent quality InGaN crystal. He realized a highly efficient blue LED for the first time in the world.

Implementing: Nichia Corp. established the manufacturing system of blue LEDs and mass-produced them. Implementing process presented fewer issues because the strong need for blue LEDs already existed worldwide.

2) LED lamps

The application of blue LEDs has been widened from spot lighting to decorative illumination. However, the greatest innovation derived from the success of blue LEDs was LED lamps, which are replacing incandescent or fluorescent lamps. Nichia Corp., which was originally a phosphor manufacturer, developed phosphor-converted white LEDs by putting phosphor on LED chips. This success led to the next spiral of the MECI cycle for innovation of LED lamps from blue LED development.

Mining: LED lamps were expected to show longer life and higher energy efficiency, although initial costs were higher than those of fluorescent and incandescent lamps. Many electric researchers had the idea that there were some applications for LED lamps for the application where the long-life feature was an important benefit for users.

Exploring and Converging: LEDs are driven by low-voltage DC power. The LED lamps need internal or external rectifier circuits that provide a regulated current at low voltage to be operated by regular circuits to provide the power from a standard AC voltage supply. These technological developments belonged to mature electronics engineering. Therefore, development was simple for any electronics manufacturer.

Implementing: LED lamps must be interchangeable with lamps of other types such as incandescent or fluorescent lamps to be accepted in the market. A standard bayonet cap has to be adopted and same external shape as existed with earlier lamps was necessary to fit with conventional illumination. These issues in the Implementation process were matters of industrial design, which is one aspect of engineering.

White LED lamps have a longer life expectancy and higher efficiency than most other lamps have. Most engineers thought at first that the long-life characteristic was the key to the application. However, LED lamps have achieved market dominance in applications where high efficiency is important because of worldwide trends toward energy saving. The worldwide market size of the LED apparatus for general lighting was estimated as $2.5 billion in 2011, and is expected to reach $12 billion in 2018, as shown in Fig. 9 [9].

Fig. 9 Revenue of packaged LEDs for general lighting

B. WALKMAN

In this case, Mining process, finding out the latent demand of people, was the key to innovation. Technologies necessary for innovation had already been prepared before Mining. The obstacles to innovation in such cases are that most marketing, sales, and engineering workers have a negative opinion and object to the development. For the WALKMAN case, they
were strongly against the idea of cassette tape recorders without a recording function. However, an executive decision was made, Masaru Ibuka and Akio Morita, founders of Sony, strongly led the development. Strong leadership is apparently indispensable for innovation. We will review first how various technologies necessary for the WALKMAN had been developed. The MECI cycle was also active in this development.

First, a necessary technology was a small size cassette, lately called a compact cassette. Reel-to-reel tape recorders were popular in the 1960s. They required some skill for easy operation. Household electric appliance manufacturers were searching for technologies to improve user friendliness. Mining processes were already finished in this case because the user demand was created by the leaders' strong marketing appeals. In the Exploring process, most companies selected technologies of putting the tape into some carrier box, called a “cartridge” or “cassette”. They were realized using existing technologies, so that there were not so many difficulties in the Exploring and Converging process. The difficulty existed in the Implementing process, namely in the standardization. There was severe competition and negotiation among many companies. The compact cassette developed by Philips of the Netherlands won the competition for the standardization.

Second, a necessary technology was the headphones. Headphones had been heavy and bulky before the 1970s. Sony developed a light and small headphone called “H·AIR” in 1978. The motivation of engineers for the development was apparently some technological interest in the light weight headphone, which was almost unnoticeable when worn on the head. However, this was just a prototype because it was uncertain whether there was any demand for light weight headphones.

In the late 1970s stereo cassette recorders became popular, but the audio function of portable cassette players remained monaural. Sony launched the very small monaural cassette recorder “Pressman” in 1977, and also the small stereo cassette recorder “TC-DS” in 1978. Masaru Ibuka used a “TC-DS” regularly when he went on business trips. However, he felt it was too heavy to carry it around himself. One day, Ibuka asked some manager of the audio product section to make a small stereo cassette player by removing the recording function from the “Pressman”. The engineers of the section happily accepted the request, and made a new small stereo player in a short time. Ibuka took it when he went on a business trip. He loved it so much because of the light weight and good sound quality. After the business trip, he showed it to Akio Morita. Morita liked it and proposed immediately that it be commercialized. The MECI cycle for “WALKMAN” started its progress here.

Mining: The talk between two founders about the commercialization of portable stereo cassette player without a recording function was truly a Mining process. This example illustrates superior sensitivity in people’s latent demand triggered innovations. Most managers in the manufacturing and sales division objected against the plan of commercialization, however, because the cassette player without a recording function would not seem to impact the market for them in any way. Ibuka and Morita were able to overcome the resistance to promote its commercialization. The decision of the people holding the positions of power was absolutely necessary to perform any plan entailing uncertainties such as this.

Exploring and Converging: The prototype of miniature stereo cassette player had been developed. Therefore, the key point for commercialization was the combination of the small headphones with the cassette player. The small cassette player combined with heavy headphones would not move the market. There was apparently no obvious difficulty in development of the product because the small headphone had already been available. Fig. 10 shows the first WALKMAN model [10].

Implementing: The new cassette player was named “WALKMAN”. The first announcement of WALKMAN did not draw any response from the media. The amount of sales at one month after launching was 3000 units. A different approach for promotion was necessary. Therefore, sales people wore headphones themselves and demonstrated them by walking around busy shopping streets or within commuting trains. They asked passersby to try listening. WALKMAN was therefore advertised gradually by word of mouth. The first lot of 30,000 units was sold out during the next month. Market volume grew rapidly from that time. The sales attained 50 million units during the 10 years after launching, and reached 100 million in 13 years. Finally, WALKMAN has innovated new audio listening around the world.

V. CONCLUSIONS

The authors proposed Meta-Engineering to create breakthrough innovation to alleviate stagnation of the global economy. Meta-Engineering comprises the four key processes of Mining, Exploring, Converging, and
Implementing: the MECI cycle. The authors described the importance of the field, or “Ba” in Japanese, to accelerate the spiral of MECI cycle and create continuous innovation.

The reality of this concept was explained by application to the current innovation: on-demand bus service. Furthermore, it is applied to historical applications such as blue LEDs, and LED lamps, and the WALKMAN. These applications imply the validity of Meta-Engineering.

The authors have concluded that Meta-Engineering is a sufficiently useful model to promote innovation with much more of a breakthrough characteristic.

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