INDUSTRIAL DESIGN METHODS FOR PRODUCT INTEGRATED PEM FUEL CELLS

dr. A. Reinders, prof. dr. ir. F.J.A.M. van Houten¹

1. Introduction
In the next decade, proton exchange membrane fuel cells (PEM FC) will become an energy technology of great importance for mobile applications. PEM fuel cells are not only an environmentally sound alternative to high power internal combustion engines in transportation; thanks to their modular structure they can also silently provide clean electricity to products that are currently powered by batteries. Despite that current technology already makes a broad range of applications possible, the use of PEM FC in mass produced consumer products is still rare. Technical and financial challenges related to fuel cell engineering may explain this in part. We believe, however, that the need for modifications in design to adapt consumer products for use with PEM fuel cells has also slowed down the product innovation process. Further, many product designers are unaware of the benefits of using fuel cells in consumer products. In this paper, we shall discuss how certain industrial design methods can be applied during the product creation process in order to facilitate the integration of fuel cells in consumer products. By virtue of their participation in product development, industrial designers can serve as the connecting link between scientists, manufacturers and consumers, helping to package new technology in a form useful to consumers. Moreover, feedback from end-users and difficulties that appear during the conceptual design of technology based products can help technology developers better focus their ongoing research. As such, industrial designers could play a crucial role in making fuel cell technology fit for consumer applications.

2. Industrial design methods
Industrial design is represented in Figure 1 as a four-leaf clover involving the following four fields: technology, design & styling, human factors and marketing. In Figure 1, Technology refers to product technologies and materials, as well as manufacturing processes. Design & styling refers to the appearance of products and their image in the market. Human factors cover the user context of consumer products and the physical ergonomics. Marketing refers to market value costs and sales. We believe that all four components of product development are equally important to the final success of a product.

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Industrial design methods (IDMs) play an important role in product development processes. IDMs convert market needs into detailed information for products that can be manufactured. They focus on the utility of consumer products. IDMs vary in their approaches to problem-solving. A generally accepted approach is described in detail by Pahl and Beitz [2] (see Figure 2). It consists in 4 phases:

1. Clarification of the task
2. Conceptual design
3. Embodiment design
4. Detail design

In the first three phases, product designers seek to optimize the working principle, i.e. technology, of a product. The last three phases involve optimizing the layout and form of a product. Thus, conceptual and embodiment design form the connecting links between technology, on the one hand, and design and ergonomics, on the other. For the project described in this paper, we used Pahl and Beitz’s model as a blueprint for applying various IDMs to the development of new products with PEM FC.

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2 In technological engineering design, design processes are generally viewed as heuristics [1]. That is to say, we assume that design goals can be defined by carefully describing a problem prior to formulating possible solutions to this problem. Through problem decomposition, the complexity of the problem is reduced. Next, the designer evaluates how solutions to sub-problems can be merged into a solution composition that meets the design goals. The embodiment of the solution is a product.
In the automotive sector, ‘design & styling’ is traditionally viewed as a decisive factor for a car’s success in the market. As a result, developers of fuel cell powered cars have included design & styling early in the development process. Industrial product design, however, has not yet become common practice for product integrated fuel cell systems. This may be because fuel cell systems are a new technology. Thus, when designing products with integrated PEM fuel cells, it may be helpful to pay attention to issues related generally to the implementation of innovative technology in conventional product design processes [3] [4].

3. Integrating innovative technology in products
Theoretically, innovations improve product performance over time [5]. Introducing major innovations such as PEM fuel cells, however, is not easy, owing to the dual effect of innovations. On the one hand, people resist innovations because they render corporate expertise and existing manufacturing structures obsolete. On the other hand, innovations are essential because of the competitive significance resulting from functional improvements and cost reductions [6].

PEM fuel cells are considered an innovative technology on the threshold between what Little [7] refers to as “packing” and “key” technologies 3. Potential applications are being assessed through research and development, and they are still in the process of being integrated into products. Figure 3 shows how technological research and product design may both contribute to innovations at this stage in the development of PEM FC. On the one hand, the development of promising technologies may initiate product design. On the other, problems with the design of products based on existing technology may stimulate further technological research.

Figure 3. Innovative products result from the conjunction of technology research and product design.

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3 Arthur D. Little distinguishes four types of technologies depending on their level of implementation in product development. Emerging technologies have not yet demonstrated clear product potential. Scientists discover emerging technologies in the course of explaining working principles. Next, packing technologies have demonstrated market potential and are the subject of ongoing R&D to make them fit for applications. Finally, the purpose is to embed the technology in products. Such key technologies may be patented. Technologies that have become common to all competitors – they are a commodity – are called base technologies [7].
Given that technological research has already suggested several marketable applications for PEM fuel cells, it seems to us that an impetus from product designers may be needed to exploit their market potential. Designers need to package existing technology in a way appealing to consumers. Further, they need to assess the weaknesses of products using established technologies, such as batteries, so as to focus future technological research on solving those problems with PEM FC applications.

Design is often regarded as purely aesthetic or superficial. Recent research, however, has highlighted the crucial role played by design in the economy of the Netherlands, and in product innovation [8]. The Premsela Foundation study found that, with a value added of € 2.6 billion, design is on a par with such large sectors in the Dutch economy as the petroleum industry (excluding mineral extraction) and the air transportation industry. Design is both a service purchased by companies in the marketplace and an activity carried out in-house on a large scale by companies, as part of their own production and marketing processes. The Premsela Foundation study concluded that companies combining technological innovation with new product design increase their market share relative to other companies. It therefore seems likely that industrial designers will provide significant added value to products with integrated PEM FC. Our students’ case studies on product integrated PEM fuel cells, presented below, illustrate how this may work.

4. Description of case studies
In the period from September to November of 2005, students in the masters program for Emerging Technology Design of the School of Industrial Design Engineering at University of Twente (the Netherlands) developed conceptual designs for consumer products based on PEM fuel cell technology. Their goal was to use PEM FC in products that would increase personal mobility. We present some of our students’ designs in Section 5 below. Each product design is preceded by a brief discussion of the product’s function and technology.

All students had graduated with a bachelor’s degree in Industrial Design Engineering. Therefore, they had all had some experience in designing a product containing key and base technologies. Seventeen pairs of students successfully completed the project. The students began as laymen and were introduced to fuel cell technology by NedStack Fuel Cell Technology, the Dutch PEM fuel cell manufacturer [9], and by reading literature on the subject [10] [11] [12]. Students were informed about several methods for and approaches towards innovative product design: innovation journey, lead user study, innovation phase model, innovative design & styling, technology roadmapping by TRIZ, platform driven product development, risk diagnosis and constructive technology assessment. In Section 5, we illustrate how each of these methods informed the design of a product by one pair of students.

Students could freely choose a product concept related to either transportation (7 concepts) or portable consumer products (10 concepts). Table 1 lists the products they designed, sorted by type of application. The power of portable devices ranges from 0.7 Watt to 2 Watt. The power of vehicles ranges from 0.6 kW to 200 kW. Based on
assumptions we gave them, the student designers predicted that their fuel cell powered products would be commercially viable in certain niches of the market as early as 2007.

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*) Fuel is either hydrogen (H) or methanol (M).

**) Year in which students have estimated the product would be commercially viable, assuming fuel cell break-even costs of € 45 / kW in 2010.

5. Evaluation of product concepts and IDMs used

In this paper, we present some of the students’ product designs, emphasizing the portable consumer products. Each design illustrates one of the industrial design methods or innovation theories set forth in Section 4.

5.1 Innovation journey

In the case of technology-based product design, product development often follows certain patterns. By examining the so-called innovation journeys [13] of products in different fields, one may gain tools for assessing the potential innovation journeys of new products using PEM FC.

One pair of students used this approach to design an induction cooking device powered by a PEM FC (see Figure 4). They evaluated the evolution of technologies for cooking dinner, starting with plain fire and leading to the principles of electrical cooking. Comparing plain electrical elements, ceramic, halogen, infrared and induction cooking, they found the last method most suitable in relation to customers’ demands for an easy-to-use and light-weight cooking device.

The black box in Figure 4 accommodates all electrical components, including a replaceable hydrogen cartridge, a fuel cell of 500 Watts and an induction coil. The black box fits snugly into the cubical case, which serves as a protective shell during transportation. The device is operated by an ergonomic user interface.
5.2 Lead user study
According to the theory of Von Hippel [6], lead users can provide useful information to product designers. Lead users are those who are the first to face needs that will eventually affect a larger market (see Figure 5). By identifying and interviewing lead users, emerging market needs can be channeled into the development of innovative products.

Sixty percent of the product concepts developed by our students were based on a lead user study. Figure 6 shows a communication device for cyclists powered by PEM FC and developed on the basis of a lead user study. The students identified wireless communication experts and bicycle couriers as lead users. From interviews, they concluded that a device to improve routing for couriers was needed. The product also
incorporates WIMAX communication technology to keep couriers in touch with the office that directs the delivery of packages.

Figure 6. Communication device for bike messengers with integrated PEM FC. In this figure, the device is mounted on a bicycle’s handlebars. Designed by Renske Schijvens and Josselin Bode.

5.3 Innovation phase model
The innovation phase model [14] aims to combine the intrinsic value of technology optimally with opportunities in the market. Divergence, selection and convergence of search fields related to technology and markets lead to innovative technology-product-market combinations. The creative process is supported by visual collages and written mind maps. Figure 7 shows a communication device that has been developed by using a mind map. Mind maps of a fuel cell (Figure 8) and of lead user hikers (Figure 9) are combined to determine a suitable technology-product-market combination.

Figure 7. Communication device for hikers with integrated PEM FC. Right, front view. Left, opened back view. Designed by Kyra Adolfsen and Benne Draijer.
Figure 8. Mindmap of a PEM fuel cell. Selected search fields in green.

Figure 9. Mindmap of lead user hikers. Selected search fields in green.
5.4 Innovative design & styling
Design & styling is an asset for technological innovation [15]. More specifically, cars, modern durables, and consumer products require a high degree of integration between functional and aesthetic aspects of design [16]. A market of products with integrated PEM FC can be promoted by studying the image that potential users of a proposed product wish to project and designing the product so that it meets those aesthetic requirements. Figure 10 shows a design for a diving lamp with integrated direct methanol FC. Technology is decisive in the high-end diving market, where users require long burning-hours and reliability. In the larger market of so-called family divers, however, design and styling (see Figure 11) are more important. The ergonomics of diving with the lamp, as well as of re-filling it with methanol and air, were also important considerations in designing this product.

Figure 10. Diving lamp powered by direct methanol fuel cells. Designed by Julia Garde and Annelies Brummelman.

Figure 11. Design and styling of a diving lamp by diverging, categorizing and converging in two phases. Drawing by Julia Garde and Annelies Brummelman.
5.5 Technology roadmapping by TRIZ

A technology roadmap establishes a correlation between identified market needs and trends with existing and emerging technologies for a specific industry sector [17]. Technology roadmaps usually cover 3 to 10 years and are used in strategic product planning, research planning and business planning [18]. Figure 12 shows an example of a TRM for intelligent clothing powered by direct methanol FC.

![Technology Roadmap Diagram]

Figure 12. Technology roadmap of intelligent clothing powered by fuel cell technology, by Casper Tromp and Olle Vos.

When defining a TRM, TRIZ can be applied to estimate the probability of technology developments. TRIZ is a Russian acronym meaning Theory of Inventive Problem Solving [19]. It is a comprehensive method based on long term patent research leading to certain basic rules governing problem solving in product development. As the method is complex, software has been developed to make it easier to use. Figure 13 shows in which fields TRIZ could improve product development.
5.6 Platform driven product development

A product platform defines a set of related products, a so-called product family, that can be developed and produced in a time- and cost-efficient manner. Features of a product platform are modularity, connecting interfaces and common standards [20]. By using a product platform, companies can reach different markets (and customers) with less effort than by developing separate products. In the case of PEM FC, product platforms will help manufacturers more easily to access this relatively new technology and to implement PEM FC in existing product development processes. Platform thinking is applied to the conceptual design of PEM FC powered electrical gardening equipment, such as blowers, hedgers and brush cutters. The main advantages of hydrogen technology for the functions of gardening equipment are instant power supply with high
energy density, low noise production and a new product experience. Figure 14 shows the basic backpack, which provides power to gardening equipment.

Figure 15 shows the effect of platform driven product development in a matrix of customer value perception vs. enabling technology. For a manufacturer of gardening equipment, an FC powered blower would be a breakthrough product, enhancing its portfolio of conventionally powered equipment. Thus, the risk of integrating the new PEM FC technology in products can be distributed over ongoing product development activities.

Figure 15. Product platform for gardening equipment, B1) Blower on hydrogen energy, B2) Blower with noise reduction system, B3) Blower standard, C1) Cutter with flexible drive shaft, C2) Cutter standard, S1) Chainsaw with automatic balancing system, S2) Chainsaw standard.

5.7 Risk diagnosis
Companies must take risks to launch new products speedily and successfully. In this scope Risk Diagnosing Methodology (RDM) aims to identify and evaluate technological, organizational and business risk in product innovation [21]. This methodology has been developed and applied at Philips and Unilever, and is fit for product development in diverse areas such as automobile industry, printing equipment, landing gear systems and fast-moving consumer goods such as shampoo and margarine. The risks evaluated by RDM are related to product family and brand positioning, technology, manufacturing, intellectual property, supply chain and sourcing, consumer acceptance, project management, public acceptance, screening & appraisal, trade customers, competitors and commercial viability.

One pair of students applied RDM to another product platform of PEM FC powered gardening equipment, and drew the following conclusions:

- The main risk is acceptance of the new, unknown, fuel cell technology by users
• Most risks related to the production, manufacturing and distribution of the new product can be mitigated or eliminated by forming a joint venture with several stakeholders
• A design process that involves the participation of end-users can be used to create a higher degree of acceptance for new products

5.8 Constructive technology assessment
In innovation journeys many actors play a role. New products must be promoted by manufacturers and retailers, must be approved by a competent authority in accordance with industry rules and standards, and must meet with acceptance from consumers. Constructive technology assessment focuses on these processes and how to improve them [22]. The dynamics of technological development involve a series of exchanges between technology and society. Social projects such as those shown in Figure 16 foster the acceptance of new products by teaching people about the benefits of technology for society.

Figure 16. PEM FC powered rickshaw. Designed by Simon Brandenburg and Werner Helmich.

In Asian metropolises, transportation has always been a difficult problem. Owing to outdated engine technologies, private taxies (referred to locally as rickshaws, tuk-tuks and bajajs, etc.) are a primary source of air pollution and noise. Because they require little power—about 5 kW—rickshaws could be an interesting application for PEM fuel cells. A positive social impact would result from the decrease of harmful emissions and increased comfort due to decreased noise. As a side benefit, PEM fuel cells could supply the rickshaws with electric power, enabling end-users to operate air conditioning, stoves and refrigerators from them. Moreover the rickshaw, as an icon of transportation cherished by many residents, might serve as a catalyst to accelerate social acceptance of fuel cell technology.

6. Conclusion and recommendations
The use of carefully chosen and applied industrial design methods in our project led, we believe, to fresh and unexpected product concepts. The results of this experiment have persuaded us that industrial design methods could help manufacturers to integrate PEM
FC into some their products, and begin to exploit a market with great potential for growth. Further, we believe the innovation process could be facilitated if PEM FC were integrated into products that offer a functionality and appearance that consumers perceive as novel.

In the interest of facilitating the integration of PEM FC technology into new products industry wide, we recommend the following:

**Education of Industrial Designers.** A better understanding of how PEM fuel cells are made, and what uses they may be put to, is crucial to winning acceptance of this new technology by manufacturers. Industrial designers, however, should not be burdened with more technical instruction than is necessary for the design process: the students participating in our project had no experience with PEM FC, and yet they proved quite capable of developing product concepts with this relatively new technology. It would be worthwhile, therefore, to focus attention on the development of design tools that provide easily accessible information about PEM FC. One could think about plug-ins for CADCAM models that provide information about the sizing of PEM FC and fuel storage in relation to the energy requirements of a product.

**Improvements in Methodology.** Improvements in methodology may also help speed the market acceptance of PEM FC. This was our first experiment with product design using integrated PEM FC. Our results show clearly that industrial design methods tailored specially to PEM FC could have a significant beneficial impact on the market acceptance of this technology; but these methods can be improved. In light of our experience with the first group of master students, we intend to focus specifically on improving our application of TRIZ, platform driven product development and risk diagnosis to product integrated PEM FC.

**Taking Full Advantage of the Computer.** In this project, students recorded the results of their creative processes during product development with pen and paper. This procedure is relatively slow and does not offer much flexibility. Since the end of 2005, a new product development laboratory has been available at the University of Twente. This facility is outfitted with advanced programs for computer supported brainstorming and interactive visualization of product concepts. For our next project, we intend to meet with students in this new laboratory, and include virtual prototyping, scenario-based design and gaming [23] [24] as part of the curriculum.

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Biographies

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