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# Path generation in a path dependent industry: the influence from the established technology

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As a result, three types of influence from path dependency on the process of path generation are revealed: the dominant technology can impose barriers (negative influence), shape (neutral influence) and enable (positive influence) development of new technologies. Thus, the paper shows that previously prevailing understanding of this influence as solely negative was incomplete, and contributes to a better understanding of endogenous change sources in path dependent industries.

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This paper studies the process of development of new technologies in established multi-technology industries. More specifically, with the help of the concepts of path dependency and path generation, the paper addresses how the process of formation and early development of new technologies is influenced by previously established path dependent dynamics. Empirically, the paper is based on a case study of the lighting industry where two new technological paths (compact fluorescent lamps and light-emitting diodes) were developed under conditions of dominance of the incandescent technology.

As a result, three types of influence from path dependency on the process of path generation are revealed: the dominant technology can impose barriers (negative influence), shape (neutral influence) and enable (positive influence) development of new technologies. Thus, the paper shows that previously prevailing understanding of this influence as solely negative was incomplete, and contributes to a better understanding of endogenous change sources in path dependent industries.

## 1. Introduction

When development dynamics in mature, established industries are addressed in technology management research, the concept of path dependency is frequently used. Since the classical works by David (1985) and Arthur (1988), path dependency has been helpful in understanding such crucial aspects of technological development as the reasons of persistence and stability, the dynamics of self-reinforcing mechanisms, the reasons and sources of lock-in and the role of exogenous shocks in overcoming the negative impacts of the above processes.

With regard to technological change, the classical path dependency theory has for a long time considered self-reinforcing mechanisms to be the central driving force of economic development (Cowan and Gunby, 1996) and exogenous chocks – as the only source of change (Sydow et al., 2009). As a consequence, the role of actors remained unclear and a possibility of endogenous change was not addressed.

Such view also implied that path dependent industries were not positioned as innovative. However, the empirical evidence proves the opposite. An especially interesting example here is the case of multi-technology industries where several technological alternatives can co-exist and interact. Innovation dynamics in multi-technology industries prove that endogenous change sources can exist under conditions of path dependency and therefore require further conceptual elaboration and empirical investigation.

Among theoretical concepts that can help to analyze the dynamics of innovation in path dependent industries, the path generation framework has been chosen because it provides a comprehensive view on endogenous change sources and thus overcomes the drawbacks of "solely exogenous change" view, which is characteristic to pure path dependency. Introduced by Meyer and Schubert (2007), path generation describes the early stage of path development as influenced by both emerging events (driven by self-reinforcing mechanisms) and actors' strategies.

In the context of path dependent multi-technology industries, the process of path generation implies that a new technology is added to a number of previously existing alternatives, driven by path dependent dynamics. Therefore, understanding of endogenous change sources in such situation comes to the question of how path dependency influences the process of path generation. Answering this question by means of an empirical study of path generation in the path dependent multi-technology lighting industry has become the purpose of this study. In particular, we study how the process of path generation is affected by the old paths: while the previous research on technological paths focused mostly on barriers for new path generation (Simmie, 2012), we investigate whether other, non-negative types of influence can also be found.

The outline of the paper is the following: In Section 2, we will present the theoretical debate in the field of path dependency and path generation in order to frame the question in focus. Section 3 will present the methodological approach of the paper. Section 4 will illustrate the process of generation of new paths in the lighting industry where two new technological paths emerged during the past several decades (fluorescent lighting and light-emitting-diodes) under the conditions of dominance of the incandescent technology. In Section 5, we will analyze the empirical findings and summarize different types of influence from the established to the new technological paths. Finally, we will conclude with Section 6.

# 2. Development of a new path in path dependent context: theoretical framework

## 2.1. Exogenous vs. endogenous change sources in path dependent industries

Path dependency is one of the central theoretical concepts used to describe historically bounded technological development. For that reason, it is usually referred to when discussing development dynamics in established companies or mature industries (e.g., Cowan and Gunby, 1996; Mazzoleni, 1997; Essletzbichler and Winther, 1999).

The central features of the path dependency concept have been formulated already in classical works by Paul David and Brian Arthur. David (1985) explained and exemplified with the case of QWERTY keyboard that seemingly small historical events can have long-term consequences and that positive feedback mechanisms can eventually lead to a lock-in to a non-optimal solution. Later, Arthur (1988) contributed with the analysis of four main types of increasing returns to adoption (initial costs, learning effects, coordination effects, and self-reinforcing expectations) which were taken up by later research under the name of self-reinforcing mechanisms (see e.g., Sydow et al., 2009; Dobusch and Schüssler, 2012).

Self-reinforcing mechanisms have become the central theoretical construct in the path dependency literature (Dobusch and Schüssler, 2012). They constrain the development to one dominant solution and prevent companies from switching to other alternatives. As a result of self-reinforcing mechanisms, escape from the established path is believed to be possible only though an exogenous shock (Sydow et al., 2009) as the potential for an endogenously driven change is very low (Vergne and Durand, 2010).

Even in this strong form, path dependency concept is not completely deterministic; it does not suggest an inevitable outcome, but rather conditions the development in a certain direction and provides historical links to the decisions made (Martin and Sunley, 2006; Henning et al., 2013). Nevertheless, it is mostly used to analyze development patterns that are difficult to reverse (Schubert et al., 2013) and to explain why sometimes the changes do not happen even if they are desired (Storz, 2008). Since the development process is considered to emerge under the influence of its own history, actors, as a part of the path dependent system, are not able to deviate from pre-conditioned scenarios.

Thus, path dependency concept underestimates the role of actors and does not take into account the possibility of the endogenously driven change. Because of this, the concept has been criticized, and an alternative concept of path creation has been introduced (Garud et al., 2010). Path creation suggests that actors are crucial players in shaping the history of technological development as they are able to “mindfully deviate” from established norms and routines (Karnøe and Garud, 2000). Therefore, instead of focusing on lock-in to inferior technologies, this concept addresses the question of how interactions of actors have led to this state (Stack and Gartland, 2003).

The notion of agency is, thus, the central theoretical construct of the path creation concept, in contrast to self-reinforcing mechanisms in the path dependency concept. As the actors are able to shape their environment (Stack and Gartland, 2003), the initial conditions are not given, self-reinforcing mechanisms can be strategically influenced by actors and lock-in is a temporary, stabilized state in the development rather than the end point (Garud et al., 2010). Thus, path creation gives actors the responsibility for real-time choices. Consequently, while in path dependency research any significant change to the established path may only come in the form of an external intervention, path creation concept admits the possibility of novelty and change to be endogenously driven (Tiberius, 2011).

By stressing the role of actors, the concept of path creation highlights that an external shock is not the only way to introduce change into a path dependent environment and, thus, makes the first step in initiating a discussion about endogenous sources of change. However, in its initial conceptualization, path creation was positioned almost as opposite to path dependency. Moreover, the founders of path creation argued that viewing path dependency and path creation as complements would imply mixing ontologies and a problematic attempt to see change and continuity as driven by similar dynamics (Garud et al., 2010).

Such positioning of path creation has its downsides. If all the responsibility for change and innovation is attributed only to actors, other endogenously driven dynamics become neglected. However, a complete and balanced picture of endogenously driven change sources needs to include both emerging opportunities (the ones resulting from self-reinforcing mechanisms) and the ones actively cultivated by actors (and, thus, contradicting with the logic of self-reinforcing mechanisms). Therefore, the view of pure path creation on technological change is as unbalanced as the view of pure path dependency. To provide a comprehensive framework for understanding change process in historically bounded settings and account for a variety of change sources, some fusion between the concepts of path creation and path dependency is needed.

### 2.2. Path generation as a fusion between the logics of path dependency and path creation

An analysis of the literature about path dependency and path creation for the past decade confirmed that a closing in between the two concepts is possible. In various research streams, one can find arguments in favor of a possibility of co-existence, complementarity and eventually fusion between them[1].

In institutional studies, the logic of path creation, although different from path dependency, is considered as still complementary to the processes of stabilization and reinforcement (Djelic and Quack, 2007). In line with Garud and Karnoe (2000), this research stream highlights the role of agency, but in addition to that, acknowledges an element of emergence (self-reinforcement) in the form of unanticipated consequences of actors' behaviors. A similar approach can be found in research about socio-technical paths where emerging structures (path dependency aspect) and agency (path creation aspect) are integrated, and paths are positioned as being developed in real time (rather than observed post factum), which opens a possibility to steer path dynamics towards a desirable outcome (Robinson and Propp, 2008).

[1] Both path dependency and path creation concepts have been developed and applied in several streams of literature: economics, technological development, institutional dynamics, regional development, national innovation systems etc. From the point of view of this article, technological path dependency and technological path creation are the most relevant. However, due to numerous cross-citations between different streams of literature as well as availability of commonly accepted classical works (e.g., by David, Arthur and Garud and Karnoe) the overall trends seem quite similar. Therefore, references to different research streams are included into the below analysis.

In the field of economic geography, Martin and Sunley (2006) argue that path dependency needs to recognize endogenously enabled change and incorporate mechanisms that create novelty. Therefore, they suggest the "path as a process" approach which implies an "ongoing interplay" between path dependency, path creation and path destruction as a result of both reproduction and transformation of existing structures and practices by actors. Consequently, path creation characteristics become inherent to path dependency and the two processes can be viewed as co-existing. Having presented this perspective, the researchers go as far as to question the need to distinguish between on-path and off-path change as both are essential parts of the same process.

The above conceptualizations are united by the idea of balance, interplay between path dependency and path creation and the need to account for, on the one hand, the ability of actors to plan and shape their paths, and, on the other hand, chance events and restrictions imposed by path history (Tiberius, 2011).

In the field of technological paths, like in other literature streams, the actor model has been incorporated into the path dependency theory. Similar to "path as a process" approach by Martin and Sunley (2006), Meyer and Schubert (2007) described the process of path development as a continuum, from emergence (path dependency) to deliberate action (path creation), which implies that endogenous change is possible in a path dependent setting, while the role of self-reinforcing forces is not neglected either.

Continuing with the same logic, Meyer and Schubert (2007) introduced the notion of path generation to describe the process of appearance and early development of a new path. Path generation is represented as a continuum between path emergence (when it is mostly driven by self-reinforcing mechanisms) and path creation (when it is mostly strategically manipulated by actors). In contrast to path creation, discussion of path generation is less "loaded" with the role of agency; it describes the early stage of path development as influenced by both path internal and path external dynamics.

Thus, with regard to viewing the sources of change, path generation is a fusion between the logics of path dependency and path generation. Therefore, it is an appropriate concept to denote the process of formation and early development of a new path. With respect to the purpose of this study, it is not needed and even not considered as possible to decide in advance to what extent self-reinforcing mechanisms vs. agency contribute to development of new technologies. What is important, however, is that a variety of sources is taken into account. Another specific characteristic of this study is that a multi-technology industry is considered. The concept of path generation is well suited for this type of setting which was demonstrated by its application in the empirical study of the multi-path lithographic industry where a new path appeared while the old one continued to exist (Sydow et al., 2012). Although the dynamics of development of both studied paths were found to be driven mostly by actors' strategies, Sydow et al (2012) acknowledged the need to consider cases of more emergent technological paths in the future research.

### 2.3. Influence from path dependency on path generation

Co-existence and complementarity between the logics of path creation and path dependency imply that new paths can be developed while the older ones continue to exist. From empirical perspective, a clear example of such situation is multi-technology industries where new technologies can be developed and added into an existing technology field without destroying previously established alternatives. In such settings, previously established path dependent dynamics serve as a context in which new technologies appear. Therefore, understanding of how established technologies influence this process provides insights into what endogenously drives change and innovation in established industries. Having found a concept that in a balanced way accounts for endogenous change sources – path generation – we have now all conceptual tools to address this question. In path dependency-path generation terminology, it can be formulated as following: how does path dependency affect the process of path generation?

#### *2.3.1. Technology paths: negative influence from path dependency on path generation*

In technology paths literature, the issue of interrelationship (and not mere co-existence) between already established and newly generated paths was first explicitly addressed in a recent study by Simmie (2012), which investigated how new technological and industrial paths can be created in conditions of path dependency. Conceptually, the paper builds on the idea by Garud et al (2010) about the possibility of endogenous change and the ability of actors to deviate from the established paths. However, like the researchers in the field of economic geography (e.g., Martin and Sunley, 2006), they chose to view path dependency and path creation as continual inter-linked processes.

Simmie (2012) addressed the process of creation and establishment of the Danish wind turbine pathway under the conditions of dominance of fossil fuel-based technologies. Rather than showing both positive and negative types of influence from the established path to the new one, the study focused mostly on barriers that an established path dependent system provides, and on how a new path can be created in spite of them. It should be noted though, that the initial conditions were considered to be set by previous, path dependent dynamics. However, the *process* of path generation, in order to overcome the barriers of the established system, had to develop in niche until reaching the critical mass. Similar to, e.g. Dijk and Yarime (2010), Simmie (2012) associated path dependency with the regime and path creation – with the niche. In such setting, a possibility of endogenously driven change (establishment of a new pathway) was not supported by previous path dynamics, but framed solely as an achievement of knowledgeable agents.

Thus, in the research on technological paths only negative influence from path dependency to path generation has been considered so far. The incompleteness of this "barriers-only" view becomes evident if we consider a broader research stream on path dependency. Although the character of path dynamics cannot be exactly the same in technological and other types of paths, research on national, institutional and regional paths has a stronger tradition of considering multiple co-existing paths and therefore provides a more versatile view on possible interrelations between paths. Therefore, we will use the broader set of literature as a source of general patterns of influence from the established to the newly generated paths, which we will then verify in the empirical study of technological path generation.

#### *2.3.2. Lessons learned from broader literature: non-negative influence from the established to the newly generated paths*

Apart from barriers to new path generation, the literature on regional, national and institutional paths discussed also two additional types of influence from the old to the newly generated paths: first, the old path can be influential in defining some of the characteristics of the new path, and second, the characteristics of the old path may provide opportunities for generating a new path.

Research on national and regional innovation systems suggests that new paths may inherit some of the features of previously established pathways. For example, Schienstock (2007) suggested that on the national scale path creation happens at least partially in connection to the old path rather than in the form of a sudden break with the former practices. Further, recent research in regional economics suggested that path dependency, rather than preventing change, creates limits as well as possibilities for it. Therefore, new regional paths can be built upon previously existing ones. Moreover, even paths initiated as a result of an external shock were still considered to be technologically similar to the ones that were previously present in the region (so called related diversification) (Henning et al., 2013).

As illustrated in the two above examples, the endogenous character of path generation implies that the old path can *define some of the characteristics of the new path* which results into similarities between them.

In institutional studies, the possibility of endogenous change and path creation was integrated into the path dependency concept through the legacies of "paths not taken" (defeated by the dominant path) which remained in the form of resources (structural elements) inside the dominant path and had a potential to be developed later into alternative paths that would exist together with the dominant one (Schneiberg, 2007). Further, combinations, enlargements and transfers of the existing institutional configurations can also serve as sources for change in the system (Storz, 2008). Therefore, the characteristics of the old paths are believed to contain *potential for generating new paths*.

In sum, a broad set of literature on the dynamics of path dependency and path generation suggests that the old path can have a neutral and even positive influence on the process of new path generation. Therefore, in the remainder of this paper we will consider different types of influence from the established to the newly generated technological paths in the empirical case of the lighting industry. We thus aim to explain the process of technological path generation under the conditions of path dependency where both emerging self-reinforcing forces and strategic behaviors of actors are in place. More particularly, we address the question of whether, apart from negative influence from the old to the newly established technological paths, also neutral and positive types of influence can be found.

## 3. Research design

The empirical part of the study addresses the development of lighting technologies. Lighting industry is a path dependent industry characterized by co-existence of several technological paths which are represented by different lighting technologies. Both persistence patterns and self-reinforcing mechanisms have been traced at the level of these separate technologies as well as at the level of the lighting industry as a whole. In this paper, we focus our discussion on the development dynamics of three technological paths: those represented by the incandescent technology, the compact fluorescent lamps (CFL) and the light-emitting diodes (LED). Based on our previous findings, we conceptualize the incandescent technology as the oldest and dominant technological path, while the former two as cases of new path generation in the path dependent industry.

It should be noted that there are more than three lighting technologies in the lighting industry. Moreover, one of the chosen technologies (CFL) represents a technological improvement of another technological lighting path: linear fluorescent lamps. The choice of these three particular technologies is motivated by an intention to limit the scope of the study to one lighting sector – home lighting. Incandescent lamps, CFLs and LEDs represent the main technologies used in the home lighting sector which enhances comparisons between them along non-technological criteria (e.g., customer acceptance or dynamics of market shares).

Since two of three chosen technologies have existed for at least several decades, there is a large amount of secondary data that describes various aspects of their development, for example, materials in specialized industry journals, reports or dedicated technology studies. LED, on the other hand, is a relatively recent technology and therefore has received a lot of media attention in recent years. For that reason, media articles have become an additional source of data for the LED technology.

In total, secondary data sources used in this study can be divided into four groups:

1. Articles published in specialized industry journals: Lighting Research and Technology Journal for the period 1969-2012, Journal of Light and Visual Environment for the period 1977-2012, LEDs Magazine for the period 2005-2013;
2. Lighting industry, market and technology reports, for example, *Lighting the way: Perspectives on the global lighting market* by McKinsey & Company (McKinsey&Company, 2011), *Lighting & Bulb Manufacturing in the US* by IBISWorld (IBISWorld, 2012), *Light's Labour's Lost. Policies for Energy-Efficient Lighting* by IEA (IEA, 2006);
3. Dedicated lighting technology studies, for example, Menanteau and Lefebvre (2000), Bladh (2011);
4. Media sources, such as web-based news articles, reviews and discussions.

# 4. Lighting industry: established and new technological paths

The lighting industry has for over a century been dominated by the incandescent lamps. This dominance is especially visible in the home lighting sector which we focus on in this paper. However, during the past 40 years two new technological paths were generated in this segment and eventually added as alternatives to the incandescent lighting: compact fluorescent lamps (CFL) and light-emitting diodes (LED). Although CFL and LED together have reached 35% market share in this sector, incandescent lamps, including halogen, still maintain over 50% market share in terms of value (McKinsey&Company, 2011)[2].

## 4.1. The dominant technology: incandescent lighting

The principle of incandescent lighting was invented by Edison in 1879. The key characteristics of incandescent lamps were in place by the mid-1930s: glass composition, gas filling, and a coiled tungsten filament. After that, the development focused on solving more specific issues (such as managing lamp behavior under high voltages), followed by even smaller improvements including advancements in production processes as well as improvements for more narrow applications (Burgin, 1984). In general, it can be said that the core of the technology did not change a lot since the 1920s (Waide, 2007). The most recent addition to the family of

[2]Additionally, linear fluorescent lamps have 11% market share in this sector (McKinsey&Company, 2011).

incandescent lamps are halogen lamps which were developed in the 1950s and commercialized in the 1980s (IEA, 2006).

Incandescent lighting has a number of advantages which over time became crucial in assuring the dominance of this technology in the residential sector: incandescent lamps are cheap, easy to dim, have very high colour rendering and give a comfortable warm light (IEA, 2006). However, incandescent lamps are poorly performing with regards to two criteria which define economic performance of the lighting system: working life and energy efficiency. Working life of the first incandescent lamps grew from 40 to 800 hours before the beginning of the 20th century and soon achieved its ceiling of 1,000 hours (Menanteau and Lefebvre, 2000). The only lamps based on the incandescent technology to surpass this level were halogen with the working life of 2000-6000 hours (IEA, 2006). Similarly, energy efficiency grew from initial 1.4 lm/W to 15 lm/W already by 1936 and did not considerably change since then (Menanteau and Lefebvre, 2000), with the exception of halogen lamps that have efficiency of 18-33 lm/W.

In spite of such a weak economic performance, incandescent lamps for a long time have remained the dominant lighting technology, especially in the consumer segment. In general lighting, the volume-based share of incandescent lamps (including halogen lamps) is 64% and value-based share is 22%, while their value-based share in consumer segment is 53% (McKinsey&Company, 2011).

### 4.2. Path generation Case I: CFL

After the energy crisis of 1973, the leading manufacturers in the lighting industry expected an increase of electricity prices as well as a raise of the environmental consciousness of consumers. At the same time they saw an opportunity to sustain their technological leadership and improve profit margins with the help of new technologies. Therefore, they intensified their R&D programs in order to develop an energy efficient substitution for incandescent lamps (Menanteau and Lefebvre, 2000).

The resulting CFL lamps are technologically based on previously existing linear fluorescent lamps (LFL), but have a smaller size in order to fit into existing fixtures. Compared to the incandescent lamps, they have a considerably longer working life (5,000 – 25,000 hours) and higher energy efficiency (currently about 60 lm/W) (IEA, 2006; HSBC Trinkaus&Burkhardt, 2011). However, the initial cost of CFL lamps was at the time of introduction 20-30 times higher than that of incandescent lamps. It should be noted though, that the overall lifecycle cost of the CFL lamps (which takes into account both purchasing price, energy efficiency and working life) has always been below the level of incandescent lamps (IEA, 2006).

Apart from high purchasing price, early CFL lamps had a number of performance issues which slowed down the diffusion of this technology in the residential sector: they had delayed starts and long warm-up times, suffered from flickering, gave too much direct glare, had limited color rendering, were big and bulky and could not be dimmed (IEA, 2006; OECD/IEA, 2010). These disadvantages were accompanied by a number of market, institutional and demand-side barriers. As a result, market share of the new technology did not exceed 1% during first five years after introduction (Weiss et al., 2008).

Most of technological problems were eventually solved. In the mid-1980s, magnetic ballasts were substituted by electronic ones which made CFL lamps smaller, lighter and more efficient

(Weiss et al., 2008). Further, in the late 1990s, a new generation of smaller, brighter and less expensive CFL lamps was developed (Roisin et al., 2007). Eventually, all the incremental improvements in price, lamps range, colour quality, compatibility with a variety of existing fixtures made CFL lamps an attractive alternative to incandescent lamps. However, the further diffusion of this technology depended also on strong governmental support and intense policy programs introduced in different countries (e.g. educational and awareness campaigns, subsidies, give-away programs) (OECD/IEA, 2010).

Currently, CFL lamps still have a number of disadvantages compared to incandescent bulbs: they are still bigger and more expensive, have a lower colour rendering and decline considerably in working time when turned on and off frequently (Waide, 2007; HSBC Trinkaus&Burkhardt, 2011). Nevertheless, market statistics show that this technology has been established in general lighting as well as in residential sector: in both sectors, value-based market share of CFL lamps is about 30% (McKinsey&Company, 2011).

### 4.3. Path generation Case II: LED

LED is a semiconductor-based lighting technology in which light of a certain colour (or wavelength) is emitted by solid crystals that consist of several different inorganic elements. Thus, the principles of light generation in LED are fundamentally different from those of incandescent lamps and CFLs, and LEDs are still technologically closer to the semiconductor industry than to the other lighting technologies.

LEDs were first applied commercially in 1960s, but due to a very limited brightness were not considered as an option for general lighting until recently. LEDs were first used as indicator lamps, then penetrated the segment of traffic signals and exit signs and, more recently, vehicle lighting as well as architectural and entertainment lighting. Later advances in the development of the white LED made clear the potential of this technology in general lighting (IEA, 2006; HSBC Trinkaus&Burkhardt, 2011).

LED lamps have a number of advantages in comparison to previously existing light sources. Among them, the most crucial are considerably longer service life (25,000 – 50,000 hours) and higher energy efficiency (on average 160 lm/W for cool-white sources, and below 110 lm/W for warm-white light-sources, although recent product introductions by Philips showed that the level of 200 lm/W is attainable) (HSBC Trinkaus&Burkhardt, 2011; BBC, 2013). In addition to that, LEDs can be available in much smaller sizes, light up without delays, produce considerably less heat and perform well in cold temperatures. However, LEDs continue to be very expensive: they are about 35 times more expensive than incandescent bulbs and 5 times more expensive than CFLs (HSBC Trinkaus&Burkhardt, 2011).

Due to the high purchasing price of LEDs, they have still not completely become established in the general lighting market and especially not in the residential sector. Their market share is currently 1% with regards to volume and 14% with regards to value in the general lighting and 6% with regards to value in residential sector (McKinsey&Company, 2011). However, assessments of the position of the LED technology should take into account a very high pace of technological development in this field as well as huge institutional support (the most well-known example of institutional intervention is the effective ban of incandescent lamps that has already taken place in many countries). Considering these factors, the prospects of purchasing costs and market share of LEDs are very promising: the prices are expected to be 10 times lower by 2020 than they were in 2010, and the market share is expected to exceed 70% (value-based) in both general lighting and residential sector (McKinsey&Company, 2011).

# 5. Analysis

In this section we will trace how the established incandescent technology affected the development of two new paths (CFL and LED) in the lighting industry. We distinguish between three types of influence from the established technological path on the process of new path generation. Following our theoretical framework, we will first discuss the barriers to path generation which represent the negative influence from the dominant technology. After that, we will present and discuss the evidence of the two other types of influence: the role of the established path in shaping (neutral influence) and enabling (positive influence) the new technologies. As the two former types of influence were not explicitly pronounced in the technology literature, we will also assess how our findings are related to the existing path dependency research.

## 5.1. Negative influence: barriers to path generation imposed by the dominant path

The established path dependent lighting industry imposed a number of barriers to the development of the new paths. It should be noted that not all the barriers were caused by the incandescent technology. For example, both CFL and LED lamps at the time of market introduction had relatively poor performance, which slowed down their market penetration. However, in this study we will focus on those barriers that can be related to the characteristics of the dominant incandescent technology. Four such barriers can be distinguished: customer acceptance issues due to performance differences between the old and the new technologies; barriers related to testing and measurement of lamps; complementary resources; and other investments.

First, *performance characteristics* of CFL and LED lamps differed from the incandescent lamp. In the consumer-oriented residential lighting market, such differences led to considerable *acceptance problems*, in spite of economic arguments in favor of the new technologies. The biggest issue in both cases was the cost of the new lamps: high initial purchasing price was the largest barrier for purchasing CFL lamps (LRC, 2003)and the same issue now hinders the diffusion of LEDs in many general lighting applications (McKinsey&Company, 2011).

In addition to the difference in the initial purchasing price, the new technologies differed from incandescent lamps in a number of performance characteristics, which in the consumers' eyes constituted the quality of light and therefore an important basis for market acceptance of new technologies irrespective of their improvements in energy efficiency or lifetimes (LR&TJ, 1998). When CFLs were introduced, customers were dissatisfied with their physical shape, color of the light, flicker, and impossibility to start and warm-up instantly (LRC, 2003) – in other words, all those characteristics that are present in incandescent lamps and that made it the most purchased lamp in the world (IEA, 2006). Likewise, when LEDs were first introduced, they were frequently criticized for worse color characteristics than that of incandescent lamps. (Bladh, 2011).

Second, most of the *measurement standards and light testing procedures* were developed with the incandescent technology in mind (IEA, 2006; OECD/IEA, 2010) and therefore were not equally suitable for the new technologies. For example, established tests do not take into account that performance of CFL lamps is dependent on the length of operating periods and the frequency of on-off switching (IEA, 2006). Therefore, the absence of internationally accepted testing procedures became a barrier for distribution of CFL lamps (OECD/IEA, 2010). As for LED lamps, due to a considerably longer working life they require a complete redesign of lifetime testing procedures (Philips, 2012).

Another example is the use of the Color Rendering Index (CRI) as a measure of the ability of the light source to reflect colors. The incompatibility of this measure with all light sources except from incandescent lamps was recognized long ago (Cannon-Brookes, 1998; IEA, 2006), but it is still widely used in the assessment of lamp quality. As a consequence, non-incandescent lamps risk to show poor test results due to historically rooted characteristics of tests and measurements rather than to performance characteristics.

Third, the development of incandescent lamps has been accompanied by appearance of *complementary resources* such as fixtures and luminaires which, unlike the incandescent bulbs themselves, require higher investments and are not frequently replaced. In the residential sector, the fittings are usually installed by house builders, and the users are limited to the lamps that are compatible with them (IEA, 2006). For that reason, CFL lamps had to undergo a long way of gradual improvements until they became compatible with the existing fixtures (IEA, 2006). Similarly, LED spotlights are often too long or wide to fit into existing fixtures (Hedekvist, 2011).

Finally, investments in advanced manufacturing equipment, large-scale plants and recycling infrastructure serve as a barrier for the development of new technologies. Development of new technologies, on the one hand, requires significant spendings for construction of new facilities and, on the other hand, can lead to closing down of old plants, thus, making previously made investments obsolete (Gould and Cheng, 2011). This makes new technologies less attractive in the eyes of producers.

Barriers to the new path generation can be fully explained by the dynamics of path dependency in its classical form (e.g., David, 1985; Arthur, 1988). Self-reinforcing mechanisms associated with the established technology create forces to continue search and development along the same trajectory and consequently impede development of the new ones.

Additionally, barriers to new path generation were also explicitly covered in those parts of technology path literature that argued for the fusion between the logics of path dependency and path generation. For example, Simmie’s (2012) analysis of the process of creation of wind power path in Denmark  also presented the barriers to the new path. However, the scale of the barriers was much larger compared to those that were found in the lighting industry. Simmie (2012) explained the process of emergence of a new industry which is why the discussed barriers were at the level of technological paradigms, institutions and technological regimes. In the lighting industry, on the contrary, new technological paths emerged within the same industry which made it possible to discuss barriers at the level of self-reinforcing mechanisms: established routines, norms, standards, and investment in this particular industry.

### 5.2. Neutral influence: the role of the old path in shaping the new paths

Due to the very strong acceptance of the characteristics of incandescent lamps among consumers, all attempts to replace them involved also efforts to replicate them (de Boer, 1982).

Therefore, the established technology also played a role in shaping the characteristics of CFL and LED lamps.

With the CFLs, manufacturers started to copy various characteristics of incandescent lamps. In terms of appearance and aesthetics, CFL lamps eventually imitated the one-piece design[3], smaller size, and glass envelope of the incandescent lamps (Iwafune, 2000). From the point of view of technological characteristics, CFLs were designed to have the same luminous flux values as the standard incandescents (Heidemann et al., 1993). Further, CFLs also imitated the colour temperatures of the incandescent lamps: although fluorescent lamps can be available in the range of 2,700K to 6,500K, they are produced in the range 2,700K – 3,000K, the same in which incandescent bulbs are available (LRC, 2003). Finally, CFLs over time became dimmable as this characteristic is also available with the incandescent lamps (Weiss et al., 2008).

For the LED, there are even less technology-related explanations to mimic the appearance and characteristics of the incandescent lamps taking into account radical differences in the nature of light produced and design opportunities available. Thus, LED lamps can have miniature sizes and are well suited to be integrated with fixtures and luminaires since with such long service life there is no need to change the bulb. In spite of that, retrofit LED bulbs are being developed and leading manufacturers are competing in producing alternatives to standard incandescent lamps (for example, both Philips and Osram have recently introduced LED retrofits that correspond to 100 W incandescent bulb) (Wright, 2012). Like in the case of CFLs, LED retrofits are produced to increase acceptance of the new technology by copying the characteristics of the established product, even though it means "hiding and disguising" the new technology (Interview, Osram Manager).

In sum, similar to how the literature on institutional and national paths suggested that the newly generated paths were at least partially connected to the old ones (Schienstock, 2007; Henning et al., 2013), the new lighting paths have had to inherit some of the characteristics of the incandescent lamps to be accepted. This phenomenon can be explained with the help of multiple path framework (Bergek and Onufrey, 2013). In multi-path settings, a part of self-reinforcing mechanisms are inherent to the industry as a whole rather than to some particular path (cross-path mechanisms) which implies that they affect all technologies within the industry. Thus, inheritance of various characteristics of incandescent lamps by later technologies can be seen as a cross-path self-reinforcing mechanism initiated by the dominant incandescent technology and retained and reinforced in the process of shaping new technological paths.

A parallel can also be drawn to how Simmie (2012) discussed the impact from the established to the newly created path in the form of initial conditions that were formed as a part of path dependent development process. In the lighting industry case, consumers' preferences set by the characteristics of the incandescent bulbs can also be viewed as initial conditions. However, since the discourse of path dependency research clearly distinguished between initial conditions and self-reinforcing mechanisms, we find it important to stress that in the lighting industry case we saw how self-reinforcing mechanisms (rather than initial conditions) inherent to the established technology played a role in shaping the new paths and eventually could be viewed as cross-path (or affecting both established and new paths) self-reinforcing mechanisms. Therefore, we contribute to the previous literature by showing that not only initial conditions, but also self-

[3] In CFL lamps, ballast can either be integrated into the lamps or designed as a separate part. In home lighting, CFLs with integrated ballasts (one-piece design) are used since they fit into existing fixtures (IEA, 2006)

reinforcing mechanisms inherent to previously existing paths can have a shaping effect on the process of path generation.

### 5.3. Positive influence: the role of the old path in enabling path generation

In spite of the barriers to new technology generation provided by the old technology, some characteristics of the incandescent path were enabling for the appearance of new paths. In the literature review, we showed that the research about institutional and national paths considered a positive influence from the established path on the process of new path generation possible (Schneiberg, 2007; Storz, 2008). However, based on the previous studies it was difficult to specify how this kind of influence can be realized, especially in the context of technological paths. The case of the lighting industry confirms that the established technological path can contribute to enabling path generation. Additionally, our empirical findings suggest two factors that can be significant in this process: persistent importance of certain performance criteria (in particular energy efficiency) and inherent to the industry variety in terms of applications and technologies.

In the following sub-sections, we will take a broader view of the lighting industry and consider not only the dynamics of the incandescent technology itself, but also the properties of the whole industry (of which the incandescent technology was still a core).

#### *5.3.1. Performance criteria: improving energy efficiency*

Performance criteria have traditionally played a crucial role in the lighting industry. Not only existing products are compared along the list of generally recognized criteria, but also the future of the technological development is often defined in terms of desired characteristics of the light sources, rather than particular technological solutions (Ackerman, 1976; de Boer, 1982).

Among the long list of performance criteria, energy efficiency can be considered as the most important because this criteria defines economic benefits as well as environmental impact of the light source. The increase of importance of energy efficiency in the lighting industry if often related to the energy crisis of 1973 and its consequences. Indeed, an increase of electricity prices led to enhanced creativity of the manufacturers (Boyce, 1986) who intensified their search for alternative lighting solutions (Menanteau and Lefebvre, 2000) and eventually contributed with more new products within 10 years after the crisis than during preceding 100 years (Jewell, 1991). At the same time, consumers gradually became more conscious about the environmental impact of the lighting products (Menanteau and Lefebvre, 2000).

Thus, there is indeed a link between the energy crisis and the role of energy efficiency in performance criteria of the lighting sources. From that, one could assume that energy efficiency was brought in by an external intervention (from the landscape) rather than by the endogenous industry dynamics. However, such assumption proves incomplete if industry dynamics before the energy crisis are taken into account. Historical analyses of the lighting industry have shown that search for higher efficiency has traditionally been the main objective of lamp designers (Willoughby, 1974). In that sense, the history of the incandescent technology is a continuous strive to improve energy efficiency (de Boer, 1982), while development of new lighting technologies is a continuation of the same process, but on a broader scale (not within the same technology, but within the lighting industry). Thus, energy efficiency of incandescent lamps was improved from 1.4 lm/W in early 1880s (Menanteau and Lefebvre, 2000) to 15 lm/W in 2012 (Scholand and Dillon, 2012) and even up to 17.4 lm/W if we consider halogen lamps (Navigant

Consulting, 2012). For the CFLs, improvement curve was from 46 lm/W in 1990 (IEA, 2006) up to 60 in 2012 (Navigant Consulting, 2012). Finally, energy efficiency of LEDs was developed from 3-30 lm/W in 2001 (Navigant Consulting, 2012) and achieved 200 lm/W in 2013 (web REF). Thus, the dynamics of development of the incandescent technology initiated ongoing improvements of energy efficiency of the light sources, and this process was further enhanced by the energy crisis.

The importance of performance criteria was previously discussed in path dependency research. For example, Meyer and Schubert (2007, p. 33) noted that "criteria for technological progress are not part of a technology itself, but are a part of technological (cognitive) paradigm which can not only stabilize an existing path, but also render alternative solutions unthinkable". From our perspective, the key point here is the separation of performance criteria from the technology. If this separation is acknowledged, one might search for an optimal combination of given criteria provided by another technology. In that case, a technological paradigm not only excludes certain alternatives, but also suggests others.

#### *5.3.2. Inherent variety in the lighting industry*

The lighting industry has been traditionally characterized by a high degree of variety, first of all, in terms of lighting needs and applications. Artificial lighting is used in nearly every area of human life. Therefore, different consumers with different economic possibilities have different lighting needs (IEA, 2006) and even the same consumers may have various preferences depending on particular tasks and applications (LRC, 2003). At present, there are up to 35000 applications, among which at least several thousands are extremely unique and specific (Interview, Manager Philips). Essentially, different applications cannot be equally well served by the same type of products. On the contrary, applications often correspond to a couple of specific light sources rather than all of them (Menanteau and Lefebvre, 2000).

The need of technological variety as a consequence of applications variety was already evident by the time of introduction of CFLs since at least two different technologies were present in the industry: while residential sector was dominated solely by the incandescent bulbs, industrial and commercial sectors were increasingly served by linear fluorescent lamps (LFL). Thus, CFLs became a technological improvement of LFLs, suitable for the residential sector.

The situation is different with LEDs which from technological point of view are radically different from all other lighting technologies. Nevertheless, the analysis of industry journals shows that the industry has been traditionally open for the possibility of the new, breakthrough technology to enter the industry. Public speeches in the lighting societies and research articles in late 1960 – 1980 repeatedly mentioned the possibility and even the need for a new product or technology to appear (Willoughby, 1969; Heanly, 1982; Boyce, 1986; Waymouth, 1989).

In sum, due to a combination of historical ("built-in") variety in terms of applications and technologies together with an open search for new, even radically different technological alternatives, generation of new paths was enabled from inside of the lighting industry.

The theme of variety appeared in the part of path dependency research which (like us) acknowledge the possibility of co-existence of multiple paths. Thus, Storz (2008) considered the variety of paths within a national innovation system as a prerequisite for path plasticity which in turn explained the generation of novelty in a path dependent system. Similarly, Martin and Sunley (2006) explained opportunities for path creation by variety and heterogeneity of an economic landscape. Therefore, with our study we extend the discussion of the role of variety to the field of technological paths.

## 6. Conclusions and discussion

This paper has addressed the issue of new technology development in a path dependent industry. In particular, we have analyzed how previously established path dependent dynamics influence the process of path generation. The study of two cases of path generation in the multi-technology lighting industry revealed three types of influence from path dependency on the process of path generation.

First, self-reinforcing mechanisms associated with the established path can impose barriers for the development of the new paths. The discussed barriers were related to customer acceptance problems, testing and measurement procedures, complementary resources, and other investments. This type of influence was covered by existing literature, and our study complemented it with an empirical evidence of how technology-related self-reinforcing mechanisms (rather than previously discussed processes at the level of technology regimes and institutions) can inhibit path generation.

Second, characteristics of the established technology can directly shape the development patterns of the new paths. This types of influence was found to be enabled by cross-path self-reinforcing mechanisms which were present at the overall industry level.

Third, some emerging dynamics of the path dependent system can enable the generation of the new paths. This proves that under the conditions of inherent technological and applications variety as well as the presence of clearly defined performance criteria, a path dependent system may generate novelty.

The findings with regard to the role of path dependency in shaping and enabling path generation highlight that previously prevailing understanding of this influence as solely negative is incomplete. We thus contribute to a better understanding of endogenous change sources in established industries. Importantly, we show that endogenous novelty generation should not obligatorily happen as a result of mindful deviations by actors (as considered by path creation research), but can also be enabled by emerging processes.

This conclusion brings us back to the question of the role of agency in the process of path generation. The case used in this study is illustrative in showing the role of emerging processes in path generation. Indeed, in all three types of influences we saw a considerable degree of emerging properties: the choice of consumers was formed over long time by the characteristics of the lighting technology rather than mindfully governed by actors; further, key performance criteria as well as openness to a new technological breakthrough were hardly orchestrated by manufacturers or institutions.

Although in this paper we focused on other than actor-driven sources of endogenous change, we do not consider actors as an irrelevant factor in this process. On the contrary, our findings revealed several interesting insights with regard to the role of agency in the process of path generation. First, the lighting producers could not be characterized as locked-in: they saw the value of new technologies and were eager to promote new solutions. However, in the consumer-oriented lighting market they had to follow customer preferences by making new lamps as similar as possible to incandscents. Even though by doing that they followed established routines, one cannot neglect that such choice was rather strategic and therefore active. Thus, a difference between being locked-in due to ignorance and actively choosing to be path dependent, needs to be taken into account.

Another interesting observation with regard to agency is that the actor notion can include several different types of actors, apart from producers (or entrepreneurs) that are usually discussed. In the lighting industry, various actors took part in overcoming barriers imposed as a negative consequence of path dependency. On the one hand, governments played an important role in promoting both CFL and LED technologies through demand-side management programs (Mills, 1991; Sathaye and Murtishaw, 2004; OECD/IEA, 2010) and introducing regulations aimed at phasing-out of incandescent lamps (Waide, 2007). On the other hand, several key retailers (e.g. Walmart, IKEA) influenced the lighting market by promoting newer lamps types and thus forcing other retailers to do the same in order to remain competitive (Martinot and Borg, 1998; Bickel et al., 2010; Lighting.com, 2013).

These observations, together with previously discussed findings about the role of path dependency in shaping and enabling path generation, suggest that, eventually, both types of enabling processes are needed to generate and sustain a new path: emerging possibilities to create opportunities and initial patterns of new paths, and agency to help overcome barriers imposed by the established path. A similar, yet different, situation was observed by Djelic and Quack (2007) in the case of institutional paths: power was considered essential to generate momentum in the beginning, while more emerging processes (e.g. gaining legitimacy) appeared crucial in later stabilization.

In sum, the evidence of influence from the established path in the form of enabling and shaping new path generation proves that a path dependent industry may contain inherent potential for generation of new technological alternatives. At the same time, as the overall influence on path generation also includes negative aspects, the enabling and shaping self-reinforcing dynamics alone (without the support from actors) are not likely to be strong enough to overcome the imposed barriers.

## 7. References


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