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STANDARDIZATION AND FIRMS' INNOVATIVE ACTIVITIES WITHIN ECOSYSTEMS — TWO ESSAYS ON THE FORMULA ONE INDUSTRY

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Standardization and Firms' Innovative Activities within Ecosystems

— Two Essays on the Formula One Industry

by

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Dissertation

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Doctor of Philosophy

The University of Texas at Austin

July 2022

Abstract

Effect of Standardization on Firms' Innovative Activities within Ecosystems

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The University of Texas at Austin, 2022

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This dissertation studies how standardization can affect ecosystem member organizations' innovations and performances both in organizational and individual levels. Standardization is an effective coordination tool to help ecosystems overcome coordination challenges by providing compatibility and interoperability within ecosystems. However, to achieve compatibility, standardization needs to fix and limit core technologies and components only to standardized cores and must enforce guidelines to its member organizations. In other words, the coordinating effect of standardization may require hefty prices from its ecosystem.

To address the tension between standardization's positive role as a coordination tool and necessary organizational costs to adopt standards, the current dissertation examines how standardization can influence various aspects of organizational functions. The dissertation is organized as the following. The first section a general introduction and overview of the dissertation. Then the dissertation proceeds to a literature review of relevant prior research on ecosystems and standardization that analyze the theoretical tension between standardization as a coordination tool and required costs to

accommodate standards. The chapter will then proceed to identification of research opportunities based on the existing literature. Chapter I then demonstrates the constraining effect of standardization on firms' innovation through the theoretical lens of knowledge recombination. In addition, using the perspectives of knowledge-based view and organizational change, Chapter II will analyze the disrupting effect of standardization on human capital performances within ecosystem member organizations. Lastly, the dissertation will then provide a conclusion and message of the dissertation.

Using data on Formula One motorsports industry regarding standardization which consist of F1 teams' innovations and drivers' performances in 1970 - 2020, the dissertation empirically tests the proposed theories. The dissertation utilized machine learning based LDA topic modelling techniques to capture impacts of standardization on components of F1 race cars and track standardization activities among the components. The findings from the empirical analyses of this dissertation demonstrate that standardization can negatively affect various activities of ecosystems' member organizations.

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INTRODUCTION

Ecosystems create substantial values to firms in numerous aspects (Adner, 2017; Adner & Kapoor, 2010; Boudreau, 2012; Clarysse, Wright, Bruneel, & Mahajan, 2014). However, as ecosystems emerge, they inevitably encounter coordination challenges (Kapoor & Klueter, 2021; Kretschmer, Leiponen, Schilling, & Vasudeva, 2020; Teece, 2018). With absence of a strong leadership within the ecosystem (Bresnahan & Greenstein, 1999) and inability to utilize conventional relationships of hierarchical transactions (Kapoor, 2018), ecosystems cannot effectively coordinate themselves using traditional coordination mechanisms. Thus, with lack of order and organization, firms within the ecosystems may be hesitant to pursue innovative activities.

To provide such platform, standards provide clear guidelines of how members of the ecosystems can connect their components and technologies to the standardized core components or technologies (Jacobides, Cennamo, & Gawer, 2018; Teece, 2018). Standardization of the cores guarantees future direction of future innovation (Leiponen, 2008). Thus, firms can develop their future innovation with greater uncertainty and lower risk by clarifying basic elements of innovation.

Nevertheless, although standardization may successfully coordinate ecosystems and alleviate the coordination issue, ecosystems must sacrifice substantial amount of their innovative possibilities and already well-working organizations routines and strategies to be compatible with standards. While standards can provide pre-determined future direction of innovation, such suggestions also eliminate other possibilities of potential innovative pursuits. To be specific, the act of standardization refers to fixing of the core components or technologies to the standardized cores (Garud, Jain, & Kumaraswamy, 2002). Therefore, while the specification to the core can provide certainty, it eliminates potentials of other alternative pursuits of innovation or strategic choices.

Considering the constraints enforced by standardization to fix the core components or technologies, this dissertation studies whether standardization promotes or stifles firms' innovative activities in two different essays. First, through the theoretical lens of knowledge combination, the first chapter of the dissertation examines whether standardization helps or hinder the process of knowledge combination. Based on the knowledge combination literature, innovation is a combination of existing knowledge (Fleming, 2001; Nelson & Winter, 1982; Schumpeter, 1939). On the other hand, standardization fixes major core elements of firms' knowledge combination to limited number of standardized components. As a result, based on the combinational constraints posed by standardization, firms of ecosystem must be constrained from pursuing their own innovative combinations. As a result, the first chapter focuses on how standardization can stifle firms' combinative capabilities.

In addition, the second chapter of the dissertation studies the effect of standardization on performances of human capitals within ecosystem member organizations. Compliance with standards and regulations result in conformity of ideas and actions among the firms (Arthur, 1989). Therefore, by consolidating different technological options to few core technologies, standards force human capitals to move away from their previous organizational routines and pose disruptive organizational changes to the individuals. The negative effects of disturbances and noises from organizational changes on human capitals of the firms, (Hannan & Freeman, 1984; Singh, House, & Tucker, 1986). Therefore, standardization can pose unintended organizational changes to individuals of the ecosystem member organizations, which can undermine the personnel's performances in the firms.

I study both two chapters of my dissertation in the context of Formula One motorsports industry. Using the longitudinal data of Formula One race cars' technologies and innovations of each team, I demonstrate the stifling effects of standardization on Formula One teams' innovation and the disrupting effects of standardization on performances of F1 drivers. To capture innovation of Formula One race cars and impacts of standardization, I utilized machine learning based LDA topic modelling analysis to track the cars' changes in their technologies and designs.

The findings highlight the negative effects of standardization on both innovation of firms within ecosystems and performances of human capitals. The empirical results suggest that although standardization is an effective coordination tool to achieve order and stability within ecosystems, it can only accomplish such role by restricting various innovative endeavors of members within ecosystems.

Through my dissertation, I would like to contribute to resolving the theoretical tension of whether standardization promotes or stifles firms' innovation and performances. Although this dissertation empirically demonstrates that standardization does constrain and disrupt firms' innovative activities and performances of human capitals, it is not the intention of the dissertation to disregard the coordinating effect of standardization. Instead, the current dissertation does recognize the important benefits of standardization as a coordination tool. However, the main message that I would like to convey through this dissertation is that standardization is a complex phenomenon that affect various aspects of ecosystem member organizations. Because standardization must fix and limit core technologies and components, it is bounded to pose constraints on firms' innovative pursuits. Moreover, as standardization enforces guidelines regardless of related human capitals' prior strategic pathways, it is supposed to be disruptive to numerous personnel within ecosystems. Therefore, I hope to provide broader explanations of standardization and its potential complex effects through this dissertation.

Literature Review: Current Research on Standardization Based Ecosystems

In this section, I provide an overview and critique the current state of the literature that is relevant to the theoretical developments of my dissertation. My dissertation is interested in ecosystem-based standardization and how standardization can affect various aspects of ecosystem member organizations beyond its primary role as a coordination tool. To analyze potential impacts of standardization, the literature review will first analyze how standardization can provide coordination in ecosystems based on existing research. Then the review will focus on the current state of literatures' examinations on different stages of standardization. After that, the section will review how standardization can possibly affect ecosystem member firms' innovative activities. Lastly, this section will summarize the findings of the literature review and identify potential research opportunities in the topical area of ecosystem-based standardization.

While finding existent literature that are relevant to my theoretical focus, I paid attention to the top research journals in the topical areas of ecosystems, standardization, and innovation. To be specific, the list of management and strategy focused journals are the following in an alphabetical order: Academy of Management Journal, Academy of Management Review, Administrative Science Quarterly, Management Science, Organization Science, Strategic Management Journal. In addition, standardization is a widely used topic in the field of management information systems, economics, and sociology. As a result, I also reviewed top journals beyond the management or strategy journals as well. The following list is a top journal of the areas in the field of management information systems, economics, and sociology in an alphabetical order:

American Journal of Sociology, MIS Quarterly, RAND Journal of Economics, Research Policy.

Ecosystems Based on Standardization

Definition and Overview

In the field of strategy and entrepreneurship, ecosystem can be interpreted as a broad term that can be used to describe various communities where collaborations among their members are essential (Jones, Leiponen, & Vasudeva, 2021; Shipilov & Gawer, 2020; Stonig, Schmid, & Müller-Stewens, 2022). In fact, growing numbers of topical areas are adopting and assigning their own definition of an ecosystem and it has now become one of the most overly used jargon in the field of strategic management, sociology, and economics. However, this dissertation strictly defines an ecosystem as a community of different actors with complementarities that can bring values to the core technologies or components without hierarchical structure (Adner, 2017; Jacobides et al., 2018; Tassey, 2000). In an ecosystem, the complementarities that are owned by various related parties need to be able to operate with each other to make the entire combinational structure of system to function (Miller & Toh, 2020; Rosenkopf & Tushman, 1998).

Given the definition of an ecosystem which uses the idea of complementarity, it is necessary to understand what complementarities are to comprehend the accurate definition of ecosystems. In this dissertation, a complementarity refers to a technology or a component that can appropriate more values when it is connected to other technologies and components to make a structure of system operable (Breznitz, Forman, & Wen, 2018;

Makri, Hitt, & Lane, 2010; Toh & Miller, 2017). While a single complementarity itself does not have much or any function, it can be a powerful tool within a functioning structural system.

Considering the definitions of ecosystems, and complementarities, along with their characteristics, I will review current state of research on the topical area of ecosystems.

Ecosystem and Coordination Challenge

As defined previously, according to prior research, an ecosystem consists of numerous complementarities that are owned by multiple parties of complementors (Jacobides et al., 2018). In fact, previous research has demonstrated that large number of complementors can bring more values to ecosystems (Adner, 2017; Baldwin & Woodard, 2009; Boudreau, 2012). As a result, a plethora of complementors and other related entities. However, despite the excess number of members within ecosystems, ecosystems lack hierarchical mechanisms (Bresnahan & Greenstein, 1999) or vertical integrations to coordinate numerous members of the ecosystem (Kapoor, 2018). Without any conventional coordination mechanism, prior research note that ecosystems suffer from the coordination challenge.

Therefore, given the chaos of ecosystems, finding an effective governance structure to achieve coordination within ecosystems have been one of main topics of interests for prior research (Kretschmer et al., 2020; Tiwana, Konsynski, & Venkatraman, 2013; Wareham, Fox, & Giner, 2014). Nevertheless, considering lack of available conventional governance options in ecosystems, the coordination challenges of ecosystem is a complex puzzle that is still being studied.

Standardization as a Coordination Tool

Given the major coordination challenge within ecosystems, early research on ecosystems and standardization has identified standardization as a powerful coordination tool that can help ecosystems overcome the coordination challenges (Farrell & Saloner, 1985; Kapoor, 2018; Matutes & Regibeau, 1988; Schmidt & Werle, 1998; Teece, 2018). Because of modularity, once standardization finalize the core technologies or components, complementors can independently develop or adjust their complementary technologies or components based on the standardized cores (Sanchez, 1995; Sanchez & Mahoney, 1996; Worren, Moore, & Cardona, 2002).

Prior research has recognized various benefits of standardization as they view standardization as an effective coordination tool. The main benefits of standardization on ecosystem is reduction of uncertainty within ecosystems (Wen, Forman, & Jarvenpaa, 2022). When new ecosystems emerge, their members have multiple technological paradigms to choose from (Rosenkopf & Tushman, 1998). Firms are afraid of making wrong investment choices by choosing the wrong technological paradigms and thus suffer from uncertainty from lack of direction (Ranganathan & Rosenkopf, 2014). Nevertheless, by specifying the core technologies or components, standardization can let member organizations of ecosystems know how their complementary assets can be compatible to the core (Besen & Farrell, 1994; David & Greenstein, 1990; Jacobides et al., 2018; Teece, 2018). The assurance of technological direction can increase firms' survival in ecosystems (Suarez & Utterback, 1995).

To summarize, the previous research has done extensive examination on standardization's role as a coordination tool. In fact, it has demonstrated mechanisms that allow standardization to effectively coordinate and bring order to ecosystems.

Based on the literature review of standardization, most of the prior work circles around the coordinating role of standardization. To be specific, the existing research focus on factors that result in standardization to be a coordination tool, how the ecosystems react to or are affected by standardization, and aftermaths of standardization. Therefore, in the following section, the current dissertation will review prior literature on standardization based on different stages of standardization.

Processes of Standardization

1.1 Antecedents of Standardization

One stream of research on standardization is about antecedents of standardization. This topical areas of research on standardization examines factors that results in standardizations, and interesting organization dynamics right before and after initiation of standardization. For example, Toh and Miller (2017) examined what are features of complementors and their complementary assets that affect their propensities to initiate standardization. Moreover, Rysman and Simcoe (2008) demonstrated that standard-setting organizations can identify the best core technologies or components as standards.

In addition, some papers also analyze what are key strategies to best prepare for standardization (Shapiro & Varian, 1998).

This group of prior research regarding antecedents of standardization provides a clue of how organizations feel about standardization. If standardization is such a powerful coordination tool, all members of ecosystems should readily accept or initiate the standardization. However, considering how the research suggests various considerations prior to standardization, there must be qualities of standardization that make ecosystem members be hesitant to accept.

1.2 Firms' Reaction to Standardization

The second stream of research of standardization focus on how firms react to emergence of standardization. In most cases, this type of literature studies firms' effort and strategies to comply with standardization to achieve compatibility or refuse them. For instance, Ranganathan and Rosenkopf (2014) demonstrated how firms' position in commercialization network opposition towards standardization influence the organizations' level of opposition towards standardization. Furthermore, Miller and Toh (2020) studied how firms can maximize their return on innovations through complementary technologies following standardization.

Based on this stream of research, the existing literature's main emphasis is on how firms can maximize return while avoid losing opportunities by missing the investment opportunities of standards. In other words, this group of literature is mainly focused on consequences of betting against or not betting on technologies or components that are later standardized.

1.3 Consequences of Standardization

The last stream of extant literature that study standardization analyzes the consequences of standardization. This type of research examines what standards can do to ecosystems, how it can change value systems of ecosystems. In fact, the literature that belongs to the last stream of work extensively talk about standardization's role as a coordination tool. Following standardization, the locus of values in ecosystems move within the ecosystems (Jacobides & Tae, 2015; Kapoor, 2018). As a result, members of ecosystems need to pursue different value systems to best appropriate from the ecosystems as the main value of ecosystem shift to complementarity areas (Miller & Toh, 2020). For example, after studying the Internet Engineering Task Force (IETF), Wen et al. (2022) discovered that standards can help complementors to achieve high-impact innovations. Moreover,

Critique

Based on the overview of the current state of literature on the topical areas of ecosystems and standardization, I could identify three major research opportunities for this dissertation. This section will describe the opportunities and how they can help theory formulation of the current dissertation.

Research Opportunity 1: Process of Standardization and Modularity

The first research opportunity exists in the process of standardization and how standardization relies on modularity to coordinate ecosystems. As standardization emerges, members of ecosystems can now focus their effort and resources on complementary technology areas through modularity (Baldwin & Clark, 2000; Ethiraj & Levinthal, 2004; Shipilov & Gawer, 2020). In other words, standardization's coordination effect is only possible as members of ecosystems can recombine knowledge elements (Fleming, 2001). By providing a guideline of what an essential combinational element, called standard, looks like, standardization can coordinate the configurations of knowledge elements within ecosystems.

However, while standardization can reduce uncertainty by determining the core knowledge elements, it also fixes the core elements of firms' knowledge combinations to standards (Garud et al., 2002). Moreover, in the perspective of knowledge recombination, such enforcement of knowledge elements in firms' knowledge configuration constrains firms' innovative capabilities by limiting the number of possible knowledge combinations (Fleming & Sorenson, 2001; Kauffman, 1993).

Research Opportunity 2: Standardization and Innovation

Given the previous research opportunities of how standardization can restrict firms' knowledge recombination opportunities, another research opportunity based on the extant literature is the relationship between standardization and firms' innovation. In fact, the literature review has identified a theoretical tension between standardization's role as a coordination tool and its constraints on firms' knowledge combinational possibilities. There have been prior research that study the relationship between standardization and innovation (e.g. Wen et al., 2022). However, there is a compelling research opportunity in this relationship by focusing on how standardization affects knowledge combination.

Research Opportunity 3: Standardization and Human Capitals

Another research opportunity identified from literature review is how current literature has only focused on the effect of standardization on ecosystem member firms in the perspective of organization. As mentioned previously, standardization requires various organizational changes from members of the ecosystems by posing guidelines of accommodating standards (Kapoor & Klueter, 2021). But in the end of the day, it is individuals in ecosystem member organizations that need to comply with the guidelines of the standardization. In fact, those who recombine knowledge elements and generate innovation are individuals within organizations (Fleming, 2001). Therefore, it should be worthwhile to study the relationship between standardization and abilities of human capitals. The prior research has not paid much attention to how standardization can affect human capitals while they have done great amount of work at the organization level.

Chapter I: Fast and Furious (about Standards): Effect of Standardization on Innovation Within Ecosystems in the Formula One Industry

ABSTRACT

Following emergence of ecosystems, participating members of the ecosystems encounter coordination problems. According to extant research, standardization resolves such coordination problems by providing platforms of compatibility and thus facilitates innovation. However, I propose that standardization can also constrain innovation for participating firms by fixing major technological components to the standardized cores. With data on Formula One motorsports industry involving standard-setting in 1970 - 2020 and a measure of innovation based on machine learning techniques that analyze Formula One car designs, I find support for the proposed effect and its contingencies. The stifling effect of standardization is more salient when the non-core-owning firm has a smaller breadth of knowledge, more pre-standardized technologies that are replaced by standards, and greater technological distances between firms' technologies and standards. Findings highlight the constraining effect of standardization on firms' innovative activities within ecosystems despite its alleviation of coordination challenges.

INTRODUCTION

One of the key challenges of an ecosystem is coordination (Gulati, Puranam, & Tushman, 2012; Kretschmer et al., 2020). The inherent issue arises from the structure of an ecosystem. An ecosystem consists of numerous multilateral partners that need to cooperate with each other (Adner, 2017). In fact, the main value of an ecosystem lies on the large number of partners that belong to the ecosystem and their interactions (Baldwin & Woodard, 2009; Boudreau, 2012). However, despite the substantial number of members that form an ecosystem, an ecosystem often lacks traditional coordination mechanisms. First, ecosystems normally lack parties with leadership roles to guide technological developments of the ecosystems (Bresnahan & Greenstein, 1999). Second, the ecosystems do not typically use conventional contractual or vertical hierarchical relationships to enforce cooperation among firms (Kapoor, 2018). However, despite the challenges and obstacles of eliciting cooperation among different organizations within ecosystems, firms can capture more values of their innovation from the ecosystems when they can achieve collaboration with each other even in the face of rivalry (Jones et al., 2021). Thus, without an effective coordination tool to set rules and orders within the ecosystems to ensure positive and efficient returns on their investments, firms of ecosystems may be hesitant to innovate within the ecosystems (Kapoor & Lee, 2013).

Nonetheless, extant literature has suggested that standardization can be one of the solutions to the coordination challenge of ecosystems (Dokko, Nigam, & Rosenkopf, 2012; Rysman & Simcoe, 2008). Standardization can provide platform of compatibility that connects the firms (Farrell & Saloner, 1985; Rysman & Simcoe, 2008) by specifying what the core components look like through the standardization (Jacobides et al., 2018; Teece, 2018). As firms have clear instructions and guidelines of how to connect to the core technologies and components, firms can pursue more innovation and develop their complementary technologies based on the standardized core with more certainty and lower risk of the future (Bekkers, Catalini, Martinelli, Righi, & Simcoe, 2017; Rysman & Simcoe, 2008). The specification of the core components through standardization can provide a strong coordination mechanism to ecosystems. In fact, firms can appropriate values of innovation in core technologies in complementary areas, which can provide more opportunities for the ecosystem partners to cooperate with each other and even gather more new firms or complementors to the ecosystems (Boudreau, 2012; Miller & Toh, 2020; Teece, 2018). Considering its effective role as a coordination tool in the ecosystems, one may infer that standardization can positively impact or innovation because coordination within ecosystem can facilitate innovation (Dougherty & Dunne, 2011; Kerstan, Kretschmer, & Muehlfeld, 2012; Rosenkopf & Tushman, 1998).

Nevertheless, previous research has not paid much attention to the tradeoffs that standardization requires to specify the core components to coordinate the ecosystems. To specify the core components, standardization needs to fix the core components (Teece, 2018). By doing so, standardization imposes rules and technological instructions to the member firms (Farrell & Saloner, 1985). In other words, standardization fixes and constrains technologies and their components to the standards (Garud et al., 2002).

Based on the past literature on knowledge recombination, the fixed knowledge elements restrict knowledge combination by limiting firms' ability to recombine existing knowledge and forcing them to adjust their knowledge elements to accommodate the locked elements to their combinations (Fleming & Sorenson, 2001; Kauffman, 1993). The new hurdles and protocols posed by the specification of the core components can be major constraints of firms' innovative activities. Although firms can benefit from the coordination provided by standardization, the enforced guidelines to the members of the ecosystem can hinder the participating firms' activities as the organizations can no longer pursue and develop technologies by their free will if they want to stay in the ecosystems.

Therefore, considering its role as a coordination mechanism and the tradeoffs of eliciting such coordination, it is necessary to ask *whether standardization facilitates innovation despite the obstacles and constraints that it creates?* It is true that the relationship between standardization and firms' innovation has not been well-established based on existent literature. In fact, different perspectives and emphasis of the standardization process argue contrasting opinions on the relationships. For the literature that focus on the antecedents of standardization, such as the process and political dynamics during the process of standardization, past research has demonstrated that standardization can rather achieve inefficiency (Lemley, 2007; Shapiro & Varian, 1998; Simcoe, 2012; Updegrove, 2007). In addition, the literature has also examined how firms' innovative capabilities affect formation or success of standardization (Iansiti & Levien, 2004; Kapoor & Agarwal, 2017; Toh & Miller, 2017). However, not enough attention has been paid to elucidating the positive or negative relationship between standardization and firms' innovation by looking at the actual effect of standardization on innovation rather than antecedents or subsequence of standardization. Although standardization actually alters various aspects of firms' behaviors (Bekkers & Martinelli, 2010; Besen & Farrell, 1994; Farrell & Saloner, 1985; Rysman & Simcoe, 2008), the field still lacks an answer to how the very act of standardization affect firms' innovative processes or behaviors.

I argue that while standardization can facilitate firms' innovation within ecosystems by achieving coordination (Baldwin, 2012; Teece, 2018), it can also constrain the members of the ecosystems' innovation by fixing the core components (Jacobides et al., 2018; Wareham et al., 2014). I also propose that the constraining effect is dependent on firms' portfolio of knowledge. To be specific, the constraining effect is contingent on how well firms are prepared to overcome the constraints posed by standardization or to capture the benefits from standardization through their knowledge combinative process. I demonstrate that standardization constrains firms' innovation even more when firms have smaller breadth of knowledge, more pre-standardization technologies that are replaced by standards, and more technologies with technological areas that are close to those of standards.

From R&D to market penetration, standardization affects all stages of technology cycle (Tassey, 2000). Therefore, the relationship between standardization and innovation can be assessed in every aspect of the technology cycle. Nevertheless, I try to answer the previously mentioned research question through the theoretical lens of knowledge combination. Through this paper, I do not intend to provide a definite answer to the relationship. Instead, the main purpose of this paper is to highlight an important aspect of standardization which is standardization's potentially constraining effect on firms' innovation rather than comprehensively focusing on the effect of all different characteristics of standardization on the members of ecosystems. As a result, I refrain from proposing competing hypotheses of the relationship between standardization and innovation.

I find support for the abovementioned arguments on the stifling effect of standardization using the data on Formula One industry in 1970-2020. I empirically demonstrate how standardization affects innovative activities of Formula One teams in the industry. To capture innovation of the Formula One racing teams and how they are affected by standardization, I utilized machine learning based LDA topic modeling analysis. By using the machine learning based techniques, I could categorize different components of the F1 cars. Then I could also track which category or components of the cars are affected by the standards enforced by the standard-setting entity.

The findings of the paper show some valuable theoretical implications. The empirical results suggest that standardization does constrain firms' innovation within ecosystems. Moreover, the empirical analyses also confirmed the contingent conditions where the main effect is more salient.

Using the theoretical perspective of knowledge combination, the paper tries to shed a light on the constraining effect of standardization on firms' innovation. In other words, the paper attempts to suggest an answer to the theoretical tension between standardization's facilitation of innovation and its stifling effects on firms' innovation. Although standardization is an effective solution for ecosystems to elicit coordination within ecosystems (Chiao, Lerner, & Tirole, 2007; Farrell & Simcoe, 2012), standardization is more than a simple answer to the coordination challenge considering its mechanism of coordination by stifling firms' combinative capabilities. While standardization can be a convenient and effective tool to bring order and stability to ecosystems, it can have a potential of fettering firms' innovative pursuits. To effectively promote innovation within ecosystem, members of the ecosystem should be aware of the price they pay in exchange of the coordination tool.

THEORY AND HYPOTHESIS

Coordination for Innovation

In an ecosystem where there are multiple competing technologies to choose from, coordination is essential in guiding further development of technologies (Rosenkopf & Tushman, 1998). If an ecosystem cannot provide an effective coordination mechanism, firms can end up with wrong technological directions that can later incur significant costs (Ranganathan & Rosenkopf, 2014). As a result, without knowing which technological paradigms will prevail within the ecosystem, members of the ecosystems may be hesitant to decide and initiate major technological pursuits (Kapoor & Lee, 2013). Such hesitation can impede various technological innovation as members of ecosystems prefer not to actively join innovative activities. In fact, without any clear guideline of which core technologies or components would prevail, there are often fierce competitions or debates among firms to make their paradigms become dominant (Polidoro & Toh, 2011).

Therefore, it is crucial for ecosystems to seek an effective coordination mechanism. However, ecosystems cannot benefit from conventional coordination mechanism of contractual or hierarchical relationships due to the ecosystems' vast number of related parties that own and offer different values to the ecosystems (Adner & Kapoor, 2010; Iansiti & Levien, 2004). Therefore, coordination of ecosystem is often challenged. Given the importance of coordination to facilitate innovation and the inability of utilizing the conventional transactional coordination mechanism, ecosystems must seek their other creative solutions to answer the call of the coordination challenges.

Extant literature has argued that out of multiple solutions to resolve the coordination challenge, standardization can provide an efficacious coordination mechanism to guide different parties, complementors, components, and technologies within ecosystems (Farrell & Saloner, 1985; Kapoor, 2018; Teece, 2018). Coordination through standardization can be achieved by specifying what the core components are and how related parties and complementors can interact with each other through the standardized core components or technologies (Dokko et al., 2012; Rosenkopf, Metiu, & George, 2001; Updegrove, 2007). By specifying and detailing what the core components should look like and their functions, the standards can provide compatibility among the related parties and eventually coordination as well (Farrell & Saloner, 1985). Even the firms that have already invested on and developed technologies that are not compatible with the standardized core components or technologies will be forced to join the new standardized paradigm (Tegarden, Hatfield, & Echols, 1999).

The mechanism of facilitating innovation through specification of the core can be understood from the idea of modularity. Through the perspective of modularity, different modules of components can prevail independently if they are centrally connected to the core components or technologies (Baldwin & Clark, 2000; Ethiraj & Levinthal, 2004a;

Shipilov & Gawer, 2020). Therefore, by allowing different parties of the ecosystems to join each other, standardization can allow technological improvements of the entire ecosystems.

As standardization specifies the core components, members of the ecosystem can build on the standardized core technologies for their complementary technologies or components.

In fact, following standardization, the locus of the most values of innovation are complementary technological areas rather than the core technologies (Baldwin & Woodard, 2009; Teece, 1986; Updegrove, 2007). By being able to develop complementary technologies with greater certainty through standardization, firms can develop complementary technologies without fearing that other core paradigms can replace their core technologies (Teece, 2018). In fact, firms are highly fearful of their core technologies being replaced by other technological substitutes as it will require loss of the investments already made on the wrong technological directions and adjustment costs to the new paradigm (Ranganathan & Rosenkopf, 2014). In short, standardization seems to resolve all risk and uncertainty within ecosystems by providing clear messages of how ecosystems will be operated. However, standardization is not a silver bullet to solve all challenges of ecosystems. In fact, standardization itself can pose a new challenge to the members of the ecosystem.

Fixing Aspect of Standardization

Past literature has looked at multiple aspects of standardization that can be detrimental to coordination of ecosystem or innovation. These negative aspects of standardization in terms of failing to facilitate coordination or innovation pay attention to antecedents of standardization and subsequence of standardization. First, the past research that are focused on the antecedents of standardization mainly study how the process of standardization can result in negative side effects or non-market efficiency related motives. For example, extant literature has demonstrated that while ecosystems attempt to form standardization, the process can result in inefficient patent holdups (Lemley, 2007). Furthermore, members of standard setting organizations (SSO) may select core technologies or components as standards not only because they are the most effective options but also because they would like to expand their organizations' future influence within their ecosystems (Rysman & Simcoe, 2008). In fact, existent work has demonstrated that the SSOs are too politicized to come up with decisions for effective standards (Simcoe, 2012; Updegrove, 2007).

Second, the previous literature has also examined the effect of standardization on coordination or innovation following standardization in the context of their long-term subsequent influences on ecosystems. For instance, after standardization, standardization discourages firms from advancing from current technologies as members of the ecosystems become resistant to changing their standardized core components or technologies (Farrell & Saloner, 1985; Hemenway, 1975). As a result, it prolongs the life cycle of a technology longer than necessary and delays emergence of new technologies (Tassey, 2000). However, such resistance to change is apparent only after substantial time has passed as firms would only resist against changes after they fully adopted to the standardized paradigms.

Nevertheless, while the extant literature has investigated how standardization affects coordination or innovation in the context of antecedents and subsequent impact, the prior research has not paid much attention to how standardization itself affects firms' innovative process. To accurately capture the effect of standardization on firm's innovation, it is necessary to comprehend how the very act of standardization transforms firms' innovative process and behaviors. The very act of standardization refers to specifying and fixing the standardized components within the ecosystems (Garud et al., 2002). In other words, although standardization provides predetermined future directions of technological developments (Leiponen, 2008), it can only do so by anchoring core technological components. Thus, we must unveil how such central elements of ecosystems influence firms' innovative behavior if we want to examine the actual role and effect of standardization within ecosystems.

To participate in the standard ecosystem, firms are required to use the standardized technologies or components in their knowledge combinations. As new standards emerge, firms need to base their complementary technologies or components on the enforced knowledge components and adjust their existing knowledge components to match the specifications of the standards to create new knowledge combinations (Baldwin & Woodard, 2009; Iansiti & Levien, 2004). As more complementors join the ecosystems by utilizing the standards, more values can be created and appropriated from the ecosystems (Boudreau, 2012).

However, it is this very process of using the standardization that can create unexpected hurdles and constraints that can potentially stifle firms' innovation within ecosystems. As standardization enables related parties of ecosystems to collaborate with each other through coordination, it also constrains the members of the ecosystems to the constraining guidelines and protocols set by the standards (Garud et al., 2002). Although such restriction can be regarded as a tradeoff for the greater good of ecosystem-wide coordination, whether the opportunity cost of compromising each firm's innovative potentials for the stability of ecosystem is worth the sacrifice is unclear.

In the field of firm innovation, it is more advantageous for firms to be flexible in terms of both resources and strategies (Sanchez, 1995). To be specific, knowledge malleability is one of the key determinants of firm innovation (Yayavaram & Ahuja, 2008). However, standardization poses the exact opposite to the members of the ecosystems by enforcing more restrictions and guidelines. As a result, the act of standardization contradicts firms' objectives of strategic and resource flexibility and knowledge malleability Therefore, given how standardization has been widely used as a coordination tool within ecosystems that pursue innovation, it is also possible that the very act of standardization promotes firms' innovation or rather stifles it.

Standardization and Knowledge Combination

According to the theoretical lens of knowledge recombination, technological innovation is a combination of existing knowledge (Fleming, 2001; Nelson & Winter, 1982; Schumpeter, 1939). Prior to the knowledge combination, each knowledge element of an innovation is an independent idea (Hargadon & Sutton, 1997). However, as the elements of ideas are connected with each other and form knowledge combinations, they refer to innovation. Given the definition of innovation, firms' innovative capabilities are closely linked with their combinative capabilities. Combinative capabilities refer to organizations' ability to integrate and utilize existing knowledge of the firm to generate new knowledge (Kogut & Zander, 1992). Innovation depends on what firms already know, and combining them together (Galunic & Rodan, 1998; Hargadon & Sutton, 1997). Thus, based on this perspective, the number of possible knowledge combinations that firms can generate refers to the firms' innovative performances (Fleming & Sorenson, 2001). To be innovative, firms need to be combinative.

Being innovative by being combinative requires two conditions. First, firms need to possess enough number of knowledge elements within their knowledge-base that are ready to be used for knowledge combinations (Ahuja & Katila, 2001; Fleming, 2001). A firm knows an idea when it has that specific knowledge within its cluster of knowledge or knowledge-base (Jaffe, 1989). As a result, if a firm has large number of knowledge elements, they have more ingredients for more feasible knowledge combinations (Fleming, 2001). In fact, as the fit between knowledge elements are important to produce various knowledge combinations (Yayavaram & Ahuja, 2008), having more knowledge elements refers to higher chance of having better fit between knowledge elements. Therefore, firms can be more innovative when they have more knowledge elements so that they can be used to create knowledge combinations.

Second, having combinative capabilities also means that a firm can combine those abundant elements in its knowledge-base effectively. In their analytical framework, Fleming and Sorenson (Fleming & Sorenson, 2001) demonstrated that although the nature of knowledge components and their structures are important in determining innovative process, inventors' efforts of combining the knowledge elements are also as important to innovative process. This combinative capability allows competitive advantage to the firms as such capability is not an innate nature of organizations (Roberts & Amit, 2003). Therefore, for a firm to be innovative, it needs to be adept with integrating various ingredients of knowledge.

Stifling Effects of Standardization

However, despite the two important conditions of firms' innovative or combinative capabilities, standardization can disrupt both characteristics and stifle the organizations' innovation on two different knowledge and organizational levels. First, on the knowledge element-level, standardization restricts the number of knowledge elements in firms' knowledge-base by limiting the core components or technologies to the standardized components or technologies. As mentioned previously, the act of standardization refers to fixing and specifying the core components or technologies to certain specified standards (Garud et al., 2002). In other words, because ecosystems try to achieve coordination by standardizing the core components (Baldwin, 2012; Jacobides et al., 2018), complementary areas must advance based on the core technologies (Adner & Kapoor, 2010; Baldwin & Woodard, 2009). By directing firms' innovation and search to the standardized technologies, standardization can motivate firms to pursue focused search. In fact, locking into sub-optimal core components or technologies can hinder innovative capabilities of firms (Ethiraj & Levinthal, 2004). In addition, more innovations happen when firms seek broader knowledge search in wider technological domains (Ahuja & Katila, 2004; Riitta Katila & Ahuja, 2002). Thus, by limiting the core technologies to standards and allowing development of complementary areas that are only focused on the standards, standardization can effectively jeopardize one of the two key factors that are need for combinative capability.

Second, on the firm-level, standardization also stifles firms' very process of knowledge combination by interfering already existing innovative procedures. Changes to firms' knowledge couplings can harm firms' innovative capabilities by incurring various adjustment costs (Yayavaram & Chen, 2015). To be specific, firms' innovative capabilities are highly path dependent and the innovative progresses that firms have taken affect their technological capabilities (Cohen & Levinthal, 1990; Dosi, 1988). As a result, considering how firms' innovative capabilities are path-dependent (Helfat, 1994; Teece, 1987), any modifications to the current processes can disturb firms' innovation. In fact, even if firms can successfully overcome the path dependence, they are required to follow the technological guidelines of standardization which limit firms' free innovative activities through the regulations of standardization. Such external constraints on firms' innovative behaviors have negative impac(Garriga, von Krogh, & Spaeth, 2013)riga, von Krogh, & Spaeth, 2013). Therefore, standardization can also stifle firms' knowledge recombination behaviors by enforcing brand new organizational combinative constraints to member firms of ecosystems.

In short, standardization restricts firms' combinative capabilities both in knowledge element-level by limiting the knowledge elements available for recombination in firms' knowledge-base, and on the firm-level, by constraining their ability to utilize the knowledge elements. Therefore, given the constraining effect of standardization on firms' ability to generate new knowledge combinations by preventing firms from using all their knowledge elements and disrupting with their combinative capabilities, I propose the following main hypothesis:

H1: Standardization constrains a firm's innovation in the ecosystem.

To flesh out the mechanisms of the proposed main hypothesis and identify the boundary conditions of our main argument, I have formulated a list of contingent conditions. The conditions demonstrate situations when the stifling effect of standardization on firms' innovation are more salient. While they are different, the contingent conditions are characteristics of the firms' technological portfolio.

Breadth of Knowledge

An innovation is a combination of firms' existing knowledge elements (Fleming, 2001; Nelson & Winter, 1982; Schumpeter, 1939). Firms are "brokers" of different knowledge elements (Hargadon, 1998), and firms that can create more fusions between knowledge can be innovative. Therefore, to be innovative, firms need to be able to come up with more knowledge combinations. To generate larger number of possible knowledge combinations, extant literature has argued that the greater number of firms' existing knowledge elements can allow more potential knowledge recombination (Fleming & Sorenson, 2001; Kauffman, 1993). In fact, extant literature has demonstrated that having multiple sources of knowledge ingredients can lead to successful innovation activities (Leiponen & Helfat, 2010).

To be specific, it is not simply the total number of elements that affect firms' innovative capabilities. Previous literature has found that it is the abundant knowledge elements in wider breadth of knowledge, which refers to broader domains and types of knowledge (Zhou & Li, 2012), that determine firms' success in innovation (Ahuja & Katila, 2004; Ahuja & Lampert, 2001; Gruber, Harhoff, & Hoisl, 2013). As a result, despite the constraints from standardization which keeps the standards as the core components or technologies, having more combinational options can mitigate such challenges.

Even when major changes from standardization happen in firms' technological areas, if firms are well equipped with enough technological capabilities and resources from wide range of technological domains, they can better adapt to the changes in the new environment (Rothaermel & Hill, 2005). Although standardization forces firms to innovate based on the standardized core, firms with wide breadth of knowledge can answer the call of the challenge by finding useful knowledge elements from variety of knowledge domains that are compatible with the standards.

Furthermore, following standardization, the locus of value shifts to complementary technological areas (Miller & Toh, 2020). As a result, as standardization increases the values of more technological areas, firms with larger breadth of knowledge have higher chances of experiencing the increase of values in their technological areas. Thus, firms can also appropriate more values from standards by developing more complementary technologies using their sufficient knowledge resources. Therefore, considering the changes in the locus of value, firms with broader breadth of knowledge may be advantageous with appropriating from the new value system.

On the other hand, if firms have limited knowledge elements in narrow breadth of knowledge, their hands will be tied when new standards emerge. Firms cannot capture the advantages of producing abundant knowledge combinations that are complementary to the standards. With small breadth of knowledge, firms may not be able to effectively come up with complementary technologies based on newly standardized cores to capture values from new locus (Jacobides & Tae, 2015). Therefore, the stifling effect of standardization on firms' innovation is more pronounced when firms do not have enough knowledge elements to adopt to the new standards.

Considering the relationship between the breadth of knowledge and firms' ability to cope with the constraints from standardization, I propose the following hypothesis regarding the first contingent condition:

H2: The smaller the breadth of knowledge a firm has, the more the standardization of components will constrain the firm's innovation in the ecosystem.

Replacement of Core Components by Standardization

However, although possessing a wide breadth of knowledge may mitigate the constraints from standardization, it is not all types of knowledge or technologies that can alleviate the constraints from standardization for the firms in the ecosystems. Following emergence of new technologies, the technological discontinuities can be competence-destroying for the firms (Tushman & Anderson, 1986). The new technologies are competence-destroying because the discontinuities of innovation can make firms' existing innovation obsolete or useless. As a result, the incumbents are often vulnerable to new technological changes brought by new innovations because the core rigidities of them inhibit their abilities to desert their old technological positions and adjust to the new technological changes (Leonard-Barton, 1992). Therefore, even when new technological changes are more efficient or beneficial, incumbent firms often experience hard time adjusting to the change. Thus, as standardization forces firms to adjust to the new technological guidelines of standards, firms that have already developed or utilized similar technologies suffer from the newly enforced changes. They can either fail to move on from their existing technologies, or adapt to the new technologies, or both. In other words, the standardized components or technologies' replacement of firms' existing knowledge can expose firms to greater destruction of competence by making the adjustment more difficult.

In addition to the difficulties with adjusting to new technologies, standardization can also pose other threats to firms by lowering the values of their technological assets. Taylor and Helfat (2009) demonstrated that if the entire industry is moving towards the new emerged technologies, the new technologies will depreciate the value of the incumbent firms' technologies or their prior investments on them. As a result, the existing technologies can lose their values if new standards can replace their functions or purposes.

In short, although standardization can stifle innovation of firms in the ecosystems, the level of constraints depends on the potential of replacement of firms' existing previous technologies by the new ones provided by the standards. The firms that have substantial technologies or components that need to be replaced by standardization will suffer from greater stifling effects from standardization due to the adjustment costs and depreciation of their technologies and investments. On the other hands, the firms that do not have much existing technologies that overlap with standards and need to be replaced by standards will be less impacted by the changes from standardization. Therefore, given the challenges posed by standardization to incumbent firms with technologies that overlap with and need to be replaced by standards, I propose the following contingency hypothesis:

H3: The more technologies a firm has that are replaced by standards, the more the standardization of components will constrain the firm's innovation in the ecosystem.

Technological Distance

As mentioned previously, Standardization can shift the locus of values within the technological spaces to complementary technologies (Jacobides & Tae, 2015; Miller & Toh, 2020). Thus, following standardization, when core technology is determined, it is critical for firms within ecosystems to capture values from standardization within complementary areas (Makri et al., 2010; Toh & Miller, 2017). As standardization results in new competitive paradigms where firms need to appropriate values from the complementary technologies, members of the ecosystems that can seize more values from the complementary spaces can be more successful. Therefore, to understand firms' innovative capabilities after standardization, it is critical to comprehend how effectively firms can innovate in the complementary spaces.

In his research on exploration and exploitation, March (1991) argued that exploitation is a process of local search with familiarity of the technological spaces that can increase productivity and efficiency in short term performances (Lavie, Stettner, & Tushman, 2010). Firms can utilize already existing knowledge of the space to innovate during exploitation. On the other hand, exploration is a process that involves experimentation, distant search, and deviation from the current behaviors that are necessary for long term. In other words, exploitation requires readily available knowledge within technological spaces that firms are already familiar with while exploration involves knowledge that are not instantly usable in spaces that firms have less previous experiences with.

Broad exploration is a critical search behavior of organizations as the wide range of exploration can provide exposure to variety of new knowledge that can be utilized for other innovative inventions (Riitta Katila & Ahuja, 2002; March, 1991). However, exploration requires significant time and resources to generate enough values and such delayed reward can result in misappropriation of values by allowing competitors to capture values.

On the other hand, firms can innovate swiftly through exploitation due to familiarity with the technological spaces and less risk associated with the activities (Nelson & Winter, 1982; Sorenson & Fleming, 2004). In fact, firms' search behaviors are highly path dependent on the organizations' existing knowledge which can provide competitive advantages to firms that area already familiar with the technological spaces (Cohen & Levinthal, 1990; Dosi, 1988; Ritta Katila & Ahuja, 2002). Considering the need to innovate effectively and efficiently within complementary spaces following standardization, firms need to be able to pursue exploitations within the complementary spaces with newly placed values to appropriate enough values.

If it is more beneficial for firms to pursue exploitation within complementary spaces, we need to comprehend conditions where firms can perform exploitation rather than exploration in the complementary areas. As mentioned previously, exploitation is a process of local search through existing knowledge of the focal firms (Lavie et al., 2010;

March, 1991). As a result, for firms to perform exploitation in the complementary spaces following standardization, firms need to be already familiar with the complementary areas that are generated by standards. When standards emerge close to areas where focal firms have knowledge in, firms can better exploit the complementary areas that are associated with standardized spaces. However, when standards emerge in technological areas that are distant from those of the focal firms, it is more challenging for firms to pursue exploitation following standardization. In this case, both the standardized and complementary spaces are technological areas that firms have less knowledge in, and firms cannot perform local search without substantial familiarity of the technological space (Gupta, Smith, & Shalley, 2006; March, 1991). Therefore, the technological distance between the technological areas of the focal firms and those of standards matter when studying innovative capabilities of firms following standardization.

Thus, considering the need for firms to exploit complementary technologies, firms are more suited to pursue exploitation if the standardized areas are close to technological areas that firms already are innovating in. On the other hand, if standards emerge in technological spaces that are too distant from those of the firms, focal organizations are unable to exploit the complementary areas. Therefore, I propose the following last hypothesis regarding the contingent condition of the stifling effects of standardization:

H4: The greater the technological distance a firm has from standards, the more the standardization of components will constrain the firm's innovation in the ecosystem.

Methods

Data and Sample

To empirically test the stifling effect of standardization on firms' innovation within ecosystems, I chose to focus on innovation and standard setting behaviors in the context of Formula One racing industry from 1970 to 2020. Formula One industry is a unique industry with various interesting empirical characteristics that are suitable to test my hypotheses. First, Formula One is a highly technology-driven industry that requires each team or firm to constantly innovate its race cars with better technologies to be successful (Castellucci & Ertug, 2010; Marino, Aversa, Mesquita, & Anand, 2015). As a result, I can measure how firms' innovative activities are affected by emergence of standards. Second, the Fédération Internationale de l'Automobile (FIA), which is an independent organization that has no association with the racing teams of F1, annually announces standards for all Formula One teams. As a result, because the standard-setting organization (SSO) is independent from the parties that are directly affected by standards, standards are mostly exogenous in this context. Third, firms or teams do not have any option of not joining the standards if they would like to continue racing in the championships. Therefore, there should be less selection bias of firms that join the standards. Lastly, Formula One context allows more accurate measurement of firms' innovation compared to other standard setting contexts. In typical studies of standardization, once a firm is compatible to standard, there is another firm that is interdependent with the focal firm. Therefore, it is difficult to disentangle the actual innovative capabilities of each firm. However, in the context of Formula One, there is no other compatible party that is influencing each Formula One team's innovative performance even after joining the standards. Therefore, the context allows less biased measurement of each firm's innovation that is affected by standards.

I gathered my data regarding firm-specific and race-specific data in two data sources. I collected all race related data from the FIA race database. In addition, I got all race car design or technology related data from F1 periodicals like GP racing. I also referred to each Formula One Team's annual report and websites to collected additional information regarding their staffs, sponsorships, and budget.

To build the sample, I gathered all the race and team information based on the FIA's race database from 1970 to 2020. Then I collected all the race car and technology related data based on all the race car information provided on the Formula One periodicals during the period of interest. In the end, I collected information about 213 constructors or teams, 1047 races and 849 drivers.

Variables

The dependent variable in my analytical model is firms' innovation each year. To be specific, the dependent variable is measured by the increase of innovation in each component of Formula One cars. There has been multiple past literature that examine the context of Formula One. For examples, previous literature has utilized the context of Formula One to study status of teams (Castellucci & Ertug, 2010), vicarious performance feedback of partners (Clough & Piezunka, 2020), firm exploration (Marino et al., 2015), and knowledge transparency with coevolution (Jenkins & Floyd, 1AD). However, unlike the extant literature, to test my hypotheses, I need three distinct elements of Formula One cars that were not necessary in existent research. First, I need to know technical categories of Formula One cars, meaning different components that form Formula One cars. Second, I need to find out which of these components are being standardized each year. Lastly, I need to know how Formula One teams are innovating in each of the component.

One of the main challenges of gaining such information is that there is no ready source to categorize the Formula One car components unless I gain access to the highly confidential actual blueprints of all Formula One racing teams' car designs. As a result, instead, I utilized machine learning based LDA model to collect data on the Formula One cars' categories along with standards and innovations within the categories.

Each year, numerous Formula One periodicals release detailed reports on new car designs and technologies of all Formula One racing teams. Using these detailed descriptions, I performed LDA based topic modelling to let my machine learning model to recognize different topics or categories covered in each article. Table 2 shows the list of topics or categories identified by the machine learning model.

Then I tracked how each different car design or technological iteration of Formula One racing teams change within the identified technological categories to capture which of the categories are affected by standards set by the FIA and innovations of Formula One racing teams. I measured the total change of innovation in each category to represent Formula One racing teams' innovation. I named the variable as $Innovation_{it}$.

The key independent variable is *Standardization*$_{it-1}$. To capture the impact of standardization on firms, I first measured the number of technological categories within the Formula One race cars that are affected by standardization each year. Then I calculated the natural log of the total number of the technological categories that are affected by standardization.

The first contingent variable is the breadth of knowledge that firms have. As mentioned previously, the LDA topic modelling technique can provide the list of technological categories that each of the Formula One team is innovating in. Having knowledge in more of these categories represents having a wider breadth of knowledge. As a result, to capture the *Breadth of Knowledge*$_{it-1}$, I calculated the the number of the technological categories that each firm is innovating in and used the numbers to measure the first contingent condition.

To measure the second contingent condition, I need to measure the previous technologies that were developed based on non-standardized technologies that are later replaced by those of standards. To do so, I measured racing teams' levels of innovation in each technological category prior to emergence of standards in each of the categories. All components and technologies within a technology category are highly related and complementary to each other as all components and technologies need to be well integrated with each other to make each complex category functional. When a new standard emerges in a technology category, all configurations of the category need to be adjusted to match the standard. As a result, all the innovation in the category may be considered as lost resources and efforts if standards emerge in the category. Therefore, I measured the second contingent variable by calculating the natural log of the amount of previous innovation in each category that is affected by standardization. I call this variable *Replaced Technologies*$_{it-1}$.

Lastly, to capture the last contingent condition, I measured the topical distance between standardized categories and non-standardized categories. I calculated the topical distance by calculating the total significance of standard for each category where firms do not innovate in. Despite the significance of standards in certain categories, if firms do not innovate in the categories, the firms' final products are distant from the standardized components. I call such variable as *Technological Distance*$_{it-1}$.

In my analysis, I control for both car-specific, firm-specific features of my samples. To control for the variations in budgets of the racing teams, I tried to capture the annual budget of each Formula One team. However, because none of the motorsports companies are publicly listed, it is impossible to capture the exact budget figures for each company. However, although I cannot measure the exact amount of budget, I can also get a sense of each team's budget depending on their external funding source. In the Formula One industry, some of the teams are sponsored by parent companies while others are totally financially independent. For example, although Red Bull Racing team is a motorsports organization, it has a very successful parent company, Red Bull, the energy drink company. In addition, although Mercedes AMG Petronas F1 team is an independent team, it has a strong sponsorship from its parent automobile company, Mercedes Benz. On the other hand, Williams Racing Team lacks such parent company to financially sponsor the team. Therefore, I controlled for the existence of external financial sponsorship as a proxy measure to measure firms' budget. I called this variable as *External Funding*$_{it-1}$. If a firm has an external funding source, the company got a value of 1. If not, it received a value of 0.

Furthermore, I also controlled for *Firm Age*$_{it-1}$ by calculating the natural log of years passed from each team's appearance in the Formula One industry. To account for any noise from the change of team ownership, I added *Ownership Change*$_{it-1}$ to any year when a team experiences mergers or acquisitions. I took note of the difference between those teams that create their own engines and those that purchase engines from other teams by using the dummy variable, *Engine Buyer*$_{it.1}$.

I also controlled for previous year's car failure with *Previous Car Retirement*$_{it-1}$ by calculating the natural log of the total incident counts of race care retirements during races. Moreover, I took account of any noise from change of drivers through *Driver Change*$_{it-1}$. I also controlled for the tenure of the usage of the same engine brands as *Engine Year*$_{it-1}$ as well as previous performance by including *Previous Engine Performance*$_{\mathrm{it-1}}$. It is calculated by measuring the average rankings of cars that used the engines in previous years. In addition, I took note of each team's previous year's race performance through the natural log of average grid positions of the previous years with *Previous Grid Position*$_{it-1}$. Similarly, I controlled for the previous race results through *Previous Race Results*$_{it-1}$ by calculating the natural log of the annual average of each team's race results of previous years. Lastly, I controlled for years.

Empirical Models and Findings

Table 3 and Table 4 report descriptive statistics and correlations of my samples. *Innovation*$_{it}$ has a mean of 4.067 with standard deviation of 2.804. The measure suggests that if we add all fractional changes in technological categories of a Formula One team car, there is approximately 4 unit increase from those of the previous year. *Standardization*$_{it-1}$ reports a mean of 1.148 with standard deviation of 0.304. This suggests that 3.151 out of 9 technological categories of Formula One cars are affected by standardization.

I utilized the random effects models to test the effect of *Standardization*$_{it-1}$ on *Innovation*$_{it}$. I used the random effects models instead of the fixed effects models as some of the control variables of the model are mostly time invariant (i.e. *External Funding*$_{it-1}$) which are disregarded in the fixed effects models. Table 5 reports the random effect regression coefficient of the relationship between standardization and firms' innovation. Model 1 is the base model with the main effect. Model 2, 3 and 4 each tests two of the three contingent conditions to demonstrate how the different conditions affect the relationship between *Standardization*$_{it-1}$ and *Innovation*$_{it}$. Model 5 is the full model that contains the main effect and the entire set of contingency variables. Furthermore, Model 6, 7, and 8 test the robustness of the full model. Model 6 tests the full model using the robust standard error to check for any heteroskedasticity. In addition, Model 7 analyzes the full model using Swamy Arora Model to check for unbalanced samples. Lastly, Model 8 utilizes a first order autoregressive model to test any chance of autocorrelation within the models.

Model 1 reports that *Standardization*$_{it-1}$ decreases *Innovation*$_{it}$ (t-statistics -1.67, p-value 0.094) with marginal statistical significance. However as we include contingent variables in following models, the main effect becomes statistically significant in all different model. For example, according to Model 5, the full model, 1 unit increase in *Standardization*$_{it-1}$ decrease *Innovation*$_{it}$ by 35.66 percent (t-statistics -4.07, p-value 0.000). As a result, the negative coefficients of *Standardization*$_{it-1}$ supports H1.

Based on Model 2 and 5, the coefficients of the interaction term *Standardization*$_{it-1}$ *X Breadth of Knoweledge*$_{it-1}$ are all positive with full statistical significance in Model 2 (t-statistics 2.02, p-value 0.044), Model 3 (t-statistics 1.94, p-value 0.052), and Model 5(t-statistics 2.79, p-value 0.006). Such results suggest that higher *Breadth of Knowledge*$_{it-1}$ mitigates the constraining effect of *Standardization*$_{it-1}$ on *Innovation*$_{it}$. In other words, narrower *Breadth of Knowledge*$_{it-1}$ can also heighten the stifling effect of *Standardization*$_{it-1}$. Such findings are consistent with H2.

Similarly, Model 2 (t-statistics -1.19, p-value 0.233), 4 (t-statistics -2.53, p-value 0.011),, and 5 (t-statistics -3.23, p-value 0.001), report negative coefficients of the interaction term *Standardization*$_{it-1}$ *X Replaced Technologies*$_{it-1}$ which demonstrate that more *Replaced Technologies*$_{it-1}$ that are affected by emergence of standards strengthen the constraining effect of *Standardization*$_{it-1}$ on *Innovation*$_{it}$. Therefore, if firms have more technologies that are replaced by emergence of standards, their innovation suffers from greater constraining effects of *Standardization*$_{it-1}$. As a result, the results support H3.

Model 3 (t-statistics -1.04, p-value 0.296), 4(t-statistics -2.70, p-value 0.007), and 5 (t-statistics -3.26, p-value 0.001) provide the results to test H4. All models report negative coefficients of the interaction term *Standardization*$_{it-1}$ *X Distant Technological Areas*$_{it-1}$ with statistical significance (t-statistics -2.23, p-value 0.026; t-statistics -3.64, p-value 0.000, respectively). In other words, as standards emerge in distant technological areas where focal firms have less knowledge in, the stifling effect of *Standardization*$_{it-1}$ on *Innovation*$_{it}$ decreases. Such figures confirm H4.

The robustness checks of Model 6, 7, and 8 are all consistent with the previously mentioned results while all coefficients of interests are statistically significant. Such strong results demonstrate some level of confidence with the current paper's analysis. In short, the analyses have demonstrated statistical support for all four hypotheses of the paper.

Propensity Score Matching

To test my hypotheses on contingent conditions, the current paper utilized the interaction terms. However, the main criticisms of using the interaction terms to test the moderating effect is the possibilities that the contingent conditions only exist in the extremely high or low end levels of the variables of my interest. As a result, it may be inaccurate to call a condition as contingent if such contingency only exists in limited ranges. Moreover, studying the effects of *Standardization*$_{it-1}$ on *Innovation*$_{it}$ is vulnerable to selection biases from unobservable factors that influence a firm to behave certain ways or pursue unique innovative strategies that affect the heterogeneity in the relationship between of *Standardization*$_{it-1}$ and *Innovation*$_{it}$ Therefore, to address such possibilities of biases, I performed a propensity score analysis based on split samples to test the main effect and contingency hypotheses of the paper.

To use this analytical approach, I first identified treatment and control groups from the sample. Based on Table 2, the minimum value for $Standardization_{it-1}$ is 1. As a result, it is difficult to identify what treatment effect is based on the variable. Therefore, I used the count of standards that affect each firm as the treatment effect. I specified the control group as the Forumla One teams that was not affected by standardization in any of the technological categories (Count of $\text{Standards}_{it-1} = 0$). On the other hand, I defined the treatment group as any team that experience the effect of standardization in any of the technological categories (Count of $\text{Standards}_{it-1} > 0$). I differentiated the two groups using a dummy variable (1 for treatment, 0 for control). Then I created a list of propensity scores for all samples by regressing the dummy variable on all team-level characteristics as explained from the previous analysis (*Breadth of Knowledge*$_{it-1}$, *Replaced Technologies* $_{it-1}$, *External Funding* $_{it-1}$, *Firm age* $_{it-1}$, *Ownership Change* $_{it-1}$, *Engine Buyer* $_{it-1}$, *Past Engine Performance* $_{it-1}$, *Driver Change* $_{it-1}$, *Previous Grid Position* $_{it-1}$, *Previous Race Result* $_{it-1}$, *Total Previous Retirements* $_{it-1}$). Using the scores generated from the regression analysis, I performed pairwise matching of the treatment group with the control group. Then I measured the differences in $Innovation_{it}$ between the treatment and control groups for each matched pair. I also analyzed the differences using series of hypothesis testing that tests the differences against the null of zero.

Table 6 reports the Average Treatment Effect on the Treated (ATET), which captures variation of $Innovation_{it}$ based on the treatment ($Standardization_{it-1}$) effect on samples. Test (1) is the full sample test that compares the treatment effect between the two groups of samples. Test (1) reports a negative ATET (-0.435, p-value 0.000) which demonstrates that among the pair of a treatment and control sample, which have similar propensity to experience standardization, the sample that experienced standardization encountered negative progress of innovation. Such result is also consistent with H1.

To test the contingent conditions of H2 and H3, I split the full sample to two groups based on the median values of the contingent variables and conducted the same matching process as mentioned previously. Test (2) and (3) report the ATETs from split sample analysis based on *Breadth of Knowledge* $_{it-1}$. For High *Breadth of Knowledge* $_{it-1,}$ in Test (2), the ATET is negative (-0.102, p-value 0.073). As a result, although the result is statistically marginally significant, it suggests that *Standardization*$_{it-1}$ decreases *Innovation*$_{it}$. Similarly, for Low *Breadth of Knowledge* $_{it-1}$ in Test (3), the ATET is also negative (-0.492, p-value 0.000) with statistical significance. Therefore, I could also infer that *Standardization*$_{it-1}$ decreases *Innovation*$_{it}$ when *Breadth of Knowledge* $_{it-1}$ is low. Test (4) reports the difference in ATET between the two previously mentioned ATETs which a positive ATET (0.390, p-value 0.000) which indicates that the ATET of Low *Breadth of Knowledge* $_{it-1}$ is greater than that of High *Breadth of Knowledge* $_{it-1}$ with statistical significance. Therefore, I could infer that having smaller breadth of knowledge heightens the constraining effect of standardization on innovation which supports H2.

On a similar note, I also used the similar processes to test H3. I split a series of ATET based on the samples' level of *Replaced Technologies*$_{it-1}$. Test (5) shows negative ATET (-0.486, p-value 0.000). The numbers suggest that when *Replaced Technologies*$_{it-1}$

are high, *Standardization*$_{it-1}$ decreases *Innovation*$_{it}$. On the other hand, Test (6) reports positive ATET for samples with Low *Replaced Technologies*$_{it-1}$. However, the result is not statistically significant. With low statistical significance, we may interpret that the effect of *Standardization*$_{it-1}$ on *Innovation*$_{it}$ is not statistically significant when there are only few *Replaced Technologies*$_{it-1}$. Lastly, Test (7) reports negative ATET (-0.594, p-value 0.000) which suggests that the more technologies which are later replaced by standards that a firm has, the more that standardization constrains the firm's innovation.

Unlike the previous contingent conditions, the split sample analysis using the propensity score matching had now statistical significance for the last contingent condition. Similar to the previous analyses, I split a serious of ATET based on the samples' level of *Distant Technological Areas*$_{it-1}$. Both Test (8) and (9) reports negative ATETs (-0.259 and -0.140 respectively) with marginal statistical significance (p-value 0.065 and p-value 0.068). As a result, Test (10) which tests for difference of the two ATETs was also statistically not significant (p-value 0.106). It is difficult to conclude what the Test suggests due to its lack of statistical significance in Test (10). However, the Test still demonstrates that the treatment effect decreases the level innovation for the treatment group compared to the control group.

Visual Illustrations of Contingent Conditions

The current paper also visually represented the contingencies regarding the effect of *Standardization*$_{it-1}$ on *Innovation*$_{it}$ based on *Breadth of Knowledge*$_{it-1}$, *Replaced Technologies*$_{it-1}$ and *Distant Technological Areas*$_{it-1}$ through Figure 1, 4 and 4. I followed the same split sample logic used in the propensity score matching analysis to differentiate high and low levels of the contingent variables. Then I plotted a least-square line of *Innovation*$_{it}$ against *Standardization*$_{it-1}$ for each split sample group. Figure 1, reports that firms with Low *Breadth of Knowledge* $_{it-1}$ experience decreasing levels of *Innovation*$_{it}$ with greater level of *Standardization*$_{it-1}$. On the other hand, firms with High *Breadth of Knowledge* $_{it-1}$ encounter increasing levels of *Innovation*$_{it}$ with greater level of *Standardization*$_{it-1}$. Such differences in the slopes of the two graphs support H2. Furthermore, Figure 2 suggests that the subsample of firms with High *Replaced Technologies*$_{it-1}$ face decreasing levels of *Innovation*$_{it}$ with higher levels of *Standardization*$_{it-1}$. However, firms with Low *Replaced Technologies*$_{it-1}$ experience increasing level of *Innovation*$_{it}$ in accordance with *Standardization*$_{it-1}$. Such results also confirm H3. Lastly, Figure 3 shows that firms with High *Distant Technological Areas*$_{it-1}$ encounter lower level of *Innovation*$_{it}$. Contrastingly, the graph for Low *Distant Technological Areas*$_{it-1}$ have a flatter slope, which indicates less salient main effect of *Standardization*$_{it-1}$ on *Innovation*$_{it}$. In short, the graphs also support H4.

System Level Analysis

As previously explained, Formula One is a unique empirical context that allows the paper to successfully test the theoretical arguments. However, due to its uniqueness, one may question the relationship between standardization and innovation within the industry. Despite the multiple control variables in the main empirical models, one may suggest the possibility of omitted variable bias and claim that firms in Formula One industry may be constrained from innovation due to other factors other than standardization.

To address this concern, I also tested the effect of *Standardization*$_{it-1}$ on *Innovation*$_{it}$ at system level. By looking at how standardization affects the entire industry, we can reduce the possibilities that other firm-specific factors are restricting firms' innovation. Figure 4 reports how annual average *Standardization*$_{it-1}$ and annual average *Innovation*$_{it}$ within the entire Formula One industry changes each year. Then I drew a least-square line of annual average *Innovation*$_{it}$ against *Standardization*$_{it-1}$. Based on the least-square lines, we can infer that the two variables are moving in opposite directions each year which is consistent with my hypotheses and results from my previous empirical analyses. According to Figure 4, there is a decreasing trend in *Standardization*$_{it-1}$ while there is an increasing trend in *Innovation*$_{it}$.

In fact, based on Table 7, which reports a pairwise correlation between annual average *Standardization*$_{it-1}$ and annual average *Innovation*$_{it}$, the pairwise correlation between the two variables is negative (-0.11), which indicates that standardization and innovation are moving in opposite direction at the system level. Table 8 reports the random effect regression coefficient of the relationship between annual average *Standardization*$_{it-1}$ and annual average *Innovation*$_{it}$. Table 8 reports a negative coefficient (t-statistics -3.36, p-value 0.001) which also supports the previous argument regarding the relationship between *Standardization*$_{it-1}$ and *Innovation*$_{it}$ at the system level of the sample.

Conclusion and Discussion

This paper proposes the constraining effects of standardization on firms' innovation within ecosystems along with its contingent conditions. I test the hypotheses with the data on the Formula One industry and a measure that tracks each Formula One team's innovation and the industry's standards in 1970-2020 using a measure of innovation based on Formula One. Findings argue that although standardization may facilitate innovation through coordination of ecosystems, it can also stifle firms' innovation by fixing the core technologies or components to standards. The proposed affect is more salient when firms' portfolio of knowledge cannot accommodate the changes imposed by standardization.

Using the findings of the paper, I would like to convey the message regarding the theoretical tension regarding the relationship between standardization and firms' innovation. It is true that standardization can encourage firms' innovation by successfully coordinating the ecosystem (Baldwin, 2012; Jacobides et al., 2018; Teece, 2018). It helps firms' innovation through specification of the core components or technologies so that other firms can connect to the core with less risk and more certainty (Bekkers et al., 2017; Rysman & Simcoe, 2008). However, although standardization achieves coordination within ecosystems, it also needs to fix technological elements (Garud et al., 2002), which can pose combinational challenges to various members of ecosystems.

As I demonstrated in the paper, the fixing aspect of standardization can stifle firms in two ways. First, it limits the possibilities of new knowledge combinations to the standardized cores (Baldwin, 2012). Thus, standardization eliminates potentials and opportunities of achieving innovation in non-standardized areas. In addition, it forces firms to adapt to the new technological paradigms which can be challenging for the path-dependent organizations (Cohen & Levinthal, 1990; Dosi, 1988). Firms have to desert their existing technologies or knowledge combination activities to accommodate newly emerged standards and the adjustment cost is not negligible.

Through the paper, I do not intend to challenge the notion that standardization facilitates innovation by providing a coordination mechanism. In fact, the paper assumes that it dose promote innovation through the coordination. However, the paper tries to shed a new light on the idea that we may miss the full picture of ecosystems if we fail to recognize the situations when standardization can also constrain innovation at the same time. Although standardization is one of the effective solutions to the coordination challenges in ecosystems, we must comprehend the mechanisms behind how standardization achieves such coordination. And the main message of the paper is that the very mechanism of standardization, which was designed to facilitate innovation through coordination can also hinder innovation.

Another lesson I would like to deliver through the paper is the necessity of utilizing the theoretical perspectives of knowledge combination to examine standardization. Although standardization is closely linked with specifying the core knowledge elements (Baldwin, 2012; Teece, 2018), not much attention has been paid to studying these elements using the theoretical lens of knowledge combination. As the standardized knowledge elements are integral parts of knowledge combination, it is inevitable to use the perspective to study standardization.

In addition, I would like to highlight the empirical approach of this paper in the context of innovation and standardization. The current paper used the machine learning based LDA topic modelling to categorize technological components of the Formula One cars. Although extant research has encountered significant challenges when there is no ready source or method to categorize certain technologies or components, topic modelling can provide a systematic solution to categorizing the components and keeping track of how each technological category evolves over time. Such technological approach has great potentials for future research.

I also would like to highlight the importance of strategically considering standardization as more than a coordination mechanism for ecosystems. In addition to his achievement of coordination to ecosystems, the current paper demonstrated the side effects of standardization that stifle firms' innovation. As a result, rather than simply implementing standardization for the sake of its efficacy in achieving coordination, we need to consider strategic solutions to minimizing the various associated constraints from standardization while maximizing its coordination effect. Although the paper has demonstrated that standardization can pose negative challenges to firms and ecosystems in general, careful considerations of how standardization works and what it is capable of, ecosystems can flourish under the technological directions of standardization.

Chapter II: Need for Speed (to Adapt): Effect of Standardization on Performance of Human Capitals Within Ecosystems in the Formula One Industry

ABSTRACT

Despite the inherent problem of coordination in ecosystems, standardization is an effective coordination tool that can reduce risk and uncertainty of the ecosystems. Previous studies have highlighted the coordinating effects of standardization on various aspects of firms and how standardization can alleviate the coordination problems within ecosystems. Nevertheless, although standardization can decrease the risks associated with the ecosystems, I propose that standardization can also interfere performances of human capitals of each firm by disrupting the human resourcs' abilities to invent, complement, and utilize the standard-based technologies. With data on Formula One motorsports industry involving standard-setting in 1970-2020 and performances of Formula One drivers that are affected by the standardized technologies, I find evidence of the proposed disruption and its contingent conditions. The disrupting effects of standardization on the human capitals' abilities are contingent on similarities of innovations following standardization, statuses of human capitals and knowledge decomposability.

INTRODUCTION

Following emergence of ecosystems, the communities encounter coordination challenges (Gulati et al., 2012; Jacobides et al., 2018). There are numerous associated parties like complementors that need to be compatible with another (Adner, 2017) but lack conventional mechanisms to achieve coordination among each other (Bresnahan & Greenstein, 1999; Kapoor, 2018). In fact, firms of ecosystems prefer their own technologies or components of interest (Farrell & Simcoe, 2012), and thus coordination and compatibility challenges arise in ecosystems (Kapoor & Klueter, 2021; Kretschmer et al., 2020; Teece, 2018). Without knowing how each member can collaborate with one another,

To overcome the coordination challenge within ecosystems, extant literature has suggested standardization as one of the solutions to achieve coordination within ecosystems (Farrell & Saloner, 1988; Rysman & Simcoe, 2008). Through standardization, ecosystems can achieve compatibility or interoperability (Farrell & Simcoe, 2012; Tassey, 2000) that can allow numerous complementors of ecosystems to be able to work with another. Therefore, by providing an opportunity to interoperate with each other, standardization can achieve order through compatibility and risk uncertainty or risks that arise from the coordination challenges of ecosystems. Considering the compatibility and reduced risk within ecosystems, we may expect standardization to positively affect firms' performances.

Nevertheless, to accomplish standardization within ecosystems, ecosystems need to limit core technologies or components to the standardized cores (Garud et al., 2002).

Therefore, standardization aligns technologies and components of various members of the ecosystem only to the standardized cores (Schmidt & Werle, 1998). If organizations already subscribed to the technologies or components that are standardized, the amount of noise or disturbance from the process can be contained to minimum. However, if firms have already focused on competing core technologies or components that did not end up being standardized, the firms will need to encounter various adjustment costs to overcome the disruptions from moving away from their previous core technological pursuits to adjust to the new innovative directions set by standards.

Previous literature has paid attention to such potentially disrupting effects of standardization by focusing on how complementors adjust to the changes within ecosystems following the process of standardization. After standardization, firms need to align their knowledge of technologies to the standards and such process of alignment results in various reactions by the firms. For example, existing literature demonstrated that firms try with their best abilities to make their existing core technologies or components standardized (Ranganathan & Rosenkopf, 2014; Schilling, 2002). The propensity to maintain their technologies or components as standards is to maximize positive externalities and minimize switching costs to transition to another core technologies or components (Katz & Shapiro, 1986).

However, as the process of knowledge alignment requires understanding of what firms know and how they can be compatible to standards, it is necessary to comprehend where within the firms that such organizational knowledge resides in. According to the literature on knowledge-based view, firms' knowledge exists among employees or human capitals of the firms both individual and as a network of human capitals (Hargadon & Sutton, 1997; Kogut & Zander, 1992; Nelson & Winter, 1982; Paruchuri & Awate, 2017). Therefore, to accurately understand the effect of standardization on member firms, it is necessary to study how standardization affects human capitals of each member organization of ecosystems.

Extant literature has examined how ecosystems can affect various related human capitals like inventors or vice versa. For example, previous studies have demonstrated that inventors who are involved in the standardization process are more likely to invent technologies that are more likely to become Intellectual Property Rights (IPR) (Kang & Motohashi, 2015). Moreover, policies of ecosystems can also shape mobility patterns of inventors (Marx, Strumsky, & Fleming, 2009). These existing studies consistently argue that institutions and systems matter in terms of shaping the capabilities of personnel that are closely linked to firms' innovative activities and performances (Bozeman, Laredo, & Mangematin, 2007). At the individual level, existent research has also focused on what are human specific factors that result in firms' innovations or better performances. For instance, personal motives of both pecuniary and nonpecuniary matter that contribute to firm innovations (Sauermann & Cohen, 2010).

Considering the significant roles of human capitals to member organizations of ecosystems, we need to examine how such personnel contribute to the firms' adaptation to standardization and how their performances and behaviors are also affected by standardization. To properly understand the cost of using standardization as a coordination tool and whether such disrupting effect is worth enduring, it is worthwhile to ask *does standardization enhance human capitals' performances despite its disrupting nature?*

To answer the research question, I first recognize that standardization can enhance performances of ecosystem member organizations' human capitals through its role as an effective coordination tool (Baldwin, 2012; Miller & Toh, 2020; Teece, 2018). However, as mentioned previously, once firms fully subscribe to the core technologies or components, they are unwilling to move away from the standardized core for newly developed or standardized technologies or components (Farrell & Saloner, 1985; Hemenway, 1975). In other words, once a firm decides its own core technologies or components or subscribe to standards, it is difficult for them to accommodate newly emerged standards. If such reluctance of the member firms to change innovative and performance pursuits following standardization is true at the organization level, we may infer that such resistance of change also arises from the individual level as well. Just like organizations, human capitals may also be disrupted by standardization by losing positive externalities from previous technologies and paying switching costs. Through the loss of previous positive externalities and incurrence of switching costs, standardization can disrupt the performances of human capitals in ecosystems.

From inventors to (Kapoor & Lim, 2007; Meyer, 2006) to leadership of organizations (Buchholtz, Ribbens, & Houle, 2003; Carpenter, Sanders, Gerard, & Gregersen, 2001), human capitals of organizations influence various aspects of firms' functions. Therefore, if standardization can affect various aspects of member organizations, it can also impact the firms' human capitals in multiple roles as well. For the current research, I adopt knowledge-based approach and organization inertia to focus on how standardization affect the human capitals' knowledge and how the individuals' existing knowledge are well or ill-suited to the changes brought by standardization in ecosystems.

The paper does recognize the role of standardization as an effective coordination tool. As standardization can achieve compatibility within ecosystem (Bekkers, Bongard, & Nuvolari, 2011), standardization can also achieve order at the individual level. Therefore, I acknowledge the positive effect of standardization on human capitals' performance by achieving coordination within ecosystems. Nonetheless, through this research, I would like to demonstrate the disrupting quality of standardization to human capitals of each ecosystem member organization. To identify the boundary condition and flesh out the mechanisms of the main disrupting effects of standardization on human capitals, I also propose a list of contingent conditions that moderate the main effect.

I empirically test he abovementioned theories on disrupting nature of standardization on human capitals through the data on Formula One industry in 1970-2020. By using the data on emergence of standardization within the motorsports industry and Formula One drivers, I study whether standardization activities of the industry enhance or disrupt performances of the drivers. To capture standardization of each component of Formula One race cars and the drivers' knowledge of the components and their readiness to adapt to the standards, I used machine learning based LDA topic modelling techniques. Through the LDA topic modelling analyses, I could categorize different components of Formula One cars, identify which of the components are standardized, find innovations of the race cars in each component and determine each driver's knowledge of the components and standardization of the car parts.

The findings of the paper support the previously mentioned arguments regarding the disrupting effect of standardization on the human capitals' performances. In addition, the findings also demonstrated that the disrupting effect of standardization is contingent on the abovementioned conditions which are human capitals' prior experiences of similar innovative strategies of the firms to accommodate standardization, similarity between pre and post standardization paradigms, and previous experiences of standardization.

By borrowing the knowledge-based approach and organizational inertia perspective, the paper tries to demonstrate how standardization can be disruptive to ecosystem member firms by affecting performances of human capitals within the organizations. Although standardization is an effective mechanism to achieve coordination within ecosystems (Farrell & Saloner, 1985; Kapoor, 2018), to coordinate numerous parties of ecosystems, the process must steer the member organizations away from the technological pathways that have previously chosen and align them to the guidelines of the standards. Such changes can be disruptive to the firms and the paper provides evidence of such disruption by demonstrating how human capitals are affected by the process.

THEORY AND HYPOTHESES

Ecosystems and Coordination

Following emergence of ecosystems, ecosystems often encounter coordination problems due to numerous technological options that member firms can choose from while the communities lack guidelines of such technological choices (Gulati et al., 2012; Rietveld, Schilling, & Bellavitis, 2019; Rosenkopf & Tushman, 1998). Compatibility is essential for firms to collaborate with each other and achieve innovation (Farrell & Saloner, 1985, 1986). In a community where its members have a horizontal authority structure, compatibility is essential for the ecosystem members to be able to work with another (Besen & Farrell, 1994).

However, despite the need of coordination within ecosystems, ecosystems lack conventional mechanisms that can elicit coordination. For example, ecosystems do not have clear leaders that can guide their members to cooperate with each other (Bresnahan & Greenstein, 1999; Kapoor, 2018). In addition, ecosystems do not have contractual mechanisms to enforce compatibility among their members (Jacobides et al., 2018). Therefore, ecosystems have inherent challenges of coordination while it lacks innate structures to achieve coordination among their member organizations.

Nevertheless, extant literature has suggested standardization as one of effective solutions to establish compatibility and bring order in ecosystems (Dokko et al., 2012; Sanchez & Mahoney, 1996). Standardization fixes the core technologies and components to the standardized core (Garud et al., 2002) and guide members of ecosystems to consistent and coherent directions of innovation (Baldwin & Clark, 2000; Jiang, Zhao, Qiu, & Chen, 2012; Leiponen, 2008). In other words, standardization provides specific guidelines for complementors regarding how they can interact with one another based on the standardized core technologies or components (Baldwin & Clark, 2000; Rosenkopf et al., 2001; Updegrove, 2007).

Disrupting Effects of Standardization

However, although standardization can be an effective coordination tool that can achieve compatibility in ecosystems, the order in the communities is not without any cost. As standardization requires members of ecosystems to adhere to its guidelines to be able to interoperate, the process forces member organizations to adjust their strategies and behaviors to be compatible to the standardized cores. Previous literature has demonstrated that introduction of new technologies or paradigms to ecosystems affect and disrupt every member of ecosystems (Ansari, Garud, & Kumaraswamy, 2016). The main disruption from standardization comes from switching costs. Standardization incurs switching costs for its member firms as the organizations will need to transform all their existing innovative strategies to accommodate the newly imposed cores (Choi, 1996; Farrell & Saloner, 1985).

Regardless of standardization, firms are hesitant to transition to different core technologies or components due to the switching costs (Shapiro & Varian, 1998). The switching costs can be defined as the amount of effort and resources required to transition from one paradigm of technology to another (Klemperer, 1987). The switching costs to adopt different core technologies or components are so significant that firms are reluctant to switch to other paradigms even if the cores are clearly superior to those currently adopted by the organizations (Zhu, Kraemer, Gurbaxani, & Xu, 2006). As a result, because of the switching costs required to adopt to standards, member firms of ecosystems often fiercely resist against standardization or try various approaches to make their core technologies or components standardized (Ranganathan & Rosenkopf, 2014).

To better understand the disrupting effect of standardization on its member organizations, it is necessary to understand the details of this switching costs. First, in the perspective of knowledge-based approach, switching cost can be interpreted as changes to the already working knowledge combination configurations which can be disruptive to firms' current operations (Yayavaram & Chen, 2015). Because such changes to firms' strategies and behaviors can be costly, existing literature also notes that firms may be trapped to the core once the firms adopt the core technologies or components (Farrell & Saloner, 1985). To accommodate newly standardized core, members of ecosystems need to rearrange their knowledge element configurations which can be very disruptive to the performances of the firms.

Second, through the lens of organizational inertia, firms have routine processes of activities including innovative activities (Hannan & Freeman, 1984; Zhou & Wu, 2010) and with the well-operating systems in place, organizations are unwilling to change and adopt different systems (Chandy & Tellis, 1998). Organizational change at its core is highly correlated with probabilities of organizational failure (Hannan & Freeman, 1984; Singh et al., 1986). In other words, the disruptive nature of standardization can go beyond interrupting the organizational inertia but even go further and end the life cycle of the firm.

Ecosystems and Human Capitals

Although ecosystems consist of a group of firms, they are also affected by various features of human capitals that work for each member organization. According to the knowledge-based approach, when an organization invents a new technology, it is the inventors within the firm who creates such new knowledge by recombining existing knowledge (Fleming, 2001). Therefore, as firms' innovative activities are done at the individual level, firm's knowledge and innovative capabilities exist among the individual level as well (Hargadon & Sutton, 1997; Kozin & Young, 1994; Paruchuri & Awate, 2017; Reagans & Zuckerman, 2001).

Previous research on ecosystems has recognized the roles of human capitals in ecosystems and how they can affect various aspects of the ecosystems or their member organizations. For example, characteristics of human capitals that migrate into new ecosystems affect innovative capabilities of ecosystems in general (Howard, Boeker, & Andrus, 2019). Moreover, environments and partner firms that inventors interact with affect human capitals' performances (Li, Qiu, & Wang, 2019). As human capitals are the entities that perform knowledge recombination (Fleming, 2001), studying human capitals can provide accurate understanding of how member firms behave and innovate in ecosystems.

Standardization and Human Capitals' Performances

If standardization has disruptive effect on ecosystem member organizations' innovative pursuits, such disruption can be passed down to individual levels as well because human capitals are those who perform the knowledge recombination (Fleming, 2001). Just like organizations need to pay switching costs to new core technologies or components suggested by standardization (Farrell & Saloner, 1985), human capitals who recombine knowledge elements to generate innovation for organizations will need to go through the same process and thus pay their own switching costs as individuals. Following standardization, human capitals will need to decompose existing knowledge couplings and recombine the knowledge elements to accommodate the standardized technologies or components. Although they could spend the effort and resources to further develop their understanding of the existing knowledge combinations, substantial amount of time and resources are required to adjust to the new paradigms set by standardization. As a result, because of the switching costs required by standardization, I propose the following hypothesis regarding the disruptive effect of standardization on human capitals:

H1: Standardization disrupts human capitals' performances in the ecosystem.

Previous Innovative Pursuits

Although organizational changes can be challenging, organizations that have prior experience with the similar organizational change are better equipped with overcoming the challenges from the new change (Kelly & Amburgey, 1991). As a result, if firms' prior experiences can help the organizations' adjustments, member firms' prior experiences of standardizations in specific technologies or components can also help the organizations adjust to changes from standardization. Organizations can gain momentum from their past exposures of certain experiences and then reinforce the experiences or extend them when they encounter similar organizational events (Miller & Friesen, 1984).

Just like organizations can benefit from past events, such positive influence from the past also exists at the individual level. Individuals can learn from past experiences and utilize the lessons learned from the prior events to new situations (Argote & Ingram, 2000). Therefore, prior experiences of human capitals affect various essential aspects of the individuals like innovation, productivity, or commercialization of inventions by allowing the individuals to reuse the lessons learned from the past (Alnuaimi, Opsahl, & George, 2012; Boh, Evaristo, & Ouderkirk, 2014; Nerkar & Shane, 2007; Singh & Agrawal, 2011). Considering how prior experiences of human capitals can equip the individuals with necessary knowledge and skills, it is reasonable to expect human capitals who previously experienced similar firm strategies to overcome the challenges from standardization are less disrupted by standardization.

Even if human capitals experienced certain events in prior different organizations, their experiences could still affect or help their performances in the new organization. For example, when inventors move from one organization to another, inventors bring their knowledge, experiences, and capabilities from previous firm memberships to new ones (Agarwal, Echambadi, Franco, & Sarkar, 2004). Therefore, regardless of the human capitals' organizational memberships, all prior experiences, or events that the individuals experienced can help their adaptation to the disruptive changes from standardization.

When standardization emerges, firms have multiple innovative strategies to react to the disruptive organizational change. Therefore, human capitals who have experienced similar organizational reactions by the firms following standardization will have better knowledge and skills to cope with the changes created by standardization. Considering the effect of prior experiences and how they can better equip human capitals to adapt to the aftermaths of standardization, I propose the following contingent condition:

H2: The more the human capitals' previous firms pursued innovative strategies that are similar to those of the current firms, the less the standardization of components will disrupt the human capitals' performances in the ecosystem.

Standardization and Statuses of Human Capital

In the face of organizational change, the resistance often comes from the individuals of higher status within the organizations as the change can threaten and challenge status of individuals in upper side of the hierarchy (Hannan & Freeman, 1984). In fact, organizational change is a political event through which human capitals of varying statuses and power within the organization clash with one another in their own positions (Schein, 1985). As organizational change can affect all aspects of firms, everyone within the organizations is affected and react differently to the transformations it can bring.

Individuals with higher status within firms feel greater stress from organizational change than those with lower status especially when they do not feel like they are in control of the change (Martin, Jones, & Callan, 2006). Human capitals of higher status have spent much effort and resources to construct organizational routines and systems that best match their strategies. However, when organizational changes emerge, especially when it was enforced by an external force, the change and push organizations and their individuals to break away from their previously well-functioning structures. In fact, for best performances, individuals are better off from constant refinement of their routines (Cohen, 1991). As a result, any disruptive changes imposed by an external entity cannot benefit those who are already benefiting from the effective systems.

Despite the benefit of consistent adjustment, standardization is an opposite of the steady and refined transformation. First, standardization can also shift the locus of value by putting more emphasis on the role of complementary technologies and components (Jacobides & Tae, 2015). Second, in addition to changing the locus of the values, which is up to the firms to pursue, standardization also brings changes to the competitive pressures outside the core technology areas (Toh & Miller, 2017). In other words, human capitals with high status within organizations, who have well-functioning organizational routines to support their individual performances will encounter changes in every aspect of their structures. In fact, the change from standardization is not like any other changes initiated within their organizations as the standardization enforces guidelines set by standard-setting entities (Rysman & Simcoe, 2008). Therefore, the chances of the disruptive changes of standardization being well-curated to specifically enhance the high-status individuals of the organizations are slim. Because the organizational systems and structures are designed by high status individuals within organizations to best match their preferences to enhance their performances, the forced changes will be harder for them to adapt to. Therefore, considering the level of disruptive effect of standardization that is correlated with the status of the human capitals, I propose the following hypothesis:

H3: The lower the human capitals' statuses are, the less the standardization of components will disrupt the human capitals' performances in the ecosystem.

Standardization and Decomposability of Knowledge Element

As mentioned previously, standardization is a process of fixing a core element of knowledge recombination process by fixing the core to standardized technologies or components (Garud et al., 2002). Because all members of ecosystems need to accommodate the standardized cores regardless of their previous knowledge recombination strategies or resources, standardization is a disruptive process. Nevertheless, if firms can easily break away from their existing knowledge configurations to create new ones by including standardized technologies or components, organizations can minimize the disruptions from standardization.

Based on the simple strategy to best adjust to standardization, knowledge decomposability can be an effective mechanism for organizations to best adjust to standardization. According to knowledge-based perspective and knowledge recombination, knowledge decomposability refers to modularity of firms' knowledge base that can be broken down to smaller elements organizations (Baldwin & Clark, 2000; Sanchez & Mahoney, 1996). Such decomposability of knowledge base is an effective tool for firms to adapt to changing environments and efficiently regenerate innovations based on their resources (Yayavaram & Ahuja, 2008; Yayavaram, Srivastava, & Sarkar, 2018). By efficiently breaking away from previous knowledge configurations, firms with knowledge decomposability can efficiently adopt standardized cores to their new knowledge combinations. Therefore, considering the benefits of knowledge decomposability can bring to organizations that can benefit their ability to adapt to standardization, I propose the following last contingent condition:

> *H4: The more decomposable the knowledge of human capitals are, the less the standardization of components will disrupt the human capitals' performances in the ecosystem.*

METHODS

Data and Sample

I empirically test the disruptive effect of standardization on human capitals in the context of Formula One motorsports industry from 1970 to 2020. Formula One industry is an interesting setting that can provide valuable opportunities to test the disruptive effects of standardization on human capitals within ecosystems. First, Formula One motorsports industry is a unique ecosystem that is constantly affected by standardization (Marino et al., 2015). The Fédération Internationale de l'Automobile (FIA), which is an independent regulating entity of Formula One industry annually announces technological standards which all teams or firms need to accommodate. Therefore, standardization activities of the motorsports industry are supposedly exogenous which is an ideal condition to examine how standardization affects human capitals' performances. Moreover, Formula One is an innovation-intensive industry that can demonstrate various interesting dynamics regarding technologies and innovations of each firm (Castellucci & Ertug, 2010).

Second, the motorsports industry has drivers, which is a unique group of human capitals that can represent various aspects of human capitals. In addition to being operators of technologies within firms, drivers are also inventors who contribute to various innovations of the cars. Drivers can provide feedbacks to their teams' car designs (Adam Cooper, 2021) and the teams constantly improve and modify the cars to improve its performances. In fact, some of the most ingenious inventions of the industry were adopted by drivers (Matt Kew, 2022). A successful F1 driver needs to understand all technologies and engineering behind the cars to maximize the capabilities of the F1 cars (Serguei Beloussov, 2018). In short, from inventors to operators of technologies, F1 drivers have multiple roles of each F1 team. Therefore, analyzing how standardization affects performances of the drivers can provide valuable ideas of how the disrupting effect of standardization can affect human capitals of various roles within organizations.

I collected my data regarding driver-specific, race-specific, firm-specific, and standard-specific information from the FIA race database. In addition, I gathered all the data regarding F1 car designs and technologies from F1 periodicals like Autosport. Additional data are collected from each F1 team's annual reports and official websites.

To construct the sample, I first collected all the driver, race, and team information to construct the sample using the FIA race database. Then I added the additional information about car designs, technologies, and standards from the F1 periodicals by matching the information based on time and car models. In the end, I completed the full data which consists of 185 drivers from 250 races.

Variables

The dependent variable of the current model is human capitals' performance, which is drivers' performance each year. Drivers' performances can be measured by how fast drivers drive their race cars, which is the main task of the specific group of human capitals. As a driver, driving a race car fast is more than a simple driving. It is a demonstration of the driver's complete understanding of the engineering behind the cars. To measure *Driver Lap Time*$_{it}$, I found a natural log of an average lap time of each driver on five oldest racetracks (Autodromo Nazionale di Monza, Circuit de Monaco, Silverstone, Circuit de Spa-Francorchamps, and Circuit Gilles Villeneuve) of Formula One industry in milliseconds. During the 50 years of Formula One's race history, race tracks have been constantly added or removed from Grand Prixes. As a result, I utilized the race performance averages of the five oldest racetracks which have constantly hosted Grand Prixes during the time frame.

The main independent variable of the study is standardization. To measure the effect of standardization on performances of human capitals, I generated the variable, $Standardization_{it-1}$, by using machine learning based LDA topic modelling techniques. Each year, the FIA annually announces technological standards for the season and all F1 teams need to come up with new car designs and technologies that are compatible to the standards. As the technologies and innovations of each Formula One is a major determinant of the F1 races, F1 periodicals consistently and extensively cover detailed information of each F1 car. By running the LDA topic modelling analyses using the information of F1 cars from the F1 periodicals, I was able to categorize different components of the F1 cars and which of the components are innovated. In the end, I could identify 9 car components of F1 race cars using the information. Then I captured the total change of innovation in each category which can suggest the level of innovation by each Formula One racing team. I labeled such variable as $Innovation_{it}$ whose usage will be discussed later. Finally, I also ran the topic modelling analyses using the F1 regulation documents on its annually released technological standards. Using the analyses, I could also capture which of the F1 car components are standardized. Therefore, to measure $Standardization_{it}$, *I* calculated the natural log of the total number of F1 car components that are standardized.

The first contingent variable regards to similarity of knowledge configurations between previous and current innovations. To measure such similarity, I compared the changes in each of the race car components by using the previously mentioned measure on firms' innovation. I compared the changes of each of the car components before and after standardization based on the $Innovation_{it}$ variable mentioned previously. In other words, I compared the $Innovation_{it}$ variable of a current year with that of the previous year as new standards are announced annually and teams need to come up with new car designs each year. I named the contingent variable as *Differences of* $Innovation_{it-1}$.

The second contingent condition is about human capitals' statuses within organizations. In Formula One industry, each team can send multiple drivers to racetracks to maximize the constructor's points in tournaments. As a result, each team has had multiple drivers in each Grand Prix. However, the Formula One's scoring system heavily favors podium winners (top three positions) in each race. Thus, most top F1 teams strategize to favor their more qualified drivers to win the race while other drivers support the team strategy to put the better drivers on the podium. Therefore, there is a clear status and power dynamics among F1 drivers within each F1 team. Noting such interesting dynamics within F1 teams, I constructed the variable *Human Capital* $Status_{it-1}$ by identifying the best performing driver in each team. I identified the best driver in each team each year by calculating the average lap time of the drivers in each season. Then I input the label of 1 if they are the best performing driver in the team and 0 if otherwise.

The third contingent concerns knowledge decomposability of current knowledge configuration. In Formula One, the single most important component of F1 race cars is engine. While half of the teams construct their own engines, another half purchase the engine components from other firms. There have been cases where firms switch between making their own engines to buying the engines from other suppliers and vice versa. Because the engines is the key component of the car, the main goal for all F1 team is to construct a car where all the components are well integrated to the functions of the engine. As a result, when a driver has driven a car with the same engine for a long period, all the techniques and knowledge would be based on the specific engine. Therefore, it would be difficult for the driver to break away from his or her knowledge of current race car configuration. Therefore, to calculate the knowledge decomposability, I calculated the total continuous years that each driver has used the same engine. I named the variable as *Knowledge Indecomposability*$_{it-1}$

To ensure accuracy of my empirical analyses, I used a series of control variables to control for all team, driver, and environment specific effects. First, I controlled for each F1 team's *Breadth of Knowledge*$_{it-1}$ by calculating total number of components that firms have innovated in based on the previously mentioned topic analysis. Second, while each team's financial situation can be an important indicator of the drivers' performances, the financial data of the F1 teams are not publicly available because no F1 motorsports team is a public company. However, although I was unable to get an actual financial data of each F1 team, I utilized a proxy measure to control for the teams' finances. One of the biggest indicators of each team's financial situation is whether the team has any parent company to sponsor their operations. For example, Mercedes-AMG Petronas Formula One Team has the auto company, Mercedes-Benz, one of the largest car companies in the world, as their parent company. On the other hand, Haas F1 Team does not have a parent company and must sponsor its own operations. As a result, I controlled for whether a team has a parent company and labeled it as *Parent Company*$_{it-1}$.

For driver-specific control variables, I first controlled for whether drivers experienced any *Team Change*$_{it-1}$. In addition, I took account of drivers' personal capabilities to try to accurately isolate the effect of standardization on drivers' performances. Therefore, I controlled for drivers *Previous Rankings*$_{it-1}$, and *Previous Grid Positions*$_{it-1}$ by calculating the best ranking of the driver in the previous season and natural log of the average grid position of each driver in previous season. I also recognized drivers' *Previous Failure*$_{it-1}$ by calculating a natural log of the total number of race retirements during a previous season. Lastly, I controlled for previous performance of each driver's engine by measuring the natural log of the best grid position that the car with the specific engine won in the previous year. I named the variable is *Previous Engine Performance*$_{it-1}$.

As a season-specific control variables, I controlled for each driver's previous season team's performance and labeled it as *Previous Team Performance*$_{it-1}$. Lastly, I took note of the difficulty of each season by measuring the total number race retirements by calculating each team's average number of retirements for each season. The variable is called *Season Difficulty*$_{it-1}$. I also controlled for team and year with dummy variables.

Empirical Models and Findings

Table 9 and Table 10 report descriptive statistics and correlations of my sample. *Driver Lap Time*$_{it}$ shows a mean of 11.544 with standard deviation of 0.144, minimum value of 11.215 and maximum value of 12.258. if we calculate the inverse natural log form of the numbers, the mean average lap time of the driver is 103156.238 milliseconds, with standard deviation of 1.155 milliseconds with minimum value of 74235.667 milliseconds and maximum value of 210659.844 milliseconds. The figure is a lap time instead of race time. Thus, in the end of the race, the differences among drivers are bigger than their lap time differences. However, considering the standard deviation of 1.155 milliseconds lap time, we can infer how cutthroat the competition is in Formula One industry and how all drivers, engineers, circuit staffs, and all individuals within the team are trying their best to make that 1 millisecond of difference on the racetrack. Furthermore, if we calculate the inverse natural log of $Standardization_{it}$'s mean value of 1.183, we can interpret that on average, 3.264 number of components within F1 cars are affected by standardization. According to Table 10, which shows pairwise correlations of all models, all correlations figures are considerably low and how low chances of multicollinearity problem.

To test the effect of $Standardization_{it-1}$ on $Driver\ Lap\ Time_{it}$, I used the fixed effects models. The main challenge of testing the model is measuring the pure disruptive effect of $Standardization_{it-1}$ on $Driver\ Lap\ Time_{i+1t}$, while isolating all the variables like drivers' talent that can affect the performances of drivers. Although I utilized various control variables to control for such effects, I recognized that there may be unobserved heterogeneity that is constant over time that I could not include in my model. Based on the assumptions, I decided to use the fixed effects model to test my hypotheses. Table 11 shows the list of fixed effects regression models. Model 1 is the base model that tests the main effect. Model 2 tests the first ($Differences\ of\ Innovation_{it-1.}$) and second ($Human\ Capital\ Status_{it-1}$) contingent conditions. In addition, Model 3 tests the first (*Differences of*

Innovation$_{it-1.}$) and third (*Knowledge Indecomposability*$_{it-1}$) conditions. Lastly, Model 4 tests the second and third (*Knowledge Indecomposability*$_{it-1}$) contingent conditions. Model 5 is the full model of the analysis and Model 6 also tests the full model with robust standard error to test any chances of heteroskedasticity.

Model 1 shows that *Standardization*$_{it-1}$ does slow down *Driver Lap Time*$_{it}$ (t-statistics 4.35, p-value 0.000) with statistical significance. In all six variations of the model, the main effect holds its statistical significance. Based on Model 5, the full model, 1% increase of standardization leads to 0.223% increase (t-statistics 2.15, p-value 0.033) in drivers' lap time. While the percentage increase may look small, such difference determines winners and losers. For example, the mean lap time of our sample is 103156.238 milliseconds, with standard deviation of 1.155 milliseconds. 0.0348% of the mean value is 230.038 milliseconds. In other words, according to the results, standardization does significantly disrupt the performances of drivers based on the model and supports H1.

According to Model 2 (t-statistics 2.41 p-value 0.016), Model 3 (t-statistics 1.98 p-value 0.049) and Model 5 (t-statistics 2.41 p-value 0.016), the coefficients of the interaction term, *Standardization*$_{it-1}$ *X Differences of Innovation*$_{it-1}$, show that the disrupting effect of standardization is more salient when the innovation is more different from the previous one. In all three models, the results are statistically significant. In other words, it can be inferred that when innovations based on standardization leads to completely different innovations from previous year, standardization is more disruptive to performances of human capitals which supports the second hypothesis H2.

Based on Model 2 (t-statistics 1.98 p-value 0.048), Model 4 (t-statistics 1.98 p-value 0.048) and Model 5 (t-statistics 2.14 p-value 0.033), the interaction term, *Standardization*$_{it-1}$ *X Human Capital Status*$_{it-1}$, demonstrates that standardization slows down the drivers even further when drivers have higher status. The results are also statistically significant in all three different models. In other words, the negative effect of standardization on human capitals' performances is stronger when the individuals have higher status within organizations. Therefore, the figures also support the third hypothesis H3.

Lastly, According to Model 5(t-statistics 2.11 p-value 0.035), along with Model 3 that has marginal significance (t-statistics 1.90 p-value 0.059), the interaction term, *Standardization*$_{it-1}$ *X Knowledge Indecomposability*$_{it-1}$, shows that the standardization's disrupting effect on performances of human capitals is greater when the knowledge of individuals is indecomposable. Although Model 4(t-statistics 1.54 p-value 0.123) was statistically not significant, it can be inferred that the results of the models marginally support H4.

In addition, Model 6 which is the full model with robust standard error supports all previously mentioned hypotheses with statistical significances as following: H1(t-statistics 2.62 p-value 0.010), H2 (t-statistics 3.63 p-value 0.000), H3 (t-statistics 2.68 p-value 0.000)

Propensity Score Matching

This chapter of the dissertation examines how *Standardization*$_{it-1}$ affects *Driver Lap Time*$_{it}$. Considering how no drivers can avoid enforcement of standardization by the FIA, the chances of any selection bias that may affect heterogeneity of the analysis is very slim. Nevertheless, to minimize the chances of and unobserved factors that can influence the heterogeneity of the current research, further analyses might be beneficial. Furthermore, in the previous analyses, I utilized fixed-effects regression analyses to test the main hypothesis and its contingent conditions. However, using interaction terms to test moderating conditions may be convoluted as interaction terms may be only able to capture extreme values of the moderators to demonstrate the moderating effects. Therefore, to address the potential existence of selection bias and criticism regarding using the interaction effects, I performed matching analyses to test the main hypothesis and its contingent conditions as well. I used propensity score matching technique to report average treatment effect (ATE). Table 12 reports the results of the matching analyses.

To perform the matching analysis, I assigned a group of samples with higher level of standardization components that is above the sample median as treatment group. On the other hand, the group with lower level of standardization components that is smaller than the sample median as control group. I matched the groups using all the driver-specific variables mentioned in the previous section.

To test the contingent conditions, I divided the contingent variables by their median values to run the matching analyses separately among the different levels of contingent variables and then test for their significance of differences through the matching analysis. According to Table 12, Test 1 is the full model which tests H1, the main effect. Then Test 2 and Test, 3 test the first contingent condition hypothesis, H2 by dividing the *Differences of Innovation*$_{it-1}$ to two groups by its median value. Similarly, Test 4 and Test 5 examine the second condition, H3, and Test 6 and Test 7 study the last hypothesis, H4.

According to Test 1, the average treatment effect (ATE) is positive (0.0331 p-value 0.000). As a result, Test 1 proves that the treatment effect of standardization increases the lap time of F1 drivers and thus decreases the human capitals' performances.

Test 2 and Test 3, which is a split sample matching analysis of *Differences of Innovation*$_{it-1}$. Test 2's positive ATE (0.0355 p-value 0.000) indicates that when the difference of innovation is substantial compared to previous innovation, it also disrupts' individuals' performances. On the other hand, Test 3's statistically insignificant ATE (p-value 0.130) show that the effect of standardization on individuals' performance is insignificant when the differences between consecutive innovations are small. As a result, statistically significant positive coefficient of Test 2 and statistical insignificance of Test 3 support H2 by showing that standardization affects drivers who experience greater differences of innovation.

In addition, Test 4 and Test 5 is a split sample matching analysis of *Human Capital Status*$_{it-1}$. Both Test 4 (0.0158 p-value 0.320) and Test 5 (0.0223 p-value 0.094) have positive ATEs which demonstrate that Human Capitals' statuses of all levels are affected by the negative effects of standardization. Nevertheless, the ATE of Test 4 is statistically insignificant while Test 5 is marginally significant. As a result, it was challenging to allude much conclusion to test H3 through the propensity score matching technique..

Lastly, Test 6 and Test 7 test the contingent condition of knowledge indecomposability. Test 6 has a positive and statistically significant ATE (0.0284 p-value 0.037). Such result tells us that standardization does have significant effect when knowledge is highly indecomposable. Nevertheless, Test 7 has a statistically insignificantATE (0.0199 p-value 0.212) which indicates that standardization does not pose significant effect on drivers who experience low knowledge composability. As a result, statistical significance of Test 6 and insignificance of Test 7 support H4.

Conclusion and Discussion

The current paper demonstrates the disruptive effects of standardization on performances of human capitals within ecosystem as well as the contingent conditions of the main effect. I empirically test the hypotheses using the data on the Formula One industry by studying how standardization affects racing speed of top major Grand Prixes each year during 1970-2020. I also developed my own measure of tracking the effect of standardization and relevant innovations of the industry using the LDA topic modelling techniques. Findings highlight that while standardization can bring coordination within ecosystems, it can also bring disruption to communities by forcing the individuals of ecosystems to change their prior routinized strategies. Human capitals can weaken the disruptive effect of standardization if they have more prior experiences with the disruptions from standardization.

Despite the demonstration of the disruptive effect of standardization on performances of human capitals, the current paper does not intend to deliver any message that standardization in ecosystem only has negative effects on the member organizations. Instead, the paper fully recognizes the coordinating effect of standardization (Jacobides et al., 2018; Teece, 2018). However, the first message that the paper would like to convey through its work is that standardization is more than a simple coordination tool. In fact, standardization has multifaceted aspects that can pose various effects on member organizations of ecosystems in both organization and individual levels.

Furthermore, the second lesson that this paper wanted to show is the disruptive nature of standardization. As standardization refers to enforcing guidelines of how ecosystem members should perform their activities (Bekkers et al., 2017; Rysman & Simcoe, 2008), standardization can also be interpreted as a forced organizational change that firms did not intend or want. Considering the noise and turmoil that organizational changes can bring to the focal firms (Singh et al., 1986), the unintended changes from standardization can also be disruptive to the nature of the member organizations of ecosystems.

Furthermore, the third message the paper would like to demonstrate is the importance of human capitals when studying ecosystems and to be specific, standardization. Extant literature on firm knowledge and human capitals have recognized the roles of human capitals as those who are directly involved in activities of the firm. For example, literature on knowledge recombination showed that while it is the firm in general that come up with innovations, it is the human capitals within the firms that recombine knowledge elements to generate innovation (Fleming, 2001). As a result, when discussing the effect of standardization on the member organizations of the ecosystems, it is also necessary to consider how the influences from the phenomenon affect individuals within the organizations.

Lastly, on the empirical side, the paper also provides some valuable message in terms of the way future studies can capture standardization to analyze their effects on ecosystems. Rather than simply counting the number of standards, the current research was able to capture the actual impact of standardization activities by measuring its impact on each of the categorized components. Such categorization was possible through the machine learning based LDA topic modelling analyses. Because of its powerful ability to classify large sample text data, the topic modelling analyses can be a useful tool to categorize complex technological systems to observe how each component is affected by standardization.

The current research is not without any limitation. First, although the paper utilized the F1 drivers' performances to examine how standardization disrupts human capitals' performances, standardization can affect various other roles within ecosystem member organizations differently. As mentioned previously, because the F1 drivers have unique roles within F1 teams that can represent multiple human capital roles, future research that involves other positions or roles of human capitals may be beneficial.

Moreover, the paper measured human capitals' performances as racing speed of the drivers in top Grand Prix races. Although the racing speed is the most representative measures of capturing performances of the F1 drivers, human capitals' performances can be measured in multiple dimensions which call for future research using different measures of human capitals' performances.

As mentioned throughout the paper, standardization is an effective coordination tool that can bring stability and order to ecosystems. However, without understanding the sacrifices that member firms need to make to achieve the coordination, standardization cannot be the panacea for all coordination challenges. To fully comprehend standardization's role as a coordination tool, we need to understand what the changes are that ecosystem member firms are required to adopt and how such transitions can affect performances and behaviors of the firms.

Conclusion

Contrary to numerous extant research on standardization, which praises standardization as an effective coordination tool, the current dissertation aimed its research focus on negative effects of standardization on members of ecosystems. From the literature review, the dissertation recognized that standardization's coordination mechanisms directly affect firms' knowledge recombination processes. Nevertheless, the literature review pointed out that the current state of research on standardization lacks analyses that directly study the effect of standardization on various aspects of the firm regarding knowledge recombination process.

As a result, the dissertation empirically tested the effect of standardization on various aspects of the firm in the context of Formula One industry. First, the dissertation demonstrated the constraining effect of standardization on firms' innovative activities by pointing out that standardization fixes the core technologies and components, which can restrict firms' recombination capabilities. In the later chapter, the dissertation then established how standardization can disrupt performances of human capitals within ecosystem member firms as standardization poses unintended organizational changes to its members.

Through the dissertation, I do not intend to deny the coordinating effect of standardization on ecosystems. In fact, the dissertation fully recognizes such benefits of standardization. However, the main message that this dissertation would like to convey is the idea that the literature on standardization deserves a closer look at what standardization does to the knowledge recombination process of its member firms.

Standardization elicits coordination by directing its complementors regarding how they should accommodate the standardized cores. Therefore, to gain a full picture of what standardization can do to ecosystems, we need to understand what such imposed guidelines mean as a member organization of the ecosystems or as an individual within the firm.

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Appendix

Figure 1. *Effect of Standardization$_{it-1}$* on *Innovation$_{it}$* by *Breadth of Knowledge$_{it-1}$*

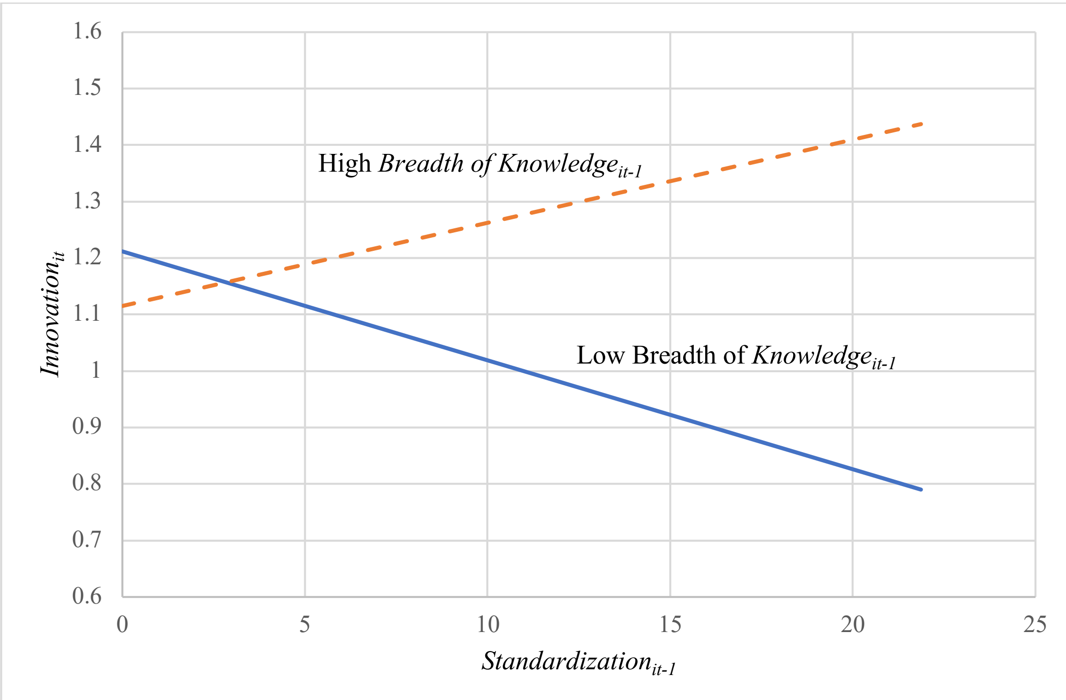

Figure 2. *Effect of Standardization$_{it-1}$* on *Innovation$_{it}$* by *Replaced Technologies$_{it-1}$*

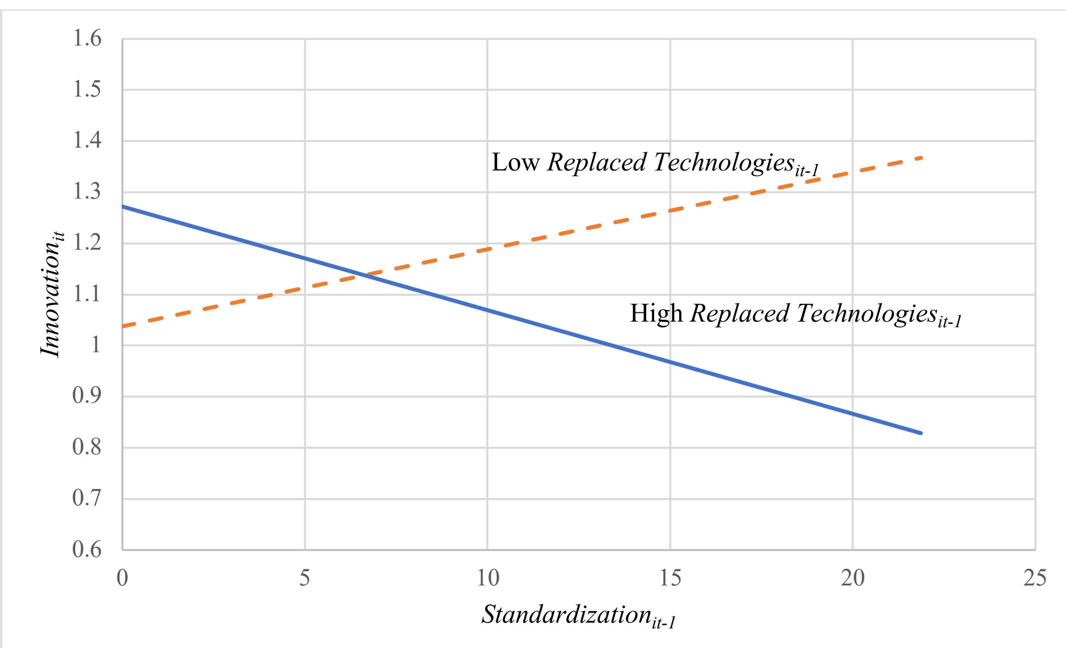

Figure 3. *Effect of Standardization$_{it-1}$* on *Innovation$_{it}$* by *Technological Distance$_{it-1}$*

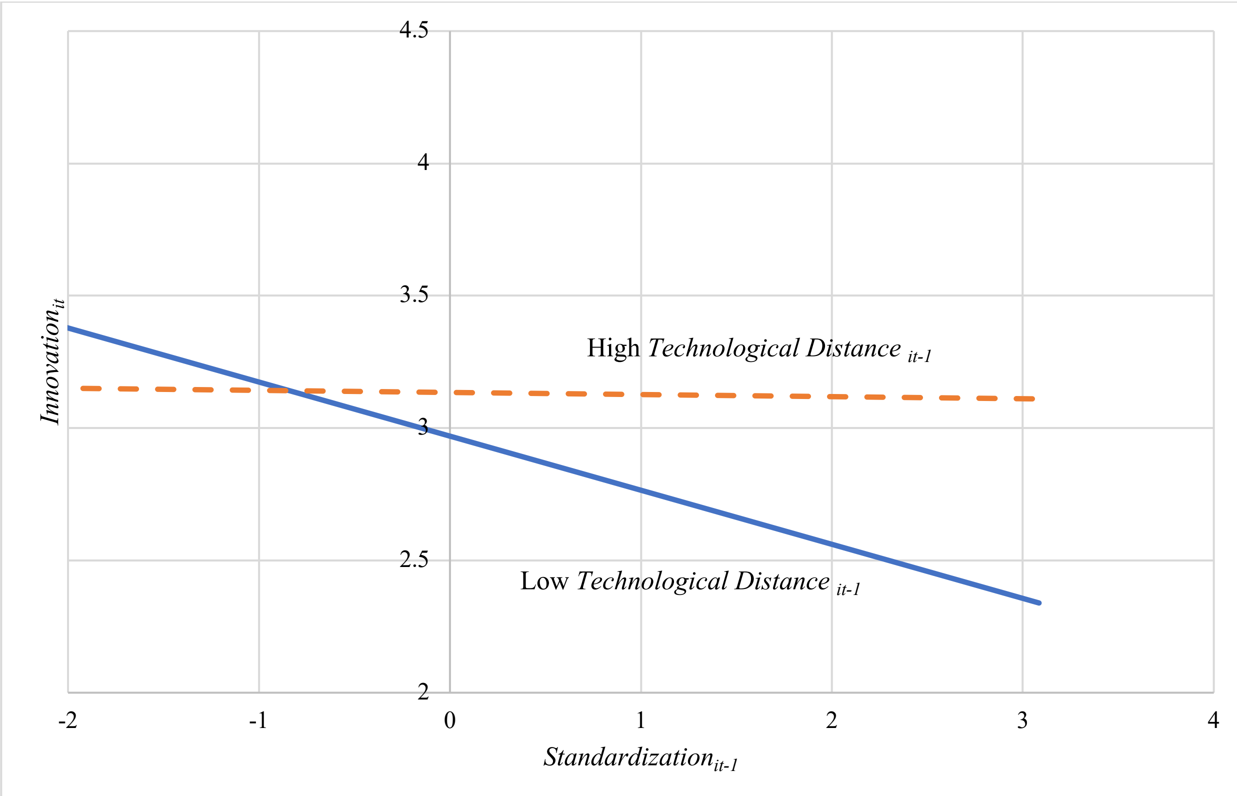

Figure 4. *Total Annual Innovation VS Total Annual Standardization*

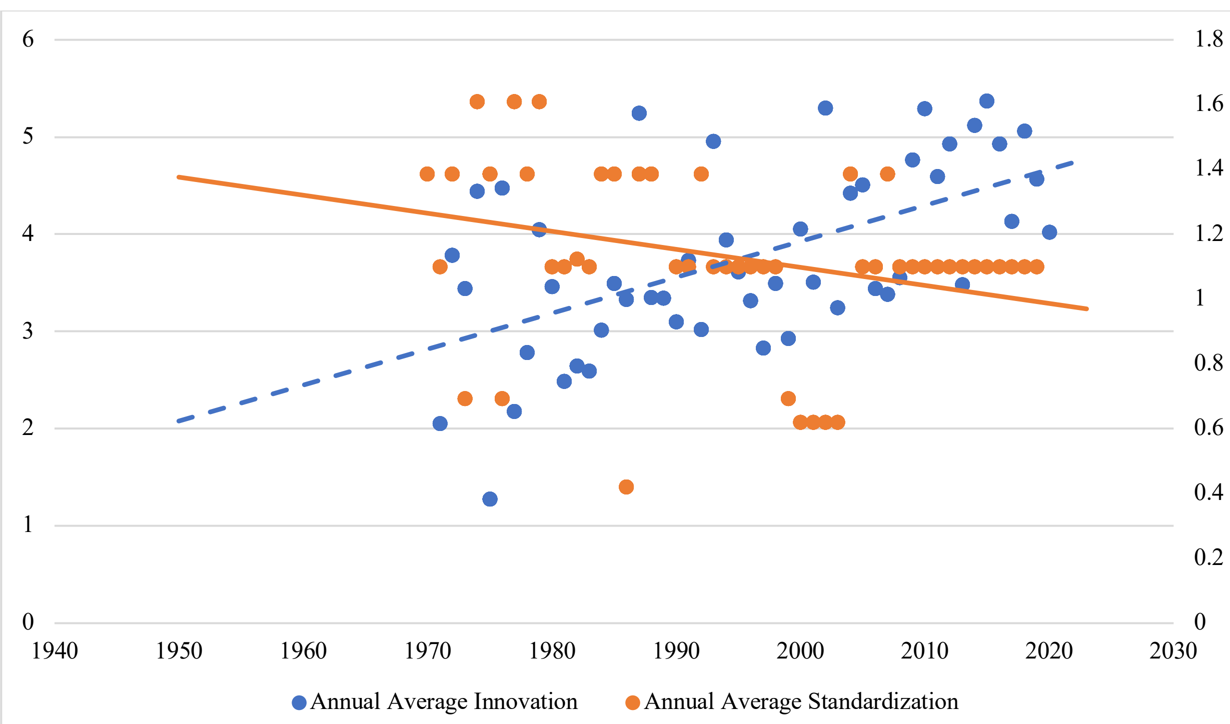

Table 1. *Summary of Literature Review*

	Antecedents of Standardization	Firms' Reaction to Standardization	Consequence of Standardization
Main Topics	Factors that affect standardization, Process of standards setting, Political dynamics of standardization	Firms' reaction to standardization, How firms comply with standardization,	What Standards do to ecosystems, Change of values within ecosystems, Coordination within ecosystems
Sample Research	Lemley, 2007; Shapiro & Varian, 1998; Simcoe, 2012; Toh & Miller, 2017; Updegrove, 2007; Rysman & Simcoe, 2008	Teece, 1986; Teece, 2018; Miller & Toh, 2021; Ranganathan & Rosenkopf, 2014; Baldwin 2012	Baldwin & Woodward, 2009; Teece, 1986; Updegrove, 2007; Jacobides & Tae, 2015; Farrell & Saloner, 1985

Table 2. *List of Identified Technology Categories based on LDA Topic Model Analysis*

	List of Identified Topics
Components Related Topics	1. Engine 2. Front Wing 3. Diffuser 4. Chassis 5. Suspension 6. Wheel 7. Gearbox 8. Fuel 9. Brake
Unrelated Topics	10. Aerodynamics 11. Standards 12. Course/Racetracks

Table 3. *Descriptive Statistics*

Variables	Mean	Std. Dev	Min	Max
Innovation $_{it}$	4.067	2.804	0.000	21.864
Standardization $_{it-1}$	1.148	0.304	0.000	1.609
Breadth of Knowledge $_{it-1}$	0.698	0.843	0.000	2.000
Replaced Technologies $_{it-1}$	-0.910	0.477	-3.880	-0.109
Technological Distance $_{it-1}$	-1.293	0.542	-3.470	-0.199
External Funding $_{it-1}$	0.530	0.500	0.000	1.000
Firm Age $_{it-1}$	2.014	1.135	0.000	3.871
Ownership Change $_{it-1}$	0.004	0.059	0.000	1.000
Total Previous Retirements $_{it-1}$	2.278	0.619	0.000	3.584
Driver Change $_{it-1}$	0.326	0.470	0.000	1.000
Engine Year $_{it-1}$	11.200	11.724	1.000	48.000
Past Engine Performance $_{it-1}$	12.095	3.342	3.306	22.292
Previous Grid Position $_{it-1}$	10.619	4.945	0.000	23.250
Previous Race Result $_{it-1}$	2.408	0.387	1.155	3.466

Table 4. *Pairwise Correlations*

	Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
(1)	*Innovation* $_{it}$	1.00													
(2)	*Standardization* $_{it-1}$	-0.02	1.00												
(3)	*Breadth of Knowledge* $_{it-1}$	0.11	0.00	1.00											
(4)	*Replaced Technologies* $_{it-1}$	-0.03	0.10	-0.11	1.00										
(5)	*Technological Distance* $_{it-1}$	-0.03	-0.19	0.17	-0.74	1.00									
(6)	*External Funding* $_{it-1}$	0.08	-0.04	0.56	-0.22	0.20	1.00								
(7)	*Firm Age* $_{it-1}$	0.11	-0.14	0.24	-0.21	0.14	0.23	1.00							
(8)	*Ownership Change* $_{it-1}$	0.06	-0.01	0.02	0.03	-0.04	0.06	-0.05	1.00						
(9)	*Total Previous Retirements* $_{it-1}$	0.03	0.13	-0.13	0.32	-0.21	-0.29	-0.24	-0.11	1.00					
(10)	*Driver Change* $_{it-1}$	0.07	0.11	-0.14	0.01	-0.03	-0.26	-0.19	-0.04	0.27	1.00				
(11)	*Engine Year* $_{it-1}$	0.10	-0.11	0.23	-0.19	0.13	0.23	0.77	-0.04	-0.31	-0.19	1.00			
(12)	*Past Engine Performance* $_{it-1}$	-0.04	0.19	-0.20	0.23	-0.15	-0.39	-0.42	-0.04	0.50	0.39	-0.34	1.00		
(13)	*Previous Grid Position* $_{it-1}$	0.01	0.00	-0.28	0.15	-0.20	-0.46	-0.33	-0.08	0.32	0.32	-0.28	0.56	1.00	
(14)	*Previous Race Result* $_{it-1}$	0.00	0.11	-0.27	0.21	-0.18	-0.46	-0.39	-0.08	0.65	0.36	-0.37	0.74	0.74	1.00

Table 5. *Random Effects Regression Model*

Dependent Variable	Innovation $_{it-1}$							
	Base Model (RE)	Breadth of Knowledge$_{it-1}$ & Replaced Technologies$_{it-1}$ (RE)	Breadth of Knowledge$_{it-1}$ & Technological Distance$_{it-1}$ (RE)	Replaced Technologies$_{it-1}$ & Technological Distance$_{it-1}$ (RE)	Full Model (RE)	OLS	Robust SE (RE)	RE with Autoregression (1)
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
Standardization $_{it-1}$	-10.10	-16.82	-15.24	-26.87	-35.66	-17.74	-35.66	-33.15
	(-1.67)	(-2.48)	(-2.41)	(-3.19)	(-4.07)	(-3.19)	(-3.22)	(-3.80)
Breadth of Knowledge $_{it-1}$		-1.191	-1.171		-1.925	-1.925	-1.925	-1.764
		(-1.37)	(-1.35)		(-2.19)	(-2.19)	(-2.23)	(-2.06)
Standardization $_{it-1}$		1.448	1.383		2.024	2.024	2.024	1.806
X Breadth of Knowledge $_{it-1}$		(2.02)	(1.94)		(2.79)	(2.79)	(2.15)	(2.59)
Replaced Technologies $_{it-1}$		3.143		10.30	13.15	13.15	13.15	11.78
		(1.26)		(2.71)	(3.39)	(3.39)	(2.56)	(3.10)
Standardization $_{it-1}$		-2.629		-8.406	-10.96	-10.96	-10.96	-10.04
X Replaced Technologies $_{it-1}$		(-1.19)		(-2.53)	(-3.23)	(-3.23)	(-2.30)	(-3.01)
Technological Distance $_{it-1}$			2.037	8.022	9.537	9.537	9.537	9.286
			(1.12)	(2.89)	(3.39)	(3.39)	(2.44)	(3.39)
Standardization $_{it-1}$			-1.547	-6.105	-7.444	-7.444	-7.444	-7.449
X Technological Distance $_{it-1}$			(-1.04)	(-2.70)	(-3.26)	(-3.26)	(-1.99)	(-3.37)
External Funding $_{it-1}$	0.611	0.0787	0.176	0.591	0.144	0.144	0.144	0.253
	(1.50)	(0.16)	(0.36)	(1.46)	(0.30)	(0.30)	(0.31)	(0.47)
Firm Age $_{it-1}$	0.221	0.120	0.133	0.182	0.0933	0.0933	0.0933	0.178
	(0.81)	(0.43)	(0.48)	(0.67)	(0.34)	(0.34)	(0.37)	(0.60)
Ownership Change $_{it-1}$	2.560	2.211	2.671	2.747	2.600	2.600	2.600	2.216
	(0.84)	(0.73)	(0.88)	(0.91)	(0.87)	(0.87)	(3.24)	(0.76)
Total Previous Retirements $_{it-1}$	0.691	0.898	0.862	0.608	0.807	0.807	0.807	0.690
	(1.45)	(1.87)	(1.78)	(1.27)	(1.69)	(1.69)	(1.76)	(1.41)
Driver Change $_{it-1}$	0.694	0.697	0.637	0.689	0.641	0.641	0.641	0.543
	(1.67)	(1.68)	(1.54)	(1.67)	(1.57)	(1.57)	(2.00)	(1.32)
Engine Year $_{it-1}$	0.00590	0.00738	0.00544	0.00350	0.00483	0.00483	0.00483	0.00356
	(0.25)	(0.31)	(0.23)	(0.15)	(0.21)	(0.21)	(0.27)	(0.13)
Past Engine Performance $_{it-1}$	-0.0117	-0.0290	-0.0175	-0.00905	-0.0166	-0.0166	-0.0166	-0.0226
	(-0.13)	(-0.34)	(-0.20)	(-0.11)	(-0.20)	(-0.20)	(-0.26)	(-0.25)
Previous Grid Position $_{it-1}$	0.0172	0.0180	0.0354	0.0329	0.0415	0.0415	0.0415	0.0428
	(0.28)	(0.30)	(0.58)	(0.54)	(0.69)	(0.69)	(0.62)	(0.68)
Previous Race Result $_{it-1}$	0.0438	-0.262	-0.294	-0.00307	-0.386	-0.386	-0.386	-0.0289
	(0.04)	(-0.26)	(-0.29)	(-0.00)	(-0.39)	(-0.39)	(-0.46)	(-0.03)
Year	On	On	On	On	On	On	On	On
Constant	13.15	21.57	19.85	34.63	45.19	24.10	45.19	40.93
	(1.74)	(2.58)	(2.49)	(3.34)	(4.20)	(3.69)	(3.64)	(3.80)
Observations	285	285	285	285	285	285	285	285

Table 6. *Propensity Score Matching ATET*

Dependent Variable: *Innovation*$_{it}$				
Test	Average Treatment Effect on the Treated	A&I Robust Standard Error	p Value	N
(1) Full Model	-0.435	0.099	0.000	501
(2) High *Breadth of Knowledge*$_{it-1}$	-0.102	0.057	0.073	351
(3) Low *Breadth of Knowledge*$_{it-1}$	-0.492	0.094	0.000	150
(4) High *Breadth of Knowledge*$_{it-1}$ - Low *Breadth of Knowledge*$_{it-1}$	0.390	0.106	0.000	501
(5) High *Replaced Technologies*$_{it-1}$	-0.496	0.061	0.000	272
(6) Low *Replaced Technologies*$_{it-1}$	0.108	0.076	0.156	229
(7) High *Replaced Technologies*$_{it-1}$ - Low *Replaced Technologies*$_{it-1}$	-0.594	0.096	0.000	201
(8) High *Technological Distance*$_{it-1}$	-0.259	0.065	0.000	336
(9) Low *Technological Distance*$_{it-1}$	-0.140	0.068	0.042	165
(10) High *Technological Distance*$_{it-1}$ - Low *Technological Distance*$_{it-1}$	-0.120	0.106	0.260	501

Table 7. *Pairwise Correlations Between Annual Average Innovation & Annual Average Standardization*

	(1)	(2)
(1) Annual Average Innovation	1.00	
(2) Annual Average Standardization	-0.11	1.00

Table 8. *Random Effects at System Level*

Dependent Variable:	Annual Average Innovation$_{it}$
	RE
Annual Average Standardization $_{it-1}$	-4.974
	(-3.36)
Year	On
Constant	10.28
	(5.78)

t statistics in parentheses

Table 9. *Descriptive Statistics*

Variable	Mean	Std. Dev.	Min	Max
Driver Lap Time $_{it}$	11.544	0.144	11.215	12.258
Standardization $_{it-1}$	1.183	0.376	0.000	2.197
Differences of Innovation $_{it-1}$	1.319	0.744	-1.577	3.089
Human Capital Status $_{it-1}$	0.505	0.500	0.000	1.000
Knowledge Indecomposability $_{it-1}$	1.142	1.457	0.000	10.000
Breadth of Knowledge $_{it-1}$	1.065	0.392	0.000	1.792
Parent Company $_{it-1}$	0.476	0.500	0.000	1.000
Team Change $_{it-1}$	0.382	0.486	0.000	1.000
Previous Ranking $_{it-1}$	5.660	3.550	1.000	17.000
Previous Grid Position $_{it-1}$	2.236	0.609	0.182	3.296
Previous Failure $_{it-1}$	0.863	0.558	0.000	1.609
Previous Engine Performance $_{it-1}$	1.571	0.652	0.000	3.296
Previous Team Performance $_{it-1}$	11.553	0.153	11.215	12.283
Season Difficulty $_{it-1}$	2.559	1.327	0.000	5.000

Table 10. *Pairwise Correlations*

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
(1) *Driver Lap Time* $_{it}$	1.00													
(2) *Standardization* $_{it-1}$	0.00	1.00												
(3) *Differences of Innovation* $_{it-1}$	-0.06	-0.04	1.00											
(4) *Human Capital Status* $_{it-1}$	-0.25	-0.02	0.01	1.00										
(5) *Knowledge Indecomposability* $_{it-1}$	-0.15	0.00	-0.04	-0.02	1.00									
(6) *Breadth of Knowledge* $_{it-1}$	0.07	0.11	-0.02	0.00	-0.03	1.00								
(7) *Parent Company* $_{it-1}$	-0.24	0.01	0.06	0.05	0.19	0.00	1.00							
(8) *Team Change* $_{it-1}$	0.03	-0.06	0.29	0.05	-0.33	-0.01	-0.15	1.00						
(9) *Previous Ranking* $_{it-1}$	0.27	0.04	-0.01	-0.09	-0.24	-0.03	-0.31	0.20	1.00					
(10) *Previous Grid Position* $_{it-1}$	0.26	-0.03	0.02	-0.14	-0.25	-0.01	-0.32	0.19	0.63	1.00				
(11) *Previous Failure* $_{it-1}$	0.16	0.03	0.01	-0.04	-0.21	0.12	-0.21	0.06	0.32	0.33	1.00			
(12) *Previous Engine Performance* $_{it-1}$	0.23	-0.03	-0.05	0.02	-0.18	-0.03	-0.17	0.04	0.29	0.38	0.23	1.00		
(13) *Previous Team Performance* $_{it-1}$	0.05	-0.11	-0.03	-0.05	-0.20	0.04	-0.25	0.11	0.24	0.23	0.18	0.10	1.00	
(14) *Season Difficulty* $_{it-1}$	0.37	0.07	-0.07	0.02	-0.30	0.07	-0.26	0.04	0.31	0.28	0.36	0.31	0.19	1.00

Table 11. *Fixed Effects Regression Model*

Dependent Variable	*Driver Lap Time $_{it}$*					
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Standardization $_{it-1}$	0.438	0.285	0.348	0.292	0.223	0.223
	(4.35)	(3.00)	(3.10)	(2.93)	(2.15)	(2.62)
Differences of Innovation $_{it-1}$		-0.0427	-0.0497		-0.0524	-0.0524
		(-2.23)	(-2.28)		(-2.67)	(-3.70)
Standardization $_{it-1}$		0.0294	0.0341		0.0375	0.0375
X Differences of Innovation $_{it-1}$		(1.94)	(1.98)		(2.41)	(3.63)
Human Capital Status $_{it-1}$		-0.121		-0.130	-0.134	-0.134
		(-4.28)		(-4.48)	(-4.64)	(-5.50)
Standardization $_{it-1}$		0.0379		0.0461	0.0495	0.0495
X Human Capital Status $_{it-1}$		(1.69)		(1.98)	(2.14)	(2.68)
Knowledge Indecomposability $_{it-1}$			-0.0276	-0.0226	-0.0299	-0.0299
			(-2.00)	(-1.81)	(-2.34)	(-2.89)
Standardization $_{it-1}$			0.0209	0.0155	0.0217	0.0217
X Knowledge Indecomposability $_{it-1}$			(1.90)	(1.54)	(2.11)	(2.56)
Breadth of Knowledge $_{it-1}$	0.00893	0.00492	0.00345	0.0110	0.00485	0.00485
	(0.58)	(0.35)	(0.22)	(0.79)	(0.35)	(0.41)
Parent Company $_{it-1}$	-0.0187	-0.0686	-0.00898	-0.0608	-0.0595	-0.0595
	(-0.33)	(-1.31)	(-0.16)	(-1.16)	(-1.14)	(-1.00)
Team Change $_{it-1}$	0.0129	0.0206	0.0145	0.0125	0.0168	0.0168
	(1.24)	(2.10)	(1.24)	(1.23)	(1.59)	(1.72)
Previous Ranking $_{it-1}$	0.00266	0.00257	0.00284	0.00274	0.00279	0.00279
	(1.23)	(1.32)	(1.31)	(1.40)	(1.43)	(1.67)
Previous Grid Position $_{it-1}$	-0.00457	-0.00973	-0.00362	-0.0130	-0.0111	-0.0111
	(-0.37)	(-0.87)	(-0.29)	(-1.15)	(-0.98)	(-1.06)
Previous Failure $_{it-1}$	-0.00411	-0.00445	-0.00579	-0.00555	-0.00593	-0.00593
	(-0.36)	(-0.43)	(-0.51)	(-0.53)	(-0.57)	(-0.68)
Previous Engine Performance $_{it-1}$	-0.00179	0.000851	-0.00121	0.00171	0.00173	0.00173
	(-0.17)	(0.09)	(-0.12)	(0.18)	(0.18)	(0.23)
Previous Team Performance $_{it-1}$	-0.200	-0.191	-0.216	-0.203	-0.208	-0.208
	(-3.27)	(-3.46)	(-3.49)	(-3.62)	(-3.73)	(-3.37)
Season Difficulty $_{it-1}$	0.0329	0.0350	0.0312	0.0340	0.0334	0.0334
	(5.58)	(6.58)	(5.22)	(6.26)	(6.20)	(5.38)
Team Control	On	On	On	On	On	On
Year	On	On	On	On	On	On
Constant	13.04	13.23	13.33	13.35	13.50	13.50
	(16.69)	(18.75)	(16.90)	(18.66)	(18.95)	(17.20)
Observations	647	647	647	647	647	647

t statistics in parentheses

Table 12. *Propensity Score Matching ATE*

Dependent Variable: *Driver Lap Time* $_{it}$				
Test	Average Treatment Effect	A&I Robust Standard Error	p Value	N
(1) Full Model	0.0331	0.009	0.000	1,261
(2) High *Differences of Innovation* $_{it-1}$	0.0355	0.007	0.000	690
(3) Low *Differences of Innovation* $_{it-1}$	0.0202	0.013	0.130	298
(4) High *Human Capital Status* $_{it-1}$	0.0158	0.016	0.320	569
(5) Low *Human Capital Status* $_{it-1}$	0.0223	0.013	0.094	692
(6) High *Knowledge Indecomposability* $_{it-1}$	0.0285	0.014	0.037	528
(7) Low *Knowledge Indecomposability* $_{it-1}$	0.0199	0.016	0.212	733