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From Garage to Grand Prix: 3 Essays on Knowledge Integration and Adaptation Across Complex Systems in the Formula 1 Motorsport Industry.

A dissertation presented

By

Jan Hendrik Voss

To

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Fuer meine Eltern,

Fuer ihre Liebe und Unterstuetzung,

dafuer, dass sie mich nie daran gehindert haben meinen Traeumen zu folgen,

auch wenn dies bedeutet hat sich voneinander zu entfernen.

A Rossana,

per il suo costante supporto,

per la sua immancabile pazienza,

per il suo entusiasmo e la positività che ha voluto trasmettermi ogni giorno.

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INTRODUCTION

My dissertation is composed of three distinct but related essays, seeking to understand how organizational structures and behaviors affect knowledge integration and adaptation across complex systems.

Research on modularity and architectural innovation has established that production systems routinize approaches to interdependency across groups or systems but struggle to manage unforeseen changes in the interdependence. Yet, we rarely observe firms in the process of adapting across complex, interdependent systems of production. This dissertation builds on modularity theory, the knowledge-based view of the firm and top management team theory, in order to investigate differences in firms’ adaptive behavior and performance in response to externally imposed governance- and supplier changes in the Formula 1 (F1) motorsport industry. Before and after a governance- or supplier change was imposed, I observe adaptations, component problems, and performance among teams that could retain the same governance mode or supplier and those that were forced to change.

F1 is a particularly relevant setting for the study of adaptation and knowledge integration. F1 cars are complex systems that consist of many different components, whose architecture, ownership, development and performance can be observed at regular, intensive intervals during the integration. Furthermore, research states that the dominant capability for competitive advantage is the integration of different component developments (Jenkins, 2010) and that car constructors require human, financial, and organizational resources in order to maintain their competitiveness, i.e. to construct competitive cars to win races and finally the World Championship (Jenkins et al., 2007).

For the purpose of this dissertation, it was imperative to collect data on firm performance, the various components of a F1 car, their interdependencies, as well as whether firms make or buy these components, and, if they buy, from whom they buy. Moreover, data had to be collected on the changes firms make to the various components at any given point in time, as well as the problems firms have with the various components at any given point in time. Finally, the dissertation required data on firms' top management teams and their level of experience. These and other data were obtained from annual publications, e.g. *Formula 1 Technical Analysis*, *The Official Formula 1 Season Review*, *Who works in Formula One*, as well as online archives, such as *ATLAS F1* or the official Formula 1 website *www.F1.com*, and expert F1 technology and engineering blogs, such as *ScarbsF1.com*. The interdependencies between the various components of a F1 car have been identified with the help expert literature on F1 engineering, as well as interviews with current and former personnel of F1 firms and their suppliers. The resulting data covers the F1 seasons from 2004 until 2012, inclusive.

Difference in difference analyses show that (i) governance changes and supplier switches in complex systems negatively affect performance, (ii) that ownership of interdependent components across the system helps when changing the governance for a particular component, and (iii) that firms integrating a new external supplier have fewer problems and perform better when they make more adaptations in related components across the system. Moreover, the analyses show (iv) that firms' architectural competences that are necessary to make such changes largely reside in firms' top management teams, and reveal (v) that a trade-off exists for stable and changing supply networks between team members' role experience, i.e. the amount of time they have been working in their respective knowledge areas, and team members' familiarity, i.e. the amount of time that they have been working together across their respective knowledge areas in the past.

In the first essay of my dissertation, I build on modularity theory and theory of the firm, specifically the knowledge-based view of the firm and the collaborative paradigm, in order to investigate differences in firms' ownership of components and their performance in relation to an industry-wide change in governance for a key component.

Today's knowledge-based economy offers opportunities for organizations to pursue increases in performance through strategic changes in governance, such as outsourcing. Trends towards product modularization enable unprecedented levels of inter-organizational design coordination, building on the intuition that complex systems such as products, technologies and organizations are adaptive if modular. As a consequence, systems integrators develop and maintain systems integration competencies to compose what they have decomposed. However, while it is widely accepted that firms produce value jointly in interconnected systems, it is less well understood whether a firm's ownership of components across a complex system allows for performance benefits from outsourcing a particular component to an external supplier. This essay shows that ownership of components across a complex system is important for effective knowledge integration when changing the governance of individual components, and concludes that modularization and governance changes should ideally be guided by architectural knowledge.

In the second essay of my dissertation, I build on modularity theory and the theory of the firm, specifically the knowledge-based view of the firm and the collaborative paradigm, in order to investigate differences in firms' adaptive behavior in relation to an externally imposed, industry-wide supplier switch.

Contemporary complex product development is carried out in supply chains, with diverse, specialized knowledge sources collaborating across firm boundaries. Sharing across supply chains has led to an amplification of the importance of supplier management during recent years and firms have become aware that the combination of critical resources with strategic supply chain partners may yield a competitive advantage. In fact, today, supply chains are becoming complex networks in which partners collaborate and experiment together, sharing the risks and benefits. As a consequence, the integration of externally sourced components is a high profile problem for firms. However, while it is widely accepted that firms produce value jointly in interconnected systems, it is less well understood how firms adapt to changes in such systems, particularly in supply networks. There is little clarity on how firms can improve in mitigating the risks of changes in components and managing the transitions across such systems. Confusion about the impact of changes in components, e.g. as a result changing suppliers, contributes to this condition. The results show that a firm's ability to integrate a new external component is largely determined by its ability to make changes internally, in related components across the system.

In the third essay of my dissertation, I build on modularity theory, top management team theory, as well as the knowledge-based view of the firm. The study investigates differences in firms' top management teams' (i) role experience and (ii) familiarity, as well as their adaptive behavior in relation to an externally imposed, industry-wide supplier switch.

Supply chains are becoming complex networks in which partners collaborate and experiment together on problem-solving, sharing the risks and benefits. However, while it is widely accepted that firms produce value jointly in interconnected systems, it is less well understood where the knowledge resides that allows to integrate different components across complex systems that span organizational boundaries. Research acknowledges that organizations design themselves at the firm-level, in part, in order to be able to cope with change. However, less is known regarding the importance of the experience of top management teams in this respect, in particular top management teams' (i) role experience, i.e. the amount of time the team members have worked in their respective knowledge areas, and (ii) familiarity, i.e. the amount of time the team members have worked together in the past. The results show that firms' architectural competence resides in their top management teams and provide evidence for a knowledge integration trade-off between (i) role experience and (ii) familiarity in stable supply networks as opposed to changing supply networks.

ESSAY 1

From Garage to Grand Prix:

Governance Changes and Knowledge Integration across Complex Systems in the Formula 1 Motor Sport Industry

ABSTRACT

Trends towards product modularization enable unprecedented levels of inter-organizational design coordination, building on the intuition that complex systems such as products, technologies and organizations are adaptive if modular. As a consequence, systems integrators develop and maintain systems integration competencies to compose what they have decomposed. However, while it is widely accepted that firms produce value jointly in interconnected systems, it is less well understood whether a firm's ownership of components across a complex system allows for performance benefits from changes in governance, such as outsourcing a particular component to an external supplier. This paper builds on modularity theory as well as the theory of the firm, specifically the knowledge-based view of the firm and the collaborative paradigm, to investigate differences in firms' ownership of components and their performance in F1 racing between 2004 and 2012, in relation to an industry-wide outsourcing of a key component, the electronic control unit, to a unique supplier in 2008. The study shows that ownership of components across a complex system is important for effective knowledge integration when changing the governance of individual components. It concludes that modularization and governance changes should ideally be guided by architectural knowledge.

1. INTRODUCTION

Today’s knowledge-based economy offers opportunities for firms to pursue performance through strategic governance changes, such as outsourcing. Recent publications argue that firms are increasingly relying on suppliers for the production of increasingly complex products (Argyres and Bigelow, 2010; Langlois, 2003). Sharing across supply chains has led to an increase in the importance of supplier management over the recent years. Firms understand that combining resources with strategic partners may provide a competitive advantage (Hardy et al., 2005; Paulraj et al., 2008). As a result, supply chains are becoming collaborative value networks where partners work and experiment together on problem solving, which, in turn, promotes interfirm learning as well as sharing risks and benefits (Malhotra et al., 2005). Successful outsourcing depends largely on effective knowledge integration, i.e. the process of absorbing knowledge from external sources and blending it with the internal technical- and business skills, know-how, and expertise (Kogut et al., 1992; Szulanski, 1996). As a result, the integration of outsourced components is a high profile problems for firms. However, the literature has paid less attention to whether and how governance changes, such as outsourcing, may affect the effectiveness with which firms integrate components across complex systems. How do firms align and manage the contributions of firm-based and network-sourced component knowledge? Do firms compete on their internal knowledge of components, or rather on their ability to access and reconfigure externally sourced components? Do these two competencies interact for the generation of a competitive advantage, and if so, how?

The business literature celebrates 'knowledge-creating companies' and 'learning organizations' for their ability to generate, acquire, and integrate both internal and external knowledge (Leonard-Barton, 1995; Nonaka and Takeuchi, 1995; Simonin, 1997). Pursuing a better understanding of how firms can improve in organizing for the integration of different components across complex systems, research has developed the concept of modular design or modularization. This approach subdivides systems into modules, which can be developed independently from one another and recombined with the system through standardized interfaces (Baldwin and Clark, 2000). A firm's ownership of components across the system is very much at the heart of the debate and trends towards product modularization enable unprecedented levels of inter-organizational design coordination (Brusoni, 2005), building on the intuition that complex systems such as products, technologies and organizations, are adaptive if modular (Simon, 1962). The firms in a supply network of a given complex product can be characterized in terms of two broad categories: (i) systems integrators and (ii) suppliers (Brusoni and Prencipe, 2006; Prencipe et al., 2003). The (i) systems integrators oftentimes are large industrial firms that act as assemblers, integrators and marketers that bridge customers and the supply chain, generally exercising a great deal of control across the supply chain. The (ii) suppliers design, develop and manufacture components, which are then integrated by systems integrators. Variation in resource and capability endowment (Bettis and Hitt, 1995; Teece, 1986) creates the need for systems integrators to contract with suppliers (Combs and Ketchen, 1999; Lavie, 2006). As a consequence, systems integrators develop and maintain systems integration capabilities to compose what they have decomposed (Prencipe, 1997).

However, while it is widely accepted that firms produce value jointly in interconnected systems (Brandenburger and Nalebuff, 1996; Normann and Ramirez, 1993; Adner and Kapoor, 2010), it is less well understood whether a firm's ownership of components across the system allows for performance benefits from governance changes, such as outsourcing, particularly when suppliers are also available to competitors. Moreover, recent empirical evidence shows that, for example in the automotive industry, modularity has produced disputable benefits (Fourcade and Midler, 2004; MacDuffie, 2013; Zirpoli and Becker, 2011). In fact, the over-reliance on the concepts of product modularity and standard interfaces as tools for easing inter-firm coordination is being criticized in the research community. For example, Cabigiosu and Camuffo (2012) find that product modularity offers little explanation in this respect, considering it may alternatively be associated with either plenty of information sharing or with little information sharing with suppliers. These results trigger research aimed at understanding why product modularity may show limited traction in coordinating the integration of outsourced components in supply chains for complex products. Finally, while the literature widely highlights the importance of integration of activities across firms' value systems, much of the existing research has focused on singular relationships or components.

This study investigates differences in firms' ownership of components and their performance in Formula 1 racing between 2004 and 2012, in relation to an industry-wide enforcement of outsourcing of a key component, the electronic control unit, to a unique supplier in 2008. This external shock required firms that previously produced the electronic control unit internally to outsource it to the exclusive, industry-wide supplier. By studying a firm's ownership of components across the system and their performance, in terms of championship points gained at each race, before and after the external shock, this paper explores how differences in firms' ownership of components may lead to differences in their abilities to effectively outsource components. F1 racing is a particularly relevant setting, since (a) the dominant capability for competitive advantage is the integration of different component developments (Jenkins, 2010) and (b) car constructors require human, financial, and organizational resources to maintain their competitiveness, i.e. to construct competitive cars to win races and finally the World Championship (Jenkins et al., 2007).

2. THEORY AND HYPOTHESES

This paper is based on modularity theory (Baldwin and Clark, 1997, 2000; Garud and Kumaraswamy, 1995; Henderson and Clark, 1990; Langlois and Robertson, 1992; Sanchez and Mahoney, 1996; Sako, 2003; Schilling, 2000; Simon, 1962; Ulrich, 1995; von Hippel, 1990), which states that product architectures are targets of design, and hence potentially serve as a source of competitive advantage, as well as the theory of the firm, specifically the knowledge-based view of the firm (Kogut and Zander, 1992, 1996; Conner and Prahalad, 1996; Grant, 1996) and the collaborative paradigm (Contractor and Lorange, 1988; Dyer, 2000; Kanter, 1994; Nielsen, 1988), which emphasizes that the business world is composed of a network of interdependent relationships, which are developed and fostered through strategic collaboration with the goal of deriving mutual benefits (Ahuja, 2000; Borys and Jemison, 1989; Chen and Paulraj, 2004; Lado et al., 1997; Madhok and Tallman, 1998; Miles and Snow, 1986; Thorelli, 1986). With respect to these literature streams, strategic management research highlights that a firm’s ability to manage technological change underlying a new product generation depends on its ability to move beyond local search and to reconfigure knowledge. This ability is typically referred to as *combinative capability* (Kogut and Zander, 1992), *dynamic capability* (Teece, Pisano, and Shuen, 1997), and *architectural competence* (Henderson and Cockburn, 1994). Research by Matusik and Hill (1998) states that, when firms act as coordinators, firm-based- and network-sourced competencies correspond to Henderson and Clark’s (1990) typology of architectural knowledge and component knowledge.

Buyer-supplier relationships achieve knowledge integration through the reliance on three mechanisms. These are (1) co-locating engineers (Dyer, 1997; Dyer and Nobeoka, 2000; Helper, MacDuffie and Sabel, 2000), (2) leveraging relationship-specific assets that were developed in prior interactions (Dyer and Singh, 1998; Kale and Singh, 2007), as well as (3) using modular architectures (Baldwin and Clark, 2000), i.e. dividing a system into modules that can be independently created and then integrated into the system through standardized interfaces. The (1) colocation of buyer- and supplier engineers has been suggested to facilitate the development of shared contextual knowledge, which in turn promotes integration (Kraut et al., 2002, Olson et al., 2002). The (2) leveraging of relationship-specific assets developed in prior interactions has been found to be enabled through collaboration over time. This results in superior knowledge exchange, as well as partner-specific experience and learning, a common language, routines for interaction and an improved understanding of partner decision-making procedures (Dyer and Singh, 1998; Gulati, Lavie and Singh, 2009). The (3) modular architectures have been suggested to facilitate the integration of external knowledge (Baldwin and Clark, 2000; Brusoni, Prencipe and Pavitt, 2001).

Importantly, entirely modular product architectures are rare. Product components frequently interact to generate system performance, which makes it practically impossible to eliminate component interdependencies entirely by design. The less modular and the more systemic products are, the more integration across the product's various components is necessary (Sosa, Eppinger and Rowles, 2004; Zirpoli and Becker, 2011). There is little clarity on technology, technological change and their impacts on organizational outcomes (Nelson, 1995; Podolny and Stuart, 1996; Teece, 1996). Confusion about the impact of governance changes, such as outsourcing, contributes to this condition. It is therefore important to better understand whether and how a firm's ownership across interdependent components in a system affects its ability to effectively outsource a particular singular component, as well as whether and how component outsourcing itself affects a firm's performance over time.

2.1 Governance Changes and Firm Performance

A firm's know-how involves knowledge that is tacit, complex and difficult to codify (Kogut and Zander, 1992; Nelson and Winter, 1982; Szulanski, 1996). Winter (1980) states that it is difficult to transfer knowledge to and from a new supplier like a book of blueprints. As a result, governance changes, such as outsourcing, create challenges for a firm that needs to integrate a particular component. The existence of transaction-specific know-how and skills, as well as the skill transfer difficulties (Teece, 1977; 1980), imply that firms changing the governance of a particular component, e.g. from make to buy, are likely to possess less effective inter-firm linkages with their supplier than firms, which have been outsourcing a particular component to a specific supplier in the past.

In order to leverage externally sourced new knowledge, firms must integrate and assimilate external technologies, as well as the new knowledge associated with them (Cassiman and Veugellers, 2006; Matusik and Hill, 1998). This process of integration and assimilation includes the acquisition of new knowledge, its dissemination within the firm, as well as its combination with existing knowledge (Huber, 1991; Leonard-Barton, 1992). A firm's ability to do so is likely to be largely dependent on its supplier-specific absorptive capacity. In the context of buyer-supplier relationships, Dyer and Singh (1998) state that partner specific absorptive capacity is a function of (i) the extent to which partners have developed routines that maximize the frequency and intensity of socio-technical interactions and (ii) the extent to which partners have developed overlapping knowledge-bases (Mowery, Oxley and Silverman, 1996; Szulanski, 1996). Certainly, the partner-specific absorptive capacity and inter-firm knowledge-sharing routines of firms with a familiar supplier will be superior to those of firms that outsource a component to a new, unfamiliar supplier.

H1: *A change of component governance has a negative effect on a firm’s performance.*

Over time, the magnitude of the outsourcing effect on firm performance is likely to change, as firms and their new suppliers communicate, learn and develop relational capital. The main assumption of research on the evolution of knowledge is that knowledge is not static, once it has been created, transferred or adopted. Instead, it evolves through application. In general, knowledge and its outcomes evolve over time, either in terms of improvement or in terms of deterioration. One evolutionary phenomenon that represents knowledge improvement is the organizational learning curve or experience curve, whereby improvements in the way things are done are a consequence of cumulative learning by doing and associated development of context specific, experience based competencies (Argote, 1999; Epple et al., 1991).

In order to gain architectural knowledge and competencies, systems integrators typically experiment with different ways of integrating the system, study the system in different environments and monitor it to observe what levels of activity or stress arise at different junctures (Baldwin and Clark, 2000; Bell and Newell, 1971; Colwell, 2005; Hennessy and Patterson, 1990; Patterson and Hennessy, 1994). By doing so, systems integrators may learn where performance is constrained by one or more components (Ethiraj, 2007), as well as how to separate some components from the rest of the system in order to encapsulate them as modules of the system (Baldwin and Clark, 2000; Parnas, 1972; Parnas et.al., 1985). Finally, systems integrators may learn that arranging some or all of the components in a new way can yield performance improvements.

Repetition plays a major role in both organizational learning (Argote et al. 1990; Dutton and Thomas 1984; Adler 1990) and in the creation of routines and capabilities in general

(Nelson and Winter, 1982; Skinner, 1974). The repeated use of the same or similar knowledge components facilitates the development of routines, which, in turn, increases search reliability (Levinthal and March, 1981). Inter-firm knowledge-sharing routines are particularly important in this respect, since organizations often learn by collaborating with others (March and Simon, 1958; Powell et al., 1996). Communication and information sharing are integration mechanisms that coordinate inter-organizational relationships (Ring and Van de Ven, 1992). Working together allows firms to develop specialized routines based on tacit knowledge of both, the tasks and each other's abilities (Berman, Down and Hill, 2002). This is usually resulting in richer interactions, improved coordination and eventually superior performance, both at the firm and the inter-firm level (Brandon and Hollingshead, 2004; Weick and Roberts, 1993). As a result, the integration of newly outsourced components into the system is likely to become more effective over time.

H2: *The negative effect of a component governance change on firm performance falls over time*.

2.2 Governance Changes, Ownership and Firm Performance

The literature states that a firm's ability to manage technological change underlying a new product generation depends on its *architectural competence* (Henderson and Cockburn, 1994). The effective integration of new technology in the product development process also requires frequent communication, high levels of coordination and intense involvement between different organizational units associated with product development within the knowledge receiving organization (Grant, 1996; Henderson and Cockburn, 1994). As a result, the knowledge of key components remains important to a firms's ability to innovate on the product architecture and to coordinate product development across the supply chain (Christensen, 2006; Sanchez and Mahoney, 1996). Considering complex systems of interrelated components (Rosenkopf and Tushman, 1992; Thomke and Kuemmerle, 2002), firms may respond to changes in external knowledge components by increasing their innovative efforts in other components (Rosenkopf and Tushman, 1992; Tushman and Murmann, 1998). Hence, it can be argued that integrating outsourced knowledge requires architectural competence, i.e. the ability to access new knowledge from outside the firm’s boundaries and the ability to integrate knowledge across disciplinary boundaries within the firm (Henderson and Cockburn, 1994).

Interdependencies among components are important in this respect. By obscuring the link between actions and outcomes, interdependences may obstruct the selection of effective routines (Sorenson, 2003). As a result, even when organizations are able to identify effective improvements for singular components, interdependence may constrain the firm’s ability to act on its knowledge. Firms may not always be able to optimize their products one component at a time, as changes in one component might need to be accompanied by changes in other components. The business history literature provides evidence of situations in which a change in a given component creates disturbances in the rest of the system, which are eventually resolved through modifications across the system (Hughes, 1983; Rosenberg, 1982). Such necessary technological changes comprise an ecosystem of mutually dependent changes. Clearly, the successful integration of outsourced components requires a combination of component knowledge and architectural knowledge (Henderson and Clark, 1990), and, therewith, knowledge regarding components and the interdependencies among them. The links between interdependent components are less likely to be obscured when a firm owns more of the interdependent components, which implies that a firm’s ability to act on its knowledge is less inhibited with increasing ownership of interdependent components. In this respect, Brusoni and Prencipe (2001) find that focal firms need to have some degree of knowledge overlap with their suppliers, in order to identify potential novelties in fast-moving technological fields, understand their implications for the others, and integrate changes in existing or new product architectures. Similarly, research by Takeishi (2001) as well as Zirpoli and Becker (2011) states that buying firms' knowledge bases should be broader than that strictly needed to manage the internal design and production.

In terms of ownership, research has argued that vertical integration functions as an internal mechanism for knowledge transfer and integration. Particularly, when interdependencies between components are involved, the sharing of technological information common to the separate stages of the system's development may be facilitated by vertical integration, specifically through the facilitation of the implementation of new technologies and through the formulation of more astute research objectives (Armour and Teece, 1980; Monteverde, 1995), which, in turn, facilitate systemic innovations (Teece, 1996). Moreover, a firm's vertical scope has been shown to affect the nature of its knowledge accumulation and capability development (Jacobides and Winter, 2005; Malerba et al., 2008), which, in turn, affect the firm's capacity to absorb new external knowledge (Cohen and Levinthal, 1990), a certain amount of which is necessary to combine internal and external components.

When integrating an externally sourced component, systems integrators can either use the supplier's knowledge (i) decoupled from related internal knowledge or (ii) coupled with related internal knowledge (Weigelt, 2013). The use of (i) supplier knowledge decoupled from the systems integrator's internal knowledge means that problem-solving occurs as the supplier carries out tasks for its clients. Hence, learning mainly takes place at the supplier, which applies its technical knowledge in order to understand successful solutions and errors, as well as to solve problems for the systems integrator. As a result, systems integrators are likely to miss opportunities to leverage supplier knowledge. Instead, the use of (ii) supplier knowledge coupled with the systems integrator's internal knowledge is likely to cause learning and search for solutions drawing on both firms' knowledge bases, as their processes are co-adapted. Schilling (2000) refers to such co-adaptation as synergistic specificity, implying that a system may achieve greater functionality when its components are specific to one another. Routines for interaction may develop between the firms, which creates potential for the development of a unique relative absorptive capacity between them (Mesquita et al., 2008). Certainly, (ii) integrating an externally sourced component coupled with related internal knowledge is more likely when firms own more of the components that interact with the externally sourced component.

H3: *The negative effect of changing the governance of a specific component on firm performance decreases with a higher percentage of ownership of the components that interact with the focal component.*

3. EMPIRICAL SETTING

This paper's empirical context is Formula 1 (F1) motor racing. F1 is a particularly relevant setting for the study of integration in an architectural system. F1 cars are complex systems that consist of many different components, whose architecture, ownership, development and performance can be observed at regular, intensive intervals during the integration. As a consequence of the immense public interest in F1 around the world, the industry enjoys heavy media coverage on and off the race track, including information about agreements between firms and their suppliers, detailed reports about the developments made on cars for every race, as well as firm performance. Research states that the dominant capability for competitive advantage is the integration of different component developments (Jenkins, 2010) and that car constructors require human, financial, and organizational resources in order to maintain their competitiveness, i.e. to construct competitive cars to win races and finally the World Championship (Jenkins et al., 2007).

Since the first official grand prix in 1950, F1 has been considered the pinnacle of automotive technology, as a result of high levels of innovation and large international exposure as a sport (Solitander and Solitander, 2010). F1 is the only form of motor sport that still requires each competing team, as a firm is customarily called in the industry, to design and assemble its own car. More specifically, a F1 team, or *constructor*, as the F1 governing body, the *Fédération Internationale l'Automobile* (FIA), officially defines them, needs to manufacture at least the chassis of its cars, whereas it can buy the other components from external suppliers. In addition to their racing departments, these firms have R&D, marketing, manufacturing, and testing departments. Furthermore, all constructors operate with complex supplier networks. The major manufacturers can have 750 suppliers who produce the approximately 16,000 parts of a F1 car (Blitz, 2007). A majority of these also supply to rival firms. Furthermore, many sponsors from more or less related industries cater to the F1 constructors. In fact, it is essential for F1 constructors to secure sponsorship deals, in order to be able to operate on a budget that is sufficiently large to design, manufacture and race competitive cars.

In F1, constructors compete for the Constructor's Championship, which is awarded to the team that scores the highest number of championship points during a season. Since 1950, between 10 and 14 constructors have been competing in any given world championship season. Drivers compete for the Driver's Championship, which is awarded to the driver that scores the highest number of championship points during a season. The constructors who compete in the F1 championship have an average budget of around $250 million (Sylt and Reid, 2008), and, as all constructors work within the same constraints and regulations, only constant refinement and innovation provides competitive advantage (Cross and Clayburn Cross, 1996). Each constructor employs hundreds of engineers, who are continuously trying to come up with new innovations (Jenkins, 2004). Knowledge is critical here, since the key asset of firms is the knowledge possessed by the designers, engineers, fitters and mechanics (Pinch and Henry, 1999). The key role of resident engineers is to facilitate the integration of the technical knowledge held by both, the racing car manufacturer and the supplier, and to engage in joint problem solving activities (Mariotti, 2007).

In financial terms, F1 is a global sport with an estimated annual worth between $4bn and $5bn. The sport counts between 500bn and 600bn unique viewers per season (Sylt and Reid, 2011), and, around 350m viewers for a single race. In professional sports, these numbers are rivaled only by the Super Bowl held by the National Football League (NFL), the Champions League Final held by the Union of European Football Associations (UEFA), the World Cup Final held by the Fédération Internationale de Football Association (FIFA), or the Olympic Games, the last two of which take place only every 4 years. The motorsport industry, to a large extent, is concentrated in Motorsport Valley, a geographical cluster in southern England. At the centre of this cluster is the F1 industry. In the UK alone the industry’s annual turnover is around $10 billion, employing approximately 40,000 people, of which 25,000 are engineers (Henry and Pinch, 2000). Across the various constructors that compete in F1 each year, annual owner spending range from nothing to some $150m for constructors backed by car manufacturers or other major corporations. Annual sponsorship revenues in F1 range from under $10m to over $200m. Another important source of revenues is prize money, which ranges from around $10m for a team that finishes outside the top 10 to around $87m for the world champion. Furthermore, teams generate between $7m and $15m of revenues per season through trade support and tyre supply, and, in some cases, up to an additional $5m from merchandise and events. In the pursuit of performance goals, typical top team expenditures amount to some $250m per season, $340m if it is a works team, i.e. if it manufactures its own engines. Instead, small team expenditures amount to some $80m per season (Sylt and Reid, 2011). Notably, F1 today is both, the world's premier motor sport and a multi-billion dollar business.

4. DATA

At the outset of the 2008 season, the governing body of Formula 1, the Fédération Internationale de l'Automobile (FIA), imposed a switch from a situation where firms could choose between producing the electonic control unit (ECU) internally or outsource it to a supplier of their choice, to a situation where one supplier became the exclusive source for the ECU component of all firms competing in Formula 1. The data collected for this study allows for observations of a firm's ownership of components and performance over time. The data is set up as a panel consisting of nine F1 seasons, or years, with the time interval of observations within a given season being the time between any two races, which typically ranges from seven to twenty-one days. A firm's ownership of components is observed for a given season, while its performance is observed at every race of a given season and varies with the amount championship points gained.

For the purpose of this study, it was imperative to collect data on whether firms owned the ECU or whether they sourced it from external suppliers, as well as on firm performance.

These data were obtained from the annual publications *Formula 1 Technical Analysis*, *The Official Formula 1 Season Review*, *Who works in Formula One*, and, *Formula Money*, as well as the online source *ATLAS F1*. These sources provide information with regarding all firms' component sourcing. The interdependences between the various components of a F1 car have been identified with the help expert literature on F1 engineering (e.g. Tremayne, 2004), as well as interviews with current and former personnel of F1 firms and their suppliers. Data on team performance and problems on the firms' cars' various components during any race weekend were obtained from the major annual publication *Formula 1 Technical Analysis*, as well as the online sources *ATLAS F1*, the Formula 1 archive of *www.autosport.com*, the official Formula One website *www.F1.com, as well as ScarbsF1.com*, an expert F1 technology and engineering blog. These sources publish information on each firm's performance, problems and developments race by race. The data for this study cover the F1 seasons from 2004 until 2012, inclusive. The time frame was chosen, because major online sources, i.e. *ATLAS F1* and *www.F1.com*, started providing detailed information technological developments for each team throughout the entire season as of 2004. Clearly, with the increasing possibilities for internet-based online journalism by specialized firms and expert blogging by qualified individuals, the reporting on Formula 1 experienced a surge of detailed information as of 2004. Moreover, *The Official Formula 1 Season Review* was released in 2004 as a major annual publication that covers facts, stories and events of a given Formula 1 season. As a consequence, the analysis has been conducted for the seasons from 2004 to 2012, thereby obtaining a balance of 4 seasons before the change and 5 seasons after the shock.

5. METHOD

In order to identify the impact of outsourcing on performance outcomes, this study exploits the regulatory enforcement of the outsourcing of the F1 cars' electronic control unit (ECU) to a unique, industry-wide supplier in 2008. To the extent that the regulatory enforcement of outsourcing is neither influenced nor predicted by individuals, temporal differences within a firm can be considered truly exogenous. Considering that some firms were internally producing their own ECUs before 2008, whereas others were already outsourcing the ECU from 2004 to 2007, this study's setting provides a natural experiment. The data underlying this study covers the years from 2004 to 2012 and therewith allow to estimate the impact of an outsourcing "treatment" by applying a difference-in-differences methodology. The difference-in-differences approach compares what happened to a treatment group before and after the treatment to what happened to a control group, i.e. a group that was not subject to the treatment, before and after the treatment. In principle, it may appear sufficient to explore the treatment group alone in order to deduce the treatment effect. However, without the counterfactual, i.e. what happened to the treated group without the treatment, the impact of the treatment may be confounded with the impact of other factors that affect the outcome variable at the same time. The control group allows to take these other factors into account under the assumption that they affect the treatment group and the control group equally (Woolridge, 2002). Hence, in this study, the firms that have to switch from make to buy represent the treatment group, whereas the firms that simply stay with outsourcing represent the control group. The following panel regression model has been estimated, in which the dependent variable is the performance of an F1 team j at any given time t between 2004 and 20012, inclusive:

$$GPPoints_{jt} = \alpha * TreatmentGroup + \beta * TreatmentPeriod + \gamma * Treatment + \delta Controls + e_{jt}$$

In this equation, *Treatment* is the enforced outsourcing. *TreatmentGroup* is a dummy variable that takes the value of 1 for teams that switched from make to buy and 0 otherwise. It captures possible differences between the treatment group and the control group prior to the external shock. *TreatmentPeriod* is a dummy variable that takes the value of 1 for races that took place after the treatment, i.e. between the years 2008 and 2012, and 0 otherwise. It captures aggregate factors that would cause changes in the dependent variable even in the absence of the external shock. The coefficient of interest is that of the variable *Treatment*, which is practically a dummy for observations in the treatment group in the treatment period. This variable is obtained by multiplying the variable *TreatmentGroup* with the variable *TreatmentPeriod*. *Z* is the vector of control variables. Moreover, a second model has been estimated, in order to test the moderating effects of firms' component ownership on the treatment effect. As a result, this model includes the independent variables *Ownership*, and its interaction with the treatment, *Ownership*Treatment*:

$$GPPoints_{jt} = \alpha * TreatmentGroup + \beta * TreatmentPeriod + \gamma * Treatment + \delta * Controls + \epsilon * Ownership_{jt} + \varepsilon * Ownership_{jt} * Treatment + e_{jt}$$

5.1 Dependent and Independent Variables

This study's dependent variable is (I) *Grand Prix Points*, i.e. the number of grand prix points that a firm gathers in any particular race with both of its cars. This variable measures the performance of a firm at any point in time. In this study's data, the number of points gained by both cars at any particular race ranges from 0 to 43 points, with the average being around 9 points. Since the point scoring system, i.e. the amount of points awarded for a given position of a firm’s car at the end of the race, has been changed in 2010, this study has translated amount of points scored at each race between 2004 and 2009 into their equivalent according to the new scoring system.

This study has three major independent variables. First, in order to observe the effect of outsourcing on performance, a variable that captures the treatment had needed to be created by multiplying the *Treatment Group* with the variable *Treatment Period*. *Treatment Group* is a binary variable that assumes the value of 1 if a firm had previously produced the ECU internally and then had to outsource it as of 2008. It assumes the value 0 otherwise. Instead, the variable *Treatment Period* is a binary variable that takes the value of 1 for races that took place after the treatment, i.e. between the years 2008 and 2012, and 0 otherwise. As a consequence, the multiplication of the two results in a variable that identifies the treatment, i.e. the firms that had to outsource the ECU and the period during which they are using an external supplier. Hence, the variable (i) *Treatment* assumes the value of 1 if a team is part of the treatment group and the performance is observed after outsourcing has been imposed. It assumes the value of 0 otherwise. Second, (ii) the variable *Ownership*, which is the percentage of components that interact with the outsourced ECU, which a firm owns. Finally, (iii) the interaction of (ii) *Ownership* with (i) variable *Treatment* is investigated, in order to explore heterogeneity in performance among the firms under treatment, according to the their ownership.

5.2 Control Variables

The analysis includes several control variables. First, (1) *Treatment Period* measures the time period after the shock. Specifically, *Treatment Period* is a binary variable that assumes the value 1 for the years 2008 to 2012 and 0 otherwise. Second, (2) *Non Participants* identifies the firms that exited the Formula 1 motor sport industry before the shock or entered after the shock, and, thus, were not subject to the treatment. In particular, *Non Participants* assumes the value 1 for firms that have not been subject to the treatment and 0 otherwise. Third, (3) *Treatment Group* identifies the firms that had to outsource the ECU. *Treatment Group* assumes the value 1 for firms that outsourced the previously owned ECU to the new exclusive supplier and 0 otherwise. Fourth, (4) *Season Clock* measures the stage of the season that firms find themselves in at any given point in time. In particular, *Season Clock* measures the percentage of a season's total number of days that have passed at any given point in time. This study considers the season to actually starts one day after the last race of the previous season in October, with teams developing the new car to be launched around January or February. The races then are taking place from March to October. As a result, the Season Clock starts for the first race takes into account that around a third of a Formula 1 season is has actually passed already. From this point on, as the season progresses, firms may slow down their product development. This is simply a consequence of the fact that, in F1, as the season proceeds, constructors need to gradually reallocate resources from the development of the car that is currently competing to the design and development of the car for the new season with its new rules and regulations. Fifth, (5) *Budget* measures the total amount of money in million US-Dollars that a specific firm had at disposition for a given season and reflects a firm's size and investments in R&D. Sixth, (6) *Firm Experience* measures the number of races that a firm has been competing for in F1 over the last three seasons. This variable accounts for age and experience of the organization. Seventh (7), *Firm Success* measures the number of points that a firm has been able to accumulate in F1 over the last three seasons. This variable accounts for success of the organization. Eight, (8) *Driver Experience* measures the average number of years that the two drivers of a firm have been competing in Formula 1. Ninth (9), *Driver Success* measures the average number of Driver Championships that the two drivers of a firm have won in the past. Both of these variables account for the driver effect on a firm's performance in any given race. Tenth, (10) *Engineers' Experience* measures the average number of years that a firm's top engineers work in F1. Eleventh, (11) *Engineers' Success* measures the average number of F1 constructor's championships that a firm's top engineers have won in the past. Twelfth, (12) *Ambient Temperature* measures the degrees Celsius in the race track location on the race day. Thirteenth, (13) *Track Temperature* measures the temperature of the race track in Celsius. Both may influence a car's reliability, with the former directly affecting the engine cooling and the latter the tyres. As a result, these factors are included in order to control for their effect on firm performance. Fourteenth, (14) *Race Distance* measures the race length in kilometers. Fifteenth, (15) *Testing* and sixteenth (16) *Practice* respectively measure the amount of testing in thousand km and laps practiced before a given race. Seventeenth (17) *Headquarters Distance* measures the distance between a firm's headquarters and a given race location in thousand kilometers. Eighteenth, (18) *Suppliers* measures the number of relationships to different suppliers that a firm entertains across all car components. Finally, the study controls for other regulatory shocks that did not equally affect all firms competing in F1 and occurred between 2004 and 2012. As a consequence, the study includes the regulatory enforcement of the supplier switch Bridgestone as a unique, industry-wide tyre supplier in 2007, as well as the regulatory engine development freeze 2008. The control variables that account for these regulatory shocks are the following. Nineteenth, (19) *Supplier Switch Regulation* measures the time period after the tyre supplier switch shock. Specifically, *Supplier Switch Regulation* is a binary variable that assumes the value 1 for the years 2007 to 2009 and 0 otherwise. Twentieth, (20) *Supplier Switch Treatment Group* identifies the firms that had to switch the tyre supplier. *Supplier Switch Treatment Group* assumes the value 1 for firms that switched from Michelin to Bridgestone and 0 otherwise. Twenty-first, (21) the variable *Interaction Supplier Switch Treatment Group _ Supplier Switch Regulation* has been generated. Hence, the variable assumes the value of 1 if a team is part of the treatment group and the performance is observed after the supplier switch has been imposed. This variable identifies the treatment, i.e. the firms that had to switch from Michelin to Bridgestone and the period during which they are using the new tyre supplier, i.e. Bridgestone. Twenty-second, (22) *Supplier Switch Non Participants* identifies the firms that exited the Formula 1 motor sport industry before the shock or entered after the shock, and, thus, were not subject to the treatment. In particular, *Supplier Switch Non Participants* assumes the value 1 for firms that have not been subject to the treatment and 0 otherwise. Twenty-third, (23) *Engine Freeze Regulation* measures the time period after the engine freeze shock, that limited the firms' possibility to develop more powerful engines and therefore limited the firms' producing their own engines in using their competence. Specifically, *Engine Freeze Regulation* is a binary variable that assumes the value 1 for the years 2008 to 2012 and 0 otherwise. Twenty-fourth, (24) *Engine Freeze Treatment Group* identifies the firms that produced their own engines and therefore had the competence of producing more powerful engines. *Engine Freeze Treatment Group* assumes the value 1 for firms that produced their own engine and 0 otherwise. The variable assumes the value of 0 otherwise. Twenty-fifth, (25) the variable *Interaction Engine Freeze Treatment Group _ Engine Freeze Regulation* has been generated. Hence, the variable assumes the value of 1 if a team is part of the engine freeze treatment group and the performance is observed after the engine freeze regulation has been imposed. This variable identifies the treatment, i.e. the firms that had the competence to develop more powerful engines and the period during which they were not allowed to do so anymore. Twenty-sixth, (26) *Engine Freeze Non Participants* identifies the firms that exited the Formula 1 motor sport industry before the shock or entered after the shock, and, thus, were not subject to the engine freeze treatment. In particular, *Engine Freeze Non Participants* assumes the value 1 for firms that have not been subject to the engine freeze treatment and 0 otherwise. Finally, twenty-seventh (27) *Trend* measures the number of years that have passed in a given condition, i.e. before and after the shock that required firms to outsource the ECU to the unique, industry-wide supplier.

5.3 Summary Statistics and Correlations

Table 1 below provides the summary statistics for the dependent-, independent- and control variables described above. As the table shows, the data includes 1819 observations of the different firms competing in Formula 1 between 2004 and 2012, inclusive.

INSERT TABLE 1 ABOUT HERE

Tables 2 to 4 break down the summary statistics by group, i.e. treatment group, control group and non-participants respectively.

INSERT TABLES 2 - 4 ABOUT HERE

Table 5 shows the correlations between the various variables used in this study. The correlations exceeding the threshold of 0.7 are highlighted. As can be seen, there are no alarming correlations, neither between his study's dependent and independent variables, nor between the main independent variables themselves.

INSERT TABLE 5 ABOUT HERE

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6. RESULTS

INSERT TABLE 6a ABOUT HERE

Table 6a reports the results of this study's statistical analysis, which have been obtained by means of quasi maximum likelihood poisson regressions. Regarding the specific effects related to this study's hypotheses, the coefficients of interest and their level of significance are highlighted in bold. The results show that outsourcing, i.e. the treatment, has a negative effect on firm performance, as evidenced by the highly significant negative effect of the treatment in all models 1 through 3. This confirms hypothesis 1. Moreover, the results of models 1 to 3 show the effect for different time windows around the shock. Specifically, model 1 shows the effect for a short-term time window from 2006 to 2009, model 2 shows the effect for a mid-term time window from 2005 to 2010 and model 3 is looking at a long-term time window from 2004 to 2012. When comparing the results in model 1 with the results in model 2 and model 3, it becomes evident that the treatment effect is more negative for a time window closer around the shock and becomes weaker in the mid-term and long-term time windows. Hence, the treatment effect is larger shortly after firms are subjected to the treatment and weakens off over time. This confirms hypothesis 2. Finally, models 1 to 3 include the effect of ownership in components related to the outsourced component and show that the interaction of such ownership and outsourcing has a positive effect on performance. Clearly, firms having had to outsource the electronic control unit (ECU) were able make up for the resulting performance decrease, and in fact could actually gain increases in performance, when they owned components interacting with the ECU. This confirms this study's hypothesis 3. Moreover, the margins for the effects of the treatment of outsourcing the ECU and the ownership of components related to the ECU have been investigated. Figure 1 below shows that, in fact, more ownership of ECU related components helps when outsourcing the ECU.

FIGURE 1 ABOUT HERE

In order to control for the robustness of the results, additional regressions have been conducted. Table 6b shows the results for the negative binomial regression and figure 2 shows its margins. The tables 6c and 6d below provide the results for panel poisson- and OLS regressions respectively. The evidence shows that even with these models, this study's results are robust.

INSERT TABLES 6b, 6c, 6d as well as FIGURE 2 ABOUT HERE

7. DISCUSSION AND CONCLUSIONS

Managing technological change across complex systems necessitates the coordination between the activities underlying the component development, as well as the assembly and integration of those components into a final product. This is true particularly when components have technological interdependencies, which often require firms to experiment and learn in order to leverage their potential. Whether and under which conditions strategic governance changes, such outsourcing, can provide performance benefits in such contexts is less well understood. This study has examined the need for buyer firms to outsource and integrate a technology in relation to their performance, in order to understand this issue more fully.

The unique data set on Formula 1 racing is relevant in this respect, as it allows to link data on outsourcing and ownership of components across the system to performance outcomes. In this study, this has been done by conducting a natural experiment, which is one of the most powerful methods to prove causality free of endogeneity. Consistent with the predictions, the results show that, in Formula 1 motor sport, governance changes like outsourcing negatively affect firm performance. It appears that firms are not necessarily able to integrate components that were previously developed internally, when they outsource them to an external supplier. This effect tends to become weaker over time as firms learn in their new relationship. Moreover, the results show that a firm's ability to benefit from changes in governance, such as outsourcing, depends on its ownership of components that interact with the outsourced component.

These findings stress that it is not sufficient to study outsourcing, and governance decisions in general, in dyadic situations. In fact, what this study shows is that the value system cannot be discarded and has to be the subject of analysis if one wants to fully understand value creation across firm- and component boundaries. Considering governance changes in such a value system, the study explains why some firms are better at outsourcing than others. It appears that effective outsourcing changes may not necessarily be entirely the result of a capability to govern supplier relationships. A firm's superior effectiveness in outsourcing may just as well derive from the firm's owns critical related knowledge, possibly allowing firms without any prior outsourcing experience to be effective outsourcers. In fact, in this respect, the study's results suggest that firms are more flexible in governing component x when they own related components y. This underlines that firms need to pay attention to linkages between components and perform better if they are able to do so, assuming that ownership of linked components determines the ability to pay attention to linkages to some extent. These findings are consistent with the theory on systems integration, which suggests that knowledge overlap with suppliers is beneficial to effective integration of knowledge from external sources. Overall, the study contributes to the literature on modularity and outsourcing, as well as knowledge integration across complex systems. It shows that modularization and outsourcing should ideally be guided by architectural knowledge. Specifically, the paper shows that ownership of components across the system is important for effective knowledge integration when outsourcing individual components, and hints at ownership as a source of architectural competence. Therewith, the study extends modularity theory and the theory of the firm, as well as the related literature streams on supply chain management and knowledge integration, the latter of which thus far tends to focus on the efficiency aspects of knowledge integration instead of effectiveness. Empirically, the study contributes to the academic discussion by underlining the importance of external shocks for the discussion around governance changes, since all prior work on governance changes is potentially endogenous. In this respect, this study's results provide some clarity regarding the confusion about the direct effect of changes in governance on performance.

Finally, this study's findings address the important question of whether and under which conditions a firm may experience performance benefits when outsourcing components to suppliers that are also available to competitors. Since firms today frequently outsource activities to suppliers that provide several competitors with the same capabilities (Jacobides and Winter, 2005), this is a particularly interesting issue that has emerged only recently. Notably, for externally sourced supplier knowledge and capabilities to generate value that is unique to the buyer firm, they need to be integrated and assimilated within the buyer firm (Purvis, Sambamurthy and Zmud, 2001). However, supplier knowledge and capabilities that are readily available to the systems integrator's competitors are believed to be a somewhat unlikely source of competitive advantage (Barney, 1986; 1991; Kim and Mahoney, 2006). This study highlights that ownership may explain some of the heterogeneity regarding firms' effectiveness in managing governance changes, as well as sourcing and integrating a component from the same suppliers as competitors. Future research should address how ownership in related components is utilized for knowledge integration across complex systems by firms and their personnel, as well as how it may translate into firm behavior.

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9. TABLES AND FIGURES

Table1: Overall Summary Statistics.

Variable	Observations	Mean	Std. Dev.	Min.	Max.
Race Points	1819	9.134	11.674	0	43
Ownership	1819	0.734	0.065	0.6087	0.8261
Budget	1819	237.518	136.052	32.25	499.05
Firm Experience	1819	37.808	20.457	0	55
Firm Success	1819	415.155	466.095	0	1619
Driver Experience	1819	4.961	3.397	0	12.5
Driver Success	1819	0.355	0.852	0	3.5
Engineers’ Experience	1779	14.502	4.722	4.4	26.2
Engineers’ Success	1779	1.947	1.973	0	6.4
Season Clock	1819	0.527	0.288	0.05	1
Testing	1819	794.941	1789.612	0	16834.57
Practice	1819	633.587	174.895	0	1297.632
Track Temperature	1819	35.281	9.497	16	63
Ambient Temperature	1819	25.579	5.462	15	42
Race Distance	1819	302.990	17.504	171.841	310.422
HQ Distance	1819	4.949	4.746	0	17.330
Suppliers	1819	15.592	2.304	11	22

Table2: Summary Statistics Treatment Group.

Variable	Observations	Mean	Std. Dev.	Min.	Max.
Race Points	560	10.8	11.185	0	43
Ownership	560	0.766	0.048	0.6957	0.8261
Budget	560	335.405	107.219	123.75	499.05
Firm Experience	560	45.761	15.444	0	55
Firm Success	560	546.223	393.441	0	1270
Driver Experience	560	5.639	3.105	0.5	11.5
Driver Success	560	0.160	0.349	0	1
Engineers’ Experience	560	15.637	6.321	5.6	26.2
Engineers’ Success	560	2.435	2.026	0	6.4
Season Clock	560	0.527	0.288	0.05	1
Testing	560	1160.437	2212.149	0	16834.57
Practice	560	632.275	182.811	92.912	1190.435
Track Temperature	560	35.921	9.860	16	63
Ambient Temperature	560	25.893	5.716	14	42
Race Distance	560	302.683	18.334	171.841	310.422
HQ Distance	560	4.823	4.773	0.011	17.005
Suppliers	560	14.411	1.633	12	18

Table3: Summary Statistics Control Group.

Variable	Observations	Mean	Std. Dev.	Min.	Max.
Race Points	619	13	13.903	0	43
Ownership	619	0.755	0.060	0.6364	0.8261
Budget	619	258.065	125.993	45.6	432.98
Firm Experience	619	43.462	17.289	0	55
Firm Success	619	633.948	556.038	0	1619
Driver Experience	619	5.3991	3.309	0	12.5
Driver Success	619	0.540	0.958	0	3.5
Engineers’ Experience	619	14.920	3.915	4.4	21.4
Engineers’ Success	619	2.647	2.054	0	6.4
Season Clock	619	0.527	0.288	0.05	1
Testing	619	873.559	1828.827	0	13899.87
Practice	619	616.460	185.285	0	1106.632
Track Temperature	619	35.719	9.788	16	63
Ambient Temperature	619	25.782	5.624	14	42
Race Distance	619	303.126	16.986	171.841	310.422
HQ Distance	619	4.862	4.732	0	17.004
Suppliers	619	16.118	1.810	12	20

Table4: Summary Statistics Non-Participants.

Variable	Observations	Mean	Std. Dev.	Min.	Max.
Race Points	640	3.936	7.307	0	43
Ownership	640	0.687	0.056	0.6087	0.8261
Budget	640	131.994	85.404	32.25	360.16
Firm Experience	640	25.381	21.257	0	55
Firm Success	640	88.855	124.805	0	446
Driver Experience	640	3.944	3.490	0	12.5
Driver Success	640	0.348	1.003	0	3.5
Engineers’ Experience	600	13.011	3.077	9.2	21.2
Engineers’ Success	600	0.770	1.119	0	3.8
Season Clock	640	0.527	0.288	0.05	1
Testing	640	399.093	1147.303	0	11649.61
Practice	640	651.299	154.879	0	1297.632
Track Temperature	640	34.298	8.797	16	63
Ambient Temperature	640	25.108	5.034	14	42
Race Distance	640	303.128	17.277	171.841	310.422
HQ Distance	640	5.142	4.737	0	17.330
Suppliers	640	16.117	2.799	11	22

Table 5: Correlations.

	Race Points	Owner-ship	Outsourcing Regulation	Treatment Group	Budget	Firm Exp.	Firm Success	Engineers' Exp.	Engineers' Success	Driver Exp.	Driver Success	Suppliers
Race Points	**1.0000**											
Ownership	0.3044	**1.0000**										
Outsourcing Regulation	-0.0268	-0.1734	**1.0000**									
Treatment Group	0.0937	0.3090	-0.1184	**1.0000**								
Budget	0.5135	**0.7348**	-0.1753	0.4749	**1.0000**							
Firm Experience	0.3139	0.3004	-0.0194	0.2550	0.4108	**1.0000**						
Firm Success	0.5710	0.4277	-0.0547	0.1776	0.6850	0.5984	**1.0000**					
Engineers' Experience	0.3445	0.1305	0.3446	0.1629	0.3034	0.3944	0.5430	**1.000**				
Engineers' Success	0.5199	0.3898	0.1005	0.1677	0.6157	0.5430	**0.8330**	**0.7262**	**1.000**			
Driver Experience	0.3030	0.5188	0.0238	0.1341	0.5318	0.0231	0.3246	13.70	0.3776	**1.0000**		
Driver Success	0.2936	0.3811	0.0574	-0.1557	0.3427	0.3514	0.4172	35.14	0.5169	0.5247	**1.0000**	
Suppliers	-0.1514	-0.4782	0.3483	-0.3386	-0.4005	-0.1947	-0.1740	-0.1162	-0.2210	-0.2760	-0.2083	**1.0000**

Table6a: Results; Quasi Maximum Likelihood Poisson Regression; Dependent variable = Points per race; Standard errors in parentheses. *significant at 10%; **significant at 5%; ***significant at 1%. Control variables not reported in this table are the following: (i) track temperature, (ii) ambient temperature, (iii) race distance, (iv) headquarters distance, (v) testing, (vi) practice and (vii) season clock, as well as (viii) other shocks.

VARIABLES	**RACE POINTS Model 1 (2006-2009)**	**RACE POINTS Model 2 (2005-2010)**	**RACE POINTS Model 3 (2004-2012)**
Outsourcing Regulation	1.142***	0.618**	0.567***
	(0.334)	(0.242)	(0.163)
Non Participant	- 1.079	- 2.048***	- 2.145***
	(0.798)	(0.723)	(0.712)
Treatment Group	- 0.853***	- 0.345***	0.556***
	(0.219)	(0.115)	(0.100)
Treatment	**- 17.157*****	**- 9.139*****	**- 3.578*****
	(2.647)	**(1.890)**	**(0.123)**
Ownership	- 6.071**	- 5.508***	- 5.602***
	(2.602)	(2.128)	(1.366)
Interaction	**21.779*****	**11.825*****	**4.773*****
Treatment _ Ownership	**(3.292)**	**(2.404)**	**(1.619)**
Budget	0.010***	0.004***	0.006***
	(0.001)	(0.001)	(0.000)
Firm Experience	0.555***	0.191***	0.204***
	(0.117)	(0.058)	(0.049)
Firm Success	- 0.002***	- 0.000	0.000
	(0.000)	(0.000)	(0.000)
Engineers’ Experience	- 0.016	0.042**	0.042***
	(0.030)	(0.020)	(0.016)
Engineers’ Success	0.479***	- 0.128**	- 0.002
	(0.109)	(0.057)	(0.036)
Driver Experience	- 0.075***	0.030*	- 0.052***
	(0.020)	(0.018)	(0.016)
Driver Success	- 0.007	- 0.007*	- 0.002
	(0.005)	(0.004)	(0.004)
Suppliers	- 0.531***	- 0.131***	- 0.104***
	(0.058)	(0.031)	(0.022)
Other Control Variables	...	...	...
Cons.	7.968***	4.613***	4.532***
	(2.616)	(1.741)	(1.116)
Observations	753	1,171	1,779
Pseudo log-likelihood	- 3689.7862	- 6610.334	- 9739.5335
Pseudo R-squares	0.4953	0.3737	0.3652

Figure 1: Margins based on the quasi-maximum-likelihood panel regression. DV = Race Points.

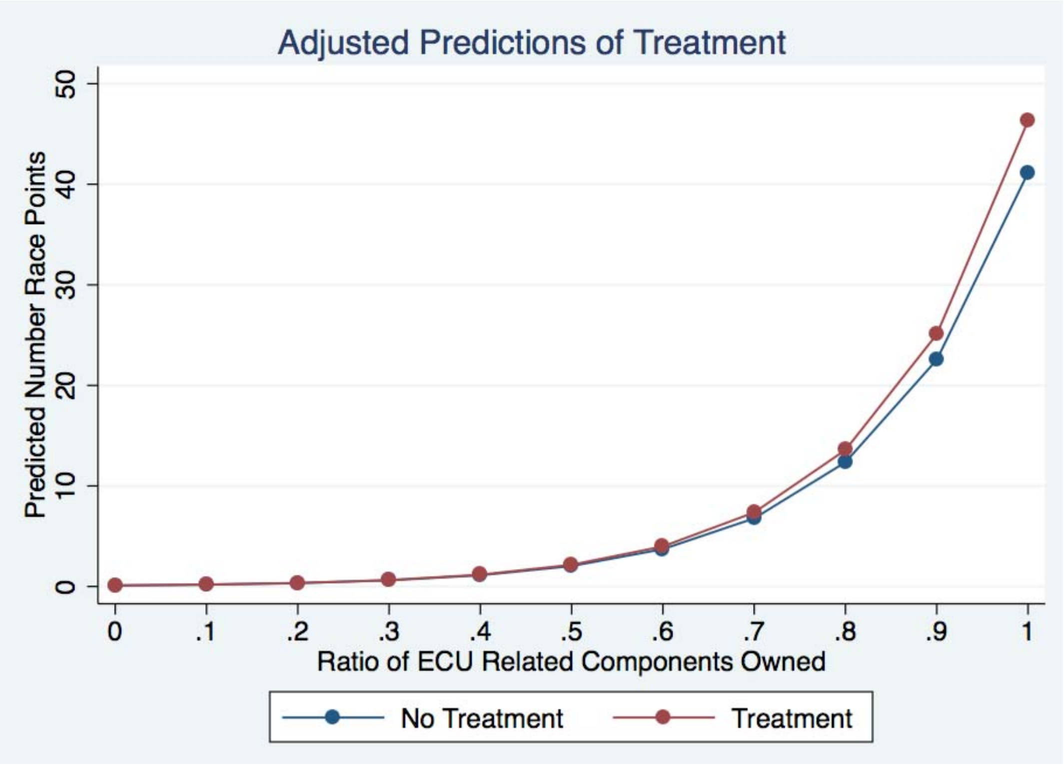

Table6b: Results; Negative binomial panel regression; Dependent variable = Points per race; Standard errors in parentheses. *significant at 10%; **significant at 5%; ***significant at 1%. Control variables not reported in this table are the following: (i) track temperature, (ii) ambient temperature, (iii) race distance, (iv) headquarters distance, (v) testing, (vi) practice and (vii) season clock, and (viii) other shocks.

VARIABLES	**RACE POINTS Model 1 (2006-2009)**	**RACE POINTS Model 2 (2005-2010)**	**RACE POINTS Model 3 (2004-2012)**
Outsourcing Regulation	0.995***	0.424*	0.243
	(0.345)	(0.243)	(0.184)
Non Participant	- 0.887	-1.876**	- 2.198**
	(0.809)	(0.806)	(0.933)
Treatment Group	- 0.446*	- 0.349**	- 0.314**
	(0.244)	(0.173)	(0.144)
Treatment	**- 16.406*** **	**- 6.586*** **	**- 5.109*** **
	(2.726)	**(2.012)**	**(1.469)**
Ownership	- 4.964*	2.552	- 2.586*
	(2.901)	(2.226)	(1.546)
Interaction	**20.797*** **	**8.616*** **	**6.647*** **
Treatment _ Ownership	**(3.401)**	**(2.568)**	**(1.911)**
Budget	0.007***	0.004***	0.005***
	(0.001)	(0.001)	(0.001)
Firm Experience	0.568***	0.214***	0.141**
	(0.130)	(0.067)	(0.053)
Firm Success	- 0.002***	- 0.001**	- 0.000
	(0.000)	(0.000)	(0.000)
Engineers’ Experience	- 0.062*	- 0.009	0.023
	(0.035)	(0.021)	(0.016)
Engineers’ Success	0.613***	0.209***	0.051
	(0.123)	(0.066)	(0.030)
Driver Experience	- 0.071***	- 0.033**	- 0.027**
	(0.024)	(0.017)	(0.013)
Driver Success	- 0.007	- 0.001	0.010**
	(0.006)	(0.005)	(0.004)
Suppliers	- 0.442***	- 0.148***	0.006
	(0.070)	(0.040)	(0.030)
Other Control Variables	...	...	...
Cons.	5.680**	- 2.363	- 0.572
	(2.422)	(1.842)	(1.264)
Observations	753	1,171	1,779
Log-likelihood	-2042.5869	-3186.0068	-4720.1858
Wald chi square	344.63	293.50	354.18
Prob > chi-square	0.0000	0.0000	0.0000

Figure 2: Margins based on the negative binomial panel regression. Dependent Variable = Race Points.

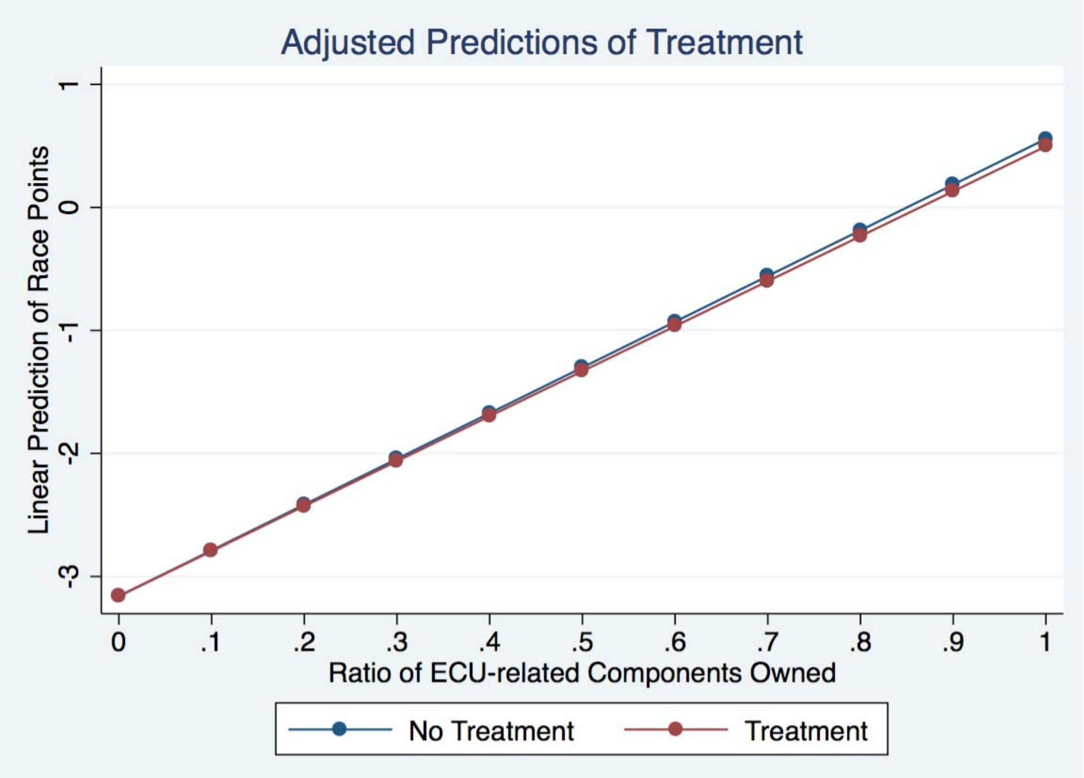

Table6c: Results; Poisson panel regression; Dependent variable = Points per race; Standard errors in parentheses. *significant at 10%; **significant at 5%; ***significant at 1%. Control variables not reported in this table are the following: (i) track temperature, (ii) ambient temperature, (iii) race distance, (iv) headquarters distance, (v) testing, (vi) practice and (vii) season clock, as well as (viii) other shocks.

VARIABLES	**RACE POINTS Model 1 (2006-2009)**	**RACE POINTS Model 2 (2005-2010)**	**RACE POINTS Model 3 (2004-2012)**
Outsourcing Regulation	1.071***	1.270***	0.826***
	(0.136)	(0.100)	(0.075)
Non Participant	- 4.055	- 4.199	- 3.296
	(2.605)	(2.605)	(2.230)
Treatment Group	- 0.244	- 0.234	0.258
	(1.936)	(1.928)	(1.309)
Treatment	**- 18.505*****	**- 18.419*****	**- 14.764*****
	(1.543)	**(1.100)**	**(0.778)**
Ownership	- 7.944***	- 7.519***	- 7.429***
	(1.690)	(1.014)	(0.688)
Interaction	**23.862*****	**23.475*****	**18.939*****
Treatment _ Ownership	**(1.944)**	**(1.391)**	**(0.992)**
Budget	0.005***	0.006***	0.005***
	(0.001)	(0.000)	(0.000)
Firm Experience	0.675***	0.153***	0.298***
	(0.090)	(0.038)	(0.026)
Firm Success	- 0.003***	- 0.001***	- 0.001***
	(0.000)	(0.000)	(0.000)
Engineers' Experience	- 0.028	0.030**	- 0.011
	(0.025)	(0.013)	(0.009)
Engineers' Success	0.064	- 0.382***	- 0.082***
	(0.085)	(0.036)	(0.022)
Driver Experience	- 0.080***	- 0.022**	- 0.030***
	(0.015)	(0.008)	(0.006)
Driver Success	- 0.017***	- 0.007***	- 0.005***
	(0.003)	(0.002)	(0.002)
Suppliers	- 0.027	0.150***	0.170***
	(0.033)	(0.021)	(0.016)
Other Control Variables	...	...	...
Cons.	7.968***	5.174***	4.438***
	(2.616)	(2.083)	(1.376)
Observations	753	1,171	1,779
Log-likelihood	-3422.269	-5424.9124	-7955.8627
Wald chi square	1062.65	1405.38	1761.74
Prob > chi-square	0.0000	0.0000	0.0000

Table6d: Results; OLS panel regression; Dependent variable = Points per race; Standard errors in parentheses. *significant at 10%; **significant at 5%; ***significant at 1%. Control variables not reported in this table are the following: (i) track temperature, (ii) ambient temperature, (iii) race distance, (iv) headquarters distance, (v) testing, (vi) practice and (vii) season clock, as well as (viii) other shocks.

VARIABLES	**RACE POINTS Model 1 (2006-2009)**	**RACE POINTS Model 2 (2005-2010)**	**RACE POINTS Model 3 (2004-2012)**
Outsourcing Regulation	8.976***	2.018	3.065**
	(2.495)	(1.736)	(1.272)
Non Participant	- 3.776*	- 0.586	- 0.804
	(2.064)	(2.026)	(1.853)
Treatment Group	- 11.746***	- 5.495***	- 6.248***
	(1.783)	(1.188)	(0.926)
Treatment	**- 202.491***	**- 98.516***	**- 39.994***
	(21.949)	**(17.193)**	**(12.204)**
Ownership	- 73.699***	- 20.174	- 35.157***
	(22.551)	(16.439)	(9.188)
Interaction	**263.191***	**132.035***	**55.937***
Treatment _ Ownership	**(27.855)**	**(22.359)**	**(16.256)**
Budget	0.079***	0.029***	0.041***
	(0.010)	(0.005)	(0.004)
Firm Experience	0.346	0.885**	0.628**
	(0.708)	(0.399)	(0.302)
Firm Success	- 0.011***	- 0.001	- 0.006***
	(0.003)	(0.002)	(0.001)
Engineers’ Experience	0.306*	0.303**	0.169*
	(0.177)	(0.137)	(0.102)
Engineers’ Success	2.749***	2.125***	- 0.370
	(0.766)	(0.497)	(0.333)
Driver Experience	- 0.802***	- 0.093	0.056
	(0.171)	(0.123)	(0.100)
Driver Success	0.009	- 0.123**	- 0.003
	(0.068)	(0.051)	(0.037)
Suppliers	- 4.050***	- 0.689***	- 0.324*
	(0.439)	(0.250)	(0.180)
Other Control Variables	...	...	...
Cons.	93.267***	14.294	22.743***
	(17.719)	(13.446)	(8.805)
Observations	753	1,171	1,779
R-squared between	0.9124	0.6531	0.6869
R-squared overall	0.4619	0.3731	0.4165

ESSAY 2

From Garage to Grand Prix:

Adaptation and Knowledge Integration in Complex Systems

ABSTRACT

Research on modularity and architectural innovation has established that production systems routinize approaches to interdependency across groups or systems but struggle to manage unforeseen changes in the interdependence. Yet we rarely observe firms in the process of adapting across complex, interdependent systems of production. This study builds on modularity theory and the knowledge-based view of the firm to investigate differences in firms' adaptive behavior in response to an externally imposed supplier change for Formula 1 teams. Before and after an official tire supplier was designated in 2007, we observe adaptations, component problems, and performance among teams that could retain the same tire supplier and those that were forced to change. Difference in difference analysis shows that a firm's ability to integrate a new external component, even a highly modular product such as a tire, is significantly affected by its ability to understand and adapt in related components across the system. Firms integrating a new tire supplier have fewer problems and perform better when they make more adaptations in tire-related components.

1. INTRODUCTION

Contemporary complex product development is carried out in supply chains, with diverse, specialized knowledge sources collaborating across firm boundaries (Helper, MacDuffie and Sabel, 2000; Powell, Koput and Smith-Doerr, 1996; Von Hippel, 1988). Recent publications argue that firms are increasingly relying on suppliers for the production of increasingly complex products (Argyres and Bigelow, 2010; Langlois, 2003). Sharing across supply chains has led to an amplifiation of the importance of supplier management during recent years (Fine, 1998; Hall and Braithwaite, 2001; Kaplan and Sawhney, 2000; Simchi-Levi et al., 2000) and firms have recognized that combining critical resources with strategic supply chain partners may provide a competitive advantage (Hardy et al., 2005; Paulraj et al., 2008). In fact, supply chains are developing towards complex value networks in which partners collaborate, learn from each other and experiment together on problem-solving, sharing the risks and benefits (Malhotra et al., 2005). However, buyer-supplier relationships are subject to a series of pressures, with buyers switching their suppliers for a variety of reasons, such as differences between performance expectations and actual performance, a lack of supply scalability, or a firm’s sourcing strategy. Today, with outsourcing relationships becoming increasingly focused on value, supplier switches are commonplace. As a consequence, supplier transition and integration of external knowledge assume particular importance.

In order to better understand how firms can improve in organizing for the integration of different components across complex systems, research has developed the concept of modular design or modularization. This approach subdivides systems into modules, which can be developed independently from one another and recombined with the system through standardized interfaces (Baldwin and Clark, 2000). Trends towards product modularization enable unprecedented levels of inter-organizational design coordination (Brusoni, 2005), building on the intuition that complex systems such as products, technologies and organizations are adaptive if modular (Simon, 1962). Nevertheless, recent empirical evidence shows that, for example in the automotive industry, modularity has produced disputable benefits (Fourcade and Midler, 2004; MacDuffie, 2013; Zirpoli and Becker, 2011). For instance, Cabigiosu and Camuffo (2012) find that product modularity offers little explanation in this respect, considering it may alternatively be associated with either plenty of information sharing or with little information sharing with suppliers.

Moreover, while it is widely accepted that firms produce value jointly in interconnected systems (Brandenburger and Nalebuff, 1996; Normann and Ramirez, 1993; Adner and Kapoor, 2010), much of the existing research has focused on singular relationships or components. It is less well understood how firms manage the challenges of integrating and coordinating activities with their suppliers across the entire value system. In fact, the extensive literature review on supply chain management by Croom et al. (2000) found very few studies that relate to the important topic of knowledge exchange in supply chain integration, and Bowersox et al. (2000) state that the most evident gaps in supply chain management research appear in terms of the knowledge and learning dimensions.

This study investigates differences in firm performance and adaptive behavior in Formula 1 racing between 2004 and 2009, in relation to an industry-wide adoption of Bridgestone as a unique supplier for a key component, the tyres, in 2007. By studying firm’s adaptive behavior, in terms of changes in tyre-related components, and performance, in terms of championship points gained at each race, before and after the external shock, this paper explores how differences in firms' adaptive behavior may lead to differences in their abilities to adapt to changes in external sources of knowledge, i.e. new suppliers. Formula 1 racing is particularly relevant in this respect, since (a) the dominant capability for competitive advantage is the integration of different component developments (Jenkins, 2010) and (b) car constructors require human, financial, and organizational resources in order to maintain their competitiveness, i.e. to construct competitive cars to win races and finally the World Championship (Jenkins et al., 2007).

2. THEORY AND HYPOTHESES

This paper is based on modularity theory (Baldwin and Clark, 1997, 2000; Garud and Kumaraswamy, 1995; Henderson and Clark, 1990; Langlois and Robertson, 1992; Sanchez and Mahoney, 1996; Sako, 2003; Schilling, 2000; Simon, 1962; Ulrich, 1995; von Hippel, 1990), which states that product architectures are targets of design, and hence potentially a source of competitive advantage for firms, as well as the theory of the firm, specifically the knowledge-based view of the firm (Kogut and Zander, 1992, 1996; Conner and Prahalad, 1996; Grant, 1996) and the collaborative paradigm (Contractor and Lorange, 1988; Dyer, 2000; Kanter, 1994; Nielsen, 1988), which emphasizes that the business world is composed of a network of interdependent relationships, which are developed and fostered through strategic collaboration with the goal of deriving mutual benefits (Ahuja, 2000; Borys and Jemison, 1989; Chen and Paulraj, 2004; Lado et al., 1997; Madhok and Tallman, 1998; Miles and Snow, 1986; Thorelli, 1986). Since the network perspective includes a focal organization's potentially influential indirect connections to third parties, it is likely to provide new or alternative insights with respect to established streams of literature, such as, among others, interorganizational knowledge creation and transfer (Ingram and Baum, 1997), knowledge adoption and development (Cohen and Levinthal, 1990), knowledge evolution (March, 1991; Miller and Chen, 1994; Levinthal and March, 1993), as well as recent research on the mechanisms firms use to obtain externally generated knowledge (Ahuja and Katila, 2001; Mowery and Ziedonis, 2001; Oxley, 1999; Song, Almeida and Wu, 2003).

Buyer-supplier relationships typically achieve the integration of knowledge through three mechanisms. These are (1) the co-location of buyer- and supplier engineers (Dyer, 1997; Dyer and Nobeoka, 2000; Helper, MacDuffie and Sabel, 2000), (2) leveraging relationship-specific assets developed in prior interactions (Dyer and Singh, 1998; Kale and Singh, 2007), and (3) using modular architectures (Baldwin and Clark, 2000), i.e. subdividing a system into modules that can be independently created and integrated into the system through standardized. The (1) co-location of buyer and supplier engineers is suggested to facilitate the development of shared contextual knowledge, which fosters integration (Kraut et al., 2002; Olson et al., 2002). The (2) leveraging of relationship-specific assets developed in prior interactions has been found to be enabled through collaboration over time, which allows for better exchange of knowledge and superior integration, as well as partner-specific experience and learning, common language, interaction routines and a better understanding of partner decision-making procedures (Dyer and Singh, 1998; Gulati, Lavie and Singh, 2009). The (3) modular architectures are suggested to facilitate the integration of external knowledge (Baldwin and Clark, 2000; Brusoni, Prencipe and Pavitt, 2001). Importantly, entirely modular product architectures are rare. Components frequently interact for system performance, which makes it practically impossible to entirely eliminate component interdependencies by design. The less modular and the more systemic products are, the more cross-team integration across different components is required (Sosa, Eppinger and Rowles, 2004; Zirpoli and Becker, 2011).

From the buyer firm's perspective, the selection, assembly, control, and linking of outsourced components to internal components may be characterized as architectural knowledge, or architectural competence. However, it is not yet well understood of how a systems integrator's competences are used in relation to their suppliers' components across the system. Moreover, the question of how a systems integrator may gain performance benefits from accessing supplier components that are also available to competitors has not yet received a lot of attention. As research has come to understand that it is likely not merely a firm's competences or a firm's access to other firms' competences that guarantee performance advantages (Barney, 1986), but rather how competences are used (Sirmon et al., 2007; Penrose, 1959), research calls for a better understanding of how resources and competences are used in order to improve performance (Priem and Butler, 2001; Sirmon et al., 2007). As a consequence, knowledge integration in buyer-supplier relationships is currently starting to receive increasing attention in the literature (e.g. Ceccagnoli and Liang, 2013). This study's objective is the investigation of the contributions and interactions of firm-based architectural knowledge and network-sourced component knowledge in the Formula 1 motor sport industry, in which firms outsource production processes that involve highly skilled labor.

2.1 Supplier Switching and Firm Performance

Recent publications argue that firms are increasingly relying on suppliers for the production of increasingly complex products (Argyres and Bigelow, 2010; Langlois, 2003). Idiosyncratic inter-firm linkages and inter-firm specialization are sources of relational rents and competitive advantage (Dyer, 1996; Dyer and Singh, 1998). Inter-firm knowledge-sharing routines are particularly important in this respect, since organizations often learn by collaborating with others (March and Simon, 1958; Powell et al., 1996). Importantly, transaction-specific know-how and skills, as well as difficulties of skill transfer make switches to alternative suppliers costly (Teece, 1977; 1980). The ability to absorb and assimilate external knowledge is a function of a firm's absorptive capacity (Cohen and Levinthal, 1990). In the context of buyer-supplier relationships, Dyer and Singh (1998) state that partner specific absorptive capacity is a function of (i) the extent to which partners have developed routines that maximize the frequency and intensity of socio-technical interactions and (ii) the extent to which partners have developed overlapping knowledge-bases (Mowery, Oxley and Silverman, 1996; Szulanski, 1996). Clearly, a firm's partner-specific absorptive capacity and inter-firm knowledge-sharing routines with a familiar supplier will be superior to those with a new, unfamiliar supplier. Experienced firms tend to invest in existing routines rather than create new ones. The fact that these firms are generally tightly coupled in their environments (Weick, 1979) and are involved in resource dependence relationships (Aldrich and Auster, 1986) further complicates navigating the changing environment.

Since know-how involves knowledge that is complex, tacit, sticky, and difficult to codify (Kogut and Zander, 1992; Nelson and Winter, 1982; Szulanski, 1996), it is difficult to transfer to and from a new supplier. Considering that know-how cannot simply be transferred from supplier to supplier like a book of blueprints (Winter, 1980), supplier switching creates costs for a firm that needs to exchange know how with a new external supplier in order to be able to successfully integrate external and internal knowledge. Famously, research has argued that experience may lead to competency traps or core rigidities (Levitt and March 1988; Leonard-Barton 1992). Moreover, research by Upton and Kim (1998) identifies the risk of lock-in with different learning modes and work by Edmondson et al. (2003) links the state of knowledge to differential learning performance. Hence, organizations may become set in their way of doing things and, as external sources of knowledge change, may not be able to adapt. As a result, even a switch to a supplier that offers superior components is likely to be associated with a decrease in the effectiveness of knowledge integration for the switching firm.

H1: *Supplier switching has a negative effect on a firm’s performance.*

Over time, the magnitude of the supplier switch effect on firm performance is likely to change, as both firms communicate, learn and develop relational capital. The main assumption of research on the evolution of knowledge is that knowledge is not static, once it has been created, transferred or adopted. Instead, it evolves through application. In general, knowledge and / or its benefits evolve over time either in terms of improvement or in terms of deterioation. One evolutionary phenomenon that represents knowledge improvement is the organizational learning cruve or experience curve, whereby improvements in the way things are done are a consequence of cumulative learning by doing and associated development of context specific, experience based competences (Argote, 1999; Epple et al., 1991).

In order to leverage externally sourced new knowledge, firms must integrate and assimilate external technologies, as well as the new knowledge associated with them

(Cassiman and Veugellers, 2006; Matusik and Hill, 1998). This process of integration and assimilation includes the acquisition of new knowledge, its dissemination within the firm, as well as its combination with existing knowledge (Huber, 1991; Leonard-Barton, 1992). Moreover, the effective integration of new technology in the product development process also requires frequent communication, high levels of coordination and intense involvement between different organizational units associated with product development within the knowledge receiving organization (Grant, 1996; Henderson and Cockburn, 1994). Communication and information sharing are integration mechanisms that coordinate inter-organizational relationships (Ring and Van de Ven, 1992).

Repetition plays a major role in both organizational learning (Adler, 1990; Argote et al. 1990; Dutton and Thomas, 1984) and in the creation of routines and capabilities in general (Nelson and Winter, 1982; Skinner, 1974). The repeated use of the same or similar knowledge components facilitates the development of routines, which, in turn, increases search reliability (Levinthal and March, 1981). Moreover, the combination of familiar components does not pose a lot of risk, since individuals can draw from past failures and successes in order to select the most appropriate combination (Fleming, 2001). By working toghether, firms develop specialized routines based on tacit knowledge of both, the tasks and each other’s abilities (Berman, Down and Hill, 2002). This is usually resulting in richer interactions, improved coordination and eventually superior performance, both at the firm and the inter-firm level (Brandon and Hollingshead, 2004; Weick and Roberts, 1993). Hence, when interdependent and complementary activities are carried out by separate firms, the integration of these activities are likely to improve with shared experiences, inter-firm communication, knowledge and routines that are developed and improved over time.

H2: *The negative effect of supplier switching on firm performance falls over time.*

2.2 Supplier Switching, Changes in Related Components and Firm Performance

The literature states that a firm’s ability to manage technological change underlying a new product generation depends on its *architectural competence* (Henderson and Cockburn, 1994). The effective integration of new technology in the product development process also requires frequent communication, high levels of coordination and intense involvement between different organizational units associated with product development within the knowledge receiving organization (Grant, 1996; Henderson and Cockburn, 1994). As a consequence, the knowledge of key components remains important to an organization’s ability to innovate on the product’s architecture and to coordinate product development across the supply chain (Christensen, 2006; Sanchez and Mahoney, 1996). Considering complex systems of interrelated components (Rosenkopf and Tushman, 1992; Thomke and Kuemmerle, 2002), firms may respond to changes in external knowledge components by increasing their innovative efforts in other components (Rosenkopf and Tushman, 1992; Tushman and Murmann, 1998). Hence, it can be argued that integrating outsourced knowledge requires architectural competence, i.e. the ability to access new knowledge from outside the boundaries of the organization and the ability to integrate knowledge across disciplinary boundaries within the organization (Henderson and Cockburn, 1994).

Interdependencies among components are important in this respect, because they may obstruct the selection of effective routines by obscuring the link between actions and outcomes (Sorenson, 2003). As a result, even when organizations are able to identify effective improvements for singular components, interdependence may constrain the firm’s ability to act on its knowledge. Firms may not always be able to optimize their products one component at a time, as changes in one component might need to be accompanied by changes in other components. The business history literature provides evidence of instances in which a change in a given component creates disturbances in the rest of the system, which are eventually resolved through modifications in other parts of the system (Hughes, 1983; Rosenberg, 1982). Such required technological changes comprise an ecosystem of mutually dependent changes. For example, research shows that in complex systems of interrelated components (Rosenkopf and Tushman, 1992; Thomke and Kuemmerle, 2002), firms may respond to changes in external knowledge components by increasing their innovative efforts in other components (Rosenkopf and Tushman, 1992; Tushman and Murmann, 1998). Clearly, the successful integration of outsourced components requires a combination of component and architectural knowledge (Henderson and Clark, 1990), and, hence, knowledge of components and the interdependencies among them. Hence, the knowledge of key components remains important to an organization's ability to innovate on the product's architecture and to coordinate product development across the supply chain (Christensen, 2006; Sanchez and Mahoney, 1996). In this respect, Brusoni and Prencipe (2001) find that focal firms need to have some degree of knowledge overlap with their suppliers, in order to identify potential novelties in fast-moving technological fields, understand their implications for the others, and integrate changes in existing or new product architectures. Similarly, research by Takeishi (2001) as well as Zirpoli and Becker (2011) states that buying firms' knowledge bases should be broader than that strictly needed to manage the internal design and production. Vertical integration may facilitate the sharing of technological information that is common to the separate stages of the development, in particular when complex interdependencies are at hand. It typically does so because it facilitates the implementation of new technology because it allows for the formulation of more astute research objectives (Armour and Teece, 1980; Monteverde, 1995), which, in turn, facilitates systemic innovations

(Teece, 1996). Moreover, a firm's vertical scope has been shown to affect the nature of its knowledge accumulation and capability development (Jacobides and Winter, 2005; Malerba et al., 2008). This, in turn, typically affects the capacity of a firm to absorb new external knowledge (Cohen and Levinthal, 1990), a certain amount of which is necessary to combine internal and external knowledge.

When integrating an externally sourced component, systems integrators can either use the supplier's knowledge (i) decoupled from related internal knowledge or (ii) coupled with related internal knowledge (Weigelt, 2013). The use of (i) supplier knowledge decoupled from the systems integrator's internal knowledge means that problem solving takes place as the supplier performs activities for its clients. Learning mainly takes place at the supplier firm, which applies its technical knowledge in order to understand successful solutions and errors, as well as to solve problems for the systems integrator. Instead, the use of (ii) supplier knowledge coupled with the systems integrator's internal knowledge is likely to cause learning and search for problem solutions drawing on both firms' knowledge bases as supplier capabilities and buyer firm processes are co-adapted. Schilling (2000) refers to such co-adaptation as synergistic specificity, meaning that a business process achieves greater functionality when its components are specific to one another. Moreover, routines for interaction may develop between firms, creating the potential for unique relative absorptive capacity between firms (Mesquita *et al*., 2008). This suggests that (ii) integrating a new externally sourced component x following a supplier switch, by coupling it with related internal knowledge, is likely to decrease problems surrounding the component x. This suggests that firms making a higher number of changes in related components *y* that interact with the externally sourced component *x* will be better at integrating component x following a supplier switch.

H3: *Following a change of supplier for a specific component, the number of changes that a firm makes in the components that interact with the focal component will reduce the negative effect of the change on firm performance*.

3. EMPIRICAL SETTING

This paper's empirical context is Formula 1 (F1) motor racing. F1 is a particularly relevant setting for the study of integration in an architectural system. F1 cars are complex systems that consist of many different components, whose architecture, ownership, development and performance can be observed at regular, intensive intervals during the integration. As a consequence of the immense public interest in F1 racing around the world, the industry is enjoying heavy media coverage on and off the race track, including information about agreements between firms and their suppliers, detailed reports about the developments made on a firm's car for every race, as well as the firm's performance. Research states that the dominant capability for competitive advantage is the integration of different component developments (Jenkins, 2010) and that car constructors require human, financial, and organizational resources in order to maintain their competitiveness, i.e. to construct competitive cars to win races and finally the World Championship (Jenkins et al., 2007).

Since the first official grand prix in 1950, F1 has been considered the pinnacle of automotive technology, as a result of high levels of innovation and large international exposure as a sport (Solitander and Solitander, 2010). F1 is the only form of motor sport that still requires each competing team, as a firm is customarily called in the industry, to design and assemble its own car. More specifically, a F1 team, or *constructor*, as the F1 governing body, the *Fédération Internationale l'Automobile* (FIA), officially defines them, needs to manufacture at least the chassis of its cars, whereas it can buy the other components from external suppliers. In addition to their racing departments, these firms have R&D, marketing, manufacturing, and testing departments. Furthermore, all constructors that compete in F1 operate with complex supplier networks. The major manufacturers may employ some 750 suppliers in order to produce the approximately 16,000 parts of a F1 car (Blitz, 2007). Many of these also supply to rival firms. Furthermore, many sponsors from more or less related industries cater to the F1 constructors. In fact, it is essential for F1 constructors to secure sponsorship deals, in order to be able to operate on a budget that is sufficiently large to design, manufacture and race competitive cars.

In F1, constructors compete for the Constructor’s Championship, which is awarded to the team that scores the highest number of championship points during a season. Since 1950, between 10 and 14 constructors have been competing in any given world championship season. Drivers compete for the Driver’s Championship, which is awarded to the driver that scores the highest number of championship points during a season. The constructors who compete in the F1 championship have an average budget of around $250 million (Sylt and Reid, 2008), and, as all constructors have to oblige to the same rules and regulations, and therefore work within the same constraints, only constant refinement and innovation can yield a competitive advantage (Cross and Clayburn Cross, 1996). As a consequence, each F1 constructor typically employs hundreds of engineers, who are continuously trying to come up with new innovations (Jenkins, 2004). Knowledge is critical here, since the key asset of firm’s is the knowledge possessed by the designers, engineers, fitters and mechanics (Pinch and Henry, 1999). The key role of resident engineers is to facilitate the integration of the technical knowledge held by both, the racing car manufacturer and the supplier, and to engage in joint problem solving activities (Mariotti, 2007).

In financial terms, F1 is a global sport with an estimated annual worth between $4bn and $5bn. The sport counts between 500bn and 600bn unique viewers per season (Sylt and Reid, 2011), and, around 350m viewers for a single race. In professional sports, these numbers are rivaled only by the Super Bowl held by the National Football League (NFL), the Champions League Final held by the Union of European Football Associations (UEFA), the World Cup Final held by the Fédération Internationale de Football Association (FIFA), or the Olympic Games, the last two of which take place only every 4 years. A large part of the motorsport industry is concentrated in a geographical cluster in southern England, which is referred to as Motorsport Valley. At the centre of this cluster is the F1 industry. In the UK alone the industry's annual turnover is around $10 billion, employing approximately 40,000 people, of which 25,000 are engineers (Henry and Pinch, 2000). Across the various constructors that compete in F1 each year, annual owner spending range from nothing to some $150m for constructors backed by car manufacturers or other major corporations. Annual sponsorship revenues in F1 range from under $10m to over $200m. Another important source of revenues is prize money, which ranges from around $10m for a team that finishes outside the top 10 to around $87m for the world champion. Furthermore, teams generate between $7m and $15m of revenues per season through trade support and tyre supply, and, in some cases, up to an additional $5m from merchandise and events. In the pursuit of performance goals, typical top team expenditures amount to some $250m per season, $340m if it is a works team, i.e. if it manufactures its own engines. Instead, small team expenditures amount to some $80m per season (Sylt and Reid, 2011).

Notably, F1 today is both, the world’s premier motor sport and a multi-billion dollar business.

4. DATA

At the outset of the 2007 season, the FIA imposed a switch from a situation where firms could choose between Bridgestone and Michelin for tyre supply, to a situation where Bridgestone was the exclusive tyre supplier for all firms competing in Formula One. Traditionally, an average car with good tyres could do well, but with bad tyres even the very best car did not stand a chance. Importantly, tyres are still a car’s biggest single performance variable and the only point of contact between car and track (www.F1.com). Hence, switching the tyre supplier is likely to have an impact on a firm’s race performance.

Interestingly, the new supplier which some firms had to switch to in 2007, Bridgestone, had been in Forumla 1 since 1997. In the ten seasons before the switch, i.e. from 1997 to 2006, Bridgestone was the tyre supplier of the world champion seven times. Hence, over their presence in Formula One until 2006, Bridgestone won the world championship 70 percent of the time. Instead, the supplier that some firms had to switch away from, Michelin, had been in Formula 1 only since 2001. In the six seasons from 2001 to 2006, Michelin was the tyre supplier of the world champion two times. Hence, over their presence in Formula One until 2006, Michelin won the world championship 33.33 percent of the time. Hence, considering the two suppliers’ Formula 1 experience and track record in terms of constructor championships won, one could not necessarily assume the supplier switch would have to be detrimental to firm performance for switching firms. Moreover, a robustness check using the tyre problems as a dependent variable confirms that firms using Michelin tyres between 2004 and 2006 had significantly more tyre problems than firms using Bridgestone tyres. Since the Michelin two championships mentioned above fall into the period from 2004 to 2006, the higher number of problems for firms using Michelin tyres is very clearly not the result of a time selection issue. In fact, it can be stated that any observed negative effect of the treatment on performance is not due to a lower quality of the new supplier's tyres, but rather due to difficulties in integrating the new supplier's tyres into the car.

For the purpose of this study, it was imperative to collect data on firms' tyre suppliers, the changes they made to the various components of their cars, the ownership of these components, as well as the firms' performances. These data were obtained from the annual publications *Formula 1 Technical Analysis*, *The Official Formula 1 Season Review*, *Who works in Formula One*, and, *Formula Money*, as well as the online source *ATLAS F1*. These sources provide information with regarding all firms' component sourcing. The interdependences between the various components of a F1 car have been identified with the help expert literature on F1 engineering (e.g. Tremayne, 2004), as well as interviews with current and former personnel of F1 firms and their suppliers. Data on team performance and problems on the firms' cars' various components during any race weekend were obtained from the major annual publication *Formula 1 Technical Analysis*, as well as the online sources *ATLAS F1*, the Formula 1 archive of *www.autosport.com*, the official Formula One website *www.F1.com, as well as ScarbsF1.com*, an expert F1 technology and engineering blog. These sources publish information on each firm's performance, problems and developments race by race. The data for this study cover the F1 seasons from 2004 until 2009, inclusive. The time frame was chosen, because major online sources, i.e. *ATLAS F1* and *www.F1.com*, started providing detailed information technological developments for each team throughout the entire season as of 2004. Clearly, with the increasing possibilities for internet-based online journalism by specialized firms and expert blogging by qualified individuals, the reporting on Formula 1 experienced surge of detailed information as of 2004. Moreover, *The Official Formula 1 Season Review* was released in 2004 as a major annual publication that covers facts, stories and events of a given Formula 1 season. The data for this particular study includes 2009 season, but not the recent seasons 2010-2012 because the exclusive tyre supplier has been switched again as of the 2010 season. Specifically, Bridgestone was replaced by Pirelli as the exclusive tyre supplier for all firms competing in F1. As a consequence, the analysis has been conducted for the seasons from 2004 to 2009, thereby obtaining a balance of 3 seasons before the change and 3 seasons after the change. Table 1 below provides a series of examples for evidence of related changes in the data. As the table shows, some changes are clearly engine related, e.g. the changes made by Super Aguri in 2006 or by Williams in 2007, while others are acknowledged to be more mysterious or may appear unrelated, e.g. the changes made by Brawn in 2009 or Ferrari in 2007 respectively. Importantly, considering that the F1 teams do not always disclose all the goals or effects of a change, it is best to impute possible interaction between components based on the known interdependencies. As a consequence, all of these changes need to be included as related changes in the variable.

INSERT TABLE 1 ABOUT HERE

5. METHOD

In order to identify the impact of outsourcing on performance outcomes, this study exploits the regulatory enforcement of the switch to a unique, industry-wide tyre supplier in 2007. To the extent that regulatory enforcement of changes in the supplier are neither influenced nor predicted by individuals, temporal differences within a firm can be considered truly exogenous. The data underlying this study covers the years from 2004 to 2009 and therewith allow to test this study's hypotheses by exploiting the natural experiment provided by the regulatory enforcement of the Formula 1 tyre supplier switch in 2007. This natural experiment allows to estimate the impact of a supplier switching "treatment", as some firms were using Michelin tyres from 2004 to 2006, whereas others were already using Bridgestone tyres from 2004 to 2006. A difference-in-differences regression method has been adopted in order to estimate the impact of supplier switching on performance, as well as the moderating impacts of the switching firm's tyre related changes. The difference-in-differences method compares what happened to a treatment group before and after the treatment to what happened to a control group, i.e. a group that was not subject to the treatment, before and after the treatment. In principle, it may appear sufficient to explore the treatment group alone in order to deduce the treatment effect. However, without the counterfactual, i.e. what happened to the treated group without the treatment, the impact of the treatment may be confounded with the impact of other factors that affect the outcome variable at the same time. The control group allows to take these other factors into account under the assumption that they affect the treatment group and the control group equally (Woolridge, 2002). The firms switching from Michelin to Bridgestone as a tyre supplier represent the treatment group, whereas the firms simply staying with Bridgestone as a tyre supplier represent the control group. The following panel regression model has been estimated, in which the dependent variable is the performance of an F1 team *j* at any given time *t* between 2004 and 2009, inclusive:

$$GPPoints_{jt} = \alpha * TreatmentGroup + \beta * TreatmentPeriod + \gamma * Treatment + \delta Controls + e_{jt}$$

In this equation, *Treatment* is the enforced supplier switch. *TreatmentGroup* is a dummy variable that takes the value of 1 for teams that switched the tyre supplier from Michelin to Bridgestone and 0 otherwise. It captures possible differences between the treatment group and the control group prior to the external shock. *TreatmentPeriod* is a dummy variable that takes the value of 1 for races from 2007 and 2009 and 0 otherwise. It captures aggregate factors that would cause changes in the dependent variable even in the absence of the external shock. The coefficient of interest is that of the variable *Treatment*, which is practically a dummy for observations in the treatment group in the treatment period. This variable is obtained by multiplying the variable *TreatmentGroup* with the variable *TreatmentPeriod*. *Z* is the vector of control variables.

Moreover, a second model has been estimated, in order to test the moderating effects of firms' innovative behaviors. As a consequence, this model includes the independent variables (i) Tyre Related Changes, *RelatedChanges*, and (ii) its interaction with the treatment, *RelatedChanges*Treatment*

$$GPPoints_{jt} = \alpha * TreatmentGroup + \beta * TreatmentPeriod + \gamma * Treatment + \delta * Controls + \epsilon * RelatedChanges_{jt} + \varepsilon * RelatedChanges_{jt} * Treatment + e_{jt}$$

5.1 Dependent and Independent Variables

This study's main dependent variable is (I) *Grand Prix Points*, i.e. the number of grand prix points that a firm gathers in any particular race with both of its cars. This variable measures the performance of a firm at any point in time. In this study's data, the number of points gained by both cars at any particular race ranges from 0 to 43 points, with the average being around 10 points. Since the point scoring system, i.e. the amount of points awarded for a given position of a firm's car at the end of the race, has been changed in 2010, and the database used covers the years from 2004 to 2012, the point scores this studies' underlying data have been translated into their equivalent according to the new scoring system for reasons of comparability of this study's results to other studies. In order to provide an analysis of an additional dimension of performance, (II) *Tyre-Related Problems* is used as a second dependent variable. This variable measures the number of problems a firm encounters in components that interact with the tyres during any race weekend, i.e. problems in tyre-related components experienced on both cars during free practice, the qualifying and the race of any race weekend. A third dependent variable is used for a robustness check, clarifying that the treatment effect is not determined by the difference in supplier quality between Michelin and Bridgestone. In order to show this, (III) *Tyre Problems* is used as a dependent variable. This variable measures the number of a firm's tyre problems during any race weekend, i.e. problems experienced on both cars during free practice, the qualifying and the race of any race weekend.

This study has three major independent variables. First, in order to observe the effect of supplier switching on performance, a variable that captures the treatment needed to be created by multiplying the *Treatment Group* with the variable *Treatment Period*. *Treatment Group* is a binary variable that assumes the value of 1 if a firm had previously used Michelin as the tyre supplier and then had to switch to Bridgestone as of 2007. It assumes the value 0 otherwise. Instead, the variable *Treatment Period* is a binary variable that takes the value of 1 for races that took place after the treatment, i.e. between the years 2007 and 2009, and 0 otherwise. As a consequence, the multiplication of the two results in a variable that identifies the treatment, i.e. the firms that had to switch from Michelin to Bridgestone and the period during which they are using the new tyre supplier, i.e. Bridgestone. Hence, the variable (i) *Treatment* assumes the value of 1 if a team is part of the treatment group and the performance is observed after the supplier switch has been imposed. The variable assumes the value of 0 otherwise. Second, (ii) *Tyre Related Changes*, which is the number of changes that a firm makes in components that interact with the tyres at any given point in time. Finally, the interaction of (ii) *Tyre Related Changes* with (i) *Treatment* is investigated, in order to explore heterogeneity in performance among the firms in the treatment grou, according to their adaptive behavior.

5.2 Control Variables

The analysis includes several control variables. First, (1) *Treatment Period* measures the time period after the shock. Specifically, *Treatment Period* is a binary variable that assumes the value 1 for the years 2007 to 2009 and 0 otherwise. Second, (2) *Non Participants* identifies the firms that exited the Formula 1 motor sport industry before the shock or entered after the shock, and, thus, were not subject to the treatment. In particular, *Non Participants* assumes the value 1 for firms that have not been subject to the treatment and 0 otherwise. Third, (3) *Treatment Group* identifies the firms that had to switch the tyre supplier. *Treatment Group* assumes the value 1 for firms that switched from Michelin to Bridgestone and 0 otherwise. Fourth, (4) *Season Clock* measures the stage of the season that firms find themselves in at any given point in time. In particular, *Season Clock* measures the percentage of a season’s total number of days that have passed at any given point in time. This study considers the season to actually starts one day after the last race of the previous season in October, with teams developing the new car to be launched around January or February. The races then are taking place from March to October. As a result, the Season Clock starts for the first race takes into account that around a third of a Formula 1 season is has actually passed already. From this point on, as the season progresses, firms may slow down their product development. This is simply a consequence of the fact that, in F1, as the season proceeds, constructors need to gradually reallocate resources from the development of the car that is currently competing to the design and development of the car for the new season with its new rules and regulations. Fifth, (5) *Budget* measures the total amount of money in million US-Dollars that a specific firm had at disposition for a given season and reflects a firm's size and investments in R&D. Sixth, (6) *Firm Experience* measures the number of years that a firm has been competing for in F1 over the last five seasons. This variable accounts for age and experience of the organization. Seventh (7), *Firm Success* measures the number of points that a firm has been able to accumulate in F1 over the last five seasons. This variable accounts for success of the organization. Eight, (8) *Driver Experience* measures the average number of years that the two drivers of a firm have been competing in Formula 1. Ninth (9), *Driver Success* measures the average number of Driver Championships that the two drivers of a firm have won in the past. Both of these variables account for the driver effect on a firm's performance in any given race. Tenth, (10) *Ambient Temperature* measures the degrees Celsius in the race track location on the race day. Eleventh, (11) *Track Temperature* measures the temperature of the race track in Celsius. Both may influence a car's reliability, with the former directly affecting the engine cooling and the latter the tyres. As a result, these factors are included in order to control for their effect on firm performance. Twelfth, (12) *Race Distance* measures the race length in kilometers. Thirteenth, (13) *Testing* and fourteenth (14) *Practice* respectively measure the amount of testing in thousand km and laps practiced before a given race. Finally, fifteenth (15) *Headquarters Distance* measures the distance between a firm's headquarters and a given race location in thousand kilometers. Sixteenth, (16) *Tyre Related Ownership* measures the percentage of components interacting with the tyres that are owned by a given firm. Seventeenth, (17) *Suppliers* measures the number of relationships to suppliers that a firm entertains across all car components. Eighteenth, (18) *Tyre Related Changes by Suppliers* measures the number of changes in tyre-related components that are introduced by a firm's suppliers at any given race. Nineteenth, (19) *Tyre Unrelated Changes* measures the number of changes in components on a firm's car that are not interacting with the tryes. Finally, the study controls for other regulatory shocks that did not equally affect all firms competing in F1 and occurred between 2004 and 2009. As a consequence, the study includes the regulatory enforcement of the outsourcing of the electronic control unit (ECU) to a unique, industry-wide supplier in 2008, as well as the regulatory engine development freeze 2008. The control variables that account for these regulatory shocks are the following. Twentieth, (20) *Outsourcing Regulation* measures the time period after the ECU outsourcing shock. Specifically, *Outsourcing Regulation* is a binary variable that assumes the value 1 for the years 2008 to 2009 and 0 otherwise. Twenty-first (21) *Outsourcing Treatment Group* identifies the firms that had to outsource the electronic control unit that they previously developed internally. *Outsourcing Treatment Group* assumes the value 1 for firms that had to outsource the ECU and 0 otherwise. Twenty-second, (22) the variable *Outsourcing Treatment* has been generated, which assumes the value of 1 if a team is part of the treatment group and the performance is observed after the outsourcing has been imposed. This variable identifies the outsourcing treatment, i.e. the firms that had to outsource the ECU, which they previously developed internally. Twenty-third, (23) *Outsourcing Non Participants* identifies the firms that exited the Formula 1 motor sport industry before the shock or entered after the shock, and, thus, were not subject to the treatment. In particular, *Outsourcing Non Participants* assumes the value 1 for firms that have not been subject to the treatment and 0 otherwise. Twenty-fourth, (24) *Engine Freeze Regulation* measures the time period after the engine freeze shock, that limited the firms' possibility to develop more powerful engines and therefore limited the firms' producing their own engines in using their competence. Specifically, *Engine Freeze Regulation* is a binary variable that assumes the value 1 for the years 2008 to 2009 and 0 otherwise. Twenty-fifth, (25) *Engine Freeze Treatment Group* identifies the firms that produced their own engines and therefore had the competence of producing more powerful engines. *Engine Freeze Treatment Group* assumes the value 1 for firms that produced their own engine and 0 otherwise. The variable assumes the value of 0 otherwise. Twenty-sixth, (26) the variable *Interaction Engine Freeze Treatment Group _ Engine Freeze Regulation* has been generated. Hence, the variable assumes the value of 1 if a team is part of the engine freeze treatment group and the performance is observed after the engine freeze regulation has been imposed. This variable identifies the treatment, i.e. the firms that had the competence to develop more powerful engines and the period during which they were not allowed to do so anymore. Twenty-seventh, (27) *Engine Freeze Non Participants* identifies the firms that exited the Formula 1 motor sport industry before the shock or entered after the shock, and, thus, were not subject to the engine freeze treatment. In particular, *Engine Freeze Non Participants* assumes the value 1 for firms that have not been subject to the engine freeze treatment and 0 otherwise. Finally, twenty-eight (28) *Trend* measures the number of years that have passed in a given condition, i.e. before and after the shock that required firms to switch to the unique, industry-wide supplier.

5.3 Summary Statistics and Correlations

Table 2 below provides the summary statistics for the dependent-, independent- and control variables described above. As the table shows, the data includes 1123 observations of the different firms competing in Formula 1 between 2004 and 2009, inclusive. The average amount of points gathered in a race was around 10 and the average role experience of a firm's top management team as a whole was 5.5years. The average familiarity of a firm's top management team as a whole was around 2 years. The average budget of a team per season was $270.5 million.

INSERT TABLE 2 ABOUT HERE

Tables 3 to 5 break down the summary statistics by group, i.e. treatment group, control group and non participants respectively. Table 6 shows the correlations between the various variables used in this study. The correlations exceeding the threshold of 0.7 are highlighted. There are no particularly suspicious correlations among the variables that one should be cautious about.

INSERT TABLES 3 - 6 ABOUT HERE

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6. RESULTS

The results show that supplier switching, i.e. the treatment, has led to an increase in problems in tyre-related components, as shown in figures 1 and 2 below. Clearly, firms that participated in Formula 1 racing during the time of the treatment had more problems after the switch than before. Moreover, among the firms participating in F1 during the treatment period, the increase in tyre-related problems manifested for firms that switched suppliers, i.e. the treatment group. Instead, the control group maintained an equal level of tyre-related problems before and after the treatment.

INSERT FIGURES 1 AND 2 ABOUT HERE

Table 7a below reports the results of this study's statistical analysis, which have been obtained by means of a quasi maximum likelihood poisson regression. The results show that supplier switching, i.e. the interaction between the treatment group and the treatment period, has a negative effect on firm performance, as evidenced by the highly significant negative effect of the treatment in all models 1a through 1e. This confirms hypothesis 1. Moreover, the results of model 1a show the effect for a time window closer around the shock. Specifically, model 1a shows the effect for a time window from 2006 to 2007 instead of looking at a time window from 2004 to 2009, which is done in model 1b. When comparing the results in model 1a with the results in model 1b, it becomes evident that the treatment effect is more negative for a time window closer around the shock. Hence, the treatment effect is larger shortly after introduction of the supplier switch and weakens over time. This confirms hypothesis 2. Model 1c includes the effect of changes in components related and unrelated to the tyres, while model 1d includes the interaction between the treatment and changes in components related to the tyres. As can be seen, the interaction is positive, highly significant. Clearly, firms having had to switch suppliers were able to recover some of the performance lost as a consequence of the tyre supplier switch by making changes in components related to the tyres. This confirms this study's hypothesis 3. Model 1e shows, that this is likely happening because the interaction between the treatment and changes in related components negatively affect the number problems that occur in these related components, which, as figures 1 and 2 above have shown, increase when switching suppliers. The margins for the effects of the treatment of switching the tyre supplier and the changes in tyre-related components on performance and tyre-related problems are shown below in figures 3 and 4, respectively. Changes in related components are shown to generate more performance benefits and decrease the amount of problems in related components after the supplier switch.

INSERT TABLE 7a, as well as FIGURES 3 AND 4 ABOUT HERE

7. ROBUSTNESS CHECKS

In order to address issues of robustness, the models from table 7a have been been regressed with negative binomial-, poisson- and OLS panel regressions. Table 7b below shows the results obtained from the negative binomial panel regression and provides evidence for the robustness of this study's results. The effects of the tyre supplier switch and the interaction of the tyre supplier switch with changes in tyre related components by the firm are highlighted in bold. Clearly, all of the results of table 7a are confirmed in direction and significance. The margins for the effects of the treatment of switching the tyre supplier and the changes in tyre-related components on performance and tyre-related problems are shown below in figures 5 and 6, respectively. Changes in related components are shown to generate more performance benefits and decrease the amount of problems in related components after the supplier switch.

INSERT TABLE 7b AND FIGURES 5 AND 6 ABOUT HERE

Table 7c below shows the results for the complete models that inlcude all variables, as obtained by the OLS- and poisson panel regressions. As can be seen, these two specifications provide additional evidence for the robustness of this study's results.

INSERT TABLE 7c ABOUT HERE

Finally, an additional quasi maximum likelihood poisson regression has been conducted, whose results are displayed in table 8 below. Table 8 clarifies that firms did not have to switch to an inferior tyre as of 2007. In particular, the results in table 8 show that the effect of the Michelin tyres-dummy on the number of problems over the course of any given race weekend in the time before the shock, i.e. between 2004 and 2006, is highly significant and positive. Hence, just by judging the quality of the two suppliers' products, one should expect firms switching from Michelin to Bridgestone to perform better. However, table 7a shows that this is not the case. Therefore, one can conclude that supplier switching is associated with difficulties in terms of knowledge integration, even if the new supplier's product is superior to the previous supplier's product. The results imply that knowledge integration difficulties and related switching costs occur every time a firm switches suppliers, regardless of the difference in the suppliers' products quality.

INSERT TABLE 8 ABOUT HERE

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8. DISCUSSION AND CONCLUSIONS

Managing technological change requires firms to closely coordinate the activities underlying the component development, as well as the assembly and integration of those components into a final product. This is true, in particular, when components have technological interdependencies that require experimentation and learning for the realization of their potential (Kapoor and Adner, 2012). Whether and under what conditions supplier switches can provide performance benefits in such contexts is less well understood. This study has examined the need for buyer firms to switch suppliers and integrate a new component in relation to their performance, in order to understand this issue more fully.

The unique data on Formula 1 racing is relevant in this respect, as it allows to link data on supplier switches for a specific component, as well as ownership of and changes in components across the system to performance outcomes. In this study, this has been done by conducting a natural experiment, which is one of the most powerful methods to prove causality free of endogeneity. Consistent with the predictions, the results show that, in Formula 1 motor sport, supplier switching negatively affects firm performance, since firms are not necessarily able to integrate a new component from a new external supplier. In fact, the results show that the new component from the new supplier does not necessarily increase the problems with that component, but rather tends to provoke problems in other components that interact with the new component. This effect tends to become weaker over time as firms learn in their new relationship. Moreover, the results show that a firm’s ability to make changes internally in components across the system that interact with the new external component positively affect the effectiveness of knowledge integration and reduces the problems in components that interact with the new external component.

These findings stress that it is not sufficient to study supplier switching, and governance decisions in general, in dyadic situations. In fact, what this study shows is that the value system cannot be discarded and has to be the subject of analysis if one wants to fully understand value creation across firm and component boundaries. In particular, problems following the supplier switch did not increase in the supplier component, i.e. the tyres, and therewith were not located in the buyer-supplier dyad. Instead, the problems increased in the parts interacting with supplier component and therewith were located in the system interacting with the buyer-supplier dyad. Considering supplier switching in such a value system, the study explains why some firms are better at integrating a new external component than others. It uncovers what making internal changes to components that interact with the new external component constitutes effective adaptive behavior of firms seeking to integrate new components across complex systems. Considering that the relationship of the particular component in this case, i.e. the tyres, to the system is fairly modular, this study provides evidence for the importance of integrative capabilities and architectural competence even for systems that are not highly systemic. This finding is consistent with qualitative research from the the systems integrators perspective by Brusoni et al. (2001), which suggests that knowledge overlap with suppliers is beneficial to effective integration of knowledge from external sources. Therewith, this study contributes to modularity theory and the theory of the firm, as well as the related literature streams on supply chain management and knowledge integration, the latter of which thus far tends to focus on the efficiency aspects of knowledge integration instead of effectiveness. Empirically, the study contributes to the academic discussion by underlining the importance of external shocks for the discussion around supplier switches, since all prior work on supplier switching is potentially endogenous. In this respect, this study's results provide some clarity regarding the confusion about the direct effect of supplier switching on performance.

Finally, this study's findings address the important question of whether and under which conditions a firm may stand to gain performance benefits when switching to suppliers that are also available to competitors. Since firms today frequently outsource activities to suppliers that provide multiple competing clients with the same capabilities (Jacobides and Winter, 2005), this is a particularly interesting issue that has emerged only recently. Notably, for externally sourced supplier knowledge and capabilities to yield unique value, they need to be integrated and assimilated within a buyer firm's business process (Purvis, Sambamurthy and Zmud, 2001). However, research suggests that supplier components that are readily available to the systems integrator's competitors are unlikely to be a source of competitive advantage for systems integrators (Barney, 1986; 1991; Kim and Mahoney, 2006). In this respect, this study provides insights regarding the performance effects that result from differences in capability deployment (Barney and Arikan 2001; Lavie, 2006; Sirmon et al., 2007) and show that internal changes in internal components that interact with the new external component can affect the extent to which buyer firms may stand to gain benefits from supplier components that are also available to competitors.

The findings are expected to be generalizeable to a variety of other industries, in particular those which emphasize new product development and outsource production capacities with the production form of component knowledge being separated from the firm, such as motion pictures, consumer electronics and semiconductors. The investigation of ownership of components across the system on the effectiveness with which externally sourced components can be integrated however, was beyond the scope of this study and is strongly suggested to be studied in future research. Moreover, future research should address whether and how differences in firms' teams and personnel in general may influence the firm's ability to make internal changes across related components for the purpose of integrating new external components.

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10. TABLES AND FIGURES

Table1: Examples of Related Changes in the Data.

Team	Year	Description	Source
BAR	2004	Starting with an engine air intake of pentagonal section to guarantee greater aeration and better aerodynamic efficiency. The intake was of triangular section on the first version of the 005.	F1 Technical Analysis
BAR	2005	After the dual engine failure last race the Honda engineers had a revised spec for Bahrain, with general improvements as well as a solution for the oil sensor failure which caused the retirements in Malaysia.	ATLAS F1
BMW	2007	The new gearbox features a seamless shift and a particular compact rear damper set up, still comprising Sachs rotary dampers.	ATLAS F1
Brawn	2009	The terminal zone of the body was modified to improve the evacuation of hot air from the sidepods. In the circle is the original solution. Note the narrow louver above the pushrod mount.	F1 Technical Analysis
Ferrari	2004	It is the fairing around the gearbox that also sees more extreme development; the suspension is now so low and neat that little shaping is required to cover the set up. Small shrouds are moulded into the fairing to cover the pushrod and wishbone mountings, but otherwise the fairing has shrunk to blend the rear profile of the engine into the tail structure The fairing is so well wrapped around the gearbox that the sidepods cooling outlet can flow over the top of the gearbox, and the driveshafts have protrude through slots rather than having a large cut-out. This level of design has been unique to Ferrari over the past few years.	ATLAS F1
Ferrari	2007	Ferrari retained the larger louvers on the left side of their car, as had already been the case in Malaysia but those of the right side were standard. A necessity that slightly influenced aerodynamic efficiency, but which turned out to be indispensable in guaranteeing the reliability of Maranello's eight cylinder.	F1 Technical Analysis
Ferrari	2007	The longer wheelbase could improve both aerodynamics and weight distribution, but is an approach that has left the other F1 designers wondering what Ferrari might know that they don't. One added benefit might be that is has enabled Ferrari to create an even larger fuel tank.	ATLAS F1
Ferrari	2009	To make the upper deck on the diffuser, the team has had to reshape the gearbox fairing and re-sited several electronic and hydraulic systems on the side of the gearbox.	ATLAS F1
Honda	2006	Under the skin, the teams carbon fibre cased gearbox is in its third generation, with the Honda developed gearshift system providing fast but, more importantly, smooth gear changes to aid the car’s stability through a corner. Starting out with the car’s layout, although Willis was not specific, the wheelbase remains similar to last year. This has been accommodated by a longer gearbox, which is mated to the V8 engine unit being shorter by 90mm to its V10 predecessor.	ATLAS F1
Honda	2008	Within the sidepods the radiators are now positioned face-up, venting through both louvers in the engine cover and a chimney - again the current preferred position for many teams.	ATLAS F1
Jaguar	2004	Moving on to the engine cover, the small airbox allows the bodywork to remain narrow over the engine, ending with an open vertical cut at the Axle line. Although the abrupt end of the cover could cause problems - creating vortices when the car yaws, upsetting the rear wing.	ATLAS F1
Jordan	2004	ATLAS: Jordan have opted to run the line of the regulation engine cover all the way to the rear of the car referring not to cut off the engine cover at the axle line.	ATLAS F1

Jordan	2005	ATLAS: Jordan were the first team to run a car to new regulations with a lifte front wing, more forward mounted rear wing and revised diffuser. This interim car initially ran with a Cosworth engine, but needed revision in light of the Toyota engine. Curiously Jordan revised their diffuser to meet the new rules demanding lower outer tunnels in a new way; rather than moulding a new floor with lower outer tunnels, the team have blanked off the old higher tunnels, leaving a void in between them.	ATLAS F1
McLaren	2005	Hungary also saw the team run the wider chimneys to cool the engine.	ATLAS F1
McLaren	2005	One weak spot which caused McLaren problems on both the MP4-18 and MP4-19A was the integration of the engine into the chassis and gearbox. Mated to the engine is a new gearbox; Whitmarsh would not be drawn on what material the casing was made in, noting "you'll see in due course. It's one of those things we keep undercover as much as we can. The gearbox is very different from last year.	ATLAS F1
Red Bull Racing	2005	The gearbox mates to the new TJ2005 Cosworth engine - again a development of the 2004 CR6 90-degree engine.	ATLAS F1
Red Bull Racing	2009	The pullrod layout was in sharp contrast to the other teams' designs and was dictated by the need to raise the lower part of the gearbox as far as possible, so increasing the space available for the diffuser. The pullrod even worked outside the suspension's lower wishbone and ended in a much advanced position on the gearbox where there was a very special rocker, inclined in relation to the vertical and fitted inside with the torsion bar. As with the front suspension, the mounts of the lower…lever on the gearbox were very high and inclined; the join with the straight line that united the mounts of the upper wishbone carried to a point, the instantaneous longtitudinal rotation centre, which is half way between those of Brawn and Williams, herefore producing medium anti-squat values.	F1 Technical Analysis
Renault	2006	Allied to the new chassis, Rob White's team have developed an all-new engine. With Renault only having run a narrower angled (72-dgeree) engine for two years, the step towards a 90-degree format for the V8 is new territory. Although the V8 with its flat plane crank is prone to more secondary vibration, Renault's experience with the vibration prone wide angled V10s and the V8 GP2 engine was not directly related to the new unit. Dyno work started very early in 2005 on the mule engine, while the testing, design and development work fed into the definitive R26 engine, built to new regulations on size, weight and materials.	ATLAS F1
Renault	2006	As the smaller capacity engine has less torque, its power delivery will be more peaky. As a result, the team has returned to a seven-speed gearbox, the extra ratio allows the driver to keep the engine in its power band for more of the time. This has made the gearbox a little longer, but with the shorter engine this hasn't been an issue.	ATLAS F1
Super Aguri	2006	The engine cover is new to accommodate the different rules from 2002, the new crash structures and the Honda engine installation.	ATLAS F1
Toro Rosso	2009	The 8-cylinder Ferrari (engine supplier) power unit required a different installation both in terms of the rear suspension and radiator dimensions, as well as the need for bigger side exits to improve cooling.	F1 Technical Analysis
Toyota	2007	Engine and gearbox are more and more a connected group. The gearbox concept is coming from Williams and we been able involve chassis side, o develop it jointly. The seamless system reduces shift times and also the requirement for the engine to come off the throttle as much during shifts.	ATLAS F1
Williams	2007	Most of the changes are aerodynamic and mechanical, the latter being largely the revised seamless shift gearbox and the packaging to install the Toyota engine.	ATLAS F1

Table2: Overall Summary Statistics.

Variable	Observations	Mean	Std. Dev.	Min.	Max.
GP Points	1123	9.557	11.862	0	43
Tyre Problems	1123	0.315	0.605	0	4
Tyre Related Problems	1123	1.060	1.320	0	12
Tyre Related Changes by Team	1123	1.825	1.919	0	15
Tyre Related Changes by Suppliers	1123	0.105	0.391	0	4
Tyre Unrelated Changes	1123	0.163	0.442	0	3
Supplier Switch Regulation	1123	0.495	0.500	0	1
Budget	1123	270.567	135.735	45.6	499.05
Firm Experience	1123	3.374	1.913	0	5
Firm Success	1123	731.131	782.075	0	2632
Driver Experience	1123	4.935	3.386	0	12.5
Driver Success	1123	0.256	0.743	0	3.5
Engineers’ Experience	1123	5.469	3.018	0.4	14.6
Season Clock	1123	0.528	0.288	0.053	1
Testing	1123	1126.471	2039.294	0	16834.57
Practice	1123	614.651	194.387	0	1297.632
Track Temperature	1123	36.450	10.040	16	63
Ambient Temperature	1123	26.215	5.877	15	42
Race Distance	1123	187.569	12.801	171.841	310.422
HQ Distance	1123	4.633	4.758	0	17.005
Tyre Related Ownership	1123	0.828	0.037	0.7561	0.9024
Suppliers	1123	15.184	2.235	11	21

Table3: Summary Statistics Treatment Group.

Variable	Observations	Mean	Std. Dev.	Min.	Max.
GP Points	496	11.383	11.883	0	43
Tyre Problems	496	0.274	0.544	0	3
Tyre Related Problems	496	0.960	1.063	0	7
Tyre Related Changes by Team	496	1.798	1.869	0	9
Tyre Related Changes by Suppliers	496	0.103	0.386	0	4
Tyre Unrelated Changes	496	0.115	0.366	0	3
Supplier Switch Regulation	496	0.595	0.491	0	1
Budget	496	308.517	115.077	75	493.1
Firm Experience	496	2.813	1.840	0	5
Firm Success	496	700.786	699.499	0	1832
Driver Experience	496	5.150	3.047	0	11.5
Driver Success	496	0.155	0.326	0	1
Engineers’ Experience	496	6.241	3.253	0.4	14.6
Season Clock	496	0.528	0.286	0.053	1
Testing	496	1208.86	2100.98	0	13453.44
Practice	496	618.117	178.316	116.14	1109.137
Track Temperature	496	36.710	10.251	16	63
Ambient Temperature	496	26.302	5.989	15	42
Race Distance	496	302.353	19.202	171.841	310.422
HQ Distance	496	4.692	4.771	0.011	16.998
Tyre Related Ownership	496	0.830	0.034	0.7561	0.878
Suppliers	496	14.956	2.078	12	20

Table4: Summary Statistics Control Group.

Variable	Observations	Mean	Std. Dev.	Min.	Max.
GP Points	409	9.667	12.455	0	43
Tyre Problems	409	0.298	0.584	0	3
Tyre Related Problems	409	0.856	1.015	0	8
Tyre Related Changes by Team	409	2.203	2.083	0	15
Tyre Related Changes by Suppliers	409	0.098	0.396	0	4
Tyre Unrelated Changes	409	0.227	0.533	0	3
Supplier Switch Regulation	409	0.509	0.501	0	1
Budget	409	287.545	145.076	45.6	499.05
Firm Experience	409	3.826	1.784	0	5
Firm Success	409	1006.296	936.031	0	2632
Driver Experience	409	5.334	3.584	0	12.5
Driver Success	409	0.491	1.135	0	3.5
Engineers’ Experience	409	5.156	3.030	0.4	10
Season Clock	409	0.528	0.289	0.053	1
Testing	409	1258.98	2221.884	0	16834.57
Practice	409	601.092	218.283	0	1190.435
Track Temperature	409	36.822	10.142	16	63
Ambient Temperature	409	26.298	5.896	15	42
Race Distance	409	302.246	19.322	171.841	310.422
HQ Distance	409	4.609	4.755	0	17.005
Tyre Related Ownership	409	0.845	0.034	0.7805	0.9024
Suppliers	409	15.320	1.716	12	19

Table5: Summary Statistics Non-Participants.

Variable	Observations	Mean	Std. Dev.	Min.	Max.
GP Points	218	5.197	9.327	0	43
Tyre Problems	218	0.440	0.743	0	4
Tyre Related Problems	218	1.670	2.005	0	12
Tyre Related Changes by Team	218	1.557	2.374	0	17
Tyre Related Changes by Suppliers	218	1.179	1.487	0	8
Tyre Unrelated Changes	218	0.151	0.396	0	2
Supplier Switch Regulation	218	0.239	0.427	0	1
Budget	218	152.366	87.233	50.31	360.16
Firm Experience	218	3.803	1.982	0	5
Firm Success	218	283.922	241.678	0	695
Driver Experience	218	3.700	3.466	0	12.5
Driver Success	218	0.044	0.141	0	0.5
Engineers’ Experience	218	4.3	1.664	2	7.2
Season Clock	218	0.528	0.289	0.053	1
Testing	218	690.410	1382.728	0	11649.61
Practice	218	632.206	180.480	0	1297.632
Track Temperature	218	35.161	9.271	16	55
Ambient Temperature	218	25.862	5.590	15	42
Race Distance	218	300.028	25.439	171.841	310.422
HQ Distance	218	4.543	4.754	0	16.974
Tyre Related Ownership	218	0.789	0.014	0.7619	0.8049
Suppliers	218	15.450	3.196	11	21

Table 6: Correlations

	Race Points	Tyre Probl.	Tyre Related Probl.	Tyre Related Changes Team	Tyre Related Changes Suppliers	Tyre Unrelated Changes	Treat. Group	Budget	Firm Exp.	Firm Success	Driver Exp.	Driver Success	Tyre Related Ownshp	Suppliers
Race Points	**1.0000**													
Tyre Problems	-0.0312	**1.0000**												
Tyre Related Problems	-0.1887	0.0389	**1.0000**											
Tyre Related Changes Team	0.2170	0.0521	-0.0863	**1.0000**										
Tyre Related Changes Suppliers	0.0561	0.0332	0.0258	0.2751	**1.0000**									
Tyre Unrelated Changes	0.1828	0.1144	0.0139	0.3205	0.3185	**1.0000**								
Treatment Group	0.1370	-0.0604	-0.0674	-0.0126	-0.0051	-0.0967	**1.0000**							
Budget	0.4343	0.0368	-0.1742	0.3071	0.0473	0.1514	0.2488	**1.0000**						
Firm Experience	0.2304	0.0475	0.0092	0.1652	0.0713	0.1429	-0.0639	0.3303	**1.0000**					
Firm Success	0.4618	0.0025	-0.1415	0.3016	0.0869	0.2562	0.0060	0.5588	0.6745	**1.0000**				
Driver Experience	0.2541	0.0380	-0.0915	0.1534	0.0384	0.1485	0.0564	0.4955	-0.1110	0.1840	**1.0000**			
Driver Success	0.3314	0.0156	-0.0878	0.1423	0.0822	0.3084	-0.1207	0.3162	0.2658	0.6103	0.3901	**1.0000**		
Tyre Related Onwership	0.2674	0.0353	-0.1171	0.2658	0.0234	0.1148	0.0628	**0.7383**	0.2572	0.3865	0.4745	0.1879	**1.0000**	
Suppliers	-0.2310	-0.1657	0.0216	-0.1571	-0.1150	-0.1153	-0.0911	-0.4180	-0.2317	-0.2024	-0.1956	-0.0502	0.2298	**1.0000**

Figure1: Tyre-Related Problems, Participants vs Non-Participants

Figure2: Tyre-Related Problems, Treatment Group vs Control Group vs Non-Participants

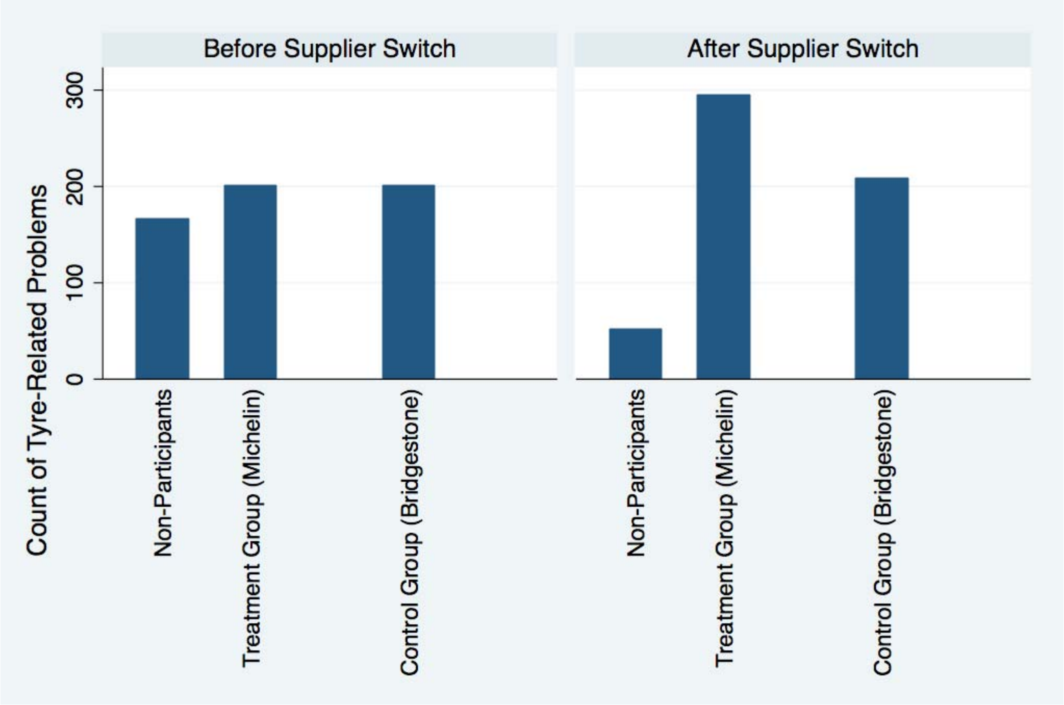

Table7a: Results; Quasi Maximum Likelihood Poisson Regression; Dependent variables = Race points, tyre-related problems; Standard errors in parentheses. *significant at 10%; **significant at 5%; ***significant at 1%. Control variables not reported are: (i) track temperature, (ii) ambient temperature, (iii) race distance, (iv) headquarters distance, (v) testing, (vi) practice, (vii) season clock, (viii) trend and (ix) other shocks.

VARIABLES	RACE POINTS (1a)	RACE POINTS (1b)	RACE POINTS (1c)	RACE POINTS (1d)	TYRE RELATED PROBLEMS (1e)
Supplier Switch Regulation	0.504*	0.608***	0.591***	0.603***	0.827***
	(0.276)	(0.154)	(0.157)	(0.154)	(0.148)
Non Participant	0	2.651***	2.641	2.632***	0.093
	(omitted)	(0.729)	(0.727)	(0.727)	(0.224)
Treatment Group	1.956***	0.366**	0.401***	0.380**	- 0.265**
	(0.453)	(0.150)	(0.154)	(0.153)	(0.125)
Treatment	**- 1.416*****	**- 1.106*****	**- 1.100*****	**- 1.274*****	**0.847*****
	(0.281)	**(0.154)**	**(0.155)**	**(0.172)**	**(0.174)**
Tyre Related Changes by Team			0.025	- 0.003	0.006
			(0.021)	(0.021)	(0.025)
Tyre Related Changes by Suppliers			- 0.058	- 0.035	0.069
			(0.090)	(0.085)	(0.082)
Tyre Unrelated Changes			0.051	0.071	- 0.028
			(0.069)	(0.069)	(0.088)
Interaction Treatment _ Tyre Related Changes				**0.086****	**- 0.144*****
				(0.038)	**(0.046)**
Budget	0.010***	0.004***	0.004***	0.004***	- 0.002***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Firm Experience	- 0.068	0.013	0.055	0.056	0.025
	(0.071)	(0.015)	(0.040)	(0.040)	(0.034)
Firm Success	0.000	- 0.000	- 0.000*	- 0.000	- 0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Driver Experience	- 0.324***	0.013	0.014	0.015	0.041***
	(0.038)	(0.015)	(0.015)	(0.015)	(0.015)
Driver Success	0.632***	0.168***	0.170***	0.160***	- 0.161*
	(0.085)	(0.060)	(0.061)	(0.061)	(0.089)
Engineers' Experience	- 0.131**	0.075***	0.073***	0.072***	0.042***
	(0.053)	(0.019)	(0.019)	(0.019)	(0.015)
Suppliers	- 0.184***	- 0.144***	- 0.142***	- 0.147***	0.054***
	(0.055)	(0.022)	(0.022)	(0.022)	(0.019)
Tyre-related Ownership	47.876***	- 7.172**	- 7.020**	- 7.011**	- 8.664***
	(9.200)	(3.203)	(3.212)	(3.232)	(2.897)
Other Control Variables	...	...	...	...	...
Cons.	- 34.360***	7.847***	7.684***	7.791	6.322***
	(7.247)	(2.550)	(2.563)	(2.579)	(2.276)
Observations	385	1123	1123	1,123	1,123
Pseudo log-likelihood	- 1330.5302	- 6545.6816	- 6529.3867	- 6499.7131	-1472.2956
Pseudo R-squared	0.7275	0.3368	0.3359	0.3406	0.2348

Figure3: Margins of quasi-maximum-likelihood regression; Dependent Variable = Race Points.

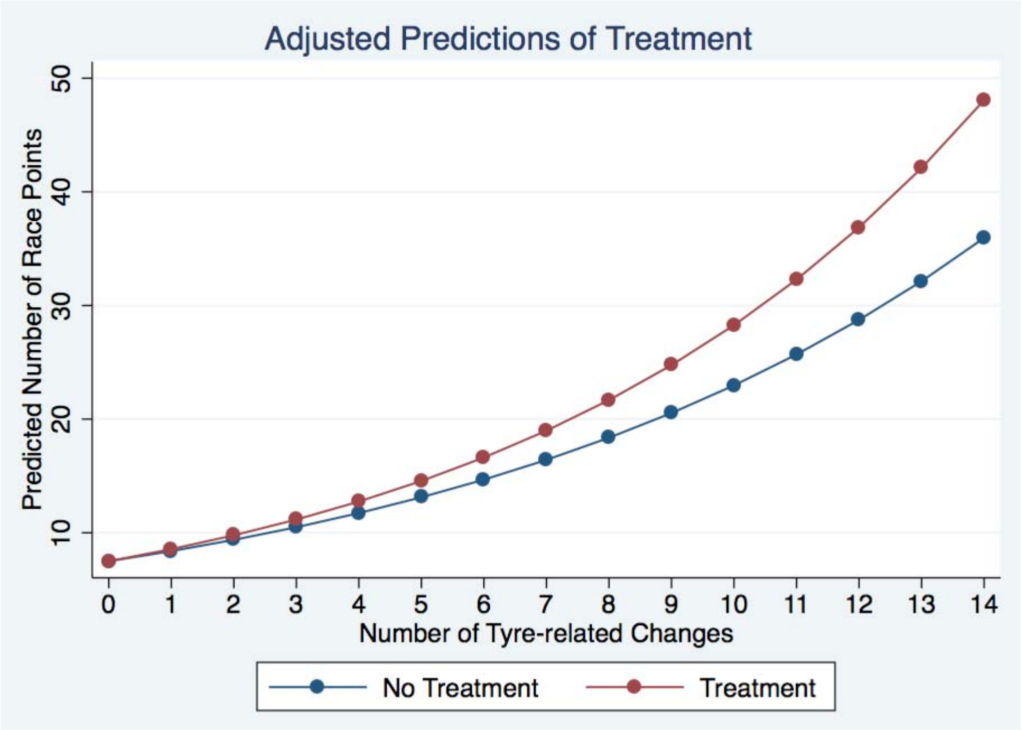

Figure4: Margins of quasi-maximum-likelihood regression; Dependent Variable = Tyre Related Problems.

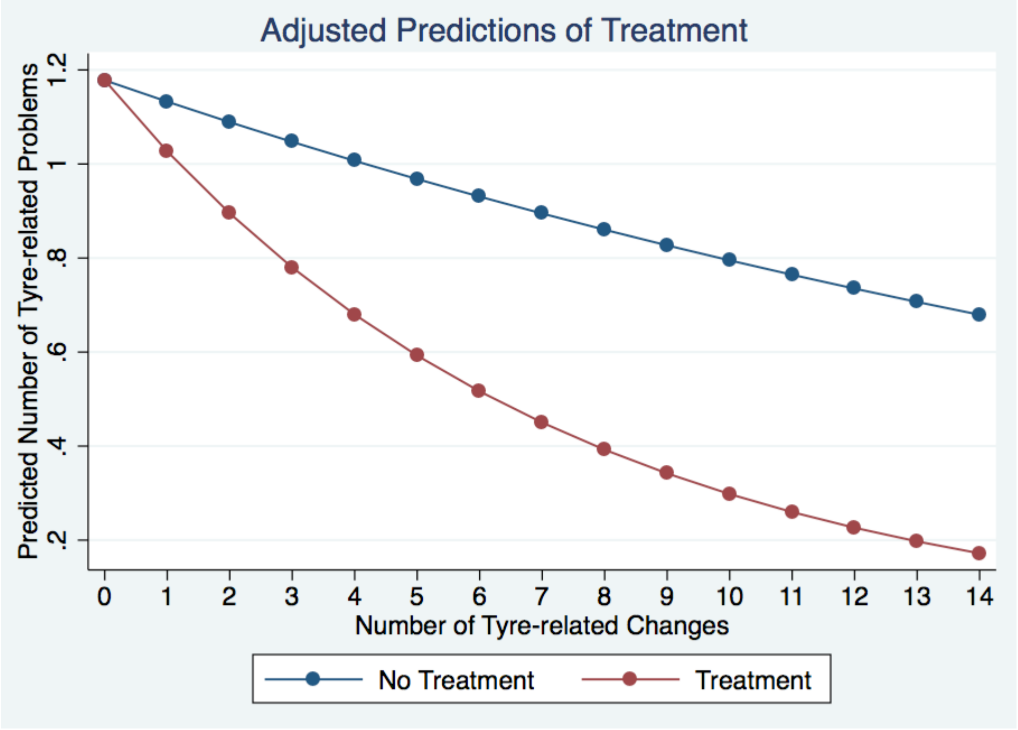

Table7b: Results; Negative binomial panel regression; Dependent variables = Race points and tyre-related problems; Standard errors in parentheses. *significant at 10%; **significant at 5%; ***significant at 1%. Control variables not reported are: (i) track temperature, (ii) ambient temperature, (iii) race distance, (iv) headquarters distance, (v) testing, (vi) practice, (vii) season clock, (viii) trend and (ix) other shocks.

VARIABLES	RACE POINTS (2a)	RACE POINTS (2b)	RACE POINTS (2c)	RACE POINTS (2d)	TYRE RELATED PROBLEMS (2e)
Supplier Switch Regulation	0.607**	0.532***	0.506***	0.526***	- 0.781***
	(0.279)	(0.174)	(0.176)	(0.176)	(0.152)
Non Participant	0	2.002**	1.992**	1.967	0.158
	(omitted)	(0.782)	(0.783)	(0.783)	(0.271)
Treatment Group	1.765***	0.846***	0.891***	0.881***	- 0.284*
	(0.405)	(0.209)	(0.210)	(0.210)	(0.149)
Treatment	**- 1.456*****	**- 1.235*****	**- 1.222*****	**- 1.423*****	**0.830*****
	(0.314)	**(0.176)**	**(0.176)**	**(0.189)**	**(0.177)**
Tyre Related Changes by Team			**0.033***	- 0.000	0.006
			(0.018)	(0.022)	(0.022)
Tyre Related Changes by Suppliers			- 0.037	- 0.007	0.068
			(0.078)	(0.079)	(0.082)
Tyre Unrelated Changes			- 0.006	0.038	- 0.039
			(0.072)	(0.071)	(0.081)
Interaction Treatment _ Tyre Related Changes				**0.097*****	**- 0.140*****
				(0.033)	**(0.044)**
Budget	0.009***	0.005***	0.005***	0.005***	- 0.002***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Firm Experience	0.113	0.130***	0.135***	0.142***	0.007
	(0.116)	(0.047)	(0.047)	(0.047)	(0.042)
Firm Success	0.000	- 0.000*	- 0.000*	- 0.000*	- 0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Driver Experience	- 0.253***	- 0.039**	- 0.038**	- 0.035**	0.038**
	(0.036)	(0.018)	(0.018)	(0.018)	(0.016)
Driver Success	0.381***	0.176**	0.182**	0.169**	- 0.172*
	(0.095)	(0.071)	(0.072)	(0.072)	(0.086)
Engineers’ Experience	0.030	0.049**	0.046**	0.046**	0.042***
	(0.043)	(0.024)	(0.023)	(0.023)	(0.016)
Suppliers	0.029	- 0.091***	- 0.091***	- 0.097***	0.041*
	(0.061)	(0.026)	(0.026)	(0.026)	(0.024)
Tyre-related Ownership	11.501*	4.889	5.002	5.115	- 8.296***
	(5.902)	(3.668)	(3.668)	(3.678)	(2.791)
Other Control Variables	...	...	...	...	...
Cons.	- 12.801**	- 5.392*	- 5.504*	- 5.500*	8.567***
	(5.194)	(3.032)	(3.033)	(3.041)	(2.326)
Observations	385	1123	1123	1,123	1,123
Log-likelihood	- 946.0232	- 3150.1144	- 3148.3015	-3144.1486	-1469.6286
Wald chi square	196.48	254.13	261.35	271.84	214.90
Prob > chi-square	0.0000	0.0000	0.0000	0.0000	0.0000

Figure5: Margins of negative binomial panel regression; Dependant Variable = Race Points.

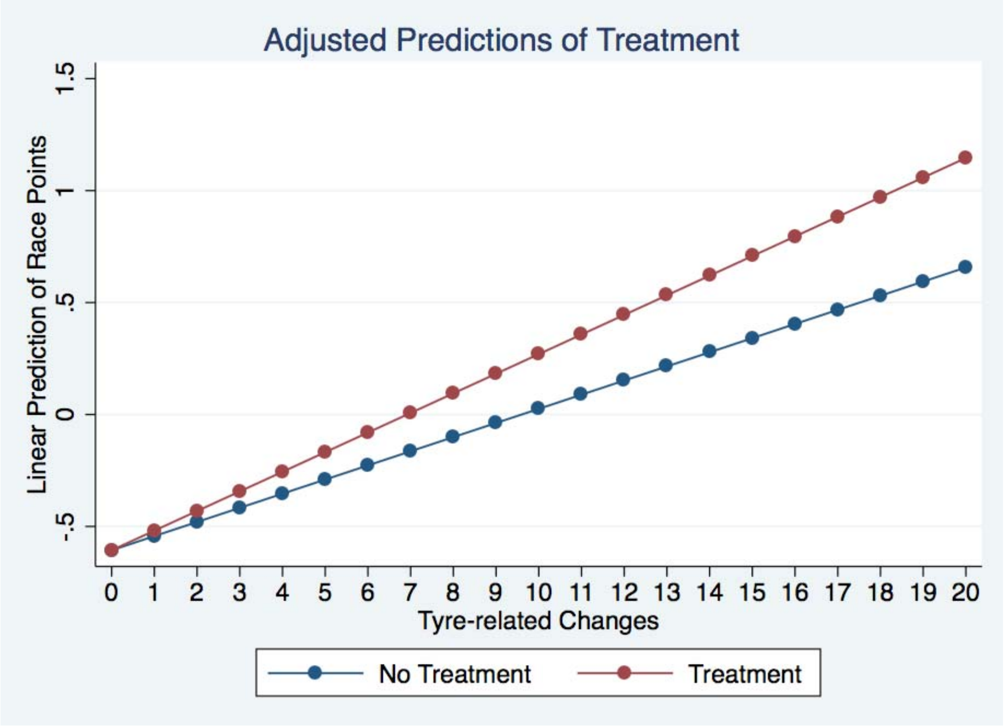

Figure6: Margins of negative binomial panel regression; Dependant Variable = Tyre Related Problems.

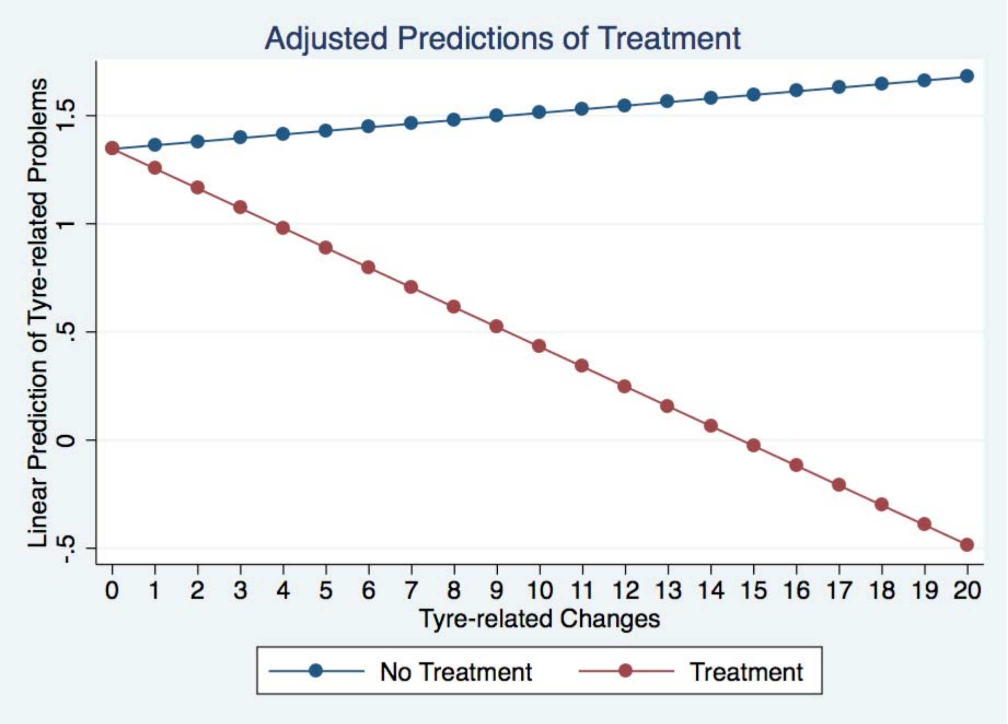

Table 7c: Results; Poisson and OLS panel regressions; Dependent variables = race points and tyre related problems; Standard errors in parentheses. *significant at 10%; **significant at 5%; ***significant at 1%. Control variables not reported here are: (i) track temperature, (ii) ambient temperature, (iii) race distance, (iv) headquarters distance, (v) testing, (vi) practice, (vii) season clock, (viii) trend and (ix) other shocks.

VARIABLES	OLS RACE POINTS (3a)	OLS TYRE RELATED PROBLEMS (3b)	POISSON RACE POINTS (3c)	POISSON TYRE RELATED PROBLEMS (3d)
Supplier Switch Regulation	3.645***	- 0.988***	- 0.881***	- 0.807***
	(1.350)	(0.169)	(0.081)	(0.134)
Non Participant	3.744*	0.164	5.070***	0.168
	(2.176)	(0.273)	(1.879)	(0.267)
Treatment Group	3.388***	- 0.312*	0.856	- 0.292**
	(1.295)	(0.162)	(1.193)	(0.145)
Treatment	**- 10.057*****	**0.860*****	**- 0.691*****	**0.856*****
	(1.556)	**(0.195)**	**(0.120)**	**(0.170)**
Tyre Related Changes by Team	0.013	- 0.012	- 0.022***	0.005
	(0.212)	(0.027)	(0.007)	(0.021)
Tyre Related Changes by Suppliers	- 0.495	0.067	0.020	0.068
	(0.811)	(0.102)	(0.026)	(0.078)
Tyre Unrelated Changes	1.103	- 0.033	0.034	- 0.028
	(0.767)	(0.096)	(0.021)	(0.077)
Interaction	**0.894****	**- 0.122*****	**0.082*****	**- 0.143*****
Treatment _ Tyre Related Changes	**(0.353)**	**(0.044)**	**(0.011)**	**(0.042)**
Budget	0.030***	- 0.003***	0.004***	- 0.002***
	(0.005)	(0.001)	(0.000)	(0.001)
Firm Experience	- 0.073	0.072*	0.816***	0.005
	(0.301)	(0.038)	(0.029)	(0.041)
Firm Success	0.001	- 0.000	- 0.002***	- 0.000
	(0.001)	(0.000)	(0.000)	(0.000)
Driver Experience	- 0.135	0.044**	- 0.148***	0.037**
	(0.137)	(0.017)	(0.010)	(0.016)
Driver Success	1.183***	- 0.180**	0.067**	- 0.176**
	(0.710)	(0.089)	(0.029)	(0.085)
Engineers' Experience	0.607***	0.059***	- 0.070***	0.044***
	(0.137)	(0.017)	(0.013)	(0.016)
Suppliers	- 0.876***	0.090***	0.044***	0.042
	(0.182)	(0.023)	(0.013)	(0.023)
Other Control Variables	...	...	...	...
Cons.	41.072*	8.957***	- 1.179	6.373***
	(21.119)	(2.646)	(1.910)	(2.181)
Observations	1123	1123	1,123	1,123
Log-likelihood (Poisson); R-squared between (OLS)	0.7559	0.7797	- 5360.9201	-1471.8846
Wald chi square	617.53	256.75	1508.78	251.71
Prob > chi-square	0.0000	0.0000	0.0000	0.0000

Table8: Pre-Shock Tyre Problems; Negative binomial panel regression; Dependent variable = Number of tyre problems; Standard errors in parentheses. *significant at 10%; **significant at 5%; ***significant at 1%. Standard errors in parentheses. *significant at 10%; **significant at 5%; ***significant at 1%.

VARIABLES	NUMBER OF PRE-SHOCK TYRE PROBLEMS
Michelin	**0.801*** (0.300)**
Budget	- 0.003** (0.001)
Firm Experience	0.177*** (0.059)
Firm Success	- 0.000 (0.000)
Driver Experience	0.074 (0.048)
Driver Success	0.108 (0.238)
Engineers’ Experience	- 0.041 (0.032)
Testing	- 0.000 (0.000)
Practice	0.001** (0.000)
Season Clock	- 0.332 (0.268)
Race Distance	0.000 (0.004)
TrackTemperature	- 0.018* (0.010)
Ambient Temperature	0.048*** (0.018)
Headquarters Distance	0.027* (0.016)
Suppliers	- 0.105 (0.066)
Tyre-related Ownership	4.676 (2.193)
Cons.	- 4.896 (2.798)
Observations	568
Log-likelihood	-453.09116
R-squared	0.0996

ESSAY 3

From Garage to Grand Prix:

Team Experience and Knowledge Integration across Complex Systems

ABSTRACT

Supply chains are becoming complex networks in which partners collaborate and experiment together on problem-solving, sharing the risks and benefits. However, while it is widely accepted that firms produce value jointly in interconnected systems, it is less well understood where the knowledge resides that allows to integrate different components across complex systems that span organizational boundaries. Research acknowledges that organizations design themselves at the firm-level, in part, in order to be able to cope with change. However, less is known regarding the importance of the experience of top management teams in this respect, in particular top management teams' (i) role experience, i.e. the amount of time the team members have worked in their respective knowledge areas, and (ii) familiarity, i.e. the amount of time the team members have worked together in the past. This study investigates differences in firms' top management teams' (i) role experience and (ii) familiarity, as well as their adaptive behavior in F1 racing between 2004 and 2009, in relation to an industry-wide adoption of a single supplier for a key component, the tyres, in 2007. The results show that firms' architectural competence resides in their top management teams and provide evidence for a knowledge integration trade-off between (i) role experience and (ii) familiarity in stable supply networks as opposed to changing supply networks.

1. INTRODUCTION

Contemporary complex product development is carried out in supply chains, with diverse, specialized knowledge sources collaborating across organizational boundaries (Helper, MacDuffie and Sabel, 2000; Powell, Koput and Smith-Doerr, 1996; Von Hippel, 1988). Sharing across supply chains has led to an amplifiation of the importance of supplier management during recent years (Fine, 1998; Hall and Braithwaite, 2001; Kaplan and Sawhney, 2000; Simchi-Levi et al., 2000) and firms are increasingly recognizing that the combination of critical resources with strategic partners may yield a competitive advantage (Hardy et al., 2005; Paulraj et al., 2008). In fact, supply chains are becoming complex, collaborative value networks whose partners work and experiment together on problem-solving, which fosters interorganizational learning and sharing of risks and benefits (Malhotra et al., 2005). As a consequence, firms face the challenge of acquiring external knowledge and effectively integrating it with internal knowledge (Dyer and Hatch, 2006; Wadhwa and Kotha, 2006). However, while it is widely accepted that firms produce value jointly in interconnected systems (Brandenburger and Nalebuff, 1996; Normann and Ramirez, 1993; Adner and Kapoor, 2010), it is less well understood how the experience of a firm’s top management team affects the firm’s ability to effectively integrate different components across such complex systems that span organizational- and component boundaries.

The business literature celebrates 'knowledge-creating companies' and 'learning organizations' for the ability to generate, acquire, and integrate both internal and external sources of knowledge (Leonard-Barton, 1995; Nonaka and Takeuchi, 1995; Simonin, 1997). In order to better understand how firms can organize for the integration of different components across complex systems, research has developed the concept of modular design. This approach subdivides systems into modules, which can be developed independently from one another and recombined with the system through standardized interfaces (Baldwin and Clark, 2000). Trends towards product modularization enable unprecedented levels of inter-organizational design coordination (Brusoni, 2005), building on the intuition that complex systems such as products, technologies and organizations, are adaptive if modular (Simon, 1962). The firms in a supply network of a given complex product can be characterized in terms of two broad categories: (i) systems integrators and (ii) suppliers (Brusoni and Prencipe, 2006; Prencipe et al., 2003). The (i) systems integrators oftentimes are large industrial firms that act as assemblers, integrators and marketers that bridge customers and the supply chain, generally exercising a great deal of control across the supply chain. The (ii) suppliers design, develop and manufacture components, which are then integrated by systems integrators. As a consequence of variation in resource and capability endowment (Bettis and Hitt, 1995; Teece, 1986) firms need to contract with suppliers (Combs and Ketchen, 1999; Lavie, 2006). As a result, systems integrators develop and maintain systems integration capabilities to compose what they have decomposed (Prencipe, 1997). The ability to do so has been referred to in the literature as *combinative capability* (Kogut and Zander, 1992), *dynamic capability* (Teece, Pisano, and Shuen, 1997), and *architectural competence* (Henderson and Cockburn, 1994). In fact, research by Matusik and Hill (1998) states that, when a firm acts as a coordinator, firm-based and network-sourced competences correspond to Henderson and Clark’s (1990) typology of architectural knowledge and component knowledge.

However, altough the literature stresses that the integration of components and activities across firms’ value systems is important, much of the existing research has focused on singular relationships or components. Less is known regarding how firms manage the challenges of integrating and coordinating activities with their suppliers across the entire value system. Recent work has established that the integration of external components is more effective if firms are able to make related changes internally across the system (Voss and Williams, 2013). Nonetheless, we know little about where the knowledge resides that allows firms to make such changes. Morover, while research states that organizations design themselves at the firm-level, in part, in order to be able to cope with environmental change (Burns and Stalker, 1961; Chandler, 1962; Lawrence and Lorsch, 1967), less is known about how teams are designed in order to integrate knowledge across complex architectures that span organizational- and component boundaries. In fact, even though human resources have been found to play a key role in enabling organizations to respond to environmental opportunities and threats (Andrews, 1971; Child, 1997), it is less well understood how top management teams may contribute to an organization's architectural competence. The experience of top management teams, in particular their (i) role experience, i.e. the amount of time the team members have worked in their respective knowledge areas, and (ii) familiarity, i.e. the amount of time the team members have worked together in the past, are likely to be important in this respect. Crossan et al. (1999) describe the integration of knowledge as a process of organizational learning. This typically requires individuals to explore and share their tacit knowledge with each other, as well as to combine their explicit knowledge into new conceptualizations (Nonaka, 1994).

This study explores differences in firms' top management teams' (i) role experience and (ii) familiarity, as well as their adaptive behavior in F1 racing between 2004 and 2009, in relation to an industry-wide adoption of a single supplier for a key component, the tyres, in 2007. In doing so, this paper studies how differences in experience may lead to differences in their abilities to integrate external components across complex systems that span organizational boundaries. F1 racing is relevant in this respect, since (a) the dominant capability for competitive advantage is the integration of different component developments

(Jenkins, 2010) and (b) firms require human, financial, and organizational resources to maintain their competitiveness, i.e. to build competitive cars to win races and finally the World Championship (Jenkins et al., 2007).

2. THEORETICAL BACKGROUND

This paper is based on modularity theory (Baldwin and Clark, 1997, 2000; Garud and Kumaraswamy, 1995; Henderson and Clark, 1990; Langlois and Robertson, 1992; Sanchez and Mahoney, 1996; Sako, 2003; Schilling, 2000; Simon, 1962; Ulrich, 1995), which suggests that product architectures are targets of design, and hence potentially a source of competitive advantage for firms, as well as top management team theory (Boone and Hendriks, 2009; Hambrick and Mason, 1984; Nielsen, 2009), which suggests that strategic choice and organizational performance are largely determined by process of cognitive psychology in the organizations' top management teams. The top management team literature uses top management team characteristics such as age, work experience, educational background and others, in order to approximate underlying differences in the cognitions, values, and perceptions that determine organizational outcomes. Moreover the study builds on the theory of the firm, specifically the knowledge-based view of the firm (Kogut and Zander, 1992, 1996; Conner and Prahalad, 1996; Grant, 1996) and the collaborative paradigm (Contractor and Lorange, 1988; Dyer, 2000; Kanter, 1994; Nielsen, 1988), which emphasizes that the business world is composed of a network of interdependent relationships, which are developed and fostered through strategic collaboration with the goal of deriving mutual benefits (Ahuja, 2000; Borys and Jemison, 1989; Chen and Paulraj, 2004; Lado et al., 1997; Madhok and Tallman, 1998; Miles and Snow, 1986; Thorelli, 1986).

Research has proposed that product modularity helps break down problems so that interdependencies can be handled within closely governed teams and economic units. In rapidly developing complex products, however, many problems can still span component- and organizational boundaries. Knowledge transfer across organizational boundaries may be challenging, in particular because the production process requries tacit personal skills or connections among individuals that the involved parties themselves do not consciously understand (Polanyi, 1966; von Hippel, 1988), or that elude codification (Zander and Kogut, 1995). Moreover, interfirm knowledge transfer may be hindered by causal ambiguity (Lippman and Rumelt, 1982; Reed and DeFillippi, 1990). There is little clarity on technology, technological change and their impacts on organizational outcomes (Nelson, 1995; Podolny and Stuart, 1996; Teece, 1996). Confusion about the impact of changes in external suppliers contributes to this condition. Buyer-supplier relationships in interconnected value networks are subject to a series of pressures, with buyers switching their suppliers for a variety of reasons, such as differences between performance expectations and actual performance, a lack of supply scalability, or a firm’s sourcing strategy. Today, with outsourcing relationships becoming increasingly focused on value, supplier switches are commonplace. As a result, supplier transition and integration of external knowledge assume particular importance, especially since the risks associated with a supplier switch can result in financial damages and business disruption. Interdependencies among components are important in this respect, since they may obstruct the selection of effective routines by obscuring the link between actions and outcomes (Sorenson, 2003). The business history literature provides evidence of situations and scenarios in which a change in a given component creates disturbances in the rest of the system, which, eventually, are resolved through modifications in other parts of the system (Hughes, 1983; Rosenberg, 1982). Such required technological changes comprise an ecosystem of mutually dependent changes. Research has shown that the integration of externally sourced components is more effective if firms are able to make internal changes to related components across the system (Voss and Williams, 2013). Top management teams' experience, in particular their (i) role experience, i.e. the amount of time the team members have worked in their respective knowledge areas, and (ii) familiarity, i.e. the amount of time the team members have worked together in the past, are likely to be major determinants of a firm's ability to make those integrative changes.

Organizations, teams, and individuals develop problem-solving routines, which may include rules, strategies or technologies upon which their operations are based. Therefore, a considerable amount of organizational knowledge resides in groups of employees and the routines that connect them (Nelson and Winter, 1982). The knowledge that pertains to discrete aspects of a firm's resources, skills, technical systems and processes has been defined as component knowledge (Amit and Schoemaker, 1993; Henderson and Cockburn, 1994; Leonard-Barton, 1992). A related dimension of knowledge pertains to the architecture of its technical systems, processes, and products, and has been defined as the knowledge about the components of complex systems and their interrelationships (Baldwin, 2010), i.e. how the components and system function, are linked together, and perform under different conditions. It includes knowledge about whether and with what effect components can be separated from the system, and whether and how they can be rearranged in new ways to deliver specific system-level outcomes (Baldwin, 2010; Baldwin and Clark, 2000). The extent to which a team is able to create, capture and apply knowledge for performance enhancement is determined the human- and social capital in its component- and architectural knowledge. Typically, human capital refers to attributes, such as the knowledge, experience and abilities of individuals (Becker, 1993), which are observable in their creative and technical skills

(Miller and Shamsie, 1996). Instead, by social capital the literature understands the resources that are created by and accessed through relationships (Coleman, 1988; Burt, 1992; Nahapiet and Ghoshal, 1998). Social capital connects knowledge sources with each other through relationships, advice networks and boundary spanners (Cohen and Levinthal 1990, Matusik and Hill 1998), and therefore determines how knowledge flows. It can thus be argued that human- and social capital relate to component- and architectural knowledge, with human capital relating being reflected in a team's (i) role experience and social capital being reflected in a team's (ii) familiarity.

2.1 Supplier Switching, Team Role Experience and Changes in Related Components

When a firm's suppy network does not change over time it can be described as stable. Research argues that stable environments enable firms to manage by established routines (Aldrich, 1979; Porter, 1980), in particular because learning requirements are minimal (Keck and Tushman, 1993). As a consequence, in stable environments, an essential role of managers is considered to be symbolical management (Ancona, 1990) by legitimization and enforcement of the current system and core values (Keck and Tushman, 1993), while relying on routinized problem solving (Eisenhardt, 1989). In this respect, repeated experience with an external partner, such as a supplier, may allow the dialogue around potential solutions to become more structured, which facilitates the management of this vital, but difficult to transfer information (von Hippel 1994; Monteverde 1995). Hence, as team members' experience with, and repeated use of, the same components and their interdependencies across a complex system increases over time, teams likely become more able to integrate external components by making the necessary changes across related components in the system.

The transfer of technical knowledge is a social and costly process (Arrow 1969; Teece 1981). Routines for the codification of knowledge or special arrangements for the transfer of tacit knowledge need to be developed (Zollo and Singh, 1997). Exploring, selecting and replicating new routines for performance improvement constitutes learning (Nelson and Winter, 1982; Zollo and Winter, 2002). Studies have shown that organizations may learn at different rates (Dutton and Thomas, 1984; Pisano et al., 2001) and that they may forget (Argote et al., 1990; Benkard, 2000; Thompson, 2007). Repetition has an important role for both, organizational learning (Argote et al., 1990; Dutton and Thomas, 1984; Adler, 1990; Wright, 1936) as well as the creation of routines, capabilities and competences (Nelson and Winter, 1982; Skinner, 1974). The repeated use of the same or similar knowledge components facilitates the development of routines, which, in turn, increases search reliability (Levinthal and March, 1981) and specialization. Specialization is understood as the degree to which an individual, group, or organization performs a narrow range of activities. It is considered a primary structural dimension of organizational design (Daft, 1995; Pugh et al., 1968) and is frequently referred to as division of labor. Research suggests that the different team members tend to become increasingly specialized over time (Katz, 1982). Hence, as team members' role experience increases, so will the degree of specialization, and therewith the division of labor, within the team.

H1a: *In a stable supply network, the number of changes that a team makes in the components y, which interact with an externally sourced component x, increases with the team's role experience.*

When a firm's suppy network changes over time it can be described as unstable. A challenge resulting from environmental instability is the need to constantly adapt one's perception of the environment in order for it to match the current reality (Wiersema and Bantel, 1993). Although managers need to change their routines, in order to scan the environment and solve problems in a more structured and vigilant manner (Ancona, 1990: Eisenhardt, 1989), many managers are likely to be reluctant to invest such time and effort (Tushman and Anderson, 1986), typically because they are unwilling to abandon their past frames of reference (Fiske and Taylor, 1984). In particular, this may be true for managers that partially obtained their organizational power through their ability to handle certain environmental contingencies (Pfeffer and Salancik, 1978), such as a particular combination of externally sourced components. A shift in those contingencies, for example as a resukt of a change in a particular externally sourced component, may threaten to diminish those managers' power (Hambrick, 1981).

Experts may encounter difficulties in viewing domain-related problems from the perspectives of others (Camerer, et al., 1989; Hinds, 1999) and adapting to new rules, regulations and conditions within their domain (Canas et al., 2003; Sternberg and Frensch, 1992). In this respect, research states that experience result in competency traps or core rigidities (Levitt and March 1988; Leonard-Barton 1992). Furthermore, research by Upton and Kim (1998) identifies the risk of lock-in with different learning modes and Edmondson et al. (2003) link the state of knowledge to heterogeneous learning performance. Moreover, Staw (1980) provides evidence for the potential negative effect of experience and suggests that, while skill may increase with tenure, effort and drive tend to diminish over time. Learning tends to crowd out exploration (Ahuja and Katila, 2004; Cyert and March, 1963;

Levinthal and March, 1993). Over time, teams typically exploit more often, making their search more reliable at the expense of variation. In fact, empirical results show that increases in domain specific expertise typically lead to a decrease in flexibility regarding problem solving and the generation of creative ideas (Chi, 2006; Lewandowsky et al., 2007; Sternberg, 1996). Over time, while a team's members tend to become more specialized, they also tend to become less open to new information in the environment (Katz, 1982) and therefore develop more narrow perceptions. As a consequence, increasing specialization and division of labor in teams, which result from increasing role experience, are likely to lead to thin handling of interdependencies, i.e. teams with high role experience are less likely to communicate about or around interdependencies across the system.

H1b: *When switching the external supplier for a component x, the number of changes that a team makes in the components y that interact with the externally sourced component x decreases with the team's role experience.*

2.2 Supplier Switching, Team Familiarity and Changes in Related Components

The team learning literature understands experience as a unidimensional concept that may for example be captured by a team's output in terms of the cumulative volume produced or the number of projects completed. This approach implicitly assumes that the composition of teams is stable over time and frequently refers to individuals' team membership as team tenure (Cohen and Bailey, 1997; Hackman, 2002). However, in practice, stability is rare. The composition and structure of teams often changes over time. When team composition is not stable, familiarity and cumulative experience of team members are distinct concepts. In fact, research has shown that teams may differ, e.g. in terms of the degree to which individuals observe others and the extent to which their experience is team context specific (Huckman and Pisano, 2006). The importance of familiarity in teams has found theoretical and empirical support in studies by Edmondson et al. (2001), who use detailed case studies, and Reagans et al. (2005), who rely on longitudinal data in teams of surgeons.

Search for solutions to integrate an externally sourced component consists of sampling opportunities from the pool of technological possibilities (Levinthal and March, 1981). Firms manipulate, relocate and recombine knowledge within a technological knowledge space (Nelson and Winter, 1982). In a limited knowledge space, individuals may gradually exhaust the possible combinations over time (Kim and Kogut, 1996), which makes the development of new knowledge increasingly expensive or complicated (Katila and Ahuja, 2002). Teams that continuously work together in the same composition, although gaining familiarity, do not gain new external knowledge embodied by new team members. Therefore, in a stable supply network where teams repeatedly integrate the same externally sourced components, such teams are likely to exhaust the development opportunities in their knowledge spaces. Team longevity and cohesion may influence information processing behaviors through the reduction of the team's willingness to search and internalize new or conflicting knowledge (Caldwell and O'Reilly, 1982; Janis and Mann, 1977; Katz, 1982; Pelz and Andrews, 1966). Studies exploring product development in natural sciences (Skilton, 2009) and Hollywood motion picture production (Skilton, 2008) show that team members who have worked together repeatedly tend to produce less successful products. Uzzi and Spiro (2005) confirm this negative relationship in the Broadway musical theatre industry.

Team familiarity, independent of the team members' knowledge, implies higher degrees of shared, collaborative experience and knowledge at the expense of specialized knowledge and division of labor. As a result, when sourcing a component x from the same external supplier over time, the team's ability to generate new ways to integrate it by making the necessary changes across the system will likely decrease with increasing team familiarity.

H2a: *In a stable supply network, the number of changes that a team makes in the components y that interact with the externally sourced component x decreases with the team's familiarity.*

Instead, when changes occur in a firm's supply network, the team's role experience is likely to have the opposing effect on a firm's ability to make changes in related components across the system. For the team to be effectively integrate a new external component, members must be able to share, adapt, learn and perform as a team. Learning occurs through the discussions and knowledge sharing between team members as they complete the tasks. Knowledge integration and assimilation includes the acquisition of new knowledge, its dissemination within the firm, as well as its combination with existing knowledge (Huber, 1991; Leonard-Barton, 1992). It requires frequent communication, high levels of coordination and intense involvement between different organizational units associated with product development within the knowledge receiving organization (Grant, 1996; Henderson and Cockburn, 1994). Knowledge creation, knowledge recombination, and learning take place through interactions among employees (Simon, 1991), as well as the sharing of tacit knowledge and routines among individuals with context specific experience, deep expertise in their technical field and knowledge of the firms' existing capabilities, and rich experience in prior integration efforts is critical to the integration of technologies (Iansiti, 1995; Matusik and Hill, 1998). The continuity and retention of such individuals ensures that firms preserve the learning from prior integration efforts (Iansiti, 1995). Because integral development tasks share extensive interdependencies, they necessarily require (a) extensive communication and exchange among the individuals who perform them, as well as (b) efficient resolution of disputes arising from the individuals' differing technical perspectives, product knowledge, and / or self-interests. Different perspectives and the lack of shared information among team members may result in lower consensus within the team (Dess, 1987), which, in turn, may yield lower performance outcomes (Bourgeois, 1980; Dess, 1987).

Team familiarity generates benefits of (i) coordination and (ii) willingness to engage in a relationship (Reagans et al. 2005), both of which are likely to increase a team's ability to adapt to a change in external sources of knowledge. With respect to (i) coordination, familiarity may increase a team's ability to act in a coordinated fashion (Moreland et al. 1998), particularly if the team carries out tasks that require joint activity and shared tacit knowledge (Polanyi, 1967). For example, Weick and Roberts (1993) explain the near flawless operation of an aircraft carrier's flight deck by arguing that familiarity leads to "heedful interrelating", which provides teams with a common platform for learning and action. Furthermore, the development of team human capital (Chillemi and Gui, 1997) or network-specific human capital (Mailath and Postlewaite 1990), which results from shared experiences, may aid performance. With respect to (ii) willingness to engage in a relationship, familiarity may contribute to positive team beliefs, in particular "psychological safety" (Edmondson, 1999). This, in turn, may affect learning and performance, particualry when team members are not comfortable with taking risks. Studies have shown that shared experience increases the amount and quality of information shared by individuals by building to trust among team members (Granovetter 1985; McEvily et al. 2003; O'Reilly, Snyder and Boothe, 1993; Uzzi 1997). A team's members may be more willing to put their reputations at risk by asking questions and sharing errors earlier in the process, when they are more familiar with the other team members (Edmondson, 1999). Successful innovative solutions to problems that result from a changing environment often require the combination of technological components in a novel manner (Nelson and Winter, 1982). In this respect, studies by Altschuler (1998) and Goldenberg et al. (1999) show that applying and recombining existing knowledge in novel contexts benefits innovativeness. However, the recombination, particularly of distant knowledge domains, can only occur when individuals have experience in different technical domains or if the members of team contribute their experience of different technical fields (Fleming et al., 2007; Taylor and Greve, 2006; Hargadon and Sutton, 1997). Team familiarity in terms of both, (i) communication and (ii) willingness to engage in a relationship, is crucial in this respect. In fact, Murmann and Tushman (1997) find that increased top management team tenure is associated with faster speed of organizational reorientations.

Finally, familiarity among team members may facilitate the development of informal advice seeking networks (Leonardi, 2007). As a result, when sourcing a component x from a new external supplier, a higher team familiarity allows the team to communicate and collaborate better across different knowledge areas that are related to the component x. This in turn, will increase the team's ability to notice and react to unexpected and unpredicted interdependencies after a supplier switch.

H2b: *When switching the external supplier for a component x, the number of changes that a team makes in the components y that interact with the externally sourced component x increases with the team's familiarity.*

3. EMPIRICAL SETTING

This paper's empirical context is Formula 1 (F1) motor racing. This paper's empirical context is Formula 1 (F1) motor racing. F1 is a particularly relevant setting for the study of integration in an architectural system. F1 cars are complex systems that consist of many different components, whose architecture, ownership, development and performance can be observed at regular, intensive intervals during the integration. As a consequence of the immense public interest in F1 racing around the world, the industry is enjoying heavy media coverage on and off the race track, including information about agreements between firms and their suppliers, detailed reports about the developments made on a firm's car for every race, as well as the firm's performance. Research states that the dominant capability for competitive advantage is the integration of different component developments (Jenkins, 2010) and that car constructors require human, financial, and organizational resources in order to maintain their competitiveness, i.e. to construct competitive cars to win races and finally the World Championship (Jenkins et al., 2007).

Since the first official grand prix in 1950, F1 has been considered the pinnacle of automotive technology, as a result of high levels of innovation and large international exposure as a sport (Solitander and Solitander, 2010). F1 is the only form of motor sport that still requires each competing team, as a firm is customarily called in the industry, to design and assemble its own car. More specifically, a F1 team, or *constructor*, as the F1 governing body, the *Fédération Internationale l'Automobile* (FIA), officially defines them, needs to manufacture at least the chassis of its cars, whereas it can buy the other components from external suppliers. In addition to their racing departments, these firms have R&D, marketing, manufacturing, and testing departments. Furthermore, all constructors rely on complex supplier networks and major manufacturers may have 750 suppliers who produce the approximately 16,000 parts of a F1 car (Blitz, 2007). A majority of these also supply to rival firms. Furthermore, many sponsors from more or less related industries cater to the F1 constructors. In fact, it is essential for F1 constructors to secure sponsorship deals, in order to be able to operate on a budget that is sufficiently large to design, manufacture and race competitive cars.

In F1, constructors compete for the Constructor’s Championship, which is awarded to the team that scores the highest number of championship points during a season. Since 1950, between 10 and 14 constructors have been competing in any given world championship season. Drivers compete for the Driver’s Championship, which is awarded to the driver that scores the highest number of championship points during a season. The constructors who compete in the F1 championship have an average budget of around $250 million (Sylt and Reid, 2008), and, considering that all constructors are working within the same constraints dictated by the rules and regulations, only constant refinement and innovation can provide a competitive advantage (Cross and Clayburn Cross, 1996). Each of the constructors that compete in F1 employs hundreds of engineers, who continuously try to come up with new innovations (Jenkins, 2004). Knowledge is critical here, since the key asset of firm’s is the knowledge possessed by the designers, engineers, fitters and mechanics (Pinch and Henry, 1999). The key role of resident engineers is to facilitate the integration of the technical knowledge held by both, the racing car manufacturer and the supplier, and to engage in joint problem solving activities (Mariotti, 2007).

In financial terms, F1 is a global sport with an estimated annual worth between $4bn and $5bn. The sport counts between 500bn and 600bn unique viewers per season (Sylt and Reid, 2011), and, around 350m viewers for a single race. In professional sports, these numbers are rivaled only by the Super Bowl held by the National Football League (NFL), the

Champions League Final held by the Union of European Football Associations (UEFA), the World Cup Final held by the Fédération Internationale de Football Association (FIFA), or the Olympic Games, the last two of which take place only every 4 years. A large part of the motorsport industry is concentrated in a geographical cluster in central-south England, which is referred to as Motorsport Valley. At the centre of this cluster is the F1 industry. In the UK alone the industry's annual turnover is around $10 billion, employing approximately 40,000 people, of which 25,000 are engineers (Henry and Pinch, 2000). Across the various constructors that compete in F1 each year, annual owner spending range from nothing to some $150m for constructors backed by car manufacturers or other major corporations. Annual sponsorship revenues in F1 range from under $10m to over $200m. Another important source of revenues is prize money, which ranges from around $10m for a team that finishes outside the top 10 to around $87m for the world champion. Furthermore, teams generate between $7m and $15m of revenues per season through trade support and tyre supply, and, in some cases, up to an additional $5m from merchandise and events. In the pursuit of performance goals, typical top team expenditures amount to some $250m per season, $340m if it is a works team, i.e. if it manufactures its own engines. Instead, small team expenditures amount to some $80m per season (Sylt and Reid, 2011). Notably, F1 today is both, the world's premier motor sport and a multi-billion dollar business.

4. DATA

At the outset of the 2007 season, the FIA imposed a switch from a situation where firms could choose between Bridgestone and Michelin for tyre supply, to a situation where Bridgestone was the exclusive tyre supplier for all firms competing in Formula One.

Traditionally, an average car with good tyres could do well, but with bad tyres even the very best car did not stand a chance. Importantly, tyres are still a car's biggest single performance variable and the only point of contact between car and track (www.F1.com). Hence, switching the tyre supplier is likely to have an impact on a firm's race performance.

Interestingly, the new supplier which some firms had to switch to in 2007, Bridgestone, had been in Forumla 1 since 1997. In the ten seasons before the switch, i.e. from 1997 to 2006, Bridgestone was the tyre supplier of the world champion seven times. Hence, over their presence in Formula One until 2006, Bridgestone won the world championship 70 percent of the time. Instead, the supplier that some firms had to switch away from, Michelin, had been in Formula 1 only since 2001. In the six seasons from 2001 to 2006, Michelin was the tyre supplier of the world champion two times. Hence, over their presence in Formula One until 2006, Michelin won the world championship 33.33 percent of the time. Hence, considering the two suppliers' Formula 1 experience and track record in terms of constructor championships won, one could not necessarily assume the supplier switch would have to be detrimental to firm performance for switching firms. Moreover, a robustness check using the tyre problems as a dependent variable confirms that firms using Michelin tyres between 2004 and 2006 had significantly more tyre problems than firms using Bridgestone tyres. Since the Michelin two championships mentioned above fall into the period from 2004 to 2006, the higher number of problems for firms using Michelin tyres is very clearly not the result of a time selection issue. In fact, it can be stated that any observed negative effect of the treatment on performance is not due to a lower quality of the new supplier's tyres, but rather due to difficulties in integrating the new supplier's tyres into the car.

For the purpose of this study, it was imperative to collect data on firms' tyre suppliers, as well as data regarding their top management teams, in terms of team principal, technical director, chief designer, chief aerodynamicist and team manager. These data were obtained from the annual publications *Formula 1 Technical Analysis*, *The Official Formula 1 Season Review*, *Who works in Formula One*, and, *Formula Money*, as well as the online source *ATLAS F1*. These sources provide information with regarding all firms' component sourcing as well as information regarding the members of all firms' top management teams and their current and past employments in terms of employer, position and duration. Data on team performance and problems on the firms' cars' various components during any race weekend were obtained from the major annual publication *Formula 1 Technical Analysis*, as well as the online sources *ATLAS F1*, the Formula 1 archive of *www.autosport.com*, the official Formula One website *www.F1.com, as well as ScarbsF1.com*, an expert F1 technology and engineering blog. These sources provide information with regarding all firms' component sourcing. The interdependences between the various components of a F1 car have been identified with the help expert literature on F1 engineering (e.g. Tremayne, 2004), as well as interviews with current and former personnel of F1 firms and their suppliers. Data on team performance and problems on the firms' cars' various components during any race weekend were obtained from the major annual publication *Formula 1 Technical Analysis*, as well as the online sources *ATLAS F1*, the Formula 1 archive of *www.autosport.com*, the official Formula One website *www.F1.com, as well as ScarbsF1.com*, an expert F1 technology and engineering blog. These sources publish information on each firm's performance, problems and developments race by race.

The data for this study cover the F1 seasons from 2004 until 2009, inclusive. The time frame was chosen, because major online sources, i.e. *ATLAS F1* and *www.F1.com*, started providing detailed information technological developments for each team throughout the entire season as of 2004. Clearly, with the increasing possibilities for internet-based online journalism by specialized firms and expert blogging by qualified individuals, the reporting on Formula 1 experienced surge of detailed information as of 2004. Moreover, *The Official Formula 1 Season Review* was released in 2004 as a major annual publication that covers facts, stories and events of a given Formula 1 season. The data for this particular study includes 2009 season, but not the recent seasons 2010-2012 because the exclusive tyre supplier has been switched again as of the 2010 season. Specifically, Bridgestone was replaced by Pirelli as the exclusive tyre supplier for all firms competing in F1. As a consequence, the analysis has been conducted for the seasons from 2004 to 2009, thereby obtaining a balance of 3 seasons before the change and 3 seasons after the change. Table 1 below provides a series of examples for evidence of related changes in the data. As the table shows, some changes are clearly engine related, e.g. the changes made by Super Aguri in 2006 or by Williams in 2007, while others are acknowledged to be more mysterious or may appear unrelated, e.g. the changes made by Brawn in 2009 or Ferrari in 2007 respectively. Importantly, considering that the F1 teams do not always disclose all the goals or effects of a change, it is best to impute possible interaction between components based on the known interdependencies. As a consequence, all of these changes need to be included as related changes in the variable

INSERT TABLE 1 ABOUT HERE

5. METHOD

In order to identify the impact of outsourcing on performance outcomes, this study exploits the regulatory enforcement of the switch to a unique, industry-wide tyre supplier in 2007. To the extent that regulatory enforcement of changes in the supplier are neither influenced nor predicted by individuals, temporal differences within a firm can be considered truly exogenous. The data underlying this study covers the years from 2004 to 2009 and therewith allow to test this study's hypotheses by exploiting the natural experiment provided by the regulatory enforcement of the Formula 1 tyre supplier switch in 2007. This natural experiment allows to estimate the impact of a supplier switching "treatment", as some firms were using Michelin tyres from 2004 to 2006, whereas others were already using Bridgestone tyres from 2004 to 2006. A difference-in-differences regression method has been adopted in order to estimate the impact of supplier switching on performance, as well as the moderating impacts of the switching firm's tyre related changes. The difference-in-differences method compares what happened to a treatment group before and after the treatment to what happened to a control group, i.e. a group that was not subject to the treatment, before and after the treatment. In principle, it may appear sufficient to explore the treatment group alone in order to deduce the treatment effect. However, without the counterfactual, i.e. what happened to the treated group without the treatment, the impact of the treatment may be confounded with the impact of other factors that affect the outcome variable at the same time. The control group allows to take these other factors into account under the assumption that they affect the treatment group and the control group equally (Woolridge, 2002). The firms switching from Michelin to Bridgestone as a tyre supplier represent the treatment group, whereas the firms simply staying with Bridgestone as a tyre supplier represent the control group. The following panel regression model has been estimated, in which the dependent variable is the performance of an F1 team *j* at any given time *t* between 2004 and 2009, inclusive:

$$GPPoints_{jt} = \alpha{*}TreatmentGroup+\beta{*}TreatmentPeriod+\gamma{*}Treatment+ \delta Controls + e_{jt}$$

In this equation, *Treatment* is the enforced supplier switch. *TreatmentGroup* is a dummy variable that takes the value of 1 for teams that switched the tyre supplier from Michelin to Bridgestone and 0 otherwise. It captures possible differences between the treatment group and the control group prior to the external shock. *TreatmentPeriod* is a dummy variable that takes the value of 1 for races from 2007 and 2009 and 0 otherwise. It captures aggregate factors that would cause changes in the dependent variable even in the absence of the external shock. The coefficient of interest is that of the variable *Treatment*, which is practically a dummy for observations in the treatment group in the treatment period. This variable is obtained by multiplying the variable *TreatmentGroup* with the variable *TreatmentPeriod*. *Z* is the vector of control variables.

A second model has been estimated, in order to test the moderating effects of firms' innovative behaviors. As a consequence, this model includes the independent variables (i) team role experience, *Role Experience*, and (ii) team familiarity, *Familiarity*, as well as (iii) and (iv) their respective interactions with the treatment, *Role Experience *Treatment* and *Familiarity *Treatment*

$$GPPoints_{jt} = \alpha{*}TreatmentGroup+\beta{*}TreatmentPeriod+\gamma{*}Treatment+ \delta * Controls + \epsilon * RoleExperience_{jt} + \varepsilon * RoleExperience_{jt} * Treatment + \zeta * Familiarity_{jt} + \eta * Familiarity_{jt} * Treatment + e_{jt}$$

5.1 Dependent and Independent Variables

This study's main dependent variable is *Tyre Related Changes*, which is the number of changes that a firm makes in components that interact with the tyres at any given point in time. This variable measures the adaptive behavior of a firm in integrating a new supplier's component at any point in time, before and after having been subjected to the supplier switch treatment.

This study has four major independent variables. These are (I) the top management team's role experience, (II) the top management team's familiarity, as well as (III) and (IV) their respective interactions with the treatment, i.e. the regulatory shock to the externally sourced component, i.e. the tyre supplier switch. The top management team of an F1 constructor typically consists of five people that occupy different roles. First, (i) the *team principal*, who is in charge of the day-to-day routine and responsible for contracting sponsors and suppliers, as well as for recruiting drivers and engineers. He also determines the wages, takes care of financial matters and of the factory at the headquarters. Furthermore, even if the team principal is not responsible for the construction of the car or aerodynamics, he has the final say in all strategy matters. Second, (ii) the *technical director*, who is the head of research and development division, is generally responsible for the design, development and deployment of race cars as well as for performance and reliability of the cars. His duty is to review actual technical or regulatory developments as well as to ensure overall functioning of the cars, i.e. to bring together cassis, engine, tyres, drivers, etc. Third, (iii) the *chief designer* is responsible for designing the race car, i.e. for transforming single components with potentially conflicting requirements into a competitive car. Fourth, (iv) the *chief aerodynamicist* is the head of the aerodynamics division. Aerodynamics has to create downforce, in order to keep the car onto the track and to increase cornering speed, and at the same time minimize air drag that would slow the car down. Fifth, (v) the *team manager* oversees the race team and manages the logistics. First, (I) the variable *Role Experience* measures the average number of years that the different members of a firm’s top management team have been working in their area of expertise industry. Second, (II) the variable *Familiarity* measures the average number of years that the different members of a firm’s top management team have been working together in the past in their current role. Importantly, although familiarity may be measured in terms of cumulative experience when the team composition is stable over time, familiarity and cumulative experience of a team are distinct concepts. In fact, this study explores team experience beyond its cumulative experience and investigates the degree to which team members have worked with one another in the past. Finally, this study explores the respective interactions of (I) *Role Experience* and (II) *Familiarity* with the treatment, i.e. the regulatory enforced tyre supplier switch. In order to obtain the latter, a variable that captures the treatment needed to be created by multiplying the *Treatment Group* with the variable *Treatment Period*. *Treatment Group* is a binary variable that assumes the value of 1 if a firm had previously used Michelin as the tyre supplier and then had to switch to Bridgestone as of 2007. It assumes the value 0 otherwise. Instead, the variable *Treatment Period* is a binary variable that takes the value of 1 for races that took place after the treatment, i.e. between the years 2007 and 2009, and 0 otherwise. As a consequence, the multiplication of the two results in a variable that identifies the treatment, i.e. the firms that had to switch from Michelin to Bridgestone and the period during which they are using the new tyre supplier, i.e. Bridgestone. Hence, the variable *Treatment* assumes the value of 1 if a team is part of the treatment group and the performance is observed after the supplier switch has been imposed. The variable assumes the value of 0 otherwise.

5.2 Control Variables

The analysis includes several control variables. First, (1) *Treatment Period* measures the time period after the shock. Specifically, *Treatment Period* is a binary variable that assumes the value 1 for the years 2007 to 2009 and 0 otherwise. Second, (2) *Non Participants* identifies the firms that exited the Formula 1 motor sport industry before the shock or entered after the shock, and, thus, were not subject to the treatment. In particular, *Non Participants* assumes the value 1 for firms that have not been subject to the treatment and 0 otherwise. Third, (3) *Treatment Group* identifies the firms that had to switch the tyre supplier. *Treatment Group* assumes the value 1 for firms that switched from Michelin to Bridgestone and 0 otherwise. Fourth, (4) *Season Clock* measures the stage of the season that firms find themselves in at any given point in time. In particular, *Season Clock* measures the percentage of a season’s total number of days that have passed at any given point in time. This study considers the season to actually starts one day after the last race of the previous season in October, with teams developing the new car to be launched around January or February. The races then are taking place from March to October. As a result, the Season Clock starts for the first race takes into account that around a third of a Formula 1 season is has actually passed already. From this point on, as the season progresses, firms may slow down their product development. This is simply a consequence of the fact that, in F1, as the season proceeds, constructors need to gradually reallocate resources from the development of the car that is currently competing to the design and development of the car for the new season with its new rules and regulations. Fifth, (5) *Budget* measures the total amount of money in million US-Dollars that a specific firm had at disposition for a given season and reflects a firm’s size and investments in R&D. Sixth, (6) *Firm Experience* measures the number of years that a firm has been competing for in F1 over the last three seasons. This variable accounts for age and experience of the organization. Seventh (7), *Firm Success* measures the number of points that a firm has been able to accumulate in F1 over the last three seasons. This variable accounts for success of the organization. Eight, (8) *Driver Experience* measures the average number of years that the two drivers of a firm have been competing in Formula 1. Ninth (9), *Driver Success* measures the average number of Driver Championships that the two drivers of a firm have won in the past. Both of these variables account for the driver effect on a firm's performance in any given race. Tenth, (10) *Ambient Temperature* measures the degrees Celsius in the race track location on the race day. Eleventh, (11) *Track Temperature* measures the temperature of the race track in Celsius. Both may influence a car's reliability, with the former directly affecting the engine cooling and the latter the tyres. As a result, these factors are included in order to control for their effect on firm performance. Twelfth, (12) *Race Distance* measures the race length in kilometers. Thirteenth, (13) *Testing* and fourteenth (14) *Practice* respectively measure the amount of testing in thousand km and laps practiced before a given race. Finally, fifteenth (15) *Headquarters Distance* measures the distance between a firm's headquarters and a given race location in thousand kilometers. Sixteenth, (16) *Tyre Related Ownership* measures the percentage of components interacting with the tyres that are owned by a given firm. Seventeenth, (17) *Suppliers* measures the number of relationships to different suppliers that a firm entertains across all car components. Eighteenth, (18) *Tyre Related Changes by Suppliers* measures the number of changes in tyre-related components that are introduced by a firm's suppliers at any given race. Nineteenth, (19) *Tyre Unrelated Changes* measures the number of changes in components on a firm's car that are not interacting with the tryes. Finally, the study controls for other regulatory shocks that did not equally affect all firms competing in F1 and occurred between 2004 and 2009. As a consequence, the study includes the regulatory enforcement of the outsourcing of the electronic control unit (ECU) to a unique, industry-wide supplier in 2008, as well as the regulatory engine development freeze 2008. The control variables that account for these regulatory shocks are the following. Twentieth, (20) *Outsourcing Regulation* measures the time period after the ECU outsourcing shock. Specifically, *Outsourcing Regulation* is a binary variable that assumes the value 1 for the years 2008 to 2009 and 0 otherwise. Twenty-first (21) *Outsourcing Treatment Group* identifies the firms that had to outsource the electronic control unit that they previously developed internally. *Outsourcing Treatment Group* assumes the value 1 for firms that had to outsource the ECU and 0 otherwise. Twenty-second, (22) the variable *Outsourcing Treatment* has been generated, which assumes the value of 1 if a team is part of the treatment group and the performance is observed after the outsourcing has been imposed. This variable identifies the outsourcing treatment, i.e. the firms that had to outsource the ECU, which they previously developed internally. Twenty-third, (23) *Outsourcing Non Participants* identifies the firms that exited the Formula 1 motor sport industry before the shock or entered after the shock, and, thus, were not subject to the treatment. In particular, *Outsourcing Non Participants* assumes the value 1 for firms that have not been subject to the treatment and 0 otherwise. Twenty-fourth, (24) *Engine Freeze Regulation* measures the time period after the engine freeze shock, that limited the firms' possibility to develop more powerful engines and therefore limited the firms' producing their own engines in using their competence. Specifically, *Engine Freeze Regulation* is a binary variable that assumes the value 1 for the years 2008 to 2009 and 0 otherwise. Twenty-fifth, (25) *Engine Freeze Treatment Group* identifies the firms that produced their own engines and therefore had the competence of producing more powerful engines. *Engine Freeze Treatment Group* assumes the value 1 for firms that produced their own engine and 0 otherwise. The variable assumes the value of 0 otherwise. Twenty-sixth, (26) the variable *Interaction Engine Freeze Treatment*

Group _ Engine Freeze Regulation has been generated. Hence, the variable assumes the value of 1 if a team is part of the engine freeze treatment group and the performance is observed after the engine freeze regulation has been imposed. This variable identifies the treatment, i.e. the firms that had the competence to develop more powerful engines and the period during which they were not allowed to do so anymore. Twenty-seventh, (27) *Engine Freeze Non Participants* identifies the firms that exited the Formula 1 motor sport industry before the shock or entered after the shock, and, thus, were not subject to the engine freeze treatment. In particular, *Engine Freeze Non Participants* assumes the value 1 for firms that have not been subject to the engine freeze treatment and 0 otherwise.

5.3 Summary Statistics and Correlations

Table 2 below provides the summary statistics for the dependent-, independent- and control variables described above. As the table shows, the data includes 1123 observations of the different firms competing in Formula 1 between 2004 and 2009, inclusive. Tables 3 to 5 break down the summary statistics by group, i.e. treatment group, control group and non participants respectively. Table 6 shows the correlations between the various variables used in this study. There are no particularly suspiciously strong correlations between any of the variables.

INSERT TABLES 2 - 6 ABOUT HERE

6. RESULTS

Table 7a below reports the results of this study’s statistical analysis, which have been obtained by means of a quasi maximum likelihood poisson regression. Models 1a to 1e show the results for changes in tyre related components as a dependent variable. Model 1a includes only the treatment and the control variables. Model 1b includes the treatment and the first main independent variable, *team experience*, as well as the control variables. Model 1c includes the treatment, the second main independent variable, *team familiarity*, as well as the control variables. Model 1d includes the treatment, both independent variables, *team experience* and *team familiarity*, and the control variables. Finally, model 1e 1d includes the treatment, both independent variables *team experience* and *team familiarity*, their interactions with the treatment, as well as the control variables. As for the results in relation to this study’s hypotheses, models 1b – 1e provide a series of insights. Model 1b shows that team experience has a positive direct effect on the number of changes a team makes in related components, while model 1c shows that team familiarity has a negative direct effect on the number of changes in related components. Model 1d confirms these effects even when both variables are included in the same model. Finally, model 1e provides a series of interesting results. First, the effects for team experience and team familiarity found in models 1b, 1c and 1d are confimed even when including ther interaction effects with the treatment. These results confirm this study’s hypotheses 1a and 2a. Second, model 1e includes the interaction between the treatment and role experience, as well as the treatment and familiarity. As can be seen, experience has a positive direct effect, but a negative interaction with the treatment. Moreover, familiarity has a negative direct effect, but a positive interaction with the treatment. These results confirm all of this study’s hypotheses 1b and 2b. Clearly, firms having teams with high role experience were able to make more tyre-related changes in a stable environment, while they had difficulties in making those changes when having to integrate a new supplier. Instead, firms having teams with high familiarity had difficulties to make more tyre-related changes in a stable environment, while they were more able in making those changes when having to integrate a new supplier. Moreover, the margins for the effects of the treatment of switching the tyre supplier and the top management team experience, in terms of (i) role experience and (ii) familiarity, are shown below in figures 1 and 2, respectively. The margins show that firms that do not switch suppliers benefit more from a high (i) role experience than from (ii) familiarity. Instead, firms that switch suppliers benefit less from a high (i) role experience than from (ii) familiarity.

INSERT TABLE 7a, as well as FIGURES 1 AND 2 ABOUT HERE

7. ROBUSTNESS CHECKS

In order to address issues of robustness, the models from table 7a have been regressed with negative binomial-, poisson- and OLS panel regressions. Table 7b below shows the results obtained from the negative binomial panel regression and provides evidence for the robustness of this study’s results. The interaction effects of the tyre supplier switch and top management experience in terms of (i) role experience and (ii) familiarity confirm the results obtained in table 7a. Moreover, the figures 3 and 4, which show the margins for the negative binomial panel regressions, hint in the same direction as figures 1 and 2 for the quasi maximum poisson regression.

INSERT TABLE 6b, as well as FIGURES 3 AND 4 ABOUT HERE

Table 7c below shows the results for the complete model that inlcude all variables, as obtained by the poisson (3c) and OLS (3d) panel regressions, and compares them with the quasi maximum likelihood poisson regression (3a) and the negative binomial panel regression (3b). As can be seen, the two new specifications provide additional evidence for the robustness of this study's results. Clearly, all of the results of table 6a are confirmed in direction and significance.

INSERT TABLE 7c

Finally, an additional quasi maximum likelihood poisson regression has been conducted, whose results are displayed in table 8 below. Table 8 clarifies that firms did not have to switch to an inferior tyre as of 2007. In particular, the results in table 8 show that the effect of the Michelin tyres-dummy on the number of problems over the course of any given race weekend in the time before the shock, i.e. between 2004 and 2006, is highly significant and positive. Hence, just by judging the quality of the two suppliers' products, one should expect firms switching from Michelin to Bridgestone to perform better. However, 7a showed that this is not the case. Therefore, one can conclude that supplier switching is associated with difficulties in terms of knowledge integration, even if the new supplier's product is superior to the previous supplier's product. The results imply that knowledge integration difficulties and related switching costs occur every time a firm switches suppliers, regardless of the difference in the suppliers' products quality.

INSERT TABLE 8 ABOUT HERE

8. DISCUSSION AND CONCLUSIONS

The management of technological change in complex products frequently requires close coordination between the activities underlying the component development, as well as the assembly and integration of those components into a final product. This is particularly true for complex product systems, whose components have technological interdependencies, which oftentimes require firms to experiment and learn in order to harness their potential. However, even though the literature highlights the importance of integrating activities in complex systems, much of the existing research has focused on singular relationships or components. Instead, in reality, complex systems frequently cross component- and firm boundaries. Recent work has established that the integration and coordination of activities with suppliers is more effective if firms are able to make changes in related components across the system. Nonetheless, it is less well understood where a firm's ability to make such changes resides. This study has examined the need for buyer firms to switch suppliers and integrate a new component in relation to firms' top management teams and their ability to make changes in related components across the system, in order to understand this issue more fully. It shows how differences in team experience and -composition lead to differences in teams' abilitties to integrate external components by making the necessary internal changes in related components. A comprehensive understanding of how human resources may facilitate successful operation and adaptation is important, particularly in technologically dynamic environments, where firms do not get a second chance to make up for failure to adapt.

The unique data in the setting of Formula 1 racing is relevant in this respect, as it allows to link data on supplier switches for a specific component, as well as changes in components across the system to a firm's top management team experience. Considering supplier switching in a value system, the study explains why some firms are better at integrating a new external component than others. In this study, this has been done by conducting a natural experiment, which is one of the most powerful methods to prove causality free of endogeneity. Consistent with the predictions, the results show that, in Formula 1 motor sport, there is a trade-off in terms of a firm's top management teams (i) role experience and (ii) familiarity in relation to the firm's ability to integrate a new external component by making changes in related components across the system. In partiular, (i) role experience positively affects the team's ability to make changes in related components across the system, but is relatively less beneficial after a supplier switch. Instead, (ii) familiarity has a negative effect on the team's ability to make changes in related components across the system, but is relatively more beneficial after a supplier switch.

Therewith, this study contributes to top management team theory and the theory of the firm, as well as the related literature streams on supply chain management and knowledge integration, the latter of which thus far tends to focus on the efficiency aspects of knowledge integration instead of effectiveness. Empirically, the study contributes to the academic discussion by underlining the importance of real-life settings, since much prior work on teams, or top management teams for that matter, has been conducted in lab-settings. Moreover, this study also has important implications for managers. Project teams are formed in order to to produce a definable output in a variety of settings, such as product development, consulting or investment banking. This study suggests that managers should explicitly consider both, experience within a given role as well as experience with other team members, when making decisions on staffing project teams. Such an approach may require managers to track additional data, but at the same time it provides managers with additional and relevant levers of control. Finally, this study's findings address the important question of whether and under which conditions a firm may stand to gain performance benefits when switching to suppliers that are also available to competitors. Since firms today frequently outsource activities to suppliers that provide multiple competing clients with the same activities, this is a particularly interesting issue that has emerged only recently. Specifically, the study does so by showing the differences in performance that may result from differences in team's capability deployment (Barney and Arikan 2001; Lavie, 2006; Sirmon et al., 2007). In particular, a firm's top management team's experience determines the firm's ability to make changes in internal components that interact with an external component. The investigation of ownership of components across the system on the effectiveness with which externally sourced components can be integrated however, was beyond the scope of this study and is strongly suggested to be studied in future research. Moreover, future research should address whether and how differences in firms' teams and personnel in general may interact with ownership of components across the system in determining the firm's ability to make internal changes across related components for the purpose of integrating new external components.

Overall, the results suggest that both component knowledge and architectural knowledge and competence resides in top management teams. Component knowledge appears to influence firm performance through human capital, i.e. the stand-alone experience and expertise of the various team members. Instead, architectural knowledge appears to influence firm performance through social capital, i.e. team members' familiarity with each that other allows teams to find the most beneficial combinations of component changes. This study's findings can be expected to be generalizeable, in particular to industries in which firms typically rely on project teams, as well as industries that emphasize new product development and in which firms outsource production capacities with the production form of component knowledge being separated from the firm. Examples of such industries are motion pictures, semiconductors, consumer electronics and garments.

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10. TABLES AND FIGURES

Table1: Examples of Changes to Components that are Interdependent with the Engine.

Team	Year	Description	Source
BAR	2004	Starting with an engine air intake of pentagonal section to guarantee greater aeration and better aerodynamic efficiency. The intake was of triangular section on the first version of the 005.	F1 Technical Analysis
BAR	2005	After the dual engine failure last race the Honda engineers had a revised spec for Bahrain, with general improvements as well as a solution for the oil sensor failure which caused the retirements in Malaysia.	ATLAS F1
BMW	2007	The new gearbox features a seamless shift and a particular compact rear damper set up, still comprising Sachs rotary dampers.	ATLAS F1
Brawn	2009	The terminal zone of the body was modified to improve the evacuation of hot air from the sidepods. In the circle is the original solution. Note the narrow louver above the pushrod mount.	F1 Technical Analysis
Ferrari	2004	It is the fairing around the gearbox that also sees more extreme development; the suspension is now so low and neat that little shaping is required to cover the set up. Small shrouds are moulded into the fairing to cover the pushrod and wishbone mountings, but otherwise the fairing has shrunk to blend the rear profile of the engine into the tail structure The fairing is so well wrapped around the gearbox that the sidepods cooling outlet can flow over the top of the gearbox, and the driveshafts have protrude through slots rather than having a large cut-out. This level of design has been unique to Ferrari over the past few years.	ATLAS F1
Ferrari	2007	Ferrari retained the larger louvers on the left side of their car, as had already been the case in Malaysia but those of the right side were standard. A necessity that slightly influenced aerodynamic efficiency, but which turned out to be indispensable in guaranteeing the reliability of Maranello's eight cylinder.	F1 Technical Analysis
Ferrari	2007	The longer wheelbase could improve both aerodynamics and weight distribution, but is an approach that has left the other F1 designers wondering what Ferrari might know that they don't. One added benefit might be that is has enabled Ferrari to create an even larger fuel tank.	ATLAS F1
Ferrari	2009	To make the upper deck on the diffuser, the team has had to reshape the gearbox fairing and re-sited several electronic and hydraulic systems on the side of the gearbox.	ATLAS F1
Honda	2006	Under the skin, the teams carbon fibre cased gearbox is in its third generation, with the Honda developed gearshift system providing fast but, more importantly, smooth gear changes to aid the car’s stability through a corner. Starting out with the car’s layout, although Willis was not specific, the wheelbase remains similar to last year. This has been accommodated by a longer gearbox, which is mated to the V8 engine unit being shorter by 90mm to its V10 predecessor.	ATLAS F1
Honda	2008	Within the sidepods the radiators are now positioned face-up, venting through both louvers in the engine cover and a chimney - again the current preferred position for many teams.	ATLAS F1
Jaguar	2004	Moving on to the engine cover, the small airbox allows the bodywork to remain narrow over the engine, ending with an open vertical cut at the Axle line. Although the abrupt end of the cover could cause problems - creating vortices when the car yaws, upsetting the rear wing.	ATLAS F1
Jordan	2004	ATLAS: Jordan have opted to run the line of the regulation engine cover all the way to the rear of the car referring not to cut off the engine cover at the axle line.	ATLAS F1

Jordan	2005	ATLAS: Jordan were the first team to run a car to new regulations with a lifte front wing, more forward mounted rear wing and revised diffuser. This interim car initially ran with a Cosworth engine, but needed revision in light of the Toyota engine. Curiously Jordan revised their diffuser to meet the new rules demanding lower outer tunnels in a new way; rather than moulding a new floor with lower outer tunnels, the team have blanked off the old higher tunnels, leaving a void in between them.	ATLAS F1
McLaren	2005	Hungary also saw the team run the wider chimneys to cool the engine.	ATLAS F1
McLaren	2005	One weak spot which caused McLaren problems on both the MP4-18 and MP4-19A was the integration of the engine into the chassis and gearbox. Mated to the engine is a new gearbox; Whitmarsh would not be drawn on what material the casing was made in, noting "you'll see in due course. It's one of those things we keep undercover as much as we can. The gearbox is very different from last year.	ATLAS F1
Red Bull Racing	2005	The gearbox mates to the new TJ2005 Cosworth engine - again a development of the 2004 CR6 90-degree engine.	ATLAS F1
Red Bull Racing	2009	The pullrod layout was in sharp contrast to the other teams' designs and was dictated by the need to raise the lower part of the gearbox as far as possible, so increasing the space available for the diffuser. The pullrod even worked outside the suspension's lower wishbone and ended in a much advanced position on the gearbox where there was a very special rocker, inclined in relation to the vertical and fitted inside with the torsion bar. As with the front suspension, the mounts of the lower…lever on the gearbox were very high and inclined; the join with the straight line that united the mounts of the upper wishbone carried to a point, the instantaneous longtitudinal rotation centre, which is half way between those of Brawn and Williams, herefore producing medium anti-squat values.	F1 Technical Analysis
Renault	2006	Allied to the new chassis, Rob White's team have developed an all-new engine. With Renault only having run a narrower angled (72-dgeree) engine for two years, the step towards a 90-degree format for the V8 is new territory. Although the V8 with its flat plane crank is prone to more secondary vibration, Renault's experience with the vibration prone wide angled V10s and the V8 GP2 engine was not directly related to the new unit. Dyno work started very early in 2005 on the mule engine, while the testing, design and development work fed into the definitive R26 engine, built to new regulations on size, weight and materials.	ATLAS F1
Renault	2006	As the smaller capacity engine has less torque, its power delivery will be more peaky. As a result, the team has returned to a seven-speed gearbox, the extra ratio allows the driver to keep the engine in its power band for more of the time. This has made the gearbox a little longer, but with the shorter engine this hasn't been an issue.	ATLAS F1
Super Aguri	2006	The engine cover is new to accommodate the different rules from 2002, the new crash structures and the Honda engine installation.	ATLAS F1
Toro Rosso	2009	The 8-cylinder Ferrari (engine supplier) power unit required a different installation both in terms of the rear suspension and radiator dimensions, as well as the need for bigger side exits to improve cooling.	F1 Technical Analysis
Toyota	2007	Engine and gearbox are more and more a connected group. The gearbox concept is coming from Williams and we been able involve chassis side, o develop it jointly. The seamless system reduces shift times and also the requirement for the engine to come off the throttle as much during shifts.	ATLAS F1
Williams	2007	Most of the changes are aerodynamic and mechanical, the latter being largely the revised seamless shift gearbox and the packaging to install the Toyota engine.	ATLAS F1

Table2: Overall Summary Statistics.

Variable	Observations	Mean	Std. Dev.	Min.	Max.
GP Points	1123	9.557	11.862	0	43
Tyre Problems	1123	0.315	0.605	0	4
Tyre Related Problems	1123	1.060	1.320	0	12
Tyre Related Changes by Team	1123	1.825	1.919	0	15
Tyre Related Changes by Suppliers	1123	0.105	0.391	0	4
Tyre Unrelated Changes	1123	0.163	0.442	0	3
Team Familiarity	1123	1.829	1.353	0	5.4
Team Experience	1123	13.298	4.754	4.4	26.2
Supplier Switch Regulation	1123	0.495	0.500	0	1
Budget	1123	270.567	135.735	45.6	499.05
Firm Experience	1123	2.290	1.091	0	3
Driver Experience	1123	4.935	3.386	0	12.5
Season Clock	1123	0.528	0.288	0.053	1
Track Temperature	1123	36.450	10.040	16	63
Ambient Temperature	1123	26.215	5.877	15	42
Race Distance	1123	187.569	12.801	171.841	310.422
HQ Distance	1123	4.633	4.758	0	17.005
Tyre Related Ownership	1123	0.828	0.037	0.7561	0.9024

Table3: Summary Statistics Treatment Group.

Variable	Observations	Mean	Std. Dev.	Min.	Max.
GP Points	496	11.383	11.883	0	43
Tyre Problems	496	0.274	0.544	0	3
Tyre Related Problems	496	0.960	1.063	0	7
Tyre Related Changes by Team	496	1.798	1.869	0	9
Tyre Related Changes by Suppliers	496	0.103	0.386	0	4
Tyre Unrelated Changes	496	0.115	0.366	0	3
Team Familiarity	496	1.927	1.309	0	5.2
Team Experience	496	15.015	5.805	4.4	26.2
Supplier Switch Regulation	496	0.595	0.491	0	1
Budget	496	308.517	115.077	75	493.1
Firm Experience	496	2.101	1.120	0	3
Driver Experience	496	5.150	3.047	0	11.5
Season Clock	496	0.528	0.286	0.053	1
Track Temperature	496	36.710	10.251	16	63
Ambient Temperature	496	26.302	5.989	15	42
Race Distance	496	302.353	19.202	171.841	310.422
HQ Distance	496	4.692	4.771	0.011	16.998
Tyre Related Ownership	496	0.830	0.034	0.7561	0.878

Table4: Summary Statistics Control Group.

Variable	Observations	Mean	Std. Dev.	Min.	Max.
GP Points	409	9.667	12.455	0	43
Tyre Problems	409	0.298	0.584	0	3
Tyre Related Problems	409	0.856	1.015	0	8
Tyre Related Changes by Team	409	2.203	2.083	0	15
Tyre Related Changes by Suppliers	409	0.098	0.396	0	4
Tyre Unrelated Changes	409	0.227	0.533	0	3
Team Familiarity	409	1.650	1.308	0	5.3
Team Experience	409	12.243	3.515	5.6	18
Supplier Switch Regulation	409	0.509	0.501	0	1
Budget	409	287.545	145.076	45.6	499.05
Firm Experience	409	2.482	0.973	0	3
Driver Experience	409	5.334	3.584	0	12.5
Season Clock	409	0.528	0.289	0.053	1
Track Temperature	409	36.822	10.142	16	63
Ambient Temperature	409	26.298	5.896	15	42
Race Distance	409	302.246	19.322	171.841	310.422
HQ Distance	409	4.609	4.755	0	17.005
Tyre Related Ownership	409	0.845	0.034	0.7805	0.9024

Table5: Summary Statistics Non-Participants.

Variable	Observations	Mean	Std. Dev.	Min.	Max.
GP Points	218	5.197	9.327	0	43
Tyre Problems	218	0.440	0.743	0	4
Tyre Related Problems	218	1.670	2.005	0	12
Tyre Related Changes by Team	218	1.557	2.374	0	17
Tyre Related Changes by Suppliers	218	1.179	1.487	0	8
Tyre Unrelated Changes	218	0.151	0.396	0	2
Team Familiarity	218	1.944	1.499	0	5.4
Team Experience	218	11.372	2.044	9.2	16.4
Supplier Switch Regulation	218	0.239	0.427	0	1
Budget	218	152.366	87.233	50.31	360.16
Firm Experience	218	2.362	1.165	0	3
Driver Experience	218	3.700	3.466	0	12.5
Season Clock	218	0.528	0.289	0.053	1
Track Temperature	218	35.161	9.271	16	55
Ambient Temperature	218	25.862	5.590	15	42
Race Distance	218	300.028	25.439	171.841	310.422
HQ Distance	218	4.543	4.754	0	16.974
Tyre Related Ownership	218	0.789	0.014	0.7619	0.8049

Table 6: Correlations.

	Race Points	Tyre Probl.	Tyre Related Probl.	Tyre Related Changes Team	Tyre Related Changes Suppliers	Tyre Unrelated Changes	Treat. Group	Budget	Firm Exp.	Driver Exp.	Team Familiarity	Team Exp.	Tyre Related Ownership
Race Points	**1.0000**												
Tyre Problems	-0.0312	**1.0000**											
Tyre Related Problems	-0.1887	0.0389	**1.0000**										
Tyre Related Changes Team	0.2170	0.0521	-0.0863	**1.0000**									
Tyre Related Changes Suppliers	0.0561	0.0332	0.0258	0.2751	**1.0000**								
Tyre Unrelated Changes	0.1828	0.1144	0.0139	0.3205	0.3185	**1.0000**							
Treatment Group	0.1370	-0.0604	-0.0674	-0.0126	-0.0051	-0.0967	**1.0000**						
Budget	0.4343	0.0368	-0.1742	0.3071	0.0473	0.1514	0.2488	**1.0000**					
Firm Experience	0.2226	0.0462	0.0003	0.1503	0.0663	0.1218	-0.1546	0.3447	**1.0000**				
Driver Experience	0.2541	0.0380	-0.0915	0.1534	0.0384	0.1485	-0.0355	0.4955	0.0100	**1.0000**			
Team Familiarity	0.2736	0.0978	-0.0372	0.0622	0.1396	0.1658	0.0644	0.2582	0.4213	0.2017	**1.0000**		
Team Experience	0.3853	-0.0265	-0.0900	0.1864	0.0649	0.1046	0.2675	0.3762	0.4265	0.0100	0.3965	**1.0000**	
Tyre Related Onwership	0.2674	0.0353	-0.1171	0.2658	0.0234	0.1148	0.0628	0.7383	0.3301	0.4745	0.1614	0.3371	**1.0000**

Table7a: Results; QML panel regressions; Dependent variable = tyre related changes; Standard errors in parentheses. *significant at 10%; **significant at 5%; ***significant at 1%. Control variables not reported are: (i) ambient temperature, (iii) track temperature, as well as (iii) race distance, (iv) testing, (v) trend and (vi) other shocks.

VARIABLES	**TYRE RELATED CHANGES (1a)**	**TYRE RELATED CHANGES (1b)**	**TYRE RELATED CHANGES (1c)**	**TYRE RELATED CHANGES (1d)**	**TYRE RELATED CHANGES (1e)**
Supplier Switch Regulation	0.516***	0.556***	0.452***	0.482***	0.373***
	(0.114)	(0.115)	(0.115)	(0.115)	(0.122)
Non Participant	- 0.298	- 0.078	- 0.411	- 0.192	- 0.239
	(0.329)	(0.340)	(0.330)	(0.340)	(0.340)
Treatment Group	- 0.167	- 0.340***	- 0.136	- 0.322***	- 0.376***
	(0.109)	(0.120)	(0.112)	(0.120)	(0.117)
Treatment	- 0.286**	- 0.241**	- 0.255**	- 0.197*	0.376
	(0.119)	(0.118)	(0.120)	(0.119)	(0.268)
Role Experience		**0.039*** **		**0.043*** **	**0.069*** **
		(0.012)		**(0.012)**	**(0.014)**
Familiarity			**- 0.061** **	**- 0.077*** **	**- 0.143*** **
			(0.027)	**(0.028)**	**(0.035)**
Interaction Treatment _ Role Experience					**- 0.062*** **
					(0.018)
Interaction Treatment _ Familiarity					**0.220** **
					(0.093)
Budget	0.002***	0.002***	0.001***	0.001***	0.002***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Firm Experience	0.029	- 0.001	0.001	0.027	0.034
	(0.029)	(0.030)	(0.030)	(0.032)	(0.032)
Driver Experience	- 0.002	- 0.002	0.002	0.015	0.017
	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)
Suppliers	- 0.130***	- 0.106***	- 0.106***	- 0.118***	- 0.081***
	(0.025)	(0.026)	(0.026)	(0.026)	(0.027)
Tyre-Related Ownership	1.286	- 2.581	- 2.581	- 3.006	- 4.219*
	(2.132)	(2.407)	(2.407)	(2.396)	(2.529)
Headquarters Distance	- 0.029***	- 0.029***	- 0.029***	- 0.030***	- 0.030***
	(0.007)	(0.007)	(0.007)	(0.007)	(0.006)
Season Clock	- 0.262**	- 0.263**	- 0.266**	- 0.268**	- 0.277**
	(0.123)	(0.123)	(0.122)	(0.122)	(0.121)
Other Control Variables	...	...	...	...	...
Cons.	0.292	0.421	2.834	3.307*	3.551*
	(1.666)	(1.660)	(1.800)	(1.803)	(1.871)
Observations	1123	1123	1123	1123	1123
Pseudo log-likelihood	- 1982.1622	- 1978.2468	- 1978.2468	- 1966.583	- 1954.8932
R-squared	0.2132	0.2204	0.2155	0.2243	0.2282

Figure1: Margins of quasi-maximum-likelihhod panel regression; IV = Role Experience.

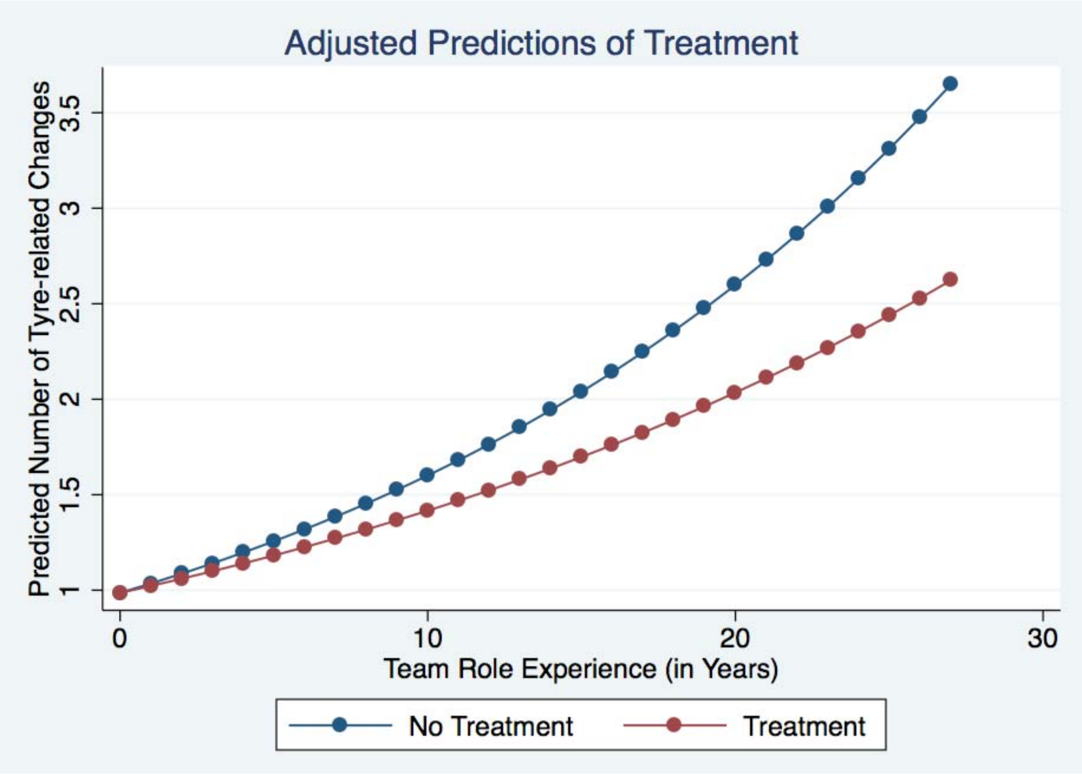

Figure2: Margins of quasi-maximum-likelihhod panel regression; IV = Familiarity.

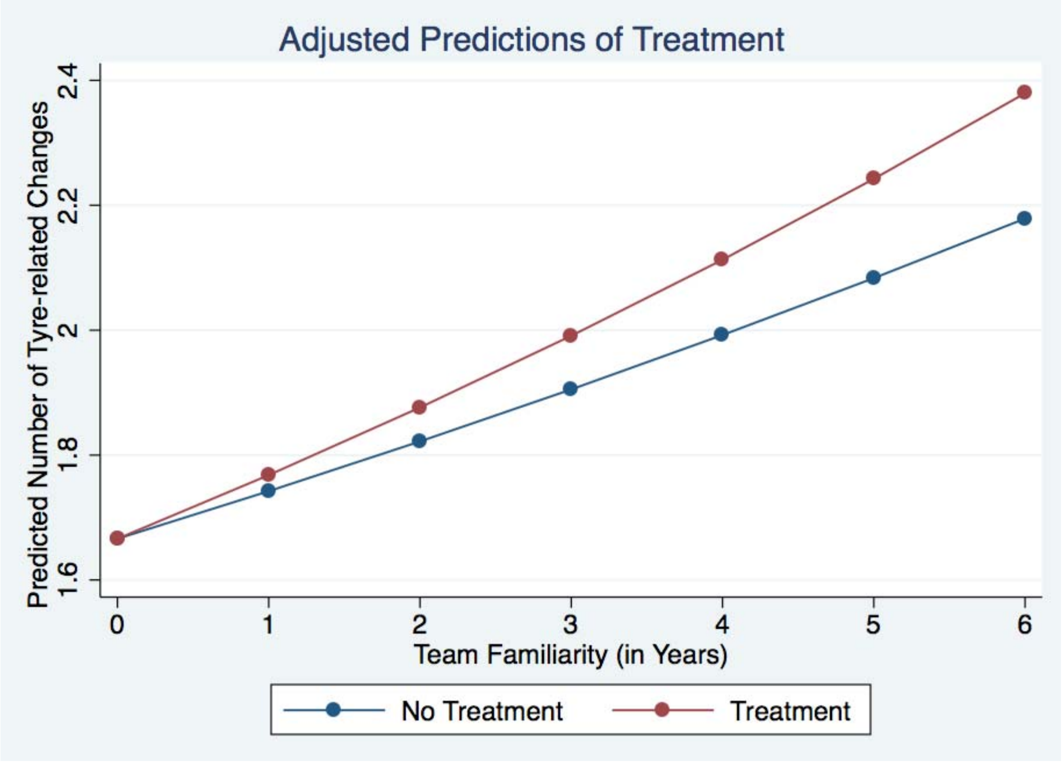

Table7b: Results; Negative binomial (1a-1e), poisson (1f) and OLS (1g) panel regressions; Dependent variable = tyre related changes; Standard errors in parentheses. *significant at 10%; **significant at 5%; ***significant at 1%. Control variables not reported are the following: (i) ambient temperature, (iii) track temperature, as well as (iii) race distance, (iv) testing, (v) trend and (vi) other shocks.

VARIABLES	TYRE RELATED CHANGES (2a)	TYRE RELATED CHANGES (2b)	TYRE RELATED CHANGES (2c)	TYRE RELATED CHANGES (2d)	TYRE RELATED CHANGES (2e)
Supplier Switch Regulation	0.567**	0.611***	0.423***	0.528***	0.354***
	(0.116)	(0.117)	(0.134)	(0.119)	(0.099)
Non Participant	- 0.084	0.156	- 0.172	0.030	- 0.234
	(0.258)	(0.265)	(0.295)	(0.269)	(0.195)
Treatment Group	- 0.163	- 0.342***	- 0.129	- 0.321***	- 0.379***
	(0.100)	(0.110)	(0.128)	(0.111)	(0.088)
Treatment	- 0.353***	- 0.314***	- 0.285**	- 0.264**	0.383*
	(0.120)	(0.120)	(0.128)	(0.121)	(0.225)
Role Experience		**0.039*****		**0.045*****	**0.068*****
		(0.011)		**(0.011)**	**(0.011)**
Familiarity			**- 0.088*****	**-0.092*****	**- 0.139*****
			(0.031)	**(0.028)**	**(0.027)**
Interaction Treatment _ Role Experience					**- 0.063*****
					(0.014)
Interaction Treatment _ Familiarity					**0.224*****
					(0.062)
Budget	0.002***	0.002***	0.002***	0.001***	0.002***
	(0.001)	(0.000)	(0.000)	(0.001)	(0.000)
Firm Experience	0.029	- 0.002	0.068**	0.028	0.034
	(0.026)	(0.027)	(0.032)	(0.029)	(0.023)
Driver Experience	- 0.003	- 0.002	0.009	0.013	0.017
	(0.012)	(0.013)	(0.014)	(0.013)	(0.011)
Suppliers	- 0.131***	- 0.105***	- 0.130***	- 0.120***	- 0.090***
	(0.024)	(0.025)	(0.032)	(0.025)	(0.022)
Tyre-Related Ownership	1.303	- 2.612	1.360	- 3.024	- 3.583*
	(2.173)	(2.439)	(2.254)	(2.426)	(2.039)
Headquarters Distance	- 0.028***	- 0.029***	- 0.029***	- 0.029***	- 0.016***
	(0.007)	(0.007)	(0.007)	(0.007)	(0.005)
Season Clock	- 0.219*	- 0.227*	- 0.218*	- 0.223*	- 0.546***
	(0.117)	(0.117)	(0.117)	(0.116)	(0.086)
Other Control Variables	...	...	...	...	...
Cons.	- 0.659	3.240	0.668	3.752**	3.314**
	(1.747)	(1.883)	(1.855)	(1.879)	(1.561)
Observations	1123	1123	1123	1123	1123
Log-likelihood	- 1900.3978	- 1894.3349	-1896.0152	- 1888.724	- 1986.7955
Wald chi square	309.90	328.33	246.13	336.15	402.30
Prob > chi-square	0.0000	0.0000	0.0000	0.0000	0.0000

Figure3: Margins of negativebinomial panel regression; IV = Role Experience.

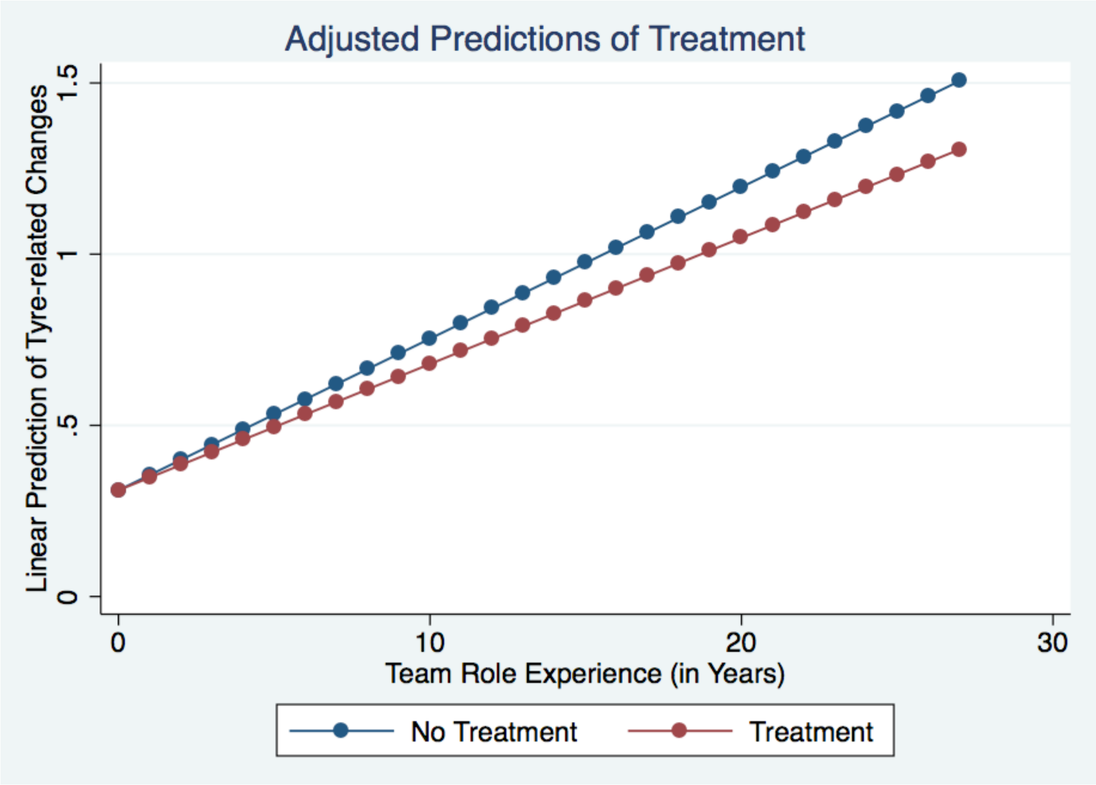

Figure4: Margins of negative binomial panel regression; IV = Familiarity.

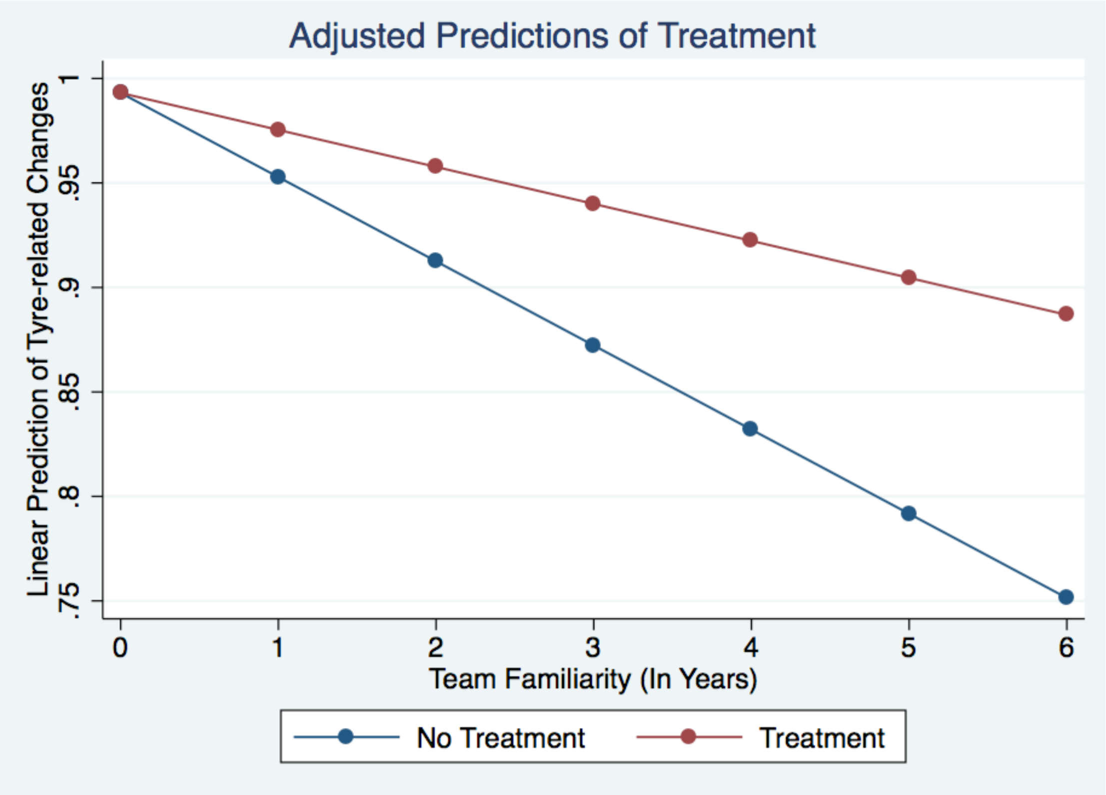

Table7c: Results; Negative Binomial panel regression (3a), Quasi Maximum Likelihood (3b), poisson (3c) and OLS (3d) panel regressions; Dependent variable = tyre related changes; Standard errors in parentheses. *significant at 10%; **significant at 5%; ***significant at 1%. Control variables not reported are: (i) ambient temperature, (iii) track temperature, (iii) race distance and (iv) other shocks.

VARIABLES	TYRE RELATED CHANGES (3a)	TYRE RELATED CHANGES (3b)	TYRE RELATED CHANGES (3c)	TYRE RELATED CHANGES (3d)
Supplier Switch Regulation	0.354*** (0.099)	0.354** (0.126)	0.354*** (0.099)	0.713*** (0.239)
Non Participant	- 0.234 (0.195)	- 0.234 (0.341)	- 0.234 (0.195)	- 0.141 (0.386)
Treatment Group	- 0.379*** (0.088)	- 0.379*** (0.118)	- 0.379*** (0.088)	- 0.711*** (0.212)
Treatment	0.383* (0.225)	0.383 (0.274)	0.383* (0.225)	0.807 (0.495)
Role Experience	**0.068*** (0.011)**	**0.068*** (0.014)**	**0.068*** (0.011)**	**0.119*** (0.023)**
Familiarity	**- 0.139*** (0.027)**	**- 0.139*** (0.035)**	**- 0.139*** (0.027)**	**- 0.198*** (0.058)**
Interaction Treatment _ Role Experience	**- 0.063*** (0.014)**	**- 0.063*** (0.018)**	**- 0.063*** (0.014)**	**- 0.111*** (0.031)**
Interaction Treatment _ Familiarity	**0.224*** (0.062)**	**0.224** (0.093)**	**0.224*** (0.062)**	**0.284** (0.133)**
Budget	0.002*** (0.000)	0.002*** (0.000)	0.002*** (0.000)	0.004*** (0.001)
Firm Experience	0.034 (0.023)	0.034 (0.032)	0.034 (0.023)	0.053 (0.050)
Driver Experience	0.017 (0.011)	0.017 (0.014)	0.017 (0.011)	0.008 (0.025)
Suppliers	- 0.090*** (0.022)	- 0.090*** (0.028)	- 0.090*** (0.022)	- 0.138* (0.049)
Tyre-Related Ownership	- 3.583* (2.039)	- 3.583 (2.578)	- 3.583* (2.039)	- 7.658* (4.533)
Headquarters Distance	- 0.016*** (0.005)	- 0.016** (0.006)	- 0.016*** (0.005)	- 0.026** (0.016)
Season Clock	- 0.546*** (0.086)	- 0.546*** (0.107)	- 0.546*** (0.086)	- 0.945*** (0.193)
Other Control Variables	...	...	...	...
Cons.	3.314** (1.561)	3.314* (1.909)	3.314*** (1.561)	7.661** (3.523)
Observations	1123	1123	1123	1123
Pseudo log-likelihood (1f), Log-likelihood (1e & 1g), R-squared between (1h)	- 1986.7955	- 1986.7955	- 1986.7955	0.9324
Wald chi square (1e &1g) Pseudo Rsquared (1f), R-squared overall (1h)	402.30	0.1948	402.30	0.1863
Prob > chi-square	0.0000	0.0000	0.000	0.0000

Table8: Pre-Shock Tyre Problems; Negative binomial panel regression; Dependent variable = Number of tyre problems; Standard errors in parentheses. *significant at 10%; **significant at 5%; ***significant at 1%. Standard errors in parentheses. *significant at 10%; **significant at 5%; ***significant at 1%.

VARIABLES	NUMBER OF PRE-SHOCK TYRE PROBLEMS
Michelin	**0.801***** **(0.300)**
Budget	- 0.003** (0.001)
Firm Experience	0.177*** (0.059)
Firm Success	- 0.000 (0.000)
Driver Experience	0.074 (0.048)
Driver Success	0.108 (0.238)
Engineers’ Experience	- 0.041 (0.032)
Testing	- 0.000 (0.000)
Practice	0.001** (0.000)
Season Clock	- 0.332 (0.268)
Race Distance	0.000 (0.004)
TrackTemperature	- 0.018* (0.010)
Ambient Temperature	0.048*** (0.018)
Headquarters Distance	0.027* (0.016)
Suppliers	- 0.105 (0.066)
Tyre-related Ownership	4.676 (2.193)
Cons.	- 4.896 (2.798)
Observations	568
Log-likelihood	-453.09116
R-squared	0.0996