Making Design Rules: A Multi-Domain Perspective

Literature on modularity suggests that the design rules that allocate functions to modules, identify operating principles, and set interfaces among modules determine how organizations evolve. An in-depth case study of radical innovation in tire manufacturing illustrates the transition from old to new design rules. At Pirelli Tires, this involved the joint adaptation of organization and product to reflect changes in the underlying engineering knowledge. Knowledge evolution mediates the relationship between organizational and technological change and makes any organization design open-ended and evolving.

1. Introduction

How do organizations adapt in response to technological innovation and environmental transformations? In trying to answer this question, a rich body of literature has conceptualized organizations as complex entities made up of many interconnected elements (Lawrence and Lorsch, 1967; Perrow, 1967; Thompson, 1967; Galbraith, 1973; Woodward, 1965; Miller, 1987; Whittington et al., 1999; Grandori, 2001). These elements can be combined in different ways so that internal fit (among their constitutive elements) and external fit (among internal configurations and environment) are correlated with superior performance (e.g. Drazin and Van de Ven, 1985). Recently, research analyzed the processes through which organizations evolve toward fit (e.g. Siggelkow, 2002). This research builds on the idea that not all organizational elements are alike: some elements are *core* to an organization others are not. Evolution toward fit is a process of strengthening and structuring connections among core elements. For example, Siggelkow (2002) analyzed the long-term evolution of the Vanguard Group identifying the processes whereby connections among existing elements emerge, adapt, vary, and disappear.

This paper extends this line of enquiry focusing on a largely understudied theme: how do new core elements emerge? In order to operationalize the analysis of the emergence of new core elements, we use the concept of design rules (Baldwin and Clark, 2000). Design rules are the principles that define how an artifact works, what it does, and how it is manufactured. They allocate functions to components, identify operating principles central to each component, and set interfaces among components (Baldwin and Clark, 2000). Design rules may also include strategic or organizational core elements, e.g. mass customization. Research on design rules revolves around the concept of *modularity*. Modular design rules are based on the twinned principles of components decoupling and interface standardization. From an organization design perspective, research on modularity argued that modular products lead to modular organizations, as products' design rules define both the technological and organizational architecture of firms (e.g. Sanchez and Mahoney, 1996; Baldwin and Clark, 2000; Schilling, 2000; Sturgeon, 2002; Langlois, 2003). Empirical studies questioned such finding: non-modular organizations that produce modular products were observed in the hard disk drive industry (Chesbrough and Kusunoki, 2001) and automotive (Takeishi, 2002). These studies illustrated that (a) firms are constituted of different domains (e.g. organizational structure,

technological architecture, etc.) that may obey to different design rules and (b) that the evolution of firms' knowledge bases plays a fundamental role in mediating the relationship between product and organization design (Brusoni, Prencipe and Pavitt, 2001). How such role unfolds remains largely understudied, however. Through an in-depth analysis of radical innovation in tire manufacturing, this paper aims to illustrate the micro-level processes whereby knowledge acts as a filter between technological and organizational evolution in order to understand how new design rules emerge. It shows that the introduction of new design rules entailed changes in three related domains: knowledge, organization, and product.

The paper is organized as follows. The next section describes the research setting and methods. Section 3 analyzes the reasons that led Pirelli to develop the new robotized tire manufacturing process. Section 4 analyses how the new process was developed highlighting the joint dynamics of technology, organization, and knowledge. Section 5 discusses the findings, whereas Section 6 presents the conclusions.

2. Research Setting and Methods

The tire industry is often depicted as an archetypical example of a mature business (Sull, Tedlow, and Rosenbloom, 1997; French, 1991). Since the early 1990s, however, it has witnessed an explosion of R&D initiatives that impinge on all levels of the value chain. In the late 1990s, trade literature described ongoing technology developments leading to a fully robotized and modular tire production process. Pirelli, a leading player, developed a process called MIRS: Modular Integrated Robotized System. The trade press reported that MIRS would usher in an era of customized tires.

We approached Pirelli to get data about MIRS. Pirelli appointed a *company tutor*, Renato Caretta, to introduce us to the manufacturing process. Our tutor was a senior engineer, a member of the managing board, a former senior R&D executive officer, and the person who led and conceived MIRS. We analyzed the development of the new robotized process and its impact on the firm's design activities because, in this sector, manufacturing processes are often the source of major bottlenecks. Traditional tire manufacturing had changed little since the radial revolution of the late 1960s. Robotized, modular production, however, had the potential to change century-old practices and the associated business models that emphasized mass

production of tires, standardization of tire products, and economies of scale. Business models based on robotized processes, in contrast, emphasize economies of scope, i.e., the production of small batches of differentiated tires; flexibility, i.e., rapid responses to changes in market trends; and customization, i.e., abilities to fulfill specific engineering requirements for different car models. In other words, we identified the diffusion of robotized production as an example of an innovation capable of generating new design rules throughout the adopting organization. In addition, the modular features of the MIRS made such an example amenable to be studied relying on methods, concepts and constructs already validated in prior research (e.g. design rules).

As our objective was to investigate empirically a phenomenon that has received little attention so far (i.e. the process whereby design rules emerge), we adopted a strategy of theoretical sampling to generate our data. First, we identified three individuals who played key roles in Pirelli's project. They defined major milestones, e.g., the opening of the first pilot plant, and major organizational transformations, e.g., when and why the team hired new people. We then expanded our interview sample to include people who influenced the product and software design. We stopped sampling when new interviews did not add new theoretical categories (Glaser and Strauss, 1967), i.e. when we concluded that the events we were discovering could be interpreted within the three domains already identified, i.e. knowledge, technology and organization.

The fieldwork began in early 2004. Between April and mid-June, we carried out a first round of interviews, analyzed the data collected, and clarified specific points via phone calls and emails. We conducted a second round of interviews between late June and the end of September and clarified details through follow-up phone calls and emails. We interviewed twenty-seven different individuals, some several times, for approximately 75 interview-hours. Initially, interviews were unstructured and unscheduled, e.g. some occurred while the interviewer and interviewee walked through the plant. In our first interviews, we focused on what Strauss (1987) calls *generative questions*. The thrust of these interviews was to understand the organization, its evolution, and to identify key events and key participants. We also sought to identify other knowledgeable people who could confirm and clarify the information we obtained, as well as what data sources which could be used to triangulate interview data. We used these interviews to distinguish the main

differences between traditional and innovative tire manufacturing in terms of their design rules (e.g. modularity vs. non-modularity; articulation of design heuristics vs. tacit knowledge; integrated know-how vs. specialized know-how). At this stage, we also singled out the core elements that constitute design rules (e.g. rigid drum vs. flat support deposition; digital control vs. visual control; asymmetric deposition vs. symmetric deposition) as well as the relevant domains of analysis for each core element identified. This is the stage when we identified the knowledge domain as key to interpret what happened in Pirelli.

The second round of interviews was problem-*oriented* (Flick, 2002: 125). We probed whether we had identified key design rules that set apart the two processes, and their core elements. For example, we discarded a few elements that we initially thought critical, e.g. issues connected to production costs. In addition, we validated the distinction between domains by gathering specific stories about difficulties and achievements related to the development of new skills at the design stage, e.g. the nylon example reported in section 4. Relying on these stories, we probed our initial expectations about the relevance of cross-domain connections, how they were activated, and by whom, e.g. the role of software engineers analyzed in sections 4 and 5.

The same researcher carried out all interviews. His role in interfacing with Pirelli changed over the course of the study. Initially, he was more like a *student,* recording the tutor's description of the industry, Pirelli, and the new technology. Interviews with the tutor consisted of a few, broad questions, with minimum interruptions. In more problem-oriented interviews with others, the researcher was more like a *curious visitor* (Agar, 1980), i.e., someone who had some knowledge but was still an outsider learning about what had occurred. As the interview focus moved to an analysis of internal documents, the researcher's role became more like that of an *initiate* (Agar, 1980). In the last stage, the researcher was treated as a *peripheral member* of the Pirelli group (Adler and Adler, 1987) who offered his views and exchanged ideas with others concerning the meaning and possible implications of events in the MIRS development process. After each interview, the interviewer wrote a short description of the 'case' he had just heard, identified the interviewee and the interview context, and summarized the main points mentioned (Stake, 1995; Creswell, 2003). The different interviewees often stressed different aspects of the project: e.g., technological aspects such as the

new know-how required to develop the new process; e.g., product issues, such as how concerns surrounding product quality using robots rather than labor-intensive processes were managed; and e.g. organization issues, such as changes in the composition of the project team during the development process.

Using Denzin's (1989) typology of triangulation, we searched for sources of quantitative and qualitative data to enable us to view the same phenomena from different viewpoints. Besides interview data, our data set includes information from other sources including patent, archival, product, and quality assurance databases. We studied archival data and trade literature to understand how Pirelli articulated its strategies in the mid-1990s immediately prior to the launch of the MIRS development project and how its strategies then changed. Internal archival documents told us about the size of the project, the numbers of people involved, the resources required, the internal visibility, and the commitment of top management. We studied industry level patent data to analyze the innovative strategies pursued by other leading industry firms (Acha and Brusoni, 2005) and we relied on European Patent Office data to identify key people at Pirelli. By using publicly available data, we verified that we interviewed all the important players in this project. Analysis of the chronology of patent applications confirmed claims by Pirelli personnel about existing in-house manufacturing process capabilities: this knowledge emerged as a key element in our theoretical interpretation.

The analysis of the Failure Mode and Effect Analysis (FMEA) database, one of the documents necessary to obtain ISO-9000 certification, was fundamental to validate claims about the technological characteristics of the robotized process. The FMEA database lists causes and solutions for all problems identified in the production process, reports the frequency of occurrences, their seriousness, and the difficulties associated with each problem. We accessed these data for two generations of the innovative process and for the most efficient traditional process in order to compare the innovative manufacturing process with the traditional one and assess the relative advantages, changes in conceptual complexity, etc. We used these data to analyze the evolution of critical components (e.g. the vulcanizer). These data helped us identify problems that we initially thought as representing actual engineering and strategic challenges encountered by Pirelli. Some of the aggregate indicators in the FMEA data did not match up with some of the perceptions presented to us

during our first round of interviews. Such discrepancies provoked general interest so that Pirelli management asked us to be available to its employees in the MIRS unit who wanted to discuss what we had found. For nearly ten weeks, one of us spent two and a half days per week at Pirelli's central office dealing with Pirelli's questions concerning how the MIRS development process had actually evolved.

3. Why did Pirelli invest in MIRS?

Although the tire industry has evolved to comprise many distinct market niches, it is characterized by a high degree of concentration across many of these niches. In 2000, trade sources reported that the top ten global tire manufacturers accounted for 83% of global sales. Over the past three decades, the industry has been characterized by shrinking margins due to declining volume of purchases deriving from increased longevity of tires, pressures from buyers to keep prices down, and increasing costs of raw materials. Consequently, leading companies have constantly been engaged in reducing costs through savings in labor costs, increases in throughput, incremental improvements in new process technologies, and rationalization of materials. In addition, the rapid emergence of new niches (e.g. ultra high performance tires for Sport Utility Vehicles, SUVs), and the availability of new materials has led many tire manufacturers to invest in major innovative efforts regarding both products and processes. For example, all major players (Goodyear, Michelin, Pirelli, Bridgestone, and Continental) have been involved in efforts to develop run-flat tires and started developing tires that embody sensors to monitor their performance in real time. Indeed, patent statistics show that microelectronics applied to the tire product exhibits the fastest growth rate compared to other technologies (Acha and Brusoni, 2005). As regards process innovations, Brusoni and Sgalari (2006) illustrated how Pirelli, Michelin, Bridgestone, Continental, and Sumitomo introduced or are about to introduce different types of robotized production processes.

Whereas efforts to introduce a fully robotized process started in the 1990s, the trend towards automation and flexibility in tire manufacturing dates back to the 1980s. As the automobile industry struggled to improve car safety and performance and increase model variety, tire manufacturers strove to reduce average batch size and to increase the range of distinguishing characteristics associated with tires, e.g., different tire widths. For example, Pirelli internal data show that, between 1996 and 2004 the number of relevant market segments

has nearly doubled. Most innovative efforts initially focused on improving tire building, the point in the manufacturing process where all raw materials and components are assembled to form the crude tire. The introduction of more flexible building machines reduced the average batch size and building setup times. Nevertheless, costs rose rapidly, as material inventories serving upstream process steps as intermediate buffers increased to accommodate the smaller batch sizes downstream.

In the early 1990s, Pirelli was in a particularly difficult position for two reasons. First, the company was traditionally specialized in the medium and high end of the market, precisely those segments in which carmakers required more performing and customized tires, and where stronger was the trend toward further segmentation and thus decrease in the average production batch. Second, Pirelli was finding increasingly difficult to defend its reputation as an innovative leader. Such weakness was further amplified by the 1992 failed bid to acquire one of its main competitors, i.e. Continental. A successful acquisition of Continental would have turned Pirelli into a mass producer of commodity tires. When this acquisition did not take place, it led to a loosening of the historical ownership grip of the Pirelli family, changes in top management, and a major strategic refocus.

In the aftermath of the failed bid, Pirelli's new top management sought to solve the firm's serious financial issues inherited from the past. Top management reorganized Pirelli around core areas, exiting, or drastically downsizing unprofitable businesses, and then investing heavily to improve the efficiency and innovativeness of its core businesses. Toward the half of the decade, some of Pirelli's non-tire product divisions, e.g., its fiber optics and real estate, began to acquire prominence and to overshadow the traditional central role played by the tire division. Archival data indicated that Pirelli's market share by tire segment was static or declining. Interviewees mentioned that some of Pirelli's key automobile customers saw Pirelli's reputation for innovation as weakening and they considered a reputation for innovation to be essential if Pirelli was to remain a supplier of top-of-the-range tires. The failed bid for Continental had indeed sent the signal that Pirelli was trying to turn itself into a commodity tires producers. Secondary sources, trade press, and our interviewees also confirmed that Pirelli's key automobile customers thought that Pirelli was too small on its own to be in the commodity tire market and too big to be a niche player. Moreover, in the early 1990s

Michelin began to develop a new robotized production process that would allow it to produce small batches of large tires. Michelin, the market leader, was targeting exactly those segments that were Pirelli's traditional strongholds.

These external and internal developments characterized the context wherein Pirelli's top management decided to invest in order to rebuild Pirelli's capabilities and reputation in innovation in tires. Innovation was to be emphasized in the rhetoric used to discuss strategy. In support of the new strategy, Pirelli built a brand new head quarters and research facilities, launched new marketing campaigns, and searched for new distribution channels. To act as flagship of this renewed emphasis on innovation, in September 1997, the CEO and owner (Marco Tronchetti Provera) gave Renato Caretta the task to develop a radically new production process. Renato Caretta held the largest number of patents in Pirelli and was central to the innovating activities in the firm as shown by its centrality in the Pirelli's inventors patenting network (Brusoni and Sgalari, 2006). The CEO gave him and his design team a very broad mandate. Reportedly, he said 'Do whatever you want, but come back with something!' The investment in what would become the MIRS project was certainly interpreted as a statement of strategic intent from Pirelli's CEO to its competitors, particularly Michelin, and to Pirelli employees. In fact, the CEO presented MIRS as the central part of a strategy intended to revitalize the entire group. MIRS signaled to the tire division and to Pirelli as a whole that the firm had to start thinking and acting innovatively again. Internal documents explicitly emphasize the role MIRS was to play in revitalizing the firm to compete internationally.

The MIRS development project was launched after only a few, very brief internal consultations. We found very few archival documents that mention any discussion. Interview data revealed, however, that some personnel disagreed with investing Pirelli's resources and reputation into what some perceived to be a very risky project. Michelin had already started investing in equipment to robotize manufacturing: Pirelli was late into this race. The strong commitment and direction of the CEO and key corporate leaders, e.g. Renato Caretta, however, minimized aversion. In fact, rather than actively resisting the project, the evidence points to passive resistance reflecting a wait-and-see attitude, possibly influenced also by strategic turmoil engendered by the unsuccessful attempt to take over Continental Tires.

4. How did Pirelli develop MIRS?

The traditional process

The traditional manufacturing process was *non-modular*: plants were characterized by many non-standardized organizational and technological interdependencies. Unlike most processes in the chemical industry, tire manufacturing has traditionally been a discontinuous process where raw materials (e.g. polymers, chemicals and fillers for the rubber compounds, fabrics, and steel reinforcements) are pre-processed, stored in batches, then cut in discrete components and assembled to form the green tire (which then needs to be vulcanized). Extruders semi-continuously produce large bands of rubberized material. Plant operators manually shape these on flat supports that are moved around by operators themselves. Plant interdependencies are managed through buffers of raw material inventories, components, and intermediate products, which coordinate and smooth production flows. Accommodating changes in product characteristics requires extensive human interventions to adapt, stop, or change machinery and to move equipment. Manual changes are a source of tire imperfections.

From an organizational viewpoint, traditional tire design and production were highly *specialized* and *disconnected* activities. Tire designers, process engineers, and plant operators worked independently: design and production processes were sequential operations with production following design. Communications among designers, engineers, and operators to fine-tune production took place through standardized organizational interfaces, e.g. paperwork exchanges and meetings. Tire designers focused on specific tire components, e.g. sidewalls, beads; or activities, e.g. choice of materials, mould design, definition of building process, etc. After completing the conceptual phase that defines the tire's performance targets, designers work in parallel on distinct tire or process components, e.g., beads, treads, and moulds. Computer aided design tools were used to a limited extent. Design data were not stored in a coordinated, centralized manner. Plant operators received tire specifications from specialist designers and adapted plant machinery to tire specifications, as they possessed the skills necessary to set up the manufacturing process to implement the design specifications. Once the tires were produced, they were sent for testing. Feedback from testing was sent back to tire designers who implemented changes and restarted another design cycle. The organization

was therefore designed in a highly decoupled fashion with few, predetermined interfaces between units and functions. *Tacitness* was a relevant feature of the knowledge underlying traditional manufacturing: rule of thumbs dominated the activities of tire design. Little articulated knowledge was available to predict accurately the impact of changes in specific tire characteristics on tires performance. Similarly, process-level expertise was people embodied.

The robotized process

The MIRS process is based on the principle of *modularity*. Plant modularity derives form the technology used. In the MIRS process, the crude tire is built directly on to a rigid drum so that manufacturing is collapsed into three steps: raw materials processing (carried out outside of MIRS), building and curing, finishing. Textile plies are knitted *in situ* around the tire, whereas bead wires, i.e., the string of rubberized metal that holds the tire to the rim, belts, and all reinforcement plies, are deposited onto the drum as pre-extruded tapes of rubber-coated cords. Each plant consists of a self-contained assembling and curing module. Within each module, pieces of equipment perform specific functions, e.g. each extruder deposits a specific component on the tire drum. Robots position the drums before the extruders, transport them between the extruders and, eventually, to the vulcanizer. The process can be scaled up by adding modules consisting of six coordinated robots and one vulcanizer, which process up to six tires at a time. After vulcanization, cured tires are removed from the drums and are ready for test and distribution. There are no material inventories between the building and curing processes. Each module is a closed unit that operates continuously and workers do not access the module unless problems emerge.

Modularity is also a property of the tire itself. Each tire component is decomposed in elementary stripes of rubberized materials each of which could be manipulated and optimized by the designer. Tires are built component by component e.g., sidewalls, belts, and beads. The decomposition of tire components means that the extruders operate discontinuously, because each extrudes a small amount of appropriate material to contribute to the tire forming on the drum. Extruders therefore are critical in the production process as discontinuous extrusion of small quantities of heterogeneous rubberized materials can lead to problems that result in tire imperfections, e.g., materials deteriorate rapidly, mechanical parts are subject to greater stress

than in the traditional process. On the other hand, the decomposition of tire components into layers enables engineers to vary the application parameters to be applied within each layer and therefore more exactly control and affect tire quality. For example, designers can vary the angle of application of certain components or their thickness in different tire areas, e.g., closer to the centre or the sidewall, and so improve tire performance. This makes the MIRS process particularly suitable for producing high performing tires.

MIRS rely on an *integrated* organization of design and production. In MIRS, tire designers gained overall control over the manufacturing process. In fact, the dedicated software that controls the robots allows engineers to simultaneously design the tires and set the process parameters that determine how robotized production will be implemented. MIRS also shifted skills and responsibilities away from the plant operators to tire designers. *Codification* and *integration* characterize MIRS underlying knowledge base. MIRS plant control depends on a sophisticated IT system that relies on a set of articulated and codified knowledge. Whereas in the traditional process plant operators set up the machinery, implement design changes, and control the process, in the MIRS process robots, whose software incorporates both design and manufacturing parameters, carry out these tasks. The development of the IT infrastructure emerged as the major source of problems and opportunities for the MIRS development team, and a key driver in changing the nature of the knowledge bases and the design of the organization. As discussed below, in order to make use and exploit the opportunities offered by the IT system, engineers articulated and codified their rules of thumb, experiential knowledge, and tacit understanding of manufacturing process. In addition, tire designers skill base had broadened to integrate skills in IT and process manufacturing.

Making MIRS: operationalizing the innovation mandate

Renato Caretta received an extremely broad mandate directly and publicly from the group's CEO and owner. How was this mandate operationalized and transformed in specific technical questions? The project started in September of 1997. Renato Caretta handpicked three engineers relying on his knowledge and trust of their technical capabilities and led the design group. These three mechanical engineers had extensive knowledge of manufacturing process and had already worked with Caretta in the past. Caretta encouraged open discussions and disagreements as long as they were supported by intensive testing of the ideas

proposed. Initially, the project objective was extremely broad: the plan was to revolutionize all phases of tire manufacturing, from rubber production to vulcanization and even tire distribution. It became clear to the group, however, that they needed to narrow their focus to draw on the team's core capabilities that centered on their knowledge of manufacturing equipment and machinery.

For example, raw materials preparation in robotized production challenged the traditional way of pre-processing raw materials. The challenge stems from the fact that tire components are decomposed in very thin stripes of materials, as opposed to the wider bands extruded in the traditional process. Raw materials are made up of rubber and a plethora of additives. If additives are unevenly distributed, some rubber layers in the crude tire might not contain them at all. This would create problems during vulcanization and in use. The group debated this problem at length and concluded that it was too complicated to be solved as it required chemical engineering skills that the design team did not master. Therefore, a dedicated R&D unit was set up to continue to work on the pre-processing of raw materials for the MIRS process. By the end of the first year, the MIRS group focused on developing a radical breakthrough in tire building and vulcanization processes. Besides the lack of chemical engineering skills, other factors led to such focus.

First, tire building was the obvious bottleneck in manufacturing. Flexible building machines could accommodate decreasing batch sizes at the price of higher inventory costs. How to solve this problem? One possibility was to develop the idea of building tires on a solid drum, an idea that dates back from the 1920s. The key advantage of a solid drum is that it eliminates several steps otherwise necessary to shape the flat support on to which tire components are extruded. Eliminating these steps is important because they are a major source of product imperfections. Caretta was the holder of patents on rigid drum technology. It seemed therefore natural to focus on this unexploited internal knowledge. The bottlenecks to the development of the solid drum technology were related to how to move the drums and how to extrude composite material of the adequate quality with the necessary uniformity. The latter problem was solved internally. The former problem was solved adopting robotized technologies. Indeed, the second reason to focus on this specific technology was Michelin. The market leader had built its first robotized plant in 1993 and it reported to have started producing commercial tires as early as 1995, even though Michelin delayed

using it for full-scale production till, at least, 1998 (Brusoni and Sgalari, 2006). Pirelli decided to follow Michelin's lead into this area. Michelin provided two things to Pirelli: a prestigious target and background information about the process through the analysis of Michelin's patent portfolio.

Having focused on building, the group started solving the first and most important technical question: 'Can rubber and other rubberized materials be extruded onto a rigid drum that moves from extruder to extruder?' Despite holding patents describing how to do this, nobody in Pirelli had actually implemented the process. Group members' core expertise centered on the manufacturing process and so the group had the knowledge to do this first phase of technological development. Our tutor stressed that although he was the group leader, everyone in the group worked together. Many anecdotes suggest that this group was characterized by tight interaction, strong opinions, rewards for solutions that worked, and direct criticism when claimed solutions turned out not to work as expected. Their task was to prove that a crude tire could be built on a rigid drum: they built crude tires driving extruders by hand and carrying the tires to vulcanizers to see what happened. There was no division of labor within the group: everyone was involved in all testing activities.

The feasibility of the building phase was quickly established. They then focused on the overall logistics of the process, e.g. where to position robots with respect to each other and extruders. Solving this and other related problems led to the first wave of systematic use of computer aided design tools. Two key problems characterized the work of the design team at this stage. First, they had to understand how to decompose the overall process in sub-tasks so that robots could perform them sequentially. Second, they had to decide robots' lay out. The latter was constrained by the available factory floor, e.g. they had to work out a sequence of movements which allowed robots to avoid colliding with a column stuck in the middle of the available floor. From the point of view of machinery, it turned out that by adapting off the shelf equipment and relying on their expertise, they could solve most of the hardware implementation problems. For example, they found that robotized arms to move crude tires could be bought from a specialized supplier and installed with little adaptation.

Making MIRS: developing the organizational and knowledge architectures

Having established the key operating principles of the plant, the group had to make it work. Robotized production requires a sophisticated IT infrastructure to pilot robots and control the process. Because traditional tire manufacturing process did not rely on such skills, Pirelli had limited software engineering capabilities. After attempting to establish a joint venture with a local university, our tutor decided that it would be cheaper and faster to develop software development capabilities in-house, and hired two software engineers. Their involvement was originally intended to solve the problem of developing the software required to pilot the robots. It became a key turning point in the project and the catalyst of major changes in the organization and knowledge domains.

In MIRS, timing of robot activities (e.g. how long robots are positioned in front of which extruder, when they remove the tire) and robot positioning (e.g. how to rotate the drum while the extruder emits the tire component) affect tire performance characteristics. Traditionally, the definition of performance characteristics is responsibility of tire designers, whereas the control of the machinery is delegated to process engineers and plant operators. Now, tire designers' expertise was required to define the operation parameters of robots. However, up to then, MIRS had been a manufacturing-oriented effort with no tire designer involved. Software engineers in charge of writing software for synchronizing robots movements made clear that tire designers had to be involved full time in the development project. Two young tire design engineers were then involved full time, further broadening the team composition.

Once included in the MIRS team, software and tire designers were confronted with a major task. Product design parameters were key inputs to the software programming that piloted robots in charge of tire building. Tire designers relied on tacit rules of thumb to evaluate the relationship between design parameters and tire performance. In addition, several key operations in traditional manufacturing were performed manually by plant operators who were expected to rely on their skills to evaluate whether, for example, materials required to be stretched a bit more or a bit less during the building phase. Such skills were plant-specific and machine-specific. In order to be able to evaluate, robots' operations, tasks, and objectives must be clearly articulated before beginning production. Skills and expertise that in traditional tire making process had been embodied in tacit problem-solving heuristics had to be articulated and codified for the software associated

with each product and process component. Tire designers were therefore required to develop new knowledge in the form of explicit cause-effect relationships between tire design parameters, tire building requirements, and tire performance.

The case of *nylon 0°* illustrates the opportunities the new process made possible and the new knowledge that was developed to exploit them. In a tire, layers of nylon (called nylon 0°) hold together the various layers of rubberized material. The tension and angle with which the nylon layers are applied are important in determining tires' performance. In the traditional manufacturing process, the application parameters of nylon cannot be varied within the same application cycle. Angle and tension are the same throughout the tires. The problem is that tires are essentially asymmetrical: at high speed, and/or with high weight loads, asymmetries create handling problems and reduce tire life. This is essentially a limit sets by the machines available: changing application parameters means stopping the line and manually adjusting the machine. It also means that the knowledge related to the appropriate tension and application angle of 'nylon 0°' in order to obtain a certain tire performance was linked to the rules of thumb and experience of plant operators who knew machines' behavior. In the new robotized process, tire designers can easily vary the angle and the tension of nylon introducing the appropriate parameters in the digital control system. Optimal nylon deposits were designed to differ in different parts of tires in order to, for example, optimize high speed performance. The possibility of systematically varying the application parameters in different parts of the tire, e.g., making the same tire component thicker or thinner according to the position of the specific layer with respect to the rim, for example, could ensure major improvements in tire performance. In order to do so, however, tire designers learned about the effects of such changes on performance and then articulated this understanding so that others could use it. As these changes were not possible using traditional technology, they had no knowledge about the actual impact on tire performance. A machine-set parameter for angle and tension became a product design variable that designers had to understand.

For each type of tire developed on MIRS, engineers tried ranges of product and process parameters, produced the tire, and tested them on cars to evaluate performance. The example given above well capture the characteristics of the expertise that was developed. First, designers developed new skills. As the

traditional process did not allow variations in the application parameters of nylon, nobody really knew how to quantify the impact of such variations on tire performance. Second, they developed a much more integrated understanding of the whole process. For example, they had to learn much more about the process machinery, e.g. extruders' behavior. Variations that could once be implemented by plant operators only, fell under the control of the designers. In addition, they learned much more about the chemical properties of the materials they used. Third, they learned how to articulate such new skills into parameters and cause-effect relationships that could be used to pilot the robotized plant through IT interfaces. Thus, over time and in contrast to the specialized and largely tacit knowledge base on which traditional manufacturing was based, the introduction of MIRS led to the development of an integrated and articulated set of skills. Robotized production required major changes in order to take advantage of the *integrated* (vs. specialized) and *articulated* (vs. tacit) knowledge base underpinning the MIRS process. New explicit knowledge had to be developed to exploit the opportunities of the new production process. The group, including also software engineers and tire designers, focused on accumulating software design parameters from the end of 1999 to 2003 and this process still goes on. This process of learning and articulation was very fruitful, but unanticipated at the beginning of the project. All interviewees confirm that it turned out to be the key bottleneck of the entire endeavor and the most rewarding too.

Making MIRS: learning processes gain strategic focus

Whereas MIRS was rapidly validated from a technological viewpoint, the role MIRS should play within Pirelli's business strategy remained unclear for a longer while. Tire designers were not included as part of the original group and they were involved in it only in late 1999, mainly in response to the need of software engineers to gain information about the kind of data they needed to include in the IT infrastructure they were developing. However, as late as early 2000, the development team did not have in mind a clear set of product segments to serve with their new process. They began to feel pressure from the top management to deliver commercially viable products.

The key problem is that, whereas it is technologically feasible to produce any kind of tire on MIRS technology, the economics of the robotized process makes MIRS tires most viable at the high end of the

market. Although market segments niches to cars made by Lamborghini and Ferrari are highly profitable, they are tiny and were served through traditional production. The fear of cannibalization might have led to serious internal conflicts. Fortunately, two new and highly profitable market niches emerged: run-flat tires (linked with the launch of the new Mini) and ultra-high performance (UHP) tires for Sports Utility Vehicles (SUVs), the fastest growing niche in Europe. The rigid sidewall of the former, and the large section width of the latter, represented major challenges for the traditional tire manufacturing process, but not for the robotized process.

The development team was quick in seizing the opportunity that was offered to them by the top management. By then, they knew very well the technical characteristics of the process and they knew that they could produce tires of the requested characteristics. Until then, MIRS had established Pirelli's role as technological leader within the industry, underscored by a stream of international technical excellence awards granted to the new process. Run flats and UHP were pivotal in proving MIRS an economically viable endeavor as they gave engineers within MIRS a business focus in their efforts to commercialize new products on the basis of the newly developed integrated body of knowledge and design organization. Ever since the development process proceeded very rapidly in terms of delivering tires and of establishing strong and stable connections between product-specific skills that product, process and software engineers co-developed; the IT infrastructure which could be deployed to support engineers' activities; and the network of MIRS plant that was being built in Germany, UK, and USA.

It is worth noting that MIRS has not replaced traditional manufacturing as the two processes coexist specializing in different product niches. New connections have been established between the two processes, however: based on the MIRS, new process innovations (e.g. new ways to fold rubber and tire components in a more uniform and controllable way) have been introduced in Pirelli's traditional manufacturing. For instance, the truck division has recently applied for a series of patents that import in the – overall – traditional process specific technical solutions learnt while developing MIRS.

5. Discussion: modularization, de-modularization and pliotropy

As we discussed the transition process from the traditional to the innovating manufacturing process, we highlighted the role played by knowledge-level developments in explaining the process of organizational evolution. Figures 1 and 2 summarize the key features of the traditional manufacturing and MIRS processes, respectively, in terms of technological, organizational and knowledge domains. The figures capture a key empirical result of the study: the adoption of modular design principles for both tires and plant did not lead to a modular organization of activities. Rather, we have observed how *modularization* at the product and plant level led to a process of *de-modularization* of the organization. Changes in the latter were driven by changes in engineering know-how in turn triggered by the adoption of new core elements, e.g. rigid drum. More specifically, it was de-modularization in the knowledge domain that enabled the effective modularization of the technological domain.

Figures 1 and 2 about here

This study shows that the evolutionary dynamics of the three domains followed complementary directions but reached different end states in their internal topology: a manufacturing process which was not modular became modular, and what was a modular system in the traditional manufacturing process (design knowledge and organization) became highly integrated. Our conceptualization of organizations as multi-domain networks that obey to different design rules is consistent with and extends extant research on the relationship between product and organization design. Drawing on an empirical study on automakers' management of suppliers' involvement in product development in Japan, Takeishi (2002) showed that whereas the actual tasks of design and manufacturing could be outsourced, automakers retain relevant knowledge to obtain better component design quality. His results illustrated that the effective pattern of knowledge partitioning differed from the pattern of task partitioning. The analysis by Chesbrough and Kusunoki (2001) on the introduction of systemic innovation in the hard disk drive industry illustrated different organizing principles for product and knowledge domains.

Our analysis is consistent with recent research on organizational evolution. Using the terminology of Siggelkow (2002), the emergence of the rigid drum element constitutes an example of *patching*, i.e. the

process of creation of a new core element. This element became core when new connections and feedback loops with other elements within the knowledge domain (e.g. asymmetric deposition) and other domains were generated. Siggelkow (2002) labeled this process *thin-to-thick*. In parallel to the *thin-to-thick* process, Pirelli underwent also a *patch-by-patch* process (Siggelkow, 2002), as new core elements were added over time as necessary for the development of MIRS (e.g. digital control of robots actions; integrated database management systems). These two processes led to a complete cross-domain *rewiring* which enabled Pirelli to introduce a radical innovation.

The Pirelli case study also highlights the importance of within and across domain connections for the emergence of new design rules. This is consistent with Padgett and Powell's work (2003) who observed the complexity of cross-domain connections in biotechnology and banking in Renaissance Florence and highlighted the critical role of cross-domain connections during phases of radical change. Padgett (2000) also emphasized that the nature of enabling connections for radical change differs from those that characterize incremental evolution. He labeled *pliotropy* the presence of non-modular connections across domains necessary to generate non-incremental evolution. Our case shows that people set in motion relevant, cross-domain connections: software engineers played a catalytic role in activating a pliotropic process which generated new, strong connections among product and process engineers and across organizational units. They contributed towards the development of new skills and capabilities by combining existing ones, pushing engineers to articulate their tacit heuristics, and creating feedback loops among areas that were previously independent. Pliotropy emerged in response to the initial effort to develop a manufacturing process around the existing core of rigid drum patents. It is worth noting that Pirelli is keenly aware of the importance of connections between process and product know-how. Many interviewees stressed that what allowed Pirelli to overtake Michelin was their clear focus on the very high end of the market, whereas Michelin used robotized process on standard tires and therefore lacked connections between technological achievements and business strategy.

Figure 3 illustrates the transition process from old to new design rules and highlights the richness and variety of connections that were established in order to move from stage one (left, which simplifies Figure 1) to

stage four (right, which simplifies Figure 2). During the 1980s and early 1990s, Pirelli research effort generated patents that remained unexploited. When created, this new element (represented by a circle in Figure 3, top left) was not central to the organization as it was linked only to the assembling phase (the dotted arrow) and had no feed back loops to other elements in other domains. When internal (financial crisis, change in ownership, and appointment of new CEO) and external conditions (new market niches and fierce competition) changed, this element became core to Pirelli's new strategy. It was only after 1997 that the rigid drum element developed with the organizational domain (solid arrow from top to middle domain in stage 2): the MIRS group was constituted through CEO direct intervention. Renato Caretta became then central in all domains: an experience process engineer (bottom domain), the holder of all rigid drum-related patents (top) and now also the leader of the MIRS group (middle). Once the design group validated the technology through prototype building, the design group was enlarged to include new people, namely software engineers and tire designers. These new people were instrumental to developing the new integrated know-how (the dotted circle in the knowledge domain in stage 3), developing new connections within the organizational domain, strengthening new connections in the knowledge domain and establishing missing connections (for example, between plant operation and tire design), and multiplying across domains connections (solid arrows). Specifically, software engineers established connections among specialized tire designers, as well as between tire designers and process engineers. Eventually, a new configuration emerged following new design rules (stage 4). The new engineering know-how became embodied into a new organization that integrated process and tire designers.

[Figure 3 about here]

The analysis of MIRS developmental path in terms of emergence of new core elements and reinforcement of their connections within and across domains constitutes a framework that can be used to provide consistent descriptions of the developmental paths of the dynamics of change of organizations. The framework presented in this paper allows to represent the evolutionary dynamics of firms as characterized by phases of stability built on stable configurations interspersed with prolonged periods of turmoil that usher in new design rules. Within each configuration, linkages and connections among domains are stable and

predictable. Changes of configuration are instead characterized by an explosion of new connections both within and across domains that are subsequently organized to reduce their frequency and unpredictability. The MIRS case provided a vivid example of the non-modular nature of connections that allowed the transition from one configuration to another.

The framework proposed in this paper also emphasizes that there may be no *one best way* to organize for radical change. Several transition paths from one configuration to another are possible, exactly because different domains may be informed by different design rules and yet act as a coordinated system. The MIRS case illustrates that coordination or, in the terminology of this paper, *rewiring* does not necessarily lead to similarity in the organizing principles of different domains. This is consistent with previous research. Focusing on the three leading firms in the aircraft engine industry, Brusoni, Prencipe, and Pavitt (2001) analyzed the dynamics of changes in product, technology, and organization that accompanied the introduction of a radical shift in one component technology. They concluded that all three firms completed the transition, yet they relied on different strategies and ended up relying on different configurations. In the terminology of this paper, the three engine manufacturers followed dissimilar developmental paths, evolving towards configurations of product, organization, and technology domains that obeyed to different design rules.

6. Conclusions

By understanding the emergence of new design rules in terms of a process of emergence of new core elements and the generation of their connections within and across organizational domains, this paper provides a bridge between research on modularity (Sanchez and Mahoney, 1996; Baldwin and Clark, 2000; Schilling, 2001) and work that has conceptualized organizations as networks of interconnected elements (Perrow, 1967; Lawrence and Lorsch, 1967; Miller, 1987; Levinthal, 1997; Rivkin, 2000). This paper has found that the introduction of new design rules require the introduction of coordinated changes across domains that include not only products and organization, but also bodies of knowledge that underlie production. Changes in knowledge, organization, production process and product are linked in a continuous seesaw pattern characterized by both designed and emerging features, ridden with unexpected and

unanticipated events, stop and go, *ad hoc* organizational and technological adjustments. The so far understudied dynamics of knowledge bases played a central role in shaping the new organization design. The new, modular tire was based on a modular production process that built on patented, yet unused, knowledge on a specific process step (i.e. rigid drums). The effort to develop these patents into a full blown production process delivered a thoroughly innovative body of engineering know-how.

The case discussed in the paper also highlights that changes must occur both *within* and *across* domains. The latter represent the most critical part of the story. If changes are not introduced in a coordinated and timely manner among all domains, radical innovations will not occur. Cross-domain connections were enabled by the hiring of holders of specialized skills (i.e. software engineers), which activated links and feed-back loops toward other specialized engineers. Such links generated new knowledge, built stable organizational connections, and finally brought about major, commercially viable changes at the process- and product-level. In addition, we have showed that fit among different domains does not imply similarity. Whereas a domain is organized modularly, others may be not.

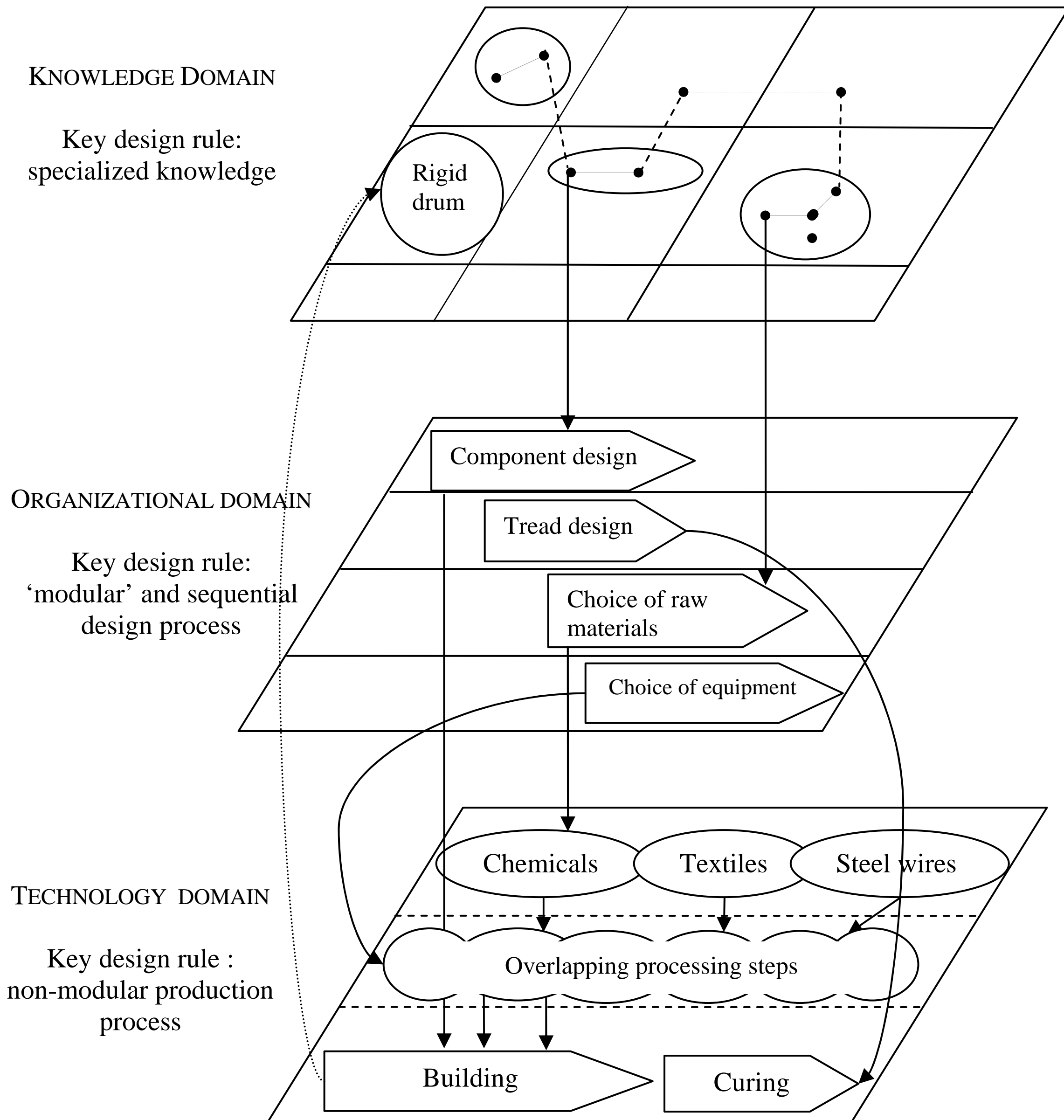
By focusing and analyzing the micro-level process whereby established organizations introduce new core elements, how they do it, and when they do it, this paper proposes provide a perspective within which to extend research on how established organizations adopt technologies or strategies that challenge their traditional ways of doing business. For example, Dunbar, Garud and Rahuram (1996) discussed how organizations change their *frames*, i.e. those values and principles that inform their selection criteria and define their decision-making premises. In terms of the framework proposed in this paper, such issues can be analyzed in terms of the analysis of the missing connections among different domains.

The analysis of multi-domain networks is also linked to research that analyzed brokering and integrating roles played by focal individuals or organizations within networks. The importance of focal individuals is consistent with studies that found successful product and process innovations require *champions* (Allen, 1977; Roberts 1987; Rothwell, 1990). Technology brokers recognize, store, blend, and transform

technologies (Hargadon and Sutton, 1997) and in so doing, they facilitate the enactment of *cross-domain rewirings* (Padgett and Powell, 2003).

In conclusion, this case study has illustrated the unexpected but explainable nature of the development process that leads to new design rules. Elements of design interact continuously and lead to emergent needs and opportunities. The dynamics of a new technology can intersect with existing organization structures at strange angles and require adjustments on all sides. Design rules play a fundamental role in explaining the evolution of products, while the rules of design remain largely people-embodied. The evolution of design rules depends on the skills and capabilities of *designers.*

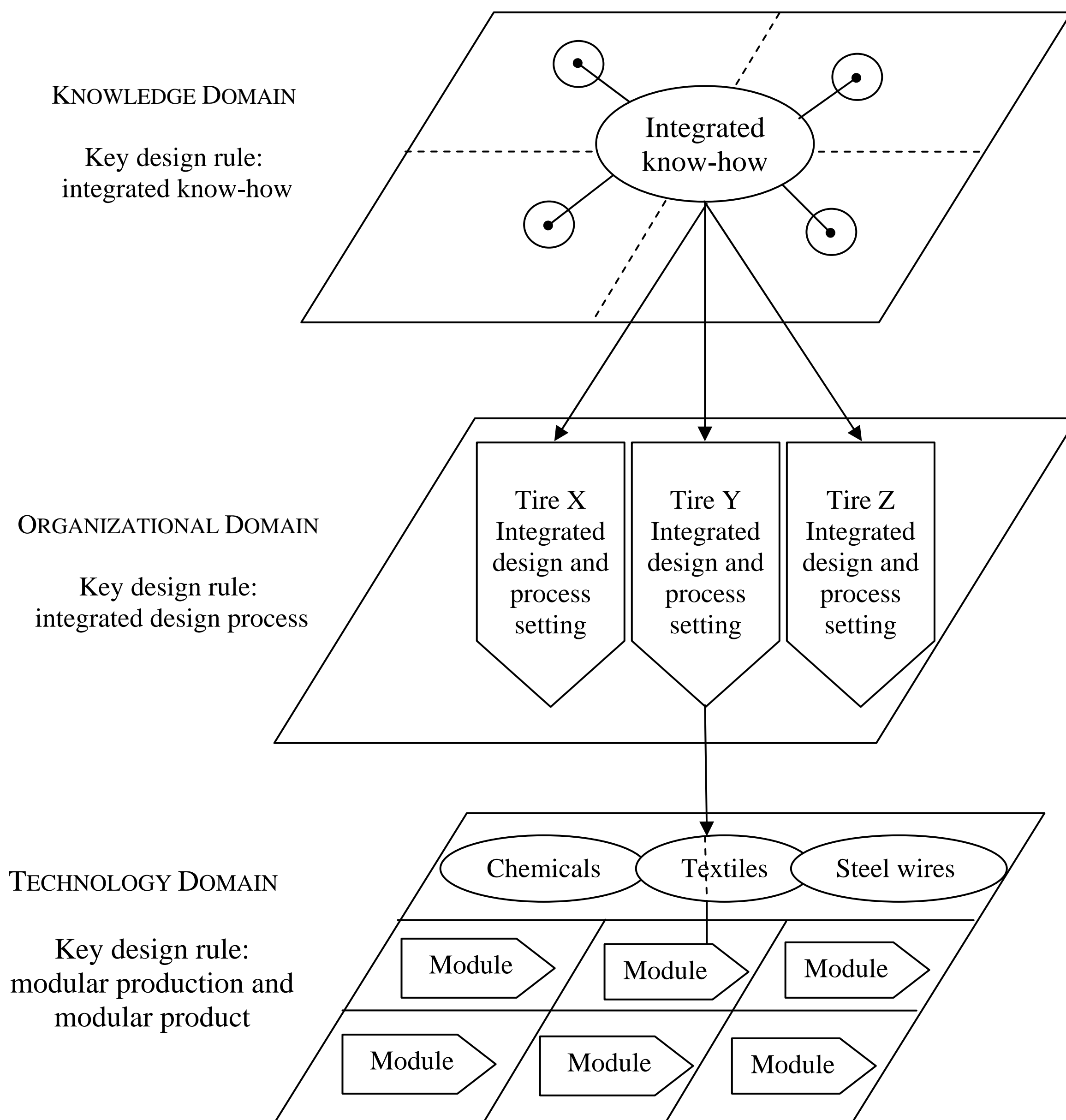
Figure 1. Traditional tires design and manufacturing system.



Note: Continuous arrows lines represent strong connections among levels or phases. Dotted arrows represent weaker connections. Horizontal continuous lines represent evidence of decoupling among phases or activities. Horizontal dotted lines represent evidence of tighter coupling among phases or activities.

Source: adapted from Padgett and Powell (2003) based on authors' interviews.

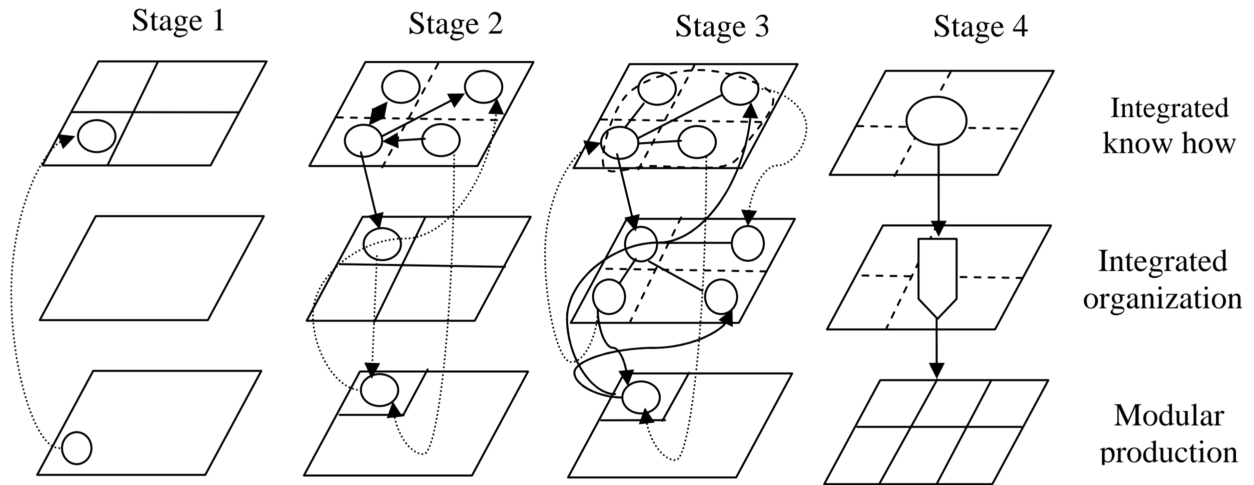
Figure 2. The new tires design and manufacturing system.



Note: Continuous arrows lines represent strong connections among levels or phases. Dotted arrows represent weaker connections. Horizontal continuous lines represent evidence of decoupling among phases or activities. Horizontal dotted lines represent evidence of tighter coupling among phases or activities.

Source: adapted from Padgett and Powell (2003) based on authors' interviews.

Figure 3. Pliotropy in the evolution of tire manufacturing technologies.



Note: Continuous arrows lines represent strong connections among levels or phases. Dotted arrows represent weaker connections. Horizontal continuous lines represent evidence of decoupling among phases or activities. Horizontal dotted lines represent evidence of tighter coupling among phases or activities.

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