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# Innovative design on the shop floor of the Saint-Nazaire Airbus factory

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## Abstract

In this study, we examine innovative design practices on the Saint-Nazaire Airbus factory shop floor. The engineering and manufacturing engineering departments are in charge of the design of products and their industrialization, even though the factory is usually seen as a place for manufacturing, rather than design. However, there is also design activity in a factory that is devoted to the optimization of manufacturing processes. In this study, we highlight an alternative form of design that relies on a collective exploratory approach. A total of 30 projects from the Saint-Nazaire Airbus factory were selected and analyzed. Of these, two were selected as case studies to illustrate the factory's different design methods. Subsequently, quantitative analysis provided evidence of the existence of two design regimes: closed prescription and expandable prescription. The resulting solutions were examined, and it was found that designs under the expandable prescription regime provided more robust long-term solutions. This study offers new perspectives for reexamining innovation in manufacturing and exploring design activity on factory shop floors.

**Keywords** Design theory; Manufacturing; Factory; Industry 4.0; Innovative design

## Compliance with ethical standards

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## 1 Introduction

The factory is generally seen as a place where plans are executed. The plans for products, processes, tools, and more generally, all of the rules (e.g., routines, instructions, gestures, and processes) used on the production line are predefined before production commences. In the Saint-Nazaire Airbus factory, production relies on numerous routines, controls, and standards, which are not designed on the shop floor, but rather are developed earlier in the company's engineering or manufacturing engineering departments (Polacsek et al. 2017a). Traditionally, manufacturing operations are included only during the implementation phase, which is the final step in the design process (Pfeiffer, Lee, and Held 2019). However, generally the engineering department's instructions

are not perfectly aligned with the target or are not fully specified. Moreover, the designs, plans, and tools used in aircraft manufacturing were developed many years ago in accordance with the prevailing practices and production rates. For instance, the A320 was designed in the 1980s. Given subsequent increases in production rates and the removal of various constraints, norms, and standards in the aeronautical field, the challenge has been to improve production processes. In addressing this challenge, two compatible strategies are possible. First, the aircraft and the production process can be designed simultaneously (Polacsek et al. 2017a). There is a higher priority allocated to involving the manufacturing operators earlier in the production design process, for instance through design-oriented thinking (Cross 2011; Johansson-Sköldberg, Woodilla, and Çetinkaya 2013) when they are viewed as users of the processes, and agile project management methods (Campanelli and Parreiras 2015). Second, the existing production line can be improved. The aforementioned design methods can be incorporated into the production line, even though the literature does not offer many examples of this occurring. Other methods can be used to enrich the factory's design and innovation activity through continuous improvement (from the original Japanese term *kaizen*), with the potential for the workers' participation in teams or semi-autonomous groups. In this study, we focus on the latter approach, which relies on the operators of the manufacturing process to detect and overcome any emerging problems. They must modify, eliminate, or improve the proposed methods for manufacturing the products. Thus, a variety of gestures, habits, and techniques are introduced at the operator level to enable the engineering department's plans to be executed in a better way. Design activity is present at the operator level in relation to several manufacturing streams (Iwao 2017). The majority of these design activities rely on decision-making and problem-solving processes (Fujimoto 2012) to detect and overcome problems. The design practices used on the shop floor have a local and controlled impact, and do not require significant resources. The identified solutions can be implemented quickly, thereby optimizing performance.

The Saint-Nazaire Airbus factory has designed and implemented significant changes to its production lines. However, the design approach was not limited to problem solving, but rather incorporated uncommon forms in unusual arrangements. The performance resulting from these experiments differed from that using local solutions generally obtained when adapting the manufacturing process using bricolage or idea collection. The factory has developed the ability to design its own rules, that is, it can create general rules for production using a wide range of applications that are sufficiently robust to accommodate the various conditions and changes in the environment.

In this study, we examined the design practices on the shop floor of the Saint-Nazaire Airbus factory using a sample of 30 innovative projects. We analyzed the types of design observed and the factory's ability to overcome its problem-solving paradigms. How did the factory go beyond mere optimization of its manufacturing rules in relation to designing on the shop floor?

The authors conducted a longitudinal study at the Saint-Nazaire Airbus factory with the aim of investigating innovation and design at the shop-floor level. From this perspective, the Airbus factory can be considered a very relevant research opportunity because innovative practices were observed despite the high level of constraints presented by the aeronautical manufacturing context. Moreover, the coexistence of several projects in the same factory enabled a comparative analysis of design activities.

This study makes several contributions to the literature. First, empirical evidence of a regime of innovative design was observed at the Saint-Nazaire Airbus factory in addition to the usual design regime that occurs during production. Second, positive and innovative effects on performance were observed. Third, the results show how a factory can establish its own rules in response to manufacturing constraints and standards to enable performance to evolve.

The rest of the paper is organized as follows. Section 2 presents a literature review of the common methods used in design processes in factories, and two design regimes are identified. Section 3 presents the research questions. Section 4 presents the methodology used. Section 5 presents the results of a quantitative study examining the relationship between the design regimes and performance. The two case studies presented in Section 6 illustrate the design regimes observed at the factory. The results are discussed in Section 7. Section 8 presents a discussion of our findings and our conclusion, focusing on the main results and implications of this study and presenting suggestions for future research.

## 2 Literature review

This literature review explores the types of design activities that generally occur in a factory setting.

### 2.1. The history of design in the manufacturing process during the 20th century

The Toyota Production System (TPS) of the 1950s was followed by lean manufacturing, both of which developed principles to improve the rules (e.g., processes, organization, gestures) at the shop-floor level. These widely adopted approaches to manufacturing, which have continued to shape factories and their work organization to the

present day, see the factory as responsible for its continuous improvement (i.e., *kaizen*) with the aim of improving productivity and quality, and reducing lead times and costs (Iwao and Marinov 2018; Anand et al. 2009). During daily production, operators are required to detect problems, wastage, and potential savings in an effort to improve manufacturing quality (Knol et al. 2019). To achieve this objective, crucial design activity is performed on the shop floor.

### **2.1.1. Methods and tools used for designing during production**

Many concepts, processes, and tools, often inherited from Toyota manufacturing system or lean management, have been developed to improve manufacturing performance, and numerous examples have been presented in previous studies. Some tools provide means to pass information from the operators to the design department. For instance, QFD tools are used to collect feedback from the shop floor for their re-use in future design projects (Fargnoli et al. 2018). Value stream mapping is the “collection of all actions (value added as well as non-value added) that are required to bring a product (or a group of products that use the same resources) through the main flows, starting with raw material and ending with the customer” (Grewal 2008). Other tools enable more explicitly the operators to design themselves. The principle of total preventive maintenance relies on shop-floor workers performing preventive maintenance and detecting anomalies. Following the 5S principles facilitates the efficiency and standardization of the workplace (Abdulmalek and Rajgopal 2007). Beyond these examples, several other tools (Vijayakumar and Robinson 2016; Shah, Deshpande, and Patil 2015) are available to guide shop-floor workers in improving performance in relation to various criteria.

### **2.1.2. Teamwork for collective design**

In addition to tools, work organization and management were also adapted to meet the objective of improved performance (Duymedjian and Rüling 2010). Collective organizations support the improvement of performance and foster the workers’ involvement and interest. For instance, in the TPS, quality circles were one method used to encourage employee participation. Manufacturing operators met regularly in these quality circles to analyze emerging problems (Rafaeli 1985). In addition to the TPS, the sociotechnical approach insists on teamwork and autonomous groups, which encourages team development (Kuipers, De Witte, and van der Zwaan 2004). The term “teamwork” covers a broad range of processes. Among them, autonomous groups are responsible for the continuous improvement of manufacturing processes and the redesign of the production process (Thompson and Wallace 1996).

### **2.1.2. The collection of individuals’ spontaneous ideas and the innovative behavior on the shop floor**

Design activity includes the collection of ideas from individuals with design skills on the shop floor. Previous studies have described employees’ innovative behavior as the “intentional creation, introduction, and application of new ideas within a work role, group, or organization to benefit the performance of the role, group, or organization” (West and Farr 1989). In this type of design, the production operators acquire a new dimension: they have the potential to exercise creativity that can benefit manufacturing performance. They have various ideas and techniques that can be used to solve the problems that he or she face. In this perspective, the operators do not only provide solutions but also carry innovation in their behavior, which, even in manufacturing, cannot be completely ruled. Employees’ innovative behavior is encouraged under the TPS and lean management through practices such as the recognition of bricolage or improvisation as a way of improving the production line, or suggestion systems that systematically collect employees’ ideas.

Bricolage was used by Lévi-Strauss to explain how the *bricoleur* offers a new solution by rearranging the available resources. Lévi-Strauss classified bricolage as “unselfconscious design” (Lévi-Strauss 1962). The terms “bricolage” and “improvisation” are often used interchangeably. However, both bricolage and improvisation can suffer from a lack of recognition, especially in a normalized sector in which processes are highly standardized (Cunha 2005).

Design activity is also supported by suggestion systems, which can be institutionalized and become routine in the organization (Ikävalko and Lempiälä 2019). Indeed, during the innovation process, the ideation phase is viewed as particularly important, and thus one that justifies the involvement of all employees. Places devoted to the collection of ideas (e.g., boxes or Intranet forms), rewards, and contests (Adamczyk, Bullinger, and Möslin 2012) are some of the elements used to support this phase of design activity. Various types of suggestion systems can be used to gather employees’ ideas (Vanharanta 2018) on ways to solve an identified problem or, more generally, to stimulate innovation (Bullinger et al. 2010).

Interpreted through the lens of design, the plethora of tools, methods, and organizations used to support the manufacturing process constitutes a type of design approach. This approach exhibits several characteristics that make it applicable within the industrial manufacturing context: it requires a scarcity of resources (e.g., time and means), and the effects of the solution are controlled and restricted to local improvements. It is generally based on a problem-solving approach in response to well-defined problems. This identifies a design regime that occurs when the problem has already been identified and the aim is to quickly find a solution while minimizing the resources used (Schön 1990; Dorst 2006). In this study, this regime is called the closed prescription regime. In such a regime, the prescription or rules remain unchanged and the rules are not reviewed. The adjective “closed” stresses the conservative effect of the regime on the system of rules, which is considered as given.

## 2.2 An alternative design regime

Other characteristics can be identified among the various design practices used in manufacturing, and the design theory literature also depicts generative design, which is an iterative process that can be used to expand the rules or create new ones.

### 2.2.1 *From simple problem solving to complex, innovative problem solving*

In addition to simple problem solving, design theory describes a more complex approach to problem solving, that is, a generative approach. Under this approach, the problem-solving process only emerges once the problem has been well-defined and several possible solutions have been proposed (Schön 1987). Hence, design implies that first, the problem must be interpreted, which is a continuous effort. The designer’s perspective leads to a coevolution of the framing of the problem and the design of the solution (Dorst 2006; Maher et al. 1996). Then, the design of solutions is not limited to choices between options based on the available criteria, but rather encompasses the generation of further possible solutions (Lu and Conger 2007). Thus, it is possible to go beyond optimization, and beyond the range of existing solutions (Hatchuel 2001; Hatchuel et al. 2018; 2013).

It can be seen that these two types of problem-solving approaches, simple and complex, or innovative, are complementary, as they address different types of problems and exhibit different degrees of elaboration in the resolution of the problem.

### 2.2.2. *Examples of methods used for complex problem solving*

Various well-known methods can be used to define the problem and generate a range of possible solutions. They are examples of this alternative type of design.

The theory of inventive problem solving (TRIZ) emerged in Russia in the 1940s. This theory suggested that “inventive problems can be codified, classified and solved methodically, just like other engineering problems” (Kaplan 1996). The aim is to arrive at inventive solutions using a structured process (Stratton and Mann 2003). TRIZ is mainly used by engineers, but is also used in manufacturing contexts (Rantanen, Domb, and Simplified 2002).

Other innovative methods consider the end user earlier in the design process, which is one of the pillars of design thinking (Micheli et al. 2019) and enables the design and industrialization of products to occur simultaneously (Polacsek et al. 2017b). The agile method is a project development approach that is used to overcome the difficulty of developing inventive solutions in complex, fixed, or standardized environments. It involves the use of short iterative loops between the designers of the new product and the customer, and relies on principles such as self-organized teams, simplicity, and continuous improvement (Campanelli and Parreiras 2015).

These methods are used in factories. They insist on the generation of innovation alternative solutions, or on the complete user-adapted solutions. However, one of the main characteristics of the manufacturing context is the constraints and complexity of the environment. In addition to being innovative, solutions designed in the factory context must comply with numerous constraints, and retain their validity in a wide variety of contexts, that is, not just for one process, one product, or one operator. Numerous studies have outlined how a robust system should be designed, as this is a crucial feature of an industrial system (e.g., Chen and Chen 1996; Sharda and Banerjee 2013; Realff, Ammons, and Newton 2004), without explaining how such a system can evolve and adapt to new rules.

### 2.2.3. *A second type of design is possible*

These practices are characteristics of another type of design. This second type of problem-solving exhibits several common characteristics in terms of the methods used and the types of results obtained, such as the

definition of the problem, the use of an iterative approach, and the generation of new solutions. Seen through the design lens, this exploratory approach, implying new measures, partial and iterative testing, the use of external resources (e.g., science, technology, and people that are not usually present in a manufacturing environment), and the introduction of new concepts and principles can be interpreted as another general design type that differs from the one presented previously. Generally speaking (i.e., in contexts beyond manufacturing), in contrast to the first paradigm of stable rules, this design approach generates new rules. The rules are modified or enriched, and continue to change during the design process. This design regime is termed an “expandable prescription regime,” which refers to the ability of the regime to expand the prescription (i.e., generate new rules for the system). In other words, this regime concerns the design of new rules despite the fact that the system already exists. Thus, a solution designed in the expandable prescription regime will be a new process, a new internal standard, or a new organization that does not exist elsewhere in the factory or in other factories. The solution is more than an adaptation of a known tool or a known method used in other contexts. It comes from the deep understanding of the problem and emerge from an original design approach.

In relation to manufacturing, it could be considered that this design regime relies on specific conditions. For example, it supposes that the operators are aware of the opportunities available to them and have high-level design skills. Moreover, the range of situations over which the solution is valid could increase. For example, these solutions should consider a maintenance plan, as well as the impact on suppliers, clients, and stocks of various materials. Thus, this regime, which is well-known in relation to new product development, is less prevalent in manufacturing.

### 2.3. Two regimes of design, their observation and their coexistence

In a factory, the first type of design regime (see Sub-section 2.1) has been set up in the factory, and is fully adapted. The second type of design regime (see Sub-section 2.2) is more innovative and can exist in the factory, but has some significant implications. It expands the system of rules by adding new rules to an already stable manufacturing system. In the factory, the second type of design regime can take several forms. It can be combined with the first type of design, it can be used in relation to only a few aspects of a project, or it can be fully deployed.

To observe the prevalence of the two types of design regimes, we needed a set of criteria with which to differentiate them. These criteria were derived from the project management and product development criteria that generally oppose two types of approaches and efficiency of design. There are numerous criteria, and they are not necessarily independent, enabling the properties of an innovative design approach to be captured as fully as possible. The categories (e.g., organization, composition of the team, and testing) are general, and not specific to the design process; they could be used to describe various types of projects.

The criteria were divided into four categories: collective organization, characterization of the problem, problem-solving approach, and characterization of the solution.

- ***Collective organization***

The criteria 1 to 4 are simultaneously derived from the literature on the team organization for project or innovative projects. In the closed-prescription regime, the solution can be chosen among the existing knowledge (Wheelwright and Clark 1992) the team is organized as a classical cross-functional team (Scott-Young and Samson 2008). The team, organized like a commando (or task-force) team gathers experts of the sub-problems and is coherent with the subject and the production organization (Engwall and Svensson 2004) (criteria 1 to 4). In the expandable prescription regime the distance with the known knowledge (Li, Vanhaverbeke, and Schoenmakers 2008) requires a collective approach by a team composed by specialists and non-specialists of the problem (Hatchuel, Le Masson, and Weil 2001) (criteria 1 to 4). The size of the team is not a criterion of the regime: it depends on the size of the project and appear not to be directly determining of the collective organization.

- ***Characterization of the problem***

There are two ways of considering the problem: the problem is not ambiguous, is well-defined and well-known in the sector, and well-measurable, or the problem is poorly understood, has to be investigated, measured, considered under various perspectives, and iteratively re-considered (Dorst 2006; Paton and Dorst 2011) (criteria 5, 6 and 7). The problem should be viewed as a wide question, and can be highlighted by less common sciences in the sector (Hooge, Chen, and Laousse 2018) (criteria 5 and 8).

- ***Problem-solving approach***

Under the first design regime, the problem is covered and can be solved by usual disciplines (Li, Vanhaverbeke, and Schoenmakers 2008) (criterion 9). The project was driven without any iterations or tests during the process, which was linear with a succession of phases and decisions. The test concerns the final solution in a validation logic, without considering the potential side results and new phenomena (Schmidt, Sarangee, and Montoya 2009) (criteria 10, 11, 12). The approach uses only internal knowledge (Caloghirou, Kastelli, and Tsakanikas 2004) (criterion 9).

Under the second design regime, the approach is exploratory; tests (partial or total) were performed to discover new potential action parameters and to improve on the solution (Simonsen and Hertzum 2012; Charue-Duboc et al. 2010). External knowledge and science can be used into the exploration (Caloghirou, Kastelli, and Tsakanikas 2004) (criteria 9, 10, 11, 12).

- ***Characterization of the solution***

In the closed prescription regime, the final step of the project is its ramp-up. The design stops at the launch of the solution (Krishnan and Ulrich 2001). In the expandable prescription regime, the launch and the exploitation are occasions to learn and to design improvements on or around the solution (Lenfle and Midler 2009) (criterion 13). The solution is rule-based, and does not change the rules in the first regime, whereas it breaks and generates new rules in the second one (Hatchuel and Chen 2017) (criterion 14).

In the first regime, the solution is adopted, the project ends, but there is no tracks or memory of the design process after its life (Rhodes and Dawson 2013; Kidder 2011). In the second regime, the design process, the solution, and the knowledge created are memorized and could be re-used in future projects (Roucoules et al. 2016; Barker and Neailey 1999) (criterion 15).

In the closed prescription regime, the resources to solve the problem are available, and can be combined to obtain the solution (“pizza bins of proven technologies” (Wheelwright and Clark 1992)). Like in bricolage, the solution is built of existing technologies and know-hows (Lévi-Strauss 1962). In the second regime, some knowledge is created to design the new solution. (Lenfle and Midler 2003; Li, Vanhaverbeke, and Schoenmakers 2008). (criterion 16).

Some of the 16 criteria used (see Table 1) might appear similar. However, they all bring subtle differences to the observed design process. We wanted to capture the various aspects and complementarity of each category of criteria.

**Table 1** Criteria for the two design regimes

	n.	Closed prescription	Expandable prescription
Collective organization	1	The team is coherent within the production organization (i.e., all involved people belong to the environment of the problem and have a manufacturing specialty corresponding to a part of the problem: e.g., quality, planning, logistics).	The team follows another organization (i.e., people who are not directly involved in the production problem).
	2	The team members want to become experts in the problem (i.e., the team is like a “commando team” where experts are tightly linked and all act with a high degree of implication).	Some people do not become experts in the problem (i.e., a core team is involved with a network of experts who gravitate around with various levels of implication. Some people will follow the whole process, while others will be called on to give a piece of knowledge).
	3	The problem is divided between fields of expertise. There is one expert for every part of the problem (i.e., each practitioner is in charge of part of the problem, according to the division of labor).	The problem is not entirely covered by expertise. There are unknown fields to investigate (e.g., the team’s experts will learn about new phenomena in their expertise that they did not previously know, or new expertise appears. The division of labor is not enough to understand the phenomenon).
	4	The solution is legitimized by expertise and approved by the nonexperts (i.e., each expert knows their part of the problem and offers an adequate solution. The solution is	The solution is collectively designed (i.e., the solution is not a combination of existing experts’ solutions. New results are designed collectively).

		a combination of the experts' solutions for each field of expertise).	
Characterization of the problem	5	The problem is local (i.e., the problem has a known and limited impact).	The question is a field for investigation (i.e., the problem is a wide question or concept, e.g., "a safe factory").
	6	The problem is considered as known and understood (i.e., the problem is about well-known manufacturing criteria of success and is not new in manufacturing).	The problem must be clarified and measured (i.e., the problem is badly understood and an investigation is required).
	7	The parameters of the problem can be measured easily.	There are new parameters to measure and new measures to implement to understand the problem (i.e., the method for investigating the problem is new and relies on data not considered previously).
	8	The problem is common in manufacturing (e.g., tools are available to tackle it).	The problem is revealed by unusual manufacturing science (e.g., the problem appears because an "external" science not directly linked to manufacturing is considered in the factory, such as human factors, psychology, safety).
Problem-solving approach: tests and experiments	9	The problem is solved using sciences commonly used in manufacturing (e.g., quality control, logistics, data analysis).	External sciences are needed to address the question (i.e., new knowledge in external sciences brings a new concept for the solution).
	10	The solution is tested according to a validation of hypotheses (i.e., there is a "yes" or "no" conclusion).	The validation of initial hypotheses is insufficient and the approach is exploratory. All the results of the tests are considered (i.e., the solution is tested, but also its impact, its behavior in the long term, its potential drawbacks, etc.).
	11	Only the final solution is tested (i.e., the team concludes on a solution and tests it).	Partial solutions are tested (i.e., some "pieces" of solutions are tested and the solution is not tested only at the end, but throughout its design).
	12	A surprising result is not considered in the final solution (i.e., only the final result is important for the design).	The surprising results are integrated to the design of the solution (e.g., if interesting phenomena are observed during the exploration and the tests, the solution will be changed).
Characterization of the solution	13	The solution is approved when it is considered satisfying (e.g., if the work is considered as done, the solution has been implemented, then the problem is considered as closed).	There is a continuous process of improvement for the solution, which can open new concepts to be explored (i.e., once a solution is found, the team follows the results and tries to improve them. The design activity does not stop).
	14	The solution keeps the rules unchanged. The prescription is not challenged.	The rules are continually modified in response to the experimental results (i.e., the norms, processes, gestures evolve in relation to the findings).
	15	The history of the design process (i.e. the steps that drove to the solution) is not kept (i.e., the case is closed and the work of the team is closed without leaving any record).	The design process (i.e. the steps that drove to the solution) is tracked (i.e., the work of the team during the design of the solution is kept for future presentations).
	16	The solution is an existing method or tool in production or a combination of them (i.e., a tool frequently used in manufacturing is chosen and implemented).	The solution must be designed from scratch, knowledge has to be developed for the design process (i.e., a ready-to-use tool is not adapted for the problem and the solution is new).



### 3 Research questions

The authors conducted a deductive research to answer to the following research questions:

**Research question 1: *What is the performance level of the two design regimes and what is the form of their coexistence in the factory?***

The literature suggests that there are two design regimes in the factory. However, the second regime, and its performance level, is less common in the manufacturing context. The ways in which the two regimes coexist is unclear, both in terms of conditions and of performance. What is the effect of the second design regime, or the combination of design regimes, on the shop floor and on the manufacturing process?

**Research question 2: *What are the necessary conditions for the existence of the second design regime?***

The second design regime depicted in the literature review seems to be less common in the manufacturing context. Thus, we explored the conditions necessary for its existence, or its coexistence with the first design regime, that is, the resources, organization, and methods that can be used in the design process.

### 4 Methodology

#### 4.1 Research settings

##### 4.1.1. *The Saint-Nazaire Airbus factory*

We conducted a longitudinal study at the Saint-Nazaire Airbus factory between 2013 and 2018 during a collaborative research project with Mines ParisTech's Center for Management Studies.

The Airbus factory is located in Saint-Nazaire, Brittany, France, and at the time of the study, it employed about 3000 people. The factory was responsible for assembling, equipping, and testing the forward and central fuselages of Airbus aircraft (especially the A320, A330, A350, and at the time of the study, A380).

The Saint-Nazaire Airbus factory is characterized by its high degree of prescription and a rigid framework of standards and norms specific to the aeronautical manufacturing sector. Lean manufacturing is deployed throughout the factory, and some programs operated in the manner of a "liberated firm" (Gilbert, Teglberg, and Raulet-Croset 2018). This implies a high level of employee responsibility, strong relationships among employees, and a less control-oriented management environment.

The issue of innovation in this type of manufacturing environment is highly relevant because innovation seems to contradict the accumulation of historical manufacturing skills, know-how, and constraints that exist in this sector. The aeronautical industry deals with numerous standards and norms, and new manufacturing solutions need to comply with these standards. Thus, organization and control are oriented toward the compliance with the rules, the preservation of the routines, and are not *a priori* in favor of innovation. At the same time, the factory needs innovation and changes to evolve and to tackle the various challenges of the aeronautical production. Hence there is an apparent contradiction between these two objectives.

##### 4.1.2. *The principle of the method*

The study took place in one factory over a period of five years. During this period, manufacturing conditions remained more or less unchanged, with a slight increase in the production rate over the period. To observe design practices, we analyzed 30 improvement projects of various sizes (from 4 to 300 people) and for various subjects (quality, delay, safety, organization, ...). These heterogeneous contexts are not necessary determining for the design approach chosen. Capturing the design in various situations, the findings reach a higher degree of generalization. The table 1 in the annex adds descriptive details about the cases.

These projects involving improvement to or innovations in the production line or the factory were undertaken in an attempt to solve an identified problem or respond to a request (e.g., to have a better understanding of the results on a specific production line, to avoid the loss of tools in the aircraft, to avoid bottlenecks in the quality control processes, and to improve the quality of aircraft leaving the factory). These projects lasted for between one month and 24 months, and involved various people, such as shop-floor operators, manufacturing experts (e.g., quality, safety, ergonomics, planning, and logistics experts), and people from outside the factory (external experts). The 30 projects were comparable because they all belonged to the same broad program for

improvement and innovation in the Airbus factory. They were implemented during the same period, concerned the same object (manufacturing performance). Thus, because the environment was the same for all projects, comparisons were possible.

Variables that are generally unable to be controlled for when projects are undertaken across various industrial fields were able to be controlled for here, including the type of manufacturing field, the worker's level of training, the economic context, and the type of management. Hence the comparison between the cases was possible. Meanwhile, the number of projects provided a broad and rich base that enabled us to observe and compare design practices using a quantitative approach based on criteria. Therefore, the paper builds an analytical framework of 30 comparable improvement projects.

## 4.2 Data sources and coding issues

### 4.2.1 Collection and coding steps

We worked with the Saint-Nazaire Airbus factory over a period of five years. In the first step, one of the authors participated in the projects as a practitioner of and researcher into design theory. As an operations manager, he worked and interacted with the teams while carrying out qualitative research, collecting both informal data (through discussions, personal notes, and informal interviews) and raw data (from presentations for the teams and for management). He reviewed the 30 projects in which he was involved and then coded them based on the list of criteria.

In the second step, a second researcher conducted six two-hour interviews with the abovementioned author to clarify his reviews of the projects, and then coded the projects independently. Emails and telephone calls were sometimes required to elicit additional information. Then, a meeting was held wherein they resolved any disagreements or doubts in relation to the coding. Very few projects required negotiation to decide on a final value for each of the criteria used. After this step, the two authors in charge of the coding estimated that they agreed on the criteria around 90% of the time. For the 10% leaving, they accessed to additional information to find a consensus on the value of the criteria.

### 4.2.2 Coding of cases

The researchers applied the criteria presented in Table 1 to each project. The criteria were allocated a value of 1 if they characterized innovative design (expandable prescription) and 0 otherwise (closed prescription). The weight was the same for each criterion. Indeed, the authors considered that there was *a priori* no reason to think that some criteria were more decisive than others. The equal weighting was also chosen for simplicity because a regression of 16 variables over 30 projects would have been unreliable. Hence, the model was simple, but sufficient for our purposes.

### 4.2.3 Design regime coding of the projects

For each of the projects, the design regime used for the strict majority of the criteria was designated as the regime used for the project. Hence, if a project had strictly more than eight – or at least 9 - design criteria with a value of 1 (expandable prescription), the project was coded 1 and treated as an expandable prescription project, and if the majority of the criteria were allocated a value of 0, the project was coded 0 (closed prescription).

### 4.2.4 Coding of project performance

A performance index was used whereby if the solution for the project was used over the long term (i.e. for more than one year) and not discarded by the managers or operators, it was coded as 1, whereas if the solution was soon discarded, it was coded as 0. Thus, this performance index indicated whether the solution was robust to the various shocks or constraints resulting from manufacturing activity.

### 4.3 Analysis of the design practices

#### 4.3.1 Examples of design regimes

Two projects were chosen as case studies to illustrate the data collection techniques and provide examples of the two design regimes. Moreover, they were selected to illustrate the diversity of the fields to which design was applied in the factory. The examples were both quite extreme in terms of the manner used to drive the design process. One was highly characteristic of the closed prescription regime, whereas the other was deeply rooted in the expandable prescription regime. This difference made it easy to distinguish between the two design regimes.

#### 4.3.2. Quantitative analysis

Quantitative analysis was undertaken in an effort to identify the nature of the design process and the relationship between the design regimes and their respective performance. After having coded the cases, two tests were performed (in the annex) to assess the homogeneity between the cases and the relation between the regime and the type of success.

## 5 Quantitative analysis

The results of the coding are presented in Table 2. The type of design is roughly homogenous, since the cases adopt massively the criteria of their regime. Indeed, the columns contain most of their criteria in the same design regime: for each case, between 11 and 16 criteria (excepted for the case 9) belong to the same design regime, and 8 cases over 30 have all their criteria of the same regime. The case 18 is an exception: with 9 criteria of its design regime, and 7 criteria of the other regime, this case is the more mixed. This indicates the potential existence of more hybrid practices. More generally, the 24 cases that have at least 1 criterion that is not coherent with their regime show that some methods and forms of organization could be used in both design regimes.

Moreover in this table, the type of design seems to be correlated with the type of success. Only 1 case (over 18) of expandable prescription regime is a short term solution, and 1 case of closed prescription regime (over 12) is a long-term solution. Hence the expandable design regime (denoted “type 1” in yellow in the table) seems to be associated with a longer term and a more robust solution than the closed design regime (denoted “type 0” in blue).

**Table 2 The 30 projects and their design characteristics and performance**

crit.	3	5	7	10	12	14	17	22	23	28	29	30	1	2	4	6	8	9	11	13	15	16	18	19	20	21	24	25	26	27	
1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	0	0	
2	0	0	1	0	0	0	0	1	0	0	0	0	1	1	1	1	0	1	1	1	0	0	1	1	1	0	0	0	0	0	
3	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	1	1	1	0	1	1	1	0	1	1	1	1	
4	1	0	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
5	0	1	0	1	0	0	0	1	0	0	0	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	
6	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	
7	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	1	0	1	1	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	1	1	1	0	1	1	1	1
10	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
11	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
12	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
13	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
14	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
15	1	1	1	0	0	0	0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
16	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
type	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
succ	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1

**Notes:** The columns represent the 30 projects, and the rows represent the 16 criteria. The final row shows the performance outcome, that is, 1 on a yellow background represents success and 0 on a blue background represents failure. The preceding row shows the type of design regime, that is, 0 on a blue background represents a closed prescription regime and 1 on a yellow background represents an expandable prescription regime.

Two further tests were performed to confirm our previous analysis. The first test checked the homogeneity of the samples, which indicated a high level of difference between the two types of design regimes in terms of the criteria. The second test assessed the link between the design type and the level of success. The details of these tests are presented in the Appendix.

This table also questions the relevance of the criteria table: which criteria inform about the design regime or about the success? Which criteria add noise and could be eliminated? Criteria 11 (the partial tests or not) and 12 (the surprising result integrated or not) are perfectly correlated in our sample. This is not surprising because of the proximity of the two criteria. One could consider them together, in one criterion. Because they show a slightly different faces of a phenomenon, the authors wanted to keep both of them. Criteria 7 (new measures to understand the problem or not) and 16 (knowledge and solutions have to be developed or not) are also perfectly correlated in our sample. One could consider that the criterion 16 “includes” the criterion 7. The authors consider that this is not a general rule and that both of the two criteria should be kept. More generally, one could have used this table to reduce the model, deleting variables or finding latent ones, and to finally find causal links between the criteria and the success. On the contrary, the aim of this article was assess the existence of two regimes of design, hence to capture the small signals of a phenomenon, in its various facets. A certain correlation was expected between them. The choice to keep all the criteria -in their complementarity and/or their similarity - for the analysis was made. Indeed, the list of the criteria is considered as a tool to separate the cases with classical criteria known in project management and new product development, but is not a result of this research.

## 6 Two illustrative case studies

Two projects were selected as case studies to illustrate the type of approach used in searching for a solution.

### 6.1 Case study 1: closed prescription – avoiding tool losses

#### 6.1.1 *The project*

This project was aimed at improving the management of tools used in the Airbus factory. Two problems were identified. First, some tools were being lost in the aircraft during manufacturing, leading to the possibility of serious accidents. Second, the morning and afternoon teams shared the shop floor but used their own tools, and thus at all times, half of the tools were not in use.

A team composed of eight production-line operators and one manager decided to address these problems. They held a meeting and decided to set up a new way of organizing the tools whereby one tool box would be shared by the two teams. Moreover, the tools would be engraved with an identifying number. If a tool was found to be missing from the box, the entire team was required to stop work and look for the lost tool. This new approach was implemented, but drawbacks soon emerged. When a tool disappeared, the morning team accused the afternoon team of having lost it, and vice versa. Moreover, the loss of tools led to considerable delays because the entire team stopped working. Consequently, this new approach led to frustration and disharmony between the morning and afternoon teams.

During the following weeks, no further meeting was organized to consider these negative and unexpected effects, and the new approach was discontinued a few weeks later.

#### 6.1.2 *The design regime*

This case study corresponds to project 23 listed in Table 2, with all criteria coded as 0, which is typical of the closed prescription regime, reflecting a problem-solving approach commonly used in manufacturing.

The problem seemed to be clearly identified and was not examined beyond a casual observation. The solution seemed to be simple, looked like a recipe to follow, and at first glance did not require investigation. However, other solutions could have been chosen, but were not examined. For example, the tools could have been designed not to fall from the operator’s grasp (e.g., they could have been attached to the operator), protective mechanisms could have been set up, or tools could have been personally assigned to operators, who were deemed responsible for them. The composition of the team was coherent with the productive organization and the concerned people were called to find a solution collectively. Other people could have been interviewed to obtain more knowledge about the phenomenon, such as the designers or suppliers of the tools, the responsible of the tools for the factory, a metrology expert, an ergonomics expert, or workers used to working at height, such as tree trimmers and

mountain climbers. The problem-solvers forgot to consider the human factor, and the solution was arrived at immediately without any testing or iterations. The drawbacks were ignored because the solution was considered sufficient to solve the problem, and thus the project was closed.

## 6.2 Case study 2: expandable prescription – safety mattresses

### 6.2.1 *The project*

A team was created to deal with safety in the factory, knowing that the primary cause of serious injuries was falls from a height. When the project started, the main means of preventing falls were safety guards and harnesses.

First, the project team had the idea of adding safety mattresses to the existing safety equipment. They obtained statistics showing that safety mattresses reduced the risk of death or serious injury from falls by a factor of 100. However, the safety experts of the factory who advised the team argued that the particular solution of the safety mattresses to prevent heavy injuries was forbidden under the factory norms. There is a principle underlying the safety rules stating that if you have two forms of defense, it means that you have acknowledged that individually, they are ineffective. The aim is to have a single efficient form of defense. The management means (training, panels etc.) will avoid this barrier of defense from being breached. The legal norms consider that the work conditions are safer without redundancy, but with a robust first line. The reader accustomed to industrial environments could be astonished of this rule, which is though in force in construction sector and for industrial environment of work at height.

The team decided to design a new solution and sought additional knowledge that could introduce new concepts that might solve the problem. They investigated the problem not only from an industrial perspective, but also from other perspectives, such as those pertaining to security and safety in nuclear plants and aerospace manufacturing. Two main concepts were identified.

The first was the two independent lines of defense principle. This was discovered in its application in particular contexts related to the system safety: in nuclear plants, as well as in aircraft manufacturing, there are two (or sometimes three) lines of defense. The probability of accidents is lower when there are two independent safety lines rather than only one that is considered unbreachable (in the case of the safety guards, simple human error can render the safety system inefficient). In an aircraft, all of the systems that enable the aircraft to fly safely are redundant. If the main system is lost, the second system replaces it.

The second was the difference between safety and conformity to the norms and standards. In the engineering department, two independent teams are responsible for ensuring the factory's conformity to the international norms and standards and for improving safety. Conformity to the standards and norms alone does not guarantee the safety of the aircraft manufacturing process.

These two concepts were combined to support the use of safety mattresses in the Saint-Nazaire Airbus factory. The mattresses were considered to provide a level of safety that was much higher than that prescribed by the industrial standards. Thus, a new prescription was issued to ensure that safety mattresses were added wherever there was a risk of falling to provide a second line of defense in addition to the safety guards and harnesses.

The team went to work on safety in the factory and applied these two concepts to other equipment and processes. All of the proposed solutions for improving safety were considered and a solution was eventually selected on the basis of the estimated probability of an accident causing death or serious injury.

In this case, the reader could find the redundancy not innovative, since it has been used for a long time in other sectors, in particular those where the security and the safety are highly critical. However, in our case, the factory could have explored this apparently forbidden principle, and could have proved that, applied to the falls, it decreased significantly the risk of high injuries. Hence, the innovativeness of this case comes from the ability the team to expand the system of rules even it is in apparent contradiction with the first safety standards.

### 6.2.2 *The design regime*

This case study corresponded to project 11 listed in Table 2, with all criteria coded as 1, which is typical of the expandable prescription regime. The team fluctuated in size between five and 10 people, but they met with a lot of other people (e.g., experts in various fields, people responsible for security, and managers). The process consisted of regular meetings with shop-floor operators, employees from the manufacturing engineering department, and industrial safety experts, among others.

Some of the criteria were more important in relation to this design regime. For example, criterion 2 (“some people do not become experts”) was coded as 1 because some people in the team were not security experts. The team included pilots, aeronautics engineers, and safety experts, and they were not integrated into the team to the same degree. They visited a nuclear plant and an airport control tower to obtain a wider perception of security

beyond the scope of the Airbus factory. These excursions introduced the principle of the second line of defense to the participants.

Criterion 6 (i.e., the problem must be clarified and measured) is also typical of an innovative design approach. Indeed, the project was an opportunity to develop a deeper understanding of the risks to the operators and to develop statistical measures of these risks. These measures were systematic, and did not previously exist. Several potential solutions were prototyped and tested, with quantitative results being obtained to enable a comparison of the efficiency of the various proposed measures before arriving at the safety mattress solution. An exploration was launched to find respectively the concept 1 and the concept 2. Finally, the mattresses have been applied as a safety solution. The team in charge of improving safety was always responsible for the improvement of the solution or the implementation of a new solution. This team examined other safety contexts and considered the concepts of two independent lines of defense and safety versus conformity in arriving at their preferred solution.

## 7 Results

### 7.1 The two design regimes coexist in the factory for two classes of problem and two classes of performance

#### 7.1.1 *The coexistence of the two design regimes*

The quantitative analysis and the case studies show that the two design regimes coexist. The reader could not be surprised by this result. Nevertheless, this reminds that in the same conditions and environment, two different regimes can occur depending on the problem and the way of designing the solution. One could have expected an alignment between the state and the regime, and that for one environment, only one regime would be more adapted and would finally “survive”. This result tells the contrary. Then, what could be said about these regimes and their relations?

The first regime combines the factory’s internal resources to optimize processes and the application of the engineering department’s prescriptions. The second regime expands the prescriptions and enables the rules to evolve. The methods used in one design regime are generally not mixed with those used in the other design regime, and thus the two regimes appear to be separate. In the factory, the two design regimes do not compete. The fact that some cases are solved in the expandable prescription regime does not prevent other cases to be solved in the closed prescription regime at the same time, and vice versa. It highlights the role played by the design management in the factory to create new rules when it is necessary.

#### 7.1.2 *Two regimes for two types of problems*

The first regime is applied when the performance is already known. In this case, the solving remains very local and there is no need to create new rules. Thus, design using a closed prescription regime seems to be a good approach. This regime remains essential for production, is easily implementable, and is adapted to the factory’s problems. Problem-solving approaches are extremely useful in relation to a specific category of problems, that is, local, immediate problems, or problems to which there are immediate, practical solutions.

The second regime is applicable to another category of problems, that is, involving situations where performance needs to evolve or where the problem is poorly defined or understood, such as:

1. Broad questions or wide performance axis, for example, providing safe working conditions. Safety must be more precisely defined in the exploration phase.
2. Difficult problems to which several possible solutions are available but no one knows *a priori* which one should be chosen, for example, installing a robot to improve the rate of production. Which robot, applied to which operation, and for which level of performance?
3. Problems that appear to lack any possible solution, and thus require a redefinition of performance to be overcome. For example, to reduce the backlog of projects requiring the resolution of quality problems, adding people to accelerate the process did not decrease the backlog. A redefinition of what it is called a “quality problem”, and a re-discussion of the process and the skills to treat them was necessary.

The capacity to answer to a new performance axis is also crucial for the factory. The innovative design literature describes innovative methods as “generative”, that is, they have “the capacity to generate new

propositions that are made of known building blocks but are still different from all previously known combinations of these building blocks” (Fantini, Pinzone, and Taisch 2018, (Hatchuel et al. 2018)). In the context of manufacturing, this involves the ability to create a new rule. In the present study, considering the initial problem as poorly known and poorly defined, new measures emerge and new performance variables appear when the solution is designed. This could be interpreted as generativity.

### **7.1.3 Two types of results**

The results showed that the performances of the two regimes differed in terms of their robustness. This is evidenced by the fact that some solutions proved to be viable in the long term, and were extended to other programs. We found that projects using the expandable prescription regime generated longer-term solutions than those using the closed prescription regime.

Robustness reflects the persistence of a solution over a wide range of conditions and shocks, and increases the possibility that the solution will not be restricted to a local field. In the majority of the projects using the second design regime, that is, an innovative design approach, the solution (or new rule) was adopted and used in other factory programs. These solutions proved robust in response to random events affecting the production line, for example, changes in employees or managers, supplier delays, new standards, new clients, a change in the production rate...

Nevertheless, this remark does not invalidate the accuracy of the closed-prescription regime. Indeed, there is a class of problems that can be treated with a scarcity of resources, in an economical way, taking advantage of the available means. They are solved in a short-term view. The expandable prescription regime seems to be favored for recurrent subjects for which none of the existing solutions hold in the long term, and which require time, financial resources, skills, and a strong design approach to be tackled. Consequently, the item “success” for each case should not be considered as a pass or fail criterion, but as a question of priority in the means allocated. This suggests two strategies of fitness that can be concomitant and complementary in the factory for the problems occurring.

## **7.2 Conditions necessary for the expandable prescription regime**

### **7.2.1 The transition to an expandable prescription regime**

The results invite us to look at the transition toward an expandable prescription regime when it is required. The 16 criteria that were identified appear to provide an insight into the factory’s requirements in terms of teams, skill sets, numbers of meetings, and experimental approaches. Nevertheless, the conditions necessary for the implementation of the expandable prescription regime are not easy to attain in a manufacturing environment already fully prescribed. In the Saint-Nazaire Airbus factory, the transition to a state where an expandable design approach could coexist with the expected closed prescription design approach took five years. It continues to evolve because it relies on specific skills in relation to the creation and training of the teams. The process also required strong support from the managers, the necessary attention and time to develop this new method, and embodiment into the future strategy of the factory. Finally, it could be said that the efforts to develop, test, and implement the expandable prescription regime were intense. This result is coherent with the PSI theory (Reich and Subrahmanian 2020), which explains that in order to address all the challenges, the organization must align the PSI (Problem, Social, Institutionnal) spaces. The support from the management to foster the design activity in the factory for some of the problems can be interpreted as the support for the necessary alignment of the skills at the operation layer.

This study follows previous studies on change management in the field of manufacturing. As Koch et al. (2016) explained, change management in a factory is very specific regarding the engineering change management. Indeed the change management in manufacturing needs a specific organization, planning, and methodology group to adapt to the factory’s needs. Thus, further research is necessary to understand what form of change management is needed to introduce innovative methods into the manufacturing process.

### **7.2.2. Means**

Some specific conditions were observed in the Airbus factory that seemed essential for the existence of the expandable prescription design regime:

- Time: The exploration could spend from few half-day meetings to a six-month intensive exploration. The meetings were generally held weekly. The time and number of the meetings required were unknown at the beginning of the project.
- People: The composition of the team was crucial. Differing from a classical multifunctional team, the expandable design regime did not necessarily correspond to the division of labor included in the composition of the team. It included external people from other sectors (e.g., nuclear energy) and other specialties (e.g., psychologists), as well as from the shop floor, but also from the manufacturing engineering department and sometimes the engineering department. The need for input from these experts was not necessarily apparent at the beginning of the project because the requirements changed depending on the exploratory path the team followed. People made themselves available and could be released from their daily work responsibilities. The team grew to include more people from more varied backgrounds as the exploration continued.
- A place dedicated to meetings: In the factory, the teams were able to meet in a comfortable room dedicated to this type of innovative project. The room contained books for documentation purpose, and charts illustrating the progress of the project were displayed. The project teams were also able to visit various experts outside the factory.
- Rapid prototyping: The teams had access to resources that enabled them to develop prototypes quickly, including a 3D printer and software for simulations and an aircraft for testing. The design solutions needed to be integrated into their existing environment without disturbing it. In contrast to designing a new product, the design solutions for the production line needed to consider potential disruptions and negative impacts on the overall production system. Therefore, partial and full prototyping were crucial for proving the efficiency of a design solution and exploring potential negative impacts. Prototypes were used not only to validate potential solutions, but also to open up new areas of investigation with the aim of improving the solution.

These resources are generally not available in a factory where all of the processes and the rate of production are optimized, people do not mix with each other because of the strict division of labor, and there are few resources, either internal or external, in the form of knowledge from other disciplines. However, our observations and informal qualitative data indicated that these material conditions and the openness of the factory to other sectors and scientific disciplines seemed to be significant factors underlying the success of the projects. It can be seen that the means necessary for the existence of an expandable design regime are those necessary for design-oriented thinking. More generally speaking, compared with the usual design process that occurs in the factory setting, the expendable prescription design regime differs not only in terms of the availability of the necessary resources (more people, more time, a dedicated meeting place, and access to prototyping), but also in the partial awareness of them at the beginning: as detailed in the previous list, the means (people, time, places...) which are going to be used in the design process are only partially known when the project starts.

### *7.2.3 Innovative design skills and an innovation leader*

A design specialist who was able to lead the investigation into the problem and the exploratory process was invaluable in terms of avoiding fixation effects and training the team in the necessary design methods. Training and the development of design skills are crucial if the team is to move beyond the usual ready-to-use solutions. The leader should be not only a very good team leader, but also a de-fixation leader, that is, he or she should be able to anticipate the fixations of the teams in relation to a particular solution or problem and should lead the team toward examining other ideas. Thus, the leader should prepare an exploration of possible solutions and should be able to detect any fixation, thereby avoiding a focus on a single trail of investigation and encouraging the systematic exploration of all possible trails. This requires constant comparisons of the various possible solutions explored and encouraging the team to go beyond the paths already explored.

### *7.2.4 Support*

Supporting this project is possible only with the voluntary support of the management of the factory. The design process is not standardized, and thus the results, that is, the emergence of new rules, are liable to change the manufacturing processes and standards. Moreover, the design process requires time and people to be made available. For these reasons, management was aware of and had investigated and gave its agreement to the 30 projects. During successive gates, it examined the solution, including the methods used and the results expected. Hence top management followed and supported the projects. The support of the employees was also required, despite the fact that the implications of the work were not always obvious because the tasks they were required to undertake in the workshops differed significantly from their usual tasks. Involvement in the more exploratory



projects required participation in several workshops over a period of several months involving new challenges including training in design, collaboration in search of new knowledge, and awareness of the fixation effect.

## 8 Discussion and conclusion

This study investigated a factory that has a significant capability to change its own rules and organization, enabling the design of innovative and robust solutions for its shop floor. The Saint-Nazaire Airbus factory provides an example of the emergence and the coexistence of two design regimes. The first one, a closed prescription regime, consists of the optimization of the manufacturing process under a given and stable system of rules by a conservative approach. The second one, an expandable prescription regime, breaks and expands the system of rules by an innovative design approach. Previous research field, for instance the literature of project management, innovation management, new product development, have described the two regimes in general terms, with a product or a project vision. Nevertheless, they have not investigated their use in a factory setting. We found that the methods and models used for product development or the management of an engineering department or an innovation laboratory are not necessarily directly suited to the complexity and specific challenges of the manufacturing context. In particular, our findings highlight the need to build robust solutions rather than extremely innovative ones.

The findings of this study invite the reader to view production systems through another lens, illustrating the value of a factory that designs its own rules, of workers with design skills, and of adaptable management. Even in a field such as aeronautical manufacturing, which includes a high level of norms regarding products and industrialization in terms of quality, safety, and traceability, the processes used and the form of organization can evolve, and new rules can be designed at the shop-floor level. Our findings indicate that the expandable design is characterized by the ability to find new performance criteria in search of robust solutions, even in a very standardized and complex environment. To that extend, the notion of creative heritage highlights this potential of novelty emerging from the constrained system of rules of the factory (Carvajal Pérez et al. 2020; Hatchuel et al. 2019). The characteristics of the expandable design tend to bring to light a very progressive approach in the design of the solution: the iteration, tests, the improvement of the solution even if the project could be considered as finished... This contradicts the expectation of disruption that is commonly expected from strong forms of innovation (Si and Chen 2020; Christensen et al. 2018). In this research, the innovation is not marginal nor disruptive, but results from the industrial rules. It conserves them, makes them evolve at the same time.

The use of this design regime despite the constraints of existing routines and norms that exist in this manufacturing sector, and the robustness of the solutions offered, could also provide lessons for Industry 4.0. In an era of industrial reshoring, it is tempting to pursue total automation of the production line. However, this strategy only seems to be relevant under certain situations in relation to existing human resource management practices and workplace skills (Lund and Steen 2020). More generally, studies on Industry 4.0 have questioned the place and work of people in a cyber-physical system (Kadir, Broberg, and Conceição 2019). The final report of the Industry 4.0 working group (Kagermann, Wahlster, and Helbig 2013) noted changes in the nature of work for people under Industry 4.0 toward tasks involving more complexity and abstraction, with an increased emphasis on problem solving. The human factors and ergonomics literature, which focuses on human-machine interactions, has emphasized the importance of ergonomics in Industry 4.0, including physical, cognitive, and organizational ergonomics (Reiman 2021). Some studies have argued for earlier entry of humans into the design of the system to avoid the “magic operator effect,” that is, an omniscient operator who only becomes involved in the production flow when problems that were not predicted by the system require solving (Trentesaux and Millot 2016). The operator can also be integrated with the system in a human-automation symbiosis (Scafà, Marconi, and Germani 2020). This study presents the keys to understanding possible ways of designing projects in conjunction with the operators to improve their ergonomics. However, the projects in which the operators can be involved are not limited to those aimed at the improvement and optimization of their own working conditions. On the contrary, the operators can be involved in broader projects, wherein their experience, expertise, knowledge of the factory, and design skills are of considerable use to an exploratory design approach. Taylor et al. (2020) describe an operator on the production line who is involved in design activities across a broader manufacturing scope than their own specialized production task. The findings of this study provide new insights regarding the types of design activity in which these operators can be involved. These operators are not only able to execute and optimize the rules in an entirely prescribed system, but also able to create new rules, and thus allow the system to evolve.

## APPENDIX

### 1. Table 1: the project characteristics

case	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
people in the core team	5	25	12	300	8	15	35	35	10	45	20	10	4	50	10	150	8	40	25	150	50	40	25	15	40	80	45	5	60	20
punctual experts advisors	1	10	2	25	2	4	3	3	2	15	3	2	3	4	2	20	2	4	5	10	3	0	5	3	0	5	3	1	8	2
number of project gates	1	8	2	12	3	2	6	6	0	10	2	3	0	2	5	8	3	0	8	4	0	0	8	3	0	4	4	3	8	0
number of meetings	3	50	5	100	5	8	15	15	>100	50	6	6	4	5	10	40	6	8	30	15	8	5	30	15	12	8	8	7	30	10

The number of people, and of the project characteristics are estimated. This table shows a high heterogeneity in the size of the projects.

### 2. Wilcoxon test

The samples seemed to be very polarized and not particularly mixed in terms of design regime; the authors wanted to test if the median of the samples were significantly different. Considering the small size of the samples, a Mann-Whitney-Wilcoxon test was performed to assess the difference between the two samples. The number of criteria coded as 1 was calculated for each project. Hence each project received a “grade” and the projects had an order between them. In presence of ex-aequo ranks, the software R used for this test computes the statistics  $W$  with a continuity correction.

#### Hypotheses

*Hypothesis zero (H0):* The means of the two samples are equal.

*Hypothesis one (H1):* The means of the two samples are not equal.

#### Results

The Wilcoxon test statistic is denoted as  $W$ , where  $W=0$  p-value =4.628e-06. Thus,  $H_0$  is rejected at the 5% level.

#### Conclusion

We found two clearly distinct populations.

Some of the projects had one or more criteria coded in accordance with the other regime. This shows that the projects were not totally homogenous, and some methods and organizations could be used under both regimes.

### 3. Chi-square test

This test checks for independence between the type of regime and the level of success achieved.

A chi-square test using one degree of freedom was implemented at the 5% level. This was consistent with the number of projects treated (30).

#### Hypotheses

*Hypothesis zero (H0):* The design regime and the level of success are independent.

*Hypothesis one (H1):* The design regime and the level of success are not independent.

#### Results

The result was a value of 18.8, which is higher than the theoretical value of 7.88. The p-value was  $1.45 \times 10^{-5}$ .

#### Conclusion

The level of success and the design regime are not independent. Thus,  $H_0$  was rejected at the 5% level.

## REFERENCES

Abdulmalek, Fawaz A., and Jayant Rajgopal. 2007. “Analyzing the Benefits of Lean Manufacturing and Value Stream Mapping via Simulation: A Process Sector Case Study.” *International Journal of Production Economics* 107 (1): 223–36.

- Adamczyk, Sabrina, Angelika C. Bullinger, and Kathrin M. Möslin. 2012. "Innovation Contests: A Review, Classification and Outlook." *Creativity and Innovation Management* 21 (4): 335–60. .
- Anand, Gopesh, Peter T. Ward, Mohan V. Tatikonda, and David A. Schilling. 2009. "Dynamic Capabilities through Continuous Improvement Infrastructure." *Journal of Operations Management* 27 (6): 444–61.
- Barker, Martin, and Kevin Neailey. 1999. "From Individual Learning to Project Team Learning and Innovation: A Structured Approach." *Journal of Workplace Learning* 11 (2): 60–67. <https://doi.org/10.1108/13665629910260752>.
- Bullinger, Angelika C., Anne-Katrin Neyer, Matthias Rass, and Kathrin M. Moeslein. 2010. "Community-Based Innovation Contests: Where Competition Meets Cooperation." *Creativity and Innovation Management* 19 (3): 290–303. <https://doi.org/10.1111/j.1467-8691.2010.00565.x>.
- Caloghirou, Yannis, Ioanna Kastelli, and Aggelos Tsakanikas. 2004. "Internal Capabilities and External Knowledge Sources: Complements or Substitutes for Innovative Performance?" *Technovation* 24 (1): 29–39.
- Campanelli, Amadeu Silveira, and Fernando Silva Parreiras. 2015. "Agile Methods Tailoring—A Systematic Literature Review." *Journal of Systems and Software* 110: 85–100.
- Carvajal Pérez, Daniel, Pascal Le Masson, Benoit Weil, Axelle Araud, and Vincent Chaperon. 2020. "Creative Heritage: Overcoming Tensions between Innovation and Tradition in the Luxury Industry." *Creativity and Innovation Management* 29: 140–51.
- Charue-Duboc, Florence, Franck Aggeri, Valérie Chanal, and Gilles Garel. 2010. "Managing Exploratory Innovation." In *Back to the Future*.
- Christensen, Clayton M., Rory McDonald, Elizabeth J. Altman, and Jonathan E. Palmer. 2018. "Disruptive Innovation: An Intellectual History and Directions for Future Research." *Journal of Management Studies* 55 (7): 1043–78. <https://doi.org/10.1111/joms.12349>.
- Cross, Nigel. 2011. *Design Thinking: Understanding How Designers Think and Work*. Berg.
- Cunha, Miguel Pina E. 2005. "Bricolage in Organizations." *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.882784>.
- Dorst, Kees. 2006. "Design Problems and Design Paradoxes." *Design Issues* 22 (3): 14.
- Duymedjian, Raffi, and Charles-Clemens Ruling. 2010. "Towards a Foundation of Bricolage in Organization and Management Theory." *Organization Studies* 31 (2): 133–51. <https://doi.org/10.1177/0170840609347051>.
- Engwall, Mats, and Charlotta Svensson. 2004. "Cheetah Teams in Product Development: The Most Extreme Form of Temporary Organization?" *Scandinavian Journal of Management* 20 (3): 297–317. <https://doi.org/10.1016/j.scaman.2003.05.001>.
- Fantini, Paola, Marta Pinzone, and Marco Taisch. 2018. "Placing the Operator at the Centre of Industry 4.0 Design: Modelling and Assessing Human Activities within Cyber-Physical Systems." *Computers & Industrial Engineering*, February, 105058. <https://doi.org/10.1016/j.cie.2018.01.025>.
- Fargnoli, Mario, Mara Lombardi, Nicolas Haber, and Francesco Guadagno. 2018. "Hazard Function Deployment: A QFD-Based Tool for the Assessment of Working Tasks—A Practical Study in the Construction Industry." *International Journal of Occupational Safety and Ergonomics*.
- Fujimoto, Takahiro. 2012. "The Evolution of Production Systems Exploring the Sources of Toyota's Competitiveness." *Annals of Business Administrative Science* 11: 25–44.
- Gilbert, Patrick, Ann-Charlotte Teglborg, and Nathalie Raulet-Croset. 2018. "The Liberated Firm, a Radical Innovation or a Mere Avatar of Participatory Management?" *Gérer et Comprendre*, no. 3: 1–10.

- Grewal, Chandandeep. 2008. "An Initiative to Implement Lean Manufacturing Using Value Stream Mapping in a Small Company." *International Journal of Manufacturing Technology and Management* 15 (3-4): 404-17.
- Hatchuel, Armand. 2001. "Towards Design Theory and Expandable Rationality: The Unfinished Program of Herbert Simon." *Journal of Management and Governance* 5 (3/4): 260-73.
- Hatchuel, Armand, and Milena Klasing Chen. 2017. "Creativity under Strong Constraints: The Hidden Influence of Design Models." *European Review* 25 (2): 194-207. <http://dx.doi.org/10.1017/S1062798716000557>.
- Hatchuel, Armand, Pascal Le Masson, Yoram Reich, and Eswaran Subrahmanian. 2018. "Design Theory: A Foundation of a New Paradigm for Design Science and Engineering." *Research in Engineering Design* 29 (1): 5-21.
- Hatchuel, Armand, Pascal Le Masson, and Benoît Weil. 2001. "From R&D to RID: Design Strategies and the Management of Innovation Fields." In *8th International Product Development Management Conference*, 415-30.
- Hatchuel, Armand, Pascal Le Masson, Benoit Weil, and Daniel Carvajal-Perez. 2019. "Innovative Design Within Tradition - Injecting Topos Structures in C-K Theory to Model Culinary Creation Heritage." *Proceedings of the Design Society: International Conference on Engineering Design* 1 (1): 1543-52. <https://doi.org/10.1017/dsi.2019.160>.
- Hatchuel, Armand, Yoram Reich, Pascal Le Masson, Benoit Weil, and Akin Kazakçi. 2013. "Beyond Models and Decisions: Situating Design through Generative Functions." In *DS 75-2: Proceedings of the 19th International Conference on Engineering Design (ICED13), Design for Harmonies, Vol. 2: Design Theory and Research Methodology, Seoul, Korea, 19-22.08. 2013*, 233-42.
- Ikävalko, Heini, and Tea Lempiälä. 2019. "Innovation Contests, Routine Dynamics and Innovation Management." *Creativity and Innovation Management* 28 (2): 191-202. <https://doi.org/10.1111/caim.12299>.
- Iwao, Shumpei. 2017. "Revisiting the Existing Notion of Continuous Improvement (Kaizen): Literature Review and Field Research of Toyota from a Perspective of Innovation," 31.
- Iwao, Shumpei, and Mihail Marinov. 2018. "Linking Continuous Improvement to Manufacturing Performance." *Benchmarking: An International Journal*.
- Johansson-Sköldberg, Ulla, Jill Woodilla, and Mehves Çetinkaya. 2013. "Design Thinking: Past, Present and Possible Futures." *Creativity and Innovation Management* 22 (2): 121-46.
- Kagermann, Henning, Wolfgang Wahlster, and Johannes Helbig. 2013. "Securing the Future of German Manufacturing Industry: Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0." *Final Report of the Industrie 4 (0)*.
- Kaplan, Stan. 1996. *An Introduction to TRIZ: The Russian Theory of Inventive Problem Solving*. Ideation International.
- Kidder, Tracy. 2011. *The Soul of a New Machine*. Hachette UK.
- Knol, Wilfred H., Jannes Slomp, Roel LJ Schouteten, and Kristina Lauche. 2019. "The Relative Importance of Improvement Routines for Implementing Lean Practices." *International Journal of Operations & Production Management*.
- Koch, J., A. Gritsch, and G. Reinhart. 2016. "Process Design for the Management of Changes in Manufacturing: Toward a Manufacturing Change Management Process." *CIRP Journal of Manufacturing Science and Technology* 14 (August): 10-19. <https://doi.org/10.1016/j.cirpj.2016.04.010>.
- Krishnan, Viswanathan, and Karl T. Ulrich. 2001. "Product Development Decisions: A Review of the Literature." *Management Science* 47 (1): 1-21.

- Kuipers, Ben S., Marco C. De Witte, and Ad H. van der Zwaan. 2004. "Design or Development? Beyond the LP-STS Debate; Inputs from a Volvo Truck Case." *International Journal of Operations & Production Management*.
- Lenfle, Sylvain, and Christophe Midler. 2003. "Innovation in Automotive Telematics Services: Characteristics of the Field and Management Principles." *International Journal of Automotive Technology and Management* 3 (1–2): 144–59.
- . 2009. "The Launch of Innovative Product-Related Services: Lessons from Automotive Telematics." *Research Policy* 38 (1): 156–69. <https://doi.org/10.1016/j.respol.2008.10.020>.
- Lévi-Strauss, Claude. 1962. *Savage Mind*. University of Chicago Chicago, IL.
- Li, Ying, Wim Vanhaverbeke, and Wilfred Schoenmakers. 2008. "Exploration and Exploitation in Innovation: Reframing the Interpretation." *Creativity and Innovation Management* 17 (2): 107–26. <https://doi.org/10.1111/j.1467-8691.2008.00477.x>.
- Lu, Stephen C-Y., and Amanda Conger. 2007. "Supporting Participative Joint Decisions in Integrated Design and Manufacturing Teams." In *Advances in Integrated Design and Manufacturing in Mechanical Engineering II*, edited by S. Tichkiewitch, M. Tollenaere, and P. Ray, 3–22. Dordrecht: Springer Netherlands. [https://doi.org/10.1007/978-1-4020-6761-7\\_1](https://doi.org/10.1007/978-1-4020-6761-7_1).
- Lund, Henrik Brynthe, and Markus Steen. 2020. "Make at Home or Abroad? Manufacturing Reshoring through a GPN Lens: A Norwegian Case Study." *Geoforum* 113 (July): 154–64. <https://doi.org/10.1016/j.geoforum.2020.04.015>.
- Micheli, Pietro, Sarah JS Wilner, Sabeen Hussain Bhatti, Matteo Mura, and Michael B. Beverland. 2019. "Doing Design Thinking: Conceptual Review, Synthesis, and Research Agenda." *Journal of Product Innovation Management* 36 (2): 124–48.
- Paton, Bec, and Kees Dorst. 2011. "Briefing and Reframing: A Situated Practice." *Design Studies* 32 (6): 573–87.
- Pfeiffer, Sabine, Horan Lee, and Maximilian Held. 2019. "Doing Industry 4.0 – Participatory Design on the Shop Floor in the View of Engineering Employees." *Cuadernos de Relaciones Laborales* 37 (2): 293–311. <https://doi.org/10.5209/crla.66039>.
- Polacsek, Thomas, Stéphanie Roussel, François Bouissiere, Claude Cuiller, Pierre-Eric Dereux, and Stéphane Kersuzan. 2017a. "Towards Thinking Manufacturing and Design Together: An Aeronautical Case Study." In *International Conference on Conceptual Modeling*, 340–53. Springer.
- . 2017b. "Towards Thinking Manufacturing and Design Together: An Aeronautical Case Study." In *International Conference on Conceptual Modeling*, 340–53. Springer.
- Rafaeli, Anat. 1985. "Quality Circles and Employee Attitudes." *Personnel Psychology* 38 (3): 603–15.
- Rantanen, Kalevi, Ellen Domb, and TRIZ Simplified. 2002. *New Problem Solving Applications for Engineers and Manufacturing Professionals*. St Lucie Press, Boca Raton, FL, USA.
- Reich, Yoram, and Eswaran Subrahmanian. 2020. "The PSI Framework and Theory of Design." *IEEE Transactions on Engineering Management*, 1–13. <https://doi.org/10.1109/TEM.2020.2973238>.
- Reiman, Arto. 2021. "Human Factors and Ergonomics in Manufacturing in the Industry 4.0 Context – A Scoping Review." *Technology in Society*, 9.
- Rhodes, Lucy, and Ray Dawson. 2013. "Lessons Learned from Lessons Learned." *Knowledge and Process Management* 20 (3): 154–60. <https://doi.org/10.1002/kpm.1415>.
- Roucoules, Lionel, Esmâ Yahia, Widad Es Soufi, and Serge Tichkiewitch. 2016. "Engineering Design Memory for Design Rationale and Change Management toward Innovation." *CIRP Annals* 65 (1): 193–96. <https://doi.org/10.1016/j.cirp.2016.04.046>.

- Scafà, Martina, Marco Marconi, and Michele Germani. 2020. "A Critical Review of Symbiosis Approaches in the Context of Industry 4.0☆." *Journal of Computational Design and Engineering* 7 (3): 269–78. <https://doi.org/10.1093/jcde/qwaa022>.
- Schmidt, Jeffrey B., Kumar R. Sarangee, and Mitzi M. Montoya. 2009. "Exploring New Product Development Project Review Practices." *Journal of Product Innovation Management* 26 (5): 520–35.
- Schön, Donald A. 1987. "Educating the Reflective Practitioner: Toward a New Design for Teaching and Learning in the Professions." *Jossey-Bass Higher Education Series.*, 1987.
- Schön, Donald A. 1990. "The Design Process." *Varieties of Thinking: Essays from Harvard's Philosophy of Education Research Center*, 110–41.
- Scott-Young, Christina, and Danny Samson. 2008. "Project Success and Project Team Management: Evidence from Capital Projects in the Process Industries." *Journal of Operations Management* 26 (6): 749–66.
- Shah, Mihir K., Vivek A. Deshpande, and Ramchandra M. Patil. 2015. "A Review on Lean Tools & Techniques: Continuous Improvement in Industry." *International Journal of Advance Industrial Engineering* 3 (4): 200–207.
- Si, Steven, and Hui Chen. 2020. "A Literature Review of Disruptive Innovation: What It Is, How It Works and Where It Goes." *Journal of Engineering and Technology Management* 56: 101568.
- Simonsen, Jesper, and Morten Hertzum. 2012. "Sustained Participatory Design: Extending the Iterative Approach." *Design Issues* 28 (3): 10–21.
- Taylor, Mark P., Peter Boxall, John J. J. Chen, Xun Xu, Angela Liew, and Adebayo Adeniji. 2020. "Operator 4.0 or Maker 1.0? Exploring the Implications of Industrie 4.0 for Innovation, Safety and Quality of Work in Small Economies and Enterprises." *Computers & Industrial Engineering* 139 (January): 105486. <https://doi.org/10.1016/j.cie.2018.10.047>.
- Thompson, Paul, and Terry Wallace. 1996. "Redesigning Production through Teamworking: Case Studies from the Volvo Truck Corporation." *International Journal of Operations & Production Management* 16 (2): 103–18. <https://doi.org/10.1108/01443579610109875>.
- Trentesaux, Damien, and Patrick Millot. 2016. "A Human-Centred Design to Break the Myth of the 'Magic Human' in Intelligent Manufacturing Systems." In *Service Orientation in Holonic and Multi-Agent Manufacturing*, 103–13. Springer.
- Vanharanta, Outi. 2018. "Whose Responsibility Is It Anyway? Competing Narratives of Suggestion System Change." *Creativity and Innovation Management* 27 (3): 244–54. <https://doi.org/10.1111/caim.12286>.
- Vijayakumar, G., and Y. Robinson. 2016. "Impacts of Lean Tools and Techniques for Improving Manufacturing Performance in Garment Manufacturing Scenario: A Case Study." *Int J AdvEngg Tech/Vol. VII/Issue II/April-June* 251: 260.
- West, Michael A., and James L. Farr. 1989. "Innovation at Work: Psychological Perspectives." *Social Behaviour* 4 (1): 15–30.
- Wheelwright, Steven C., and Kim B. Clark. 1992. *Revolutionizing Product Development: Quantum Leaps in Speed, Efficiency, and Quality*. Simon and Schuster.

