RENOVATING ENGINEERING DEPARTEMENTS' CREATION HERITAGE TO MEET CONTEMPORARY CHALLENGES: FRUGAL VALIDATION PATTERNS AND CONSTRUCTIVE PROOF LOGICS FOR NEW ENGINEERING RULES

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ABSTRACT

Engineering departments design infrastructure by applying rule systems. The latter are an old creation heritage, based on decades of engineering, that makes it possible to design and govern the operation of the physical heritage which is the infrastructure. Replacing the infrastructure is not sustainable in the meaning of grand challenges; renovating it by applying engineering rules is but could appear too expensive. The literature highlights situations where renovation by respecting the state of the art is too costly and so is the validation of new renovation rules. Are there forms of frugal validation that allow for sustainable renovation of existing systems? This paper tries to explore a third way, a renovation of the physical heritage from a renovation of the system of rules, conceiving in the system of rules, new propositions, and their validation. Using the C-K theory, a case analysis was performed within the French national rail network manager (SNCF Network), a company that has a historical engineering heritage and is at the same time implementing a renovation of it. The paper shows that the renovation of engineering departments' creation heritage can go through frugal validation patterns and constructive proof logics.

Keywords: Design theory, Infrastructure Renovation, Validation, Innovation, Sustainability

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1 INTRODUCTION

The literature on grand challenges emphasizes that improved strategic planning, and design and maintenance of transportation and transit systems can lead to more adaptable and resilient transportation systems (Kaewunruen et al., 2016). This notion of maintenance has been taken up in sociological works that invite us not to reduce the processes of maintenance and repair to a simple restoration of a pre-existing socio-material order (Denis et al., 2016; Puig de la Bellacas, 2011). On another note, some SNCF Network projects are facing a dead end: replacing the affected lines is not sustainable in the meaning of grand challenges; renovating these lines by applying engineering rules is but could appear too costly. This problem is an example of a series of problems faced by engineering departments (Gaudry et al., 2016) : how in the name of grand challenges to make sure to not redesign everything every time, but rather renovate existing systems, especially in public transport? Many engineering departments are faced with new performance objectives and new constraints (Kang et al., 2014). This presents them with a dilemma. On the one hand, it could be possible to renew, to renovate, following the known rules, the rules of the art, but this implies investments that could sometimes appear not financeable. On the other hand, it could be possible to implement attempts at optimization or readjustment of performance choices which can be financed but imply trade-offs with the rules of engineering. For a system to be reliable, it must be consistent with the set of engineering rules (Harlé et al., 2021). The latter is supposed to guarantee reliability and technical homogeneity; therefore, going beyond the rules of the art implies a validation, which in this context needs to be inexpensive. This paper is based on a rather surprising project. The French national rail network manager (SNCF Network) needs to renovate a series of railway lines and the compliance of the renovation program must be validated. To do so, a first version of the renovation program consists in bringing the lines up to the level of the existing classical conformity rules, it costs much too much. After some rework and innovation, a second program that costs much less is proposed. Yet, the performance criteria have been rediscussed for sustainability relative to the needs of the region, the cost of validation should then be not insignificant. The fact is that the costs of the renovation program have been greatly reduced. What happened? Faced with this paradox, this article will show how the latter can be understood if the variety of validation patterns implemented can be analyzed. The question of sustainable system renovation, therefore, raises a question that interests us in this paper, the possibility of a validation, which will be called frugal, of new engineering rules. Can we shed light on one or more forms of frugal validation patterns for new engineering rules enabling sustainable renovation of existing systems? If it is the case, is there a design behind this frugal validation? Thus, this article tries to explore if there would not be a third way for sustainable system renovation, which would take the question of the renovation of the physical heritage from a new way of designing in the system of rules, new propositions, and their validation. The remainder of the paper is organized as follows: Section 2 provides an overview of the literature on validating a new engineering rule. Section 3 describes the research setting and the methodology in more detail, the creation heritage's renovation case analysis is presented in this section. Following up on this, the results are illustrated in Section 4. The paper concludes with a discussion and the presentation of the next steps in Section 5.

2 REVIEW OF RELATED LITERATURE

2.1 Verification and validation through tests

In engineering, the issue of rule or design validation has often been seen as a question of testing and compliance. There is a whole stream of literature on the notions of verification and validation in response to knowledge-based design that has sometimes resulted in unreliable systems (Plant and Gamble, 2003). Verification is the evaluation of whether a product, service, or system complies with a regulation, a requirement, a specification, or an imposed condition. Validation is the assurance that a product, service, or system meets the needs of the customer and other identified stakeholders. Many methodologies and techniques for verification and validation are proposed in the literature (Wasserman, 2002). The final validation is done through experimentation and testing: system testing and user acceptance testing (Buchanan and Duda, 1983). There is then a set of tests to be verified so that the product and its design are validated. Eventually, to prove that a function is fulfilled, the right reproducible, even standardized test must be developed (Gobbi et al., 2022; Van den Bosch et al., 2021). These tests represent a development cost, which can be considerable. Moreover, since they are

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often performed in the final design phase, any deviation can have a significant impact on development time and compliance costs (Babuska and Oden, 2004; Maropoulos and Ceglarek, 2010). Thus, to validate a new project, which goes beyond the state-of-the-art, it is necessary to validate that the functions are fulfilled, to carry out the associated experimental devices and tests, and, therefore, to pay the costs related to the latter.

2.2 Validation through the application of the state-of-the-art rules

Design validation of a procedure involves testing important characteristics of the procedure to ensure that it is accurate, precise, specific, reproducible, and robust for routine (Yuwono and Indrayanto, 2005). In the pharmaceutical industry, for example, a Design Qualification is written, documenting the verification, and confirming that a design procedure results in a system that is fit for purpose. Numerous works on quality programs, in particular the work on the ISO 9000 quality assurance standard, emphasize that validation and certification more specifically require documentation of the procedures used to meet expectations (Zhu, 1999). Thus, once a process has been validated or certified, and the systematic writing of practices carried out, the process can be reused (Yao et al., 2003). The process is deemed to be of good quality because it follows the quality rule. There is then a simple proof for which it is not a question of showing that it works, but of saying that it follows the rules that say it works. Once you can say that a design process is of quality, there is no need to test all the designed systems because the design has been done according to the recommended processes.

2.3 Existence of other validation patterns

Hence, we conclude from the literature review above, the existence of two validation patterns of a new engineering rule. On the one hand, validation by testing. On the other hand, validation by applying the rules' state-of-the-art. Today, the question of compliance with the rule and the question of compliance costs is a major issue in engineering, notably due to the functional expansion leading to an increase in standards (El Qaoumi, 2016; Gilain, 2021). The literature questions the fact of setting up all the testing processes once the product has been designed and indicates the importance of the testing budget relative to the project budget (Czarnigowski and Czarnigowska, 2015; Wang and Zhang, 2020). Indeed, this can lead to paradoxical situations where design procedures are defined but appear too costly; and where the development of a new process remains problematic, the main difficulty being not the development of the new system, but its validation and more precisely, its certification. Many works then try to optimize the test design (Luecht, 2013). In particular, optimizing the number of tests, based on costs, coupling product design costs, and validation test costs, to ensure product reliability (Ahmed and Chateauneuf, 2014). Other works deal with experimentation, and the cost of experimentation, with the idea of seeing if there are ways to minimize the costs of learning through parallel strategies (Gillier and Lenfle, 2019; Thomke, 2003). These works highlight the value of not thinking about design and validation separately and propose optimal testing strategies. Thus, the literature describes situations where compliance with the state-of-the art is too expensive, and validation of new rules also. There is a problem: classical validation patterns appear to not be very frugal or to not lead to very frugal situations.

What justifies thinking that maybe there would be other validation patterns? Looking beyond engineering, in other domains, different validation patterns exist. Beyond the previous literature, what are the validation patterns implemented? In mathematics, validating a theorem means using all the available axioms to show that by combining them, the theorem is demonstrated. Validating a theorem is like validating a new rule in a system of rules. We are simply not sure of its meaning in engineering. In knowledge-based systems, is it as easy as that to implement deduction mechanisms? Moreover, there is a form of proof in mathematical constructivism based on mathematical intuitionism, which consists in saying that when combining rule 1 and rule 2, rule 2 being a proposition that still needs to be proved, the sought-after rule 3 is obtained. Thus, the validation of the rule comes from the respect of the previous rules and a delta to be designed. However, it should be noted that this is only possible thanks to an additional knowledge effort (Kazakçı, 2013). In law, case law is a technique for validating legal rules. Anglo-Saxon law has a case law where one decision is sufficient to establish a precedent and case law in this law is an important source for the law (Apple and Deyling, 1995). Moreover, in the computer science literature, there are formal machine-assisted verification methods. These methods allow us to verify that if the program construction is compliant, its execution will be. This work on proof assistants has been used to validate programs as part of the digital transformation

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of CoPS (Lakemond et al., 2022). They enable the development and formal certification of compilers. This kind of certified compiler is useful for the certification of critical software: the certification of the compiler guarantees that the safety properties proved on the source code are also valid for the executable compiled code (Leroy, 2006). On another note, there have already been works in engineering design that have thought of widening the scope of validation to more sophisticated patterns. Some work points out that medical research and development can contribute enormously to engineering design validation. Indeed, these are built on several layers: theory in chemistry and biology, clinical trials, natural experiments, in vitro experiments, and animal models, among others (Frey and Dym, 2006).

What is quite fascinating is that in all these alternative validation patterns, there is some kind of validation construction. Therefore, the framework of validation construction in engineering could probably appear more general. Finally, this notion of validation, which is often seen precisely as an end stage of design, is a very demanding design phase. As a result, it seems relevant to ask ourselves what it means to design validation.

2.4 Research questions

In the context of renovation issues, a lot of questions obviously arise. This paper will only deal with a very small part of them, the validation issues. What leads to the question of frugal validation is a rather intriguing observation on the SNCF case: the teams that worked to build new renovation proposals made relatively little modification of the original proposals, but a huge amount of work was associated with validating the new proposals. The literature review raises the fact that using existing rules can be complex and costly, but on the other hand, validating a new rule represents an impactful effort that can also be too costly. Faced with this impasse, some works underline the interest in thinking about the design and validation of new rules together and exploring new forms of validation. Moreover, looking beyond engineering, in other domains, different validation patterns exist. This leads to the following research question: **RQ1. Can we shed light on one or more forms of frugal validation patterns for new engineering rules enabling sustainable renovation of existing systems?** Knowing that there could be a validation design, it seems interesting to try to understand the underlying reasoning behind a frugal validation: **RQ2. Is there design behind frugal validation for new engineering rules that enable sustainable renovation of existing systems?**

3 RESEARCH METHODOLOGY

3.1 Research approach

The authors had the opportunity to analyse a project facing the impasse described in the literature: on the one hand, validation through the application of rules' state-of-the-art was too costly; on the other hand, validation of new rules could appear also too expensive. As innovative design workshops are institutionalized in SNCF (Laousse, 2018), in the face of this impasse, one of these was set up and allowed this project to find an outlet. We are then led to believe that perhaps this case is an anomaly, and that it could maybe allow us to understand new patterns of validation.

This paper is going to look at the design of the validation. Design theory will allow us to better understand and analyze the making of validation, and the way it is constructed. This paper will try to decode this SNCF Network case with this approach.

3.2 Data collection

The data collection was performed as part of an intervention research study (Hatchuel, 1997; Radaelli et al., 2014) by the authors from February 2022 at SNCF Network. Data collection for retrospective analysis was performed between August 2021 and now, through formal and informal interviews with the project team (innovative design experts). The data on the content, the technical feasibility, and the financial evaluations of the two renovation programs were triangulated and supplemented by information from working documents and project deliverables found in SNCF Network. A longitudinal study (Karlsson, 2016) was conducted by the first author between August 2021 and now. The data was collected through frequent participation in working sessions with the project team (35 meetings, 78 hours). Information was collected from internal documents specifying the work to be done to maintain the lines in operational conditions (diagnosis, work program letter, etc.),

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presentations and minutes of the various workshop sessions, texts specifying engineering rules, as well as notes collected during the meetings (33 documents, 370 pages). Interviews with the project team members, experts (track experts, documentation expert, …), and local actors (engineering department and work department) were conducted after the information was collected to consolidate the analysis (10 people, 21 interviews, 32 hours).

3.3 Data analysis

The case studied is the following: a region wishes to maintain in operational condition capillary freight lines, i.e., lines serving the territory with low traffic reserved for rail freight. The engineering department of SNCF Network has estimated the financial investment required for the work based on the previous technical diagnosis, considering that the system of rules is applied. However, the region has a limited budget which is insufficient. It is a very precise moment of the conception process, the moment of contradiction. A long phase of diagnosis was carried out upstream, which allowed, through an analysis of the existing system, to determine the state of the technical system and the problematic points to maintain these lines in operational condition. It will be assumed that this phase has been correctly carried out, as it is frequently done by joint work by the engineering and works departments of SNCF Network. This phase leads to incompatibility: if the system of rules is applied, it results in an unsustainable economic equation. A two-phase workshop was then organized over eight months (approximately one session per month). Following this workshop, the revision of the engineering rules is a success: it allows a satisfactory economic equation; it is accepted by the financiers; and therefore, it allows to maintain the lines in operational condition.

The two programs specifying the work to be done to maintain the project lines in operational condition, before and after the workshop, have been compared. This allowed us to identify about twenty changes. Behind these, seven new engineering rules and the different patterns implemented for their validation were identified. The gains allowed by these seven new engineering rules on the project were quantified. These gains represent 11% of the budget initially estimated at several million euros. For each of the twenty changes in the renovation program, interviews were conducted with the workshop participants. First, the proposals they had conceived were identified, then what they said about how to validate them was made explicit. Thus, from the verbatims obtained, we traced the validation processes: all the validation attempts knowing a proposal to be validated. This allowed us to see that, as our analysis started quite late, the proposition to be validated does not evolve much, but the validation attempts are much more complicated, frequent, and refined, than one might have imagined.

The analysis of the validation of these new rules was carried out using the C-K theory (Hatchuel and Weil, 2008). The C-K theory has been used because it allows us to reconstruct the design reasoning that was conducted during the design of the validation. Coding in C-K for each proposition the way it was validated then reveals validation patterns, proposition after proposition. Thus, by systematically looking at all the proposals in the seven cases, we find nine patterns that appear at least once and sometimes several times. The new engineering rules and their validation have been examined, they correspond to very original validation patterns that this paper will try to formalize and make explicit. Two case studies of validation of new engineering rules are presented to illustrate some validation patterns that the case has highlighted. Some works tell us that the design of a new proposition of rule can take quite sophisticated forms, namely, not a proposition of a new design, in fact, but a proposition of a new design in such a way that it is consistent with the previous rule set. For this purpose, the model of new rule design within the tradition (Harlé et al., 2021) is used to analyse our cases.

4 RESULTS

4.1 The case of the rolling and the complementary leveling

The case. The railway track is composed of sleepers and rail. When work is completed on the track, the latter must be stabilized before commercial trains can run on it. This stabilization is called rolling and is usually done by a machine, a dynamic stabilizer, and is therefore very expensive. After rolling, additional leveling is necessary. To maintain one of the lines of this project in operational condition, work on the track will be carried out. Stabilization of the track is thus necessary at each work pass. SNCF is therefore looking for a solution to stabilize the track after each work pass (1). The reasoning is explained in Figure 1. The rule stipulates that 20000T rolling, and complementary leveling are then

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necessary (2). A first proposition corresponds to the application of this rule (3). A second proposition corresponds to an interpretation of the rule in the local situation. Knowing that there is very little traffic and that it is only freight traffic (4), a new way could be to stabilize the track only after the work is completed (5). Is it possible to validate this proposition? It turns out that this is still a constraint for shippers, as freight trains will need to run between the different work passes (6). A new proposition corresponding to an interpretation of the rule then opens, to carry out the rolling of the track through these freight train circulations (7). Is it possible to validate this proposition? On the one hand, can the rolling of the track be carried out by the trains running on this line? A rolling is characterized by tonnage and speed of circulation. This line is only used for freight, so the trains weigh more than 30000T and run at a maximum speed of 50 km/h. Then the track stabilization could be done by a freight train (8). On the other hand, is running commercial traffic on an unstabilized track in this context an acceptable risk? If the maximum speed is 40km/h at the level of the works, then the risk of having an incident becomes acceptable in these precise conditions (9). Thus, the rolling can be carried out by commercial traffic on this line with a maximum speed of 40 km/h (7,10). A final proposition that was explored by checking the other rules, was to use a specific text for UIC (international union of railways) lines 7 to 9, which indicates the need to carry out a rolling after the work has been completed (12, 13). Thus, a solution (7,10) to stabilize the track after track work is validated by the track experts for the continuation of the project (11).

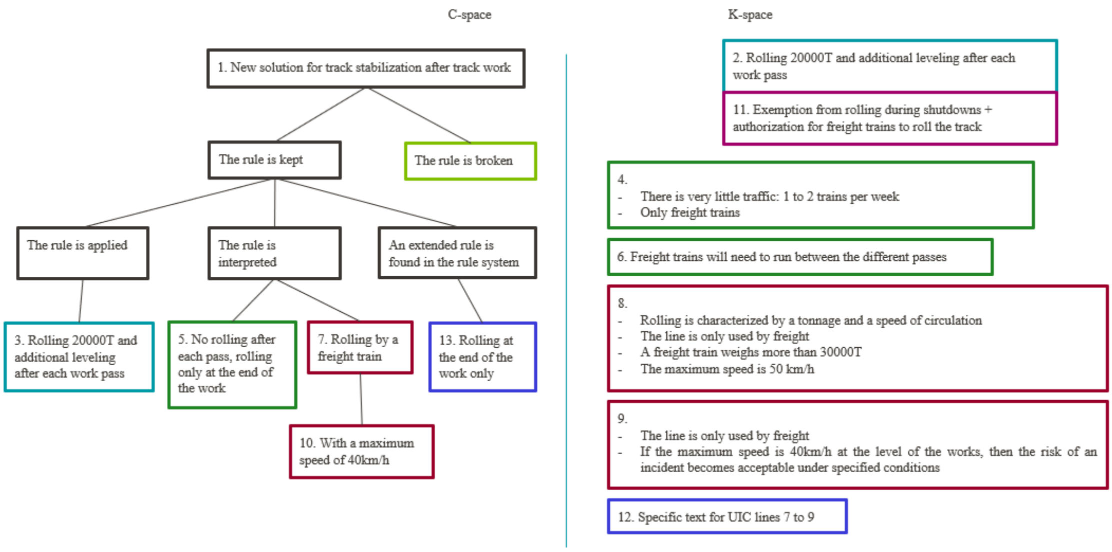

Figure 1. C-K analysis of the rolling and complementary leveling case

Analysis and comments. This case illustrates frugal validation patterns of a different nature than the usual validation patterns: proposition (7,10) is validated partly by rule compliance and partly by a collective risk analysis by experts' opinion; proposition (13) is validated by application of another rule, which is an extension of the initial rule.

This case also illustrates that a frugal validation is an extremely sophisticated validation design. A frugal validation supposes a validation-oriented exploration process: a learning process where testing and seeing if the propositions are validatable. The redesign of a new proposition is then built on the fact that one day or another it will have to be validated. Attempting to validate a certain proposition implies going and looking for knowledge. When the validation could not be done immediately, the knowledge generated allows us to complete the existing proposition or to create new ones. In other words, the attempts to construct validations are at the origin of learning processes that generate knowledge, complete the existing propositions, or create new ones. For example, proposition (7) results from a proposition validation attempt (5,6), and proposition (7) is completed by proposal (10) after a validation attempt (9).

This exploration process makes it possible to redefine the object and segment the validation into several validations. For example, the validation of (7,10) is built in several steps. The first step is the redefinition of the object "rolling": rolling was a track stabilization operation performed by a machine, which was characterized by tonnage and speed; rolling is redefined as a track stabilization operation, which is characterized by tonnage and traffic speed only. Then, the new rule is validated through

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constructive reasoning that relies on the redefinition of the object. The redefinition of the object rolling allowed the conservation of a part of the rule (the weight and the speed for the track stabilization) validated by the existing rules; and the redesign of another part of the rule (the machine) and its validation through a collective risk analysis of the local situation by experts' opinion.

4.2 The case of unmarked cables

The case. A main cable is a signal cable connecting two signal centers, two substations, or a signal center and a substation. Cables prior to 1975 are unmarked. The marking of a cable indicates information about the cable's designation, composition, and manufacture, among other things. To maintain one of the lines on this project in operational condition, a solution to the non-conformity of these cables is required (1). The reasoning is explained in Figure 2. The rule states that unmarked cables must be replaced by 2030 (2). One proposition is the application of the rule and involves the replacement of 8 unmarked cables (3). Another proposition is to interpret the rule according to the local situation. In this case, the next maintenance is scheduled for 2027 and at the last measurement in 2017, all cables were at 100MΩ (4). A second proposition would therefore be to wait for the next maintenance to replace the unmarked cables on this line (5). Is it possible to validate this proposition? What is the risk of not replacing these cables? The main risk would be an insulation fault. An insulation fault is characterized by a low resistance of the cable in question. However, during the last measurement in 2017, all the cables were at 100MΩ, which is a cable resistance in accordance with the maintenance texts for main cables. In sum, these cables do not present an unacceptable insulation fault risk. However, a second risk remains, work on the track will take place and it can generate cable manipulations that can cause insulation faults (6). This leads to exploring and validating a third proposition, to make sure that the track works do not lead to handling of cables and in this case, not to replace the unmarked cables (7,8). A final proposition that was explored was based on rule verification. It turns out that the replacement of unmarked cables is a technical policy, but the text does not imply the replacement of the latter before 2030 (9). This was another way of validating that these cables could be not replaced (10). Thus, a solution (7,8) to the non-conformity of unmarked cables is validated by the signage experts for the continuation of the project (11).

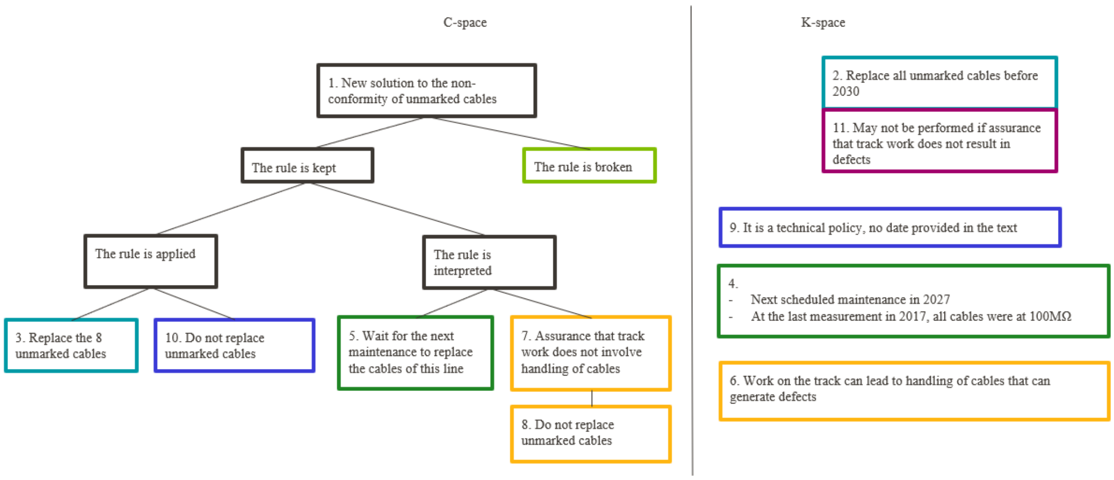

Figure 2. C-K analysis of the unmarked cables case

Analysis and comments. This case also illustrates frugal validation patterns of a different nature than the usual validation patterns: proposition (7,8) is validated partly by rule compliance and partly by a collective risk analysis by experts' opinion; proposition (10) by better knowledge of the rule.

This case also highlights that the design of the validation makes it possible to redefine the object and segment the validation into several validations. For instance, the validation of proposition (7,8) is done in several steps. A redefinition of the object "non-compliant unmarked cable" results from the proposition validation attempt (5). Indeed, a non-compliant unmarked cable initially corresponds to a cable that does not have any marking. After exploration of proposition (5), a non-compliant unmarked cable corresponds to an unmarked cable with a resistance lower than a limit fixed by the rules or an unmarked cable which is likely to be manipulated because of work on the track. The redefinition of the

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object non-compliant unmarked cable allows the conservation of a part of the existing rules (the resistance of the cable) validated by the existing rules; and the redesign of another part of the rule (the assurance on track works) and its validation through a collective risk analysis of the local situation by experts' opinion.

4.3 Case overview

Result 1: Frugal validation patterns exist and represent a range between validation by application of the rules of the state-of-the-art and validation by testing. Indeed, the two cases presented illustrate three frugal validation patterns: validation by better knowledge of the rule; validation by application of another rule, which is an extension of the initial rule; validation by collective risk analysis by experts' opinion. The systematic study of the seven cases allows us to find the previously presented frugal validation patterns as well as others. The other cases show three other patterns of frugal validation. The first one is the validation by a new specific maintenance policy. This pattern corresponds to a situation where the design and its validation are thought of by a change in the maintenance, for example, to choose to ensure the life of a component until the next maintenance at least. The second pattern observed is the taking of individual responsibility, even if everything is done on this project to avoid it. This pattern corresponds to a situation where an actor performs a risk analysis and judges that he is ready to take the risk because he can justify it. The last pattern observed that the actors tried also to avoid, is the validation by an exemption and corresponds to asking an exceptional authorization to deviate from the rule. There would probably be other frugal validation patterns, in particular patterns that are not used in these cases but that have been explored in the context of the latter and on which it would be relevant for the actors to develop skills: validation by collective probabilistic risk analysis, validation by questioning the model underlying the rule, validation by controlled live experiment. Thus, a representation of a set of frugal validation patterns alongside traditional validation patterns is proposed in Figure 3.

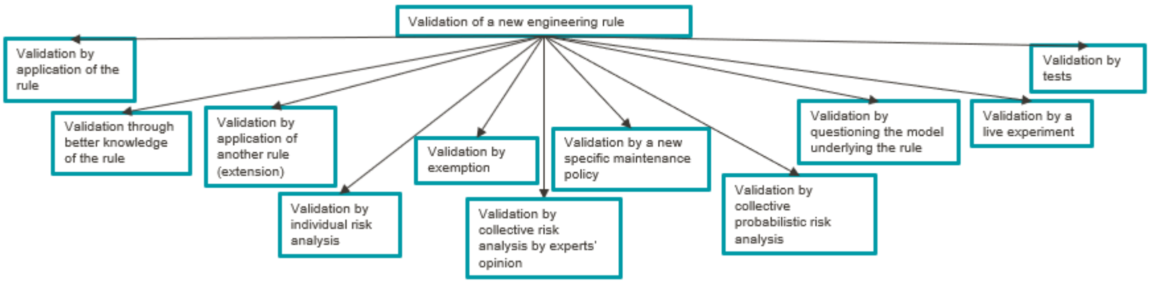

Figure 3. Set of validation patterns for new engineering rules

Result 2: There is design in frugal validation, it is a validation-oriented exploration process, a learning process that allows a segmentation of the validation in a logic of constructive proof. The set of cases studied allowed us to see that frugal validation is, in fact, a rather complex design mechanism. Frugal validation relies on an exploratory mechanism that combines several validation intents. The inability to validate a proposition leads to knowledge that allows for the completion of the proposition or the formulation of other new propositions. This learning process allows a validation that is a constructive proof that relies on a redefinition of the object and enables a segmentation of the validation in a combination of several frugal validation patterns. The design of the validation requires several expertise and the mobilization of a collective. Indeed, the design of the validation involves: technical knowledge of a different nature, from the knowledge of the local situation to the knowledge of the texts enacting the engineering rules; various skills, from the risk analysis methods to the ability to understand the scientific background underlying the engineering rules.

5 CONCLUSION, DISCUSSION AND FUTURE WORK

This paper has allowed the formalization and the explicitation of new frugal validation patterns for engineering rules allowing sustainable renovation of existing systems. Moreover, this paper highlights the presence of design in frugal validation.

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The renovation of the physical heritage that represents the existing systems can pass by a renovation of the creation heritage that are the engineering rules. The latter can be enabled by a range of frugal validation patterns. This paper shows that these frugal validation patterns have the advantage of allowing projects to be completed successfully, while allowing engineers to emerge enhanced by a better knowledge of the rules and a revision of the latter.

A frugal validation is an extremely sophisticated proof design. This paper shows that in fact, in engineering too, there is a rather sophisticated proof construction logic which is one of the rather important keys to a design to cost for contemporary renovation and maintenance issues.

More broadly, it seems to us that frugal validation patterns can help to understand the major difficulties of rule system management services. This paper shows through this case that these frugal validation patterns start from local examples, from which new rules are designed and validated. Moreover, the exploration of new propositions and their validation use knowledge of local situations. Thus, a very fine-grained knowledge of the local situation seems necessary to be able to propose the revision of a rule or the addition of a new rule compatible with the existing system of rules. The existing separation today between the designers who design the rule system and the designers who use this rule system appears perhaps not compatible with the logic of rule renovation analysed in this paper. This raises the question of new organizational forms allowing this.

We used design theories while we were analysing validation. We were at first sight very far from design, design was done, but the C-K theory reveals the effort of proof development. However, the C-K theory was cumbersome to implement. For it to work, a rich source of data is needed. Indeed, the details of the validation operations and the engineering rules are necessary, which implies interviews with many stakeholders and the study of lots of internal documents. From a scientific point of view, this is a bit expensive, however, once the patterns are identified, one can imagine going much more economically. The construction of a typology could allow us to propose to the actors to see if they are using more like this or that pattern.

Future work will aim at reflecting on the completeness of frugal validation patterns. To do so, a model based on the hypothesis that it is a sheafification operation will be built. Moreover, this paper did not look at the elegance that generated the new paths for new rules, but only at the design of their validation. There is probably an expertise, even roles. This raises the question of whether there should be a specific space dedicated to exploration and validation. Finally, now that these frugal validation patterns are known, how to explore new paths for new engineering rules?

REFERENCES

Ahmed, H., Chateauneuf, A., 2014. Optimal number of tests to achieve and validate product reliability. Reliability Engineering & System Safety 131, 242–250. https://doi.org/10.1016/j.ress.2014.04.014

Apple, J.G., Deyling, R.P., 1995. A Primer on the Civil-law System. Federal Judicial Center.

Babuska, I., Oden, J.T., 2004. Verification and validation in computational engineering and science: basic concepts. Computer Methods in Applied Mechanics and Engineering 193, 4057–4066. https://doi.org/10.1016/j.cma.2004.03.002

Buchanan, B.G., Duda, R.O., 1983. Principles of Rule-Based Expert Systems, in: Advances in Computers. Elsevier, pp. 163–216. https://doi.org/10.1016/S0065-2458(08)60129-1

Czarnigowski, J., Czarnigowska, A., 2015. Aviation Regulations and Project Management: Developing a New System for an Aircraft Piston Engine, in: Proceedings of the 2015 (6th) International Conference on Engineering, Project, and Production Management. Presented at the International Conference on Engineering, Project, and Production Management, Association of Engineering, Project, and Production Management, pp. 185–194. https://doi.org/10.32738/CEPPM.201509.0021

Denis, J., Mongili, A., Pontille, D., 2016. Maintenance & Repair in Science and Technology Studies. TECNOSCIENZA: Italian Journal of Science & Technology Studies 6, 5–16.

El Qaoumi, K., 2016. L'expansion fonctionnelle, nouvelle mesure de l'innovation. Analyse empirique et modélisation post-lancastérienne de la transformation des biens de consommation (phdthesis). Université Paris sciences et lettres.

Frey, D.D., Dym, 2006. Validation of design methods: lessons from medicine 259.

Gaudry, M., Lapeyre, B., Quinet, É., 2016. Infrastructure maintenance, regeneration and service quality economics: A rail example. Transportation Research Part B: Methodological 86, 181–210. https://doi.org/10.1016/j.trb.2016.01.015

Gilain, A., 2021. Evaluation économique de la conception dans l'inconnu - modèles basés sur la théorie de la conception au-delà de la théorie de la décision dans l'incertain (These en préparation). Université Paris sciences et lettres.

Gillier, T., Lenfle, S., 2019. Experimenting in the Unknown: Lessons from The Manhattan Project. European Management Review 16, 449–469. https://doi.org/10.1111/emre.12187
Gobbi, M., Mastinu, G., Melzi, S., Previati, G., Ronconi, L., Sabbioni, E., 2022. A Driving Simulator for UN157 Homologation Activities. Presented at the ASME 2022 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers Digital Collection. https://doi.org/10.1115/DETC2022-89909
Harlé, H., Le Masson, P., Weil, B., 2021. A model of creative heritage for industry: designing new rules wile preserving the present system of rules. Proc. Des. Soc. 1, 141–150. https://doi.org/10.1017/pds.2021.15
Hatchuel, A., 1997. Fondements des savoirs et légitimité des règles. La Découverte.
Hatchuel, A., Weil, B., 2008. C-K design theory: an advanced formulation. Res Eng Design 19, 181. https://doi.org/10.1007/s00163-008-0043-4
Kaewunruen, S., Sussman, J.M., Matsumoto, A., 2016. Grand Challenges in Transportation and Transit Systems. Front. Built Environ. 2. https://doi.org/10.3389/fbuil.2016.00004
Kang, K., Kang, C., Hong, Y.S., 2014. Determining Vehicle-Level Specifications for a New Car Program Considering Market Environments and Engineering Design Constraints. Presented at the ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers Digital Collection. https://doi.org/10.1115/DETC2013-13705
Karlsson, C. (Ed.), 2016. Research methods for operations management, Second edition. ed. Routledge, Taylor & Francis group, London New York.
Kazakçı, A.O., 2013. On the imaginative constructivist nature of design: a theoretical approach. Res Eng Design 24, 127–145. https://doi.org/10.1007/s00163-012-0150-0
Lakemond, N., Holmberg, G., Pettersson, A., 2022. Digital Transformation in Complex Systems. IEEE Trans. Eng. Manage. 1–13. https://doi.org/10.1109/TEM.2021.3118203
Laousse, D., 2018. L'institutionnalisation de l'innovation intensive dans les transports publics. Industrialiser, métaboliser et gouverner l'innovation 415.
Leroy, X., 2006. Formal certification of a compiler back-end or: programming a compiler with a proof assistant, in: Conference Record of the 33rd ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages, POPL '06. Association for Computing Machinery, New York, NY, USA, pp. 42–54. https://doi.org/10.1145/1111037.1111042
Luecht, R.M., 2013. Assessment Engineering Task Model Maps, Task Models and Templates as a New Way to Develop and Implement Test Specifications. Journal of Applied Testing Technology 1, 1–38.
Maropoulos, P.G., Ceglarek, D., 2010. Design verification and validation in product lifecycle. CIRP Annals 59, 740–759. https://doi.org/10.1016/j.cirp.2010.05.005
Plant, R., Gamble, R., 2003. Methodologies for the development of knowledge-based systems, 1982–2002. The Knowledge Engineering Review 18, 47–81. https://doi.org/10.1017/S026988890300064X
Puig de la Bellacas, M., 2011. Matters of care in technoscience: Assembling neglected things [WWW Document]. URL (accessed 11.29.22).
Radaelli, G., Guerci, M., Cirella, S., Shani, A.B., 2014. Intervention Research as Management Research in Practice: Learning from a Case in the Fashion Design Industry - Radaelli - 2014 - British Journal of Management - Wiley Online Library [WWW Document]. URL (accessed 6.9.21).
Thomke, S.H., 2003. Experimentation Matters: Unlocking the Potential of New Technologies for Innovation. Harvard Business Press.
Van den Bosch, E.H.L.A., Leensen, M.W.B.M., Klomp, N.H.M., Sauren, F.A.A.H.J., Wismans, J.S.H.M., 2021. Development of an Improved Dummy Head for Use in Helmet Certification Tests. Presented at the ASME 2000 International Mechanical Engineering Congress and Exposition, American Society of Mechanical Engineers Digital Collection, pp. 189–205. https://doi.org/10.1115/IMECE2000-2479
Wang, Y., Zhang, X., 2020. Requirements Management Applied in Airworthiness Certification in the Civil Aircraft. IOP Conf. Ser.: Mater. Sci. Eng. 751, 012028. https://doi.org/10.1088/1757-899X/751/1/012028
Wasserman, G., 2002. Reliability Verification, Testing, and Analysis in Engineering Design. CRC Press, Boca Raton. https://doi.org/10.1201/9780203910443
Yao, Y.-H., Trappey, A.J.C., Ho, P.-S., 2003. XML-based ISO9000 electronic document management system. Robotics and Computer-Integrated Manufacturing 19, 355–370. https://doi.org/10.1016/S0736-5845(03)00003-6
Yuwono, M., Indrayanto, G., 2005. Validation of Chromatographic Methods of Analysis, in: Brittain, H.G. (Ed.), Profiles of Drug Substances, Excipients and Related Methodology. Academic Press, pp. 243–259. https://doi.org/10.1016/S0099-5428(05)32009-0
Zhu, Z., 1999. A comparison of quality programmes: Total quality management and ISO 9000. Total Quality Management 10, 291–297. https://doi.org/10.1080/0954412998018