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THE FRAM AS A TOOL FOR MODELLING VARIABILITY PROPAGATION IN LEAN CONSTRUCTION

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ABSTRACT

Although the control of variability is a key concern for lean construction, there is a lack of tools for modelling how variability propagates throughout functions. This paper discusses how the Functional Resonance Analysis Method (FRAM) can be useful for this purpose. So far, the FRAM has been used mostly by the resilience engineering community, which is concerned with safety management in complex systems. In order to support this discussion, an example of applying the FRAM to safety inspections carried out by government officers in construction sites is presented.

This example draws on sources of data (e.g. participant observation) used by the author in a recent study of systems thinking applied to inspections. The case of safety inspections suggests that the FRAM can encourage managers to appreciate the variability of functions and agents apparently unrelated to the function in which the detrimental effects of variability are visible. Also, results point out that the FRAM might be useful for anticipating the impact of small intentional and non-intentional changes on the functions involved in a construction project.

KEYWORDS

FRAM, variability, safety inspections, systems thinking.

INTRODUCTION

Lean construction (LC) is well-known for being concerned with the management of variability, in internal processes and external suppliers. According to Hopp and Spearman (1996), variability is the quality of non-uniformity of a class of entities, which can be designed into a system (e.g. product variety) or be random (e.g. the time when a machine fails). Story (2011) offers a similar notion, defining variability as the range of performance measurements, values, or outcomes around the average which represents all the possible results of a given process, function or operation.

Both definitions, by Story and Hopp and Spearman, are neutral in the sense that variability is not necessarily associated with outcomes. Indeed, random variability can be

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positive (e.g. an unexpected business opportunity), while designed variability can create waste – e.g. product variety can make workflows more confusing. Regardless of this ambiguity, there seems to be a consensus in the LC community (e.g. Tommelein et al., 1999) that *workflow* variability is detrimental to the reliability of production plans, quality, and safety, creating mismatches between capacity and demand.

Nevertheless, there is still a gap related to the modelling of variability propagation in construction sites, since the theoretical foundation for construction project management, and the practical tools based on it, do not account properly for complexity (Brodetskaia and Sacks, 2007). Of course, this is in conflict with the nature of construction projects, in which uncertainty, physical proximity between processes, and the use of resources shared by many processes (Perrow, 1984), among other factors, create interactive complexity not anticipated by designers. Furthermore, the emphasis placed by LC on process simplification ultimately leads to tightly-coupled processes and, as a result, greater complexity. Therefore, both unintended interactions induced by the nature of construction and the LC objective of creating flow make the modelling of variability propagation a topic of theoretical and practical relevance.

Complexity science (CS) may be a source of insights into variability propagation, as conveyed by the notion that small changes trigger partially unpredictable interactions in a complex socio-technical system (CSS), creating emergent behaviour with disproportional consequences (Cilliers, 1998). In this paper, the Functional Resonance Analysis Method (FRAM), whose theoretical foundations are based on CS and resilience engineering (Hollnagel et al., 2006), is investigated in terms of its usefulness for modelling variability propagation in construction. The FRAM was developed by Hollnagel (2012) as a tool for the modelling of CSSs, and so far it has been used mostly with a safety management focus, in sectors such as healthcare and aviation. In fact, the FRAM has an underlying theory of how accidents occur in CSSs (Hollnagel, 2012). It assumes that accidents are emergent phenomena arising from the combination of everyday variability of functions (i.e. functional resonance); thus, there is no need for broken parts as an explanation for accidents.

In construction, the use of the FRAM is incipient. Rosa et al. (2015) applied the FRAM as a risk assessment tool for the task of reusing demolished concrete in a construction site. Von Buren (2013) used the FRAM to analyse the fall of a crane in a construction site. The remaining of this paper is structured as follows: (i) first, the FRAM principles are presented and an analysis is made of their implications to LC; (ii) second, an example of applying the FRAM to construction is presented, using the case of safety inspections carried out by government officers; and (iii) the conclusions summarize the main insights and opportunities for future research.

THE FRAM PRINCIPLES AND IMPLICATIONS FOR LC

Hollnagel (2012) presents four principles underlying the FRAM: **(i)** failures and successes are equivalent in the sense that they have the same origin - this means that things go right and wrong for the same reasons; **(ii)** everyday performance of socio-technical systems, including humans individually and collectively, always is adjusted to match the conditions;

(iii) many of the outcomes we notice, as well as many that we do not, must be described as emergent rather than resultant; and **(iv)** relations and dependencies among the functions of a system must be described as they develop in a specific situation rather than as predetermined cause-effect links. This is done by using functional resonance.

Principle **(i)** conveys the idea that variability, especially in terms of human performance, is always present in CSS, whether the outputs are desired or undesired. Of course, variability that leads to desired outcomes may involve latent conditions, which eventually may play a key role in the occurrence of wastes and accidents. However, such variability could not be, per se, *the* "cause" of said wastes and accidents, since it was always present. As applied to the Last Planner system of production control, principle (i) means, for instance, managers should not take for granted that a percentage of plans completed equal to 100% means that no relevant variability occurred. In fact, 100% may have been achieved precisely because there was relevant variability that managers should be aware of.

Principle **(ii)** conveys that adjustments are necessary because plans are inevitably underspecified and because resources are scarce. Adjustments will be approximate, but usually good enough, rather than precise (Hollnagel, 2012). LC, and more specifically Last Planner, accounts for this principle by using hierarchical planning that progressively details plans from a long-term to a short-term horizon. In fact, the idea that the "last planner" is the front-line worker recognizes the need for approximate adjustments. As a drawback, LC has not focused on how to close the feedback loop, by learning how the last planner adapts.

Principle **(iii)** relies on the concept of emergence, which is central to CS. Emergent phenomena arise from the interactions among several variables, and they have unique properties that are not found in any of the interacting variables (Cilliers, 1998). Such phenomena may be either desired or undesired, and while they cannot be fully controlled they can be influenced to some extent (Cilliers, 1998). For LC, principle (iii) implies that investigation of successes and failures should place less emphasis on finding "causes", and more stress on finding factors, and their interactions, that "set the stage" for performance. This proposed emphasis also has implications for action plans derived from said investigations, since it discourages reductionist interventions excessively focused on improving specific parts of a system.

Principle **(iv)** is based on the concept of functional resonance, which is "the detectable signal that emerges from the unintended interaction of the everyday variability of multiple functions" (Hollnagel, 2012, p. 29). The assumption is that the combination of multiple sources of everyday variability may create functional resonance, thus producing an unexpected outcome. This outcome can be, for instance, a project´s time and cost overrun, a workplace accident, or a defective product. Principle (iv) means that, in order to anticipate threats and opportunities, LC should have tools for modelling how normal variability can combine. In fact, apparently benign intentional changes introduced in a project by LC itself may trigger functional resonance.

APPLYING THE FRAM IN CONSTRUCTION: SAFETY INSPECTIONS

CONTEXT

This section presents an example of applying the FRAM in the context of safety management. The FRAM is used to model the reaction of construction companies to prohibition notices issued by a labour inspectorate. In many countries, such inspectorates are in charge of enforcing health and safety regulations, and construction sites are frequently targeted by inspectors given the poor safety record of the construction industry. The reported example uses data from a recent study by the author (Saurin, 2016), who over six years acted as a participant observer in 13 cases of prohibitions in construction sites in Southern Brazil. Over this period, other sources of data were also used, such as interviews with two inspectors, about 80 h of direct observations of construction sites with prohibited works, analysis of prohibition reports prepared by the inspectors, and analysis of reports containing the corrective measures implemented by contractors. The projects were mostly high-rise residential or commercial buildings executed by medium-sized contractors.

The labour inspectorate was widely regarded by contractors as very demanding, and the length of time of prohibitions ranged from two to eight months. In seven out of the thirteen cases, the contractor appealed to court in order to end the prohibition, usually after two or three rounds of unsuccessfully trying to end the prohibition through administrative means. Mixed outcomes resulted from the inspections, such as incremental innovations in safety equipment and time and cost overruns. A more detailed presentation of project characteristics and outcomes is made by Saurin (2016), who frames outcomes as emergent phenomena and institutional waste. According to Sarhan et al. (2014) this type of waste refers to “institutional systems, structural arrangements and cognitive undergirding assumptions that support and encourage wasteful activities in construction”.

STEPS FOR APPLYING THE FRAM

Execution of the FRAM followed steps from Hollnagel (2012):

(i) To define the purpose of the FRAM analysis: the three usual purposes of applying the FRAM are accident investigation, risk assessment, and evaluation of design changes (Hollnagel, 2012). In this study, the FRAM was applied to assess the effectiveness of actions taken by companies after the prohibitions were enforced;

(ii) To identify and describe the functions: functions are the acts or activities that are needed to produce a certain result, and the identification of functions should be preceded by the delimitation of the boundaries of the system of interest. Given the aforementioned objective of applying the FRAM, the presented example only accounts for functions involved in the processes that follow the prohibitions. Each function is described by a verb, and it has six aspects (described as nouns): input, output, precondition, resources, control, and time (Hollnagel, 2012). Not necessarily all aspects must be described, provided they do not impact on the variability of the output. Table 1 shows how functions <analyse report from inspectors>, <design corrective measures>, and <prepare report with corrections>

were described. Functions and aspects were identified from the databases produced in the study by Saurin (2016).

Table 1: Description of functions. * Ndi: Not described initially

Aspect/function	Analyse report from inspectors	Design corrective measures	Prepare report with corrections
Input (I)	New report received	Report analysed	Corrections designed
Output (O)	Report analysed	Corrections designed	Report prepared
Precondition (P)	Ndi*	Ndi*	Ndi*
Resource (R)	Ndi*	Proper H&S knowledge and skills	Proper H&S knowledge and skills
Control (C)	Ndi*	Areas and experts involved; regulations defined	Corrections implemented; Areas and experts involved
Time (T)	Ndi*	Strong time pressure by top management	Strong time pressure by top management

(iii) To identify the potential variability: the analysis of the potential variability of each function should account for what is reasonably expected to happen (Hollnagel, 2012). It is concerned with how the outputs of each function could vary in terms of time (too early, on time, too late, not at all) and precision (precise, acceptable, imprecise), from the perspective of the needs of downstream functions (Hollnagel, 2012). Table 2 presents the potential variability of some functions.

Table 2: Identification of potential variability. Note: + V = variability increases; - V = variability decreases

Function	Output	Variability of the output
Analyse report from inspectors	Reports analysed	On time: analysis starts immediately after receiving the written report informing the prohibition notice Acceptable (+ V): demands by inspectors can be ambiguous and unclear. Thus, the analysis of reports may also be flawed
Design corrective measures	Corrections designed	Too late (+ V): a number of factors, internal (e.g. slow decision-making regarding which and how corrections will be made) and external (e.g. lack of availability of designers) to the construction site may cause delays in the design of corrective measures Imprecise (+ V): the design may be technically flawed
Involve support areas and experts	Areas and experts involved	On time: support areas and experts are usually called up by the project manager soon after the prohibition notice is enforced Acceptable or imprecise (+ V): sometimes the experts do not have the expected skills. Furthermore, collaborative work among experts is not always fostered by management
Implement corrections	Corrections implemented	Too late or not at all (+ V): factors internal (e.g. low productivity) and external (e.g. inclement weather) may cause delays Imprecise (+ V): errors during the implementation of corrections Precise (- V): it was observed that workers, sometimes, fill in the gaps of incomplete design in an effective way
Prepare report with corrections	Report prepared	Too early (+ V): although the inspectors do not set any deadlines for receiving the report from contractors, these are often in an hurry to end the prohibition and therefore an incomplete report may be sent to the inspectorate, sooner than it should Imprecise (+ V): a report prepared in an hurry is more likely to be technically flawed

(iv) The aggregation of variability: this step involves an assessment of whether the actual variability of the output of a function, in a certain scenario, may affect the aspects of the other functions (Hollnagel, 2012). The scenario imagined in this study refers to work prohibitions in high-rise commercial or residential buildings, in which the construction company has financial, human, and technical resources to comply with, and perhaps question, the demands imposed by inspectors.

Table 3 illustrates the reasoning followed for analysing the aggregation of variability. Whenever an output of one function provided (impacted) an aspect of another function, a coupling between two functions is established, and therefore there is a path for variability propagation. Thus, couplings always involve links between the output of a function and any of the other aspects of other functions. The couplings are graphically represented in Figure 1, which shows the instantiation of the FRAM model for the analysed scenario. The software FRAM Model Visualizer 2.0 (available at www.functionalresonance.com) was used.

Table 3: Excerpt from the aggregation of variability (adapted from Von Buren, 2013)

The variability of the output of the function <design corrective measures>	
May propagate to the function <implement corrections>	
Affecting one or more of the aspects below – explain when and how	
Input (I)	Once corrections (e.g. repairs in physical protections, new safeguards, etc.) are designed, and approved by management, they can be implemented in the construction site. A flawed or late design may contribute to errors in implementation.
Time (T)	
Precondition (P)	
Control (C)	
Resource (R)	

Based on the aforementioned Tables (1, 2, and 3) and Figure 1, the conclusion can be made that functional resonance, with a negative outcome (i.e. corrective measures are partially or fully rejected by inspectors), is a plausible outcome of the process following the prohibition. In fact, in all of the 13 case studies of prohibitions, partial or full rejection of corrective measures occurred after the first round of changes made by the construction company. Moreover, sometimes inspectors identified new problems in their follow-up inspection, which had not been spotted in the original visit.

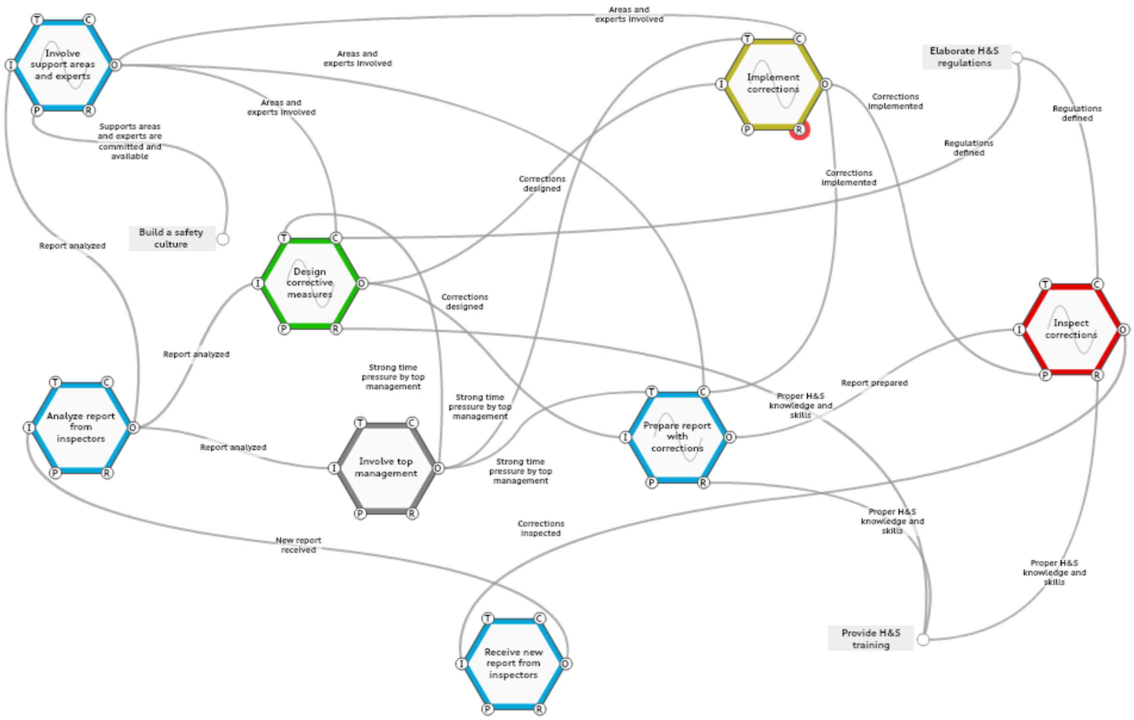

Figure 1: Instantiation of the FRAM model. Notes: (i) blue, functions primarily carried out by managers of the construction company; (ii) red: inspectors; (iii) green: outsourced designers; (iv) yellow: workers and supervisors; (v) grey: top management; (vi) rectangles: functions that are out of the boundaries of the focused system, but which may introduce variability into the system; (vii) the wave symbol inside the hexagon indicates the function has significant variability; and (viii) aspects in red circles are provided by the outputs of other functions, not represented in the model

This outcome may arise from the combination of the normal variability of functions, in a number of ways. For instance, an imprecise output of <involve support areas and experts> may be due to the involvement of low qualified or low committed experts in the design team, leading to late and technically flawed design solutions. Figure 1 indicates this variability will propagate to <implement corrections> as these will be based on a poor design. Of course, the output of <implement corrections> may be imprecise due to the variability of its own aspects, such as ineffective supervision and defective materials (resource aspect). According to Figure 1, failures in design and/or execution will also impact on the report prepared by managers. In fact, independently on the variability of upstream functions, the output of <prepare report with corrections> may also vary due to the variability of its own aspects – e.g. lack of clarity and organization of the written report, since some managers have little experience in writing this type of document (i.e. resource aspect). Eventually, the output of <inspect corrections> may also vary due to the technical background and approach used by some inspectors (i.e. resource aspect), who sometimes do not care to discuss corrective measures with managers and workers, and do not adopt consistent assessment criteria. Thus, the variability of upstream functions may be ultimately amplified by <inspect corrections>.

The mentioned couplings between functions were observed by the researcher in some of the case studies, indicating that no single failure or outstanding factor was the responsible for a negative outcome. Rather, interactions and couplings between functions, associated with everyday variability, made the outcome an emergent phenomenon.

(v) To identify consequences of the analysis: in this step, the objective is to propose ways to manage the possible occurrences of functional resonance that have been found by the preceding steps (Hollnagel, 2012, p.87).

Over the case studies, the researcher identified several countermeasures adopted by contractors in order to control variability. In order to evaluate whether the assumptions underlying these measures are theoretically sound, they are checked against six guidelines for the management of CSS (Saurin et al., 2013; Righi and Saurin, 2015): (i) give visibility to processes and outcomes; (ii) anticipate and monitor the impact of small changes; (iii) encourage diversity of perspectives when making decisions; (iv) design slack; (v) monitor and understand the gap between prescription and practice; and (vi) create an environment that supports resilience. These guidelines are in line with lean production principles, as discussed by Saurin et al. (2013). Table 4 lists four countermeasures adopted by contractors, from the perspective of the guidelines.

Table 4: Analysis of the impact of countermeasures

Countermeasures	Guidelines affected	Propagation throughout functions
Hire consultants and lawyers to review the report before sending it to inspectors	Consultants and lawyers work as extra resources (design slack) and provide an outsider perspective (encourage diversity of perspectives), spotting mistakes and errors in the report. Also, in reviewing the report, consultants and lawyers pay heed to apparently minor issues that may cause a delay in ending the prohibition (anticipate the impact of small changes)	The control and resources aspects of three functions (<design corrective measures> <implement corrections> <prepare report with corrections> may benefit from this solution. Variability of outputs of these and other downstream functions might be reduced
Implement corrections (and prepare corresponding reports) in small lots, in order to shorten the prohibition length of time	Working in small lots is mostly a lean principle. It also creates slack and supports resilience to the extent that it reduces time pressure on managers, so they can take the necessary time to design the more complex corrective measures, while at the same time the prohibition may be partially lifted	This solution seems to affect, mostly, the time and precondition aspects of <implement corrections> and <prepare report with corrections>. As a result of lower work-in-process, variability in downstream functions may be spotted early
Meet with the inspector before implementing the corrective measures, in order to get a pre-approval	This meeting(s) makes it visible to inspectors that the company is committed to find effective corrective measures, and it is also a means of obtaining the perspective of the inspector on the solution	This solution implies the creation of a new function <meet inspector before implementing corrections>), which does not appear in Fig. 1, since it does not always happen. New interactions would be triggered by the outputs of this function, which could be too late and imprecise.
Exchange experiences with other contractors in the region, which had similar prohibited works by the same inspectors, in order to learn what counted as "good enough"	Information on prohibitions usually spread quickly between construction companies. This supports resilience (i.e. quick adaptation) and offers different perspectives	This solution may be interpreted as adding more resources to <involve support areas and experts>. Based on the case studies, exchanging experiences tends to reduce the variability of downstream functions.

While Table 4 suggests that the countermeasures make sense from a theoretical viewpoint, data from the case studies indicate they are not always sufficient. As previously mentioned, contractors often need to go to court in order to end the prohibitions even if the countermeasures are in place. This may be due to the high variability of some functions, the diversity of agents, the strong time pressure involved in the process, and the fact the construction company has no control over <inspect corrections>, whose output is decisive for ending the prohibition.

Of course, a fundamental limitation of the countermeasures is their reactive nature. Saurin (2016) proposes that preventive actions should be focused on managing interactions between the: inspectorate and contractors (institutional level); inspectors and project management team (operational level); workers and managers; contractors and designers; contractors and federal government; and contractors and suppliers. For instance, concerning this last interaction, a function <purchase safety equipment from external suppliers> could have, as part of its control aspect, the use of checklists to evaluate whether the equipment complies with regulations.

CONCLUSIONS

This study was concerned with the use of the FRAM as a tool for modelling variability propagation in LC. Principles of the FRAM and LC were found to be compatible, and the analysis indicated that the insights from FRAM are valuable to LC. For instance, the FRAM makes it clear that emergence, instead of cause-effect relationships, provides a more realistic explanation of project outcomes. A focus on emergence also suggests that LC practices should place an emphasis on managing interactions, rather than fixing individual parts of the system.

The case of applying the FRAM to safety inspections was based on an ethnographic investigation of the system under analysis, which seems to be an appropriate approach for identifying variability and couplings between functions in CSS. In relation to previous studies of applying the FRAM, both in construction and other sectors, this case study made a contribution by proposing the use of six guidelines for the management of CSS as a quality check of the measures to contain variability.

Further applications of the FRAM in construction will be possibly more fruitful if focused on complex processes whose performance offers significant risks, either in terms of safety or other business dimensions. Of course, the LC community could also make a contribution to the improvement of the FRAM itself, by devising innovative ways of integrating it with other tools and principles. For instance, production planning could be modelled through the FRAM, supporting the identification of how small intentional or non-intentional changes (e.g. changing the sequencing of work packages) could provoke disproportional consequences. Quantification of variability and computer simulation of how it can propagate in different scenarios also poses opportunities for future research.

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