LEAN CONSTRUCTION AND RESILIENCE ENGINEERING: COMPLEMENTARY PERSPECTIVES OF VARIABILITY

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ABSTRACT

Lean construction (LC) emphasizes the reduction and coping with variability. Nevertheless, a portion of variability is unavoidable, and it triggers manifestations of resilience, at the individual, team and organizational level. This paper compares the perspectives of LC and resilience engineering (RE) of variability. Three criteria are adopted for the comparison: (i) commonalities and differences between the concepts of resilience and making-do, as the last is relevant for the LC view of variability; (ii) types of variability each perspective emphasizes; and (iii) tools for the description of systems, which set a basis for the identification of variability. Concerning the last criterion, a comparison is made between Value Stream Mapping, which is derived from lean, and the Functional Resonance Analysis Method, which is derived from RE. Based on this comparison, learning opportunities for LC from RE are identified.

KEYWORDS

Resilience engineering, making-do, variability, value stream mapping, FRAM.

INTRODUCTION

Lean construction (LC) is known for its emphasis on the reduction and coping with variability, in internal processes and external suppliers (Koskela, 2000). According to Hopp and Spearman (1996) variability is the quality of nonuniformity 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). In fact, little variability is a requirement for the use of several lean practices. For example, if variability is high, suppliers are unlikely to replenish stocks just-in-time, and the downstream production flow may be rapidly disrupted. Similarly, the use of fail-safe devices with a shutdown function is not recommended for highly unstable operations (Saurin et al., 2012), as they will often stop working. Nevertheless, the type of variability stressed by LC practices seems to be mostly that of managerial processes related to production and design, rather than the micro variability of front-line operations. Although Last Planner encourages workers involvement in the planning of their own work (in fact, workers are inevitably involved to some extent, regardless of Last Planner), the focus is on planning more and in "greater detail as you get closer to doing the work" (Ballard et al., 2009). However, the level of detail and contents of production plans that fit better

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the macro, and especially the micro variability of construction activities, has been often taken for granted. Thus, rather than arguing for planning more and in more detail, critical thinking is necessary on the need for planning differently. Moreover, as LC proposes that workers should be relevant planners (Ballard et al., 2009), the development of their planning skills should also be stressed.

An opportunity for LC to place a greater emphasis on the details of work at the front-line, and to encourage the development of new types of planning, has been opened by the introduction of the making-do concept. According to Koskela (2004), "making-do as a waste refers to a situation where a task is started without all its standard inputs, or the execution of a task is continued although the availability of at least one standard input has ceased". Formoso et al. (2011) add that making-do implies in a reduction of performance.

In contrast with the lean emphasis, an emerging safety management paradigm called Resilience Engineering (RE) explicitly values the positive side of variability, especially that arising from informal working practices and associated with the performance of front-line workers (Hollnagel et al., 2006). Some exploratory investigations of RE applications to construction industry have already been made (e.g., Hollnagel, 2014; Saurin et al., 2008). A core assumption of RE is that, regardless of the effectiveness of technological and management practices, variability cannot be completely eliminated from complex socio-technical systems (CSS), which are "intractable" (Hollnagel, 2012). Of course, RE does not argue against the use of practices deemed to reduce variability, as they support complexity reduction. RE recognizes that those practices are insufficient, and that they need to be re-interpreted to support the necessary and unavoidable portion of variability at the individual, team, and organizational level (Van der Vorm et al., 2011). Nevertheless, how to identify the desirable threshold of variability (and planning) remains an elusive question, both for RE and LC.

This paper has the objective of undertaking a comparison between the RE and LC views of variability, based on three criteria: (i) commonalities and differences between the concepts of resilience and making-do; (ii) types of variability each perspective emphasizes; and (iii) tools for the description of systems, which set a basis for the identification of variability. Concerning the last criterion, a comparison is made between two tools for process modelling: value stream mapping, which is derived from lean; and the Functional Resonance Analysis Method (FRAM), which is derived from RE. Based on this comparison, learning opportunities for LC from RE are identified.

MAKING-DO OR RESILIENCE?

Concerning making-do, based on the concept mentioned in the previous Section, its defining characteristic is that it is *waste* that causes *reduction of performance*. A task being initiated or continued without all its standard inputs is not the major discriminant characteristic of making-do, as resource scarcity is ubiquitous in CSS (Dekker, 2011). So far, empirical studies (e.g., Formoso et al., 2011) have not been able of quantifying the reduction of performance associated with making-do, although some of its consequences can be described qualitatively, such as the lack of safety. Another difficulty for measuring making-do is that it requires an explicit definition of the standard inputs for starting a task. Therefore, it is arguable whether existing studies are recording making-do or another phenomenon.

Concerning resilience, it is defined by Hollnagel (2006) as the "intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations even after a major mishap or in the presence of continuous stress". While the RE literature does not define precisely what is meant by "adjusting performance", we propose it involves one or more of the following: (i) the insufficiency or absence of action rules, which specify in terms of ‘if – then’ statements how people shall behave (e.g., wearing a seat belt when in a moving car) (Hale and Borys, 2013); (ii) improvisation, which is defined by Trotter et al. (2013) as the real-time conception and execution of a novel solution to an event that is beyond the boundaries for which an organization has anticipated or prepared - therefore, improvisation assumes the insufficiency or absence of action rules; and (iii) the isolated existence of performance goals and/or process oriented rules. While performance goals define only what has to be achieved and not how it must be done, process oriented rules define the process by which the person or organization should arrive at the way they will operate – e.g., requirements to consult with defined people when an emergency situation arises in order to decide how to handle it (Hale and Borys, 2013).

In fact, resilience is defined as a *functional property of a CSS*, while making-do is defined as a system *outcome*. As another difference, the concept of resilience is neutral in the sense that it does not specify at which costs required operations are maintained. Reduction of performance may or may not occur as a result of resilience. Wears and Vincent (2013) discuss examples of overusing and misusing resilience in healthcare, and the resulting side-effects such as staff burnout, frustration and resistance to change. Wachs et al. (2012) report examples of how resilience may be a way of masking waste in the work of grid electricians.

Both phenomena also share commonalities, such as: (i) they are triggered by scarcity of resources; (ii) they are emergent, which means that they arise from the interactions among several variables, and that they have unique properties that are not found in any of the interacting variables (Cilliers, 1998); and (iii) manifestations of both can occur at the individual, team, and organizational level. Figure 1 summarizes the main relationships between the concepts of making-do and resilience. According to Figure 1, the definition of making-do conveys the message that it is intrinsically negative, and that learning from making-do equals to learning from failure. That Figure also indicates that the consequences of working without all standard inputs can only be fully assessed in hindsight, and thus it seems that any measurement of making-do cannot be completely conducted on real time.

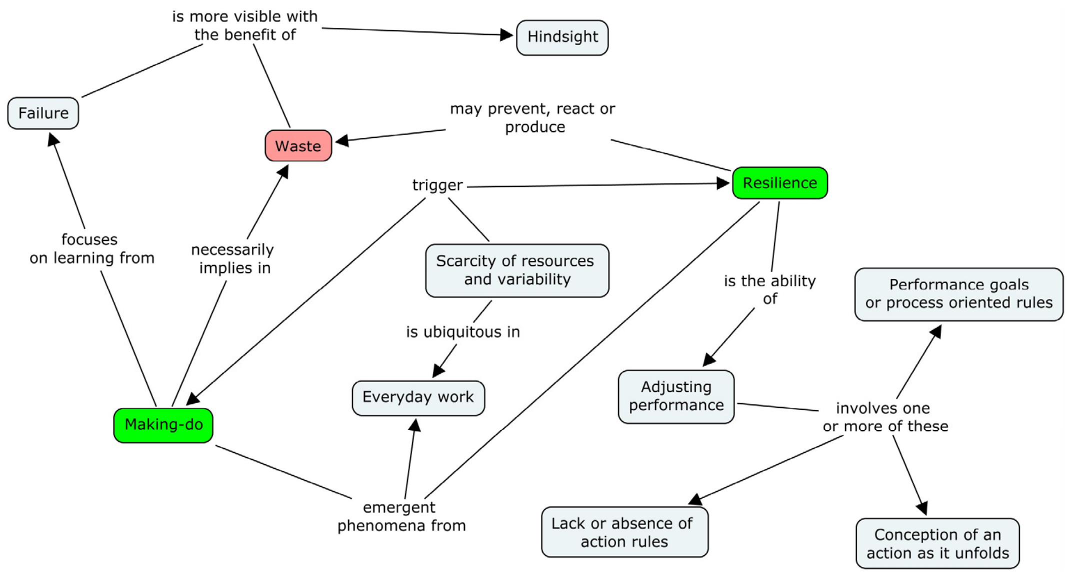

Figure 1: Relationships between the concepts of making-do and resilience

EMPIRICAL EXAMPLE OF MAKING-DO AND RESILIENCE

In this Section, an empirical example of concepts mentioned in Figure 1 is presented. The example involves the steel structure assembly of a commercial building. It has nine floors and twenty workers have been involved in the assembly, which is expected to take four months. The company responsible for assembling the structure is the same that designs and manufactures it. In turn, this company is subcontracted by the main contractor. Data collection involved three visits of one researcher to the construction site, and it included about eight hours of observations of work at the front-line, the analysis of standardized operating procedures, and interviews with two workers, focusing on the reasons underlying their actions.

Figure 2 illustrates the analyzed situation, in which a worker is hammering a beam so as to fit it in-between the columns. This operation is required because the columns and beams are not placed by the crane at the right position. However, the worker who makes the adjustments is in an unsafe position, as he is using a 5 kg hammer and his feet are on the top of the guardrail around the mobile work platform. The hammerings can displace the columns even further, which implies in rework to reposition it after connecting all pieces.

In this example, making-do is characterized by: (i) the lack of a standard input for starting the task of connecting beams and columns, which corresponds to columns and beams out of the right position; (ii) reduction of performance, represented by the need for using labor to carry out an adjustment under unsafe conditions, and by the rework necessary for repositioning the columns. In turn, resilience is characterized by: (i) the lack of any formal standardized operating procedure to carry out the adjustment; (ii) the need for deciding how to do the adjustment as the action unfolds – e.g., the worker has to decide, on the spot, how to get access to the beam, and where to hammer. Thus, resilient performance compensates, inefficiently, for the lack of standard inputs, and it is fully deployed at the individual level, without adequate organizational support. An aggravating condition is that the discussed situation was reported to be normal in all sites of this company, and it is tolerated by management as it has produced the expected outputs. Thus, this is also an example of misusing and overusing resilience.

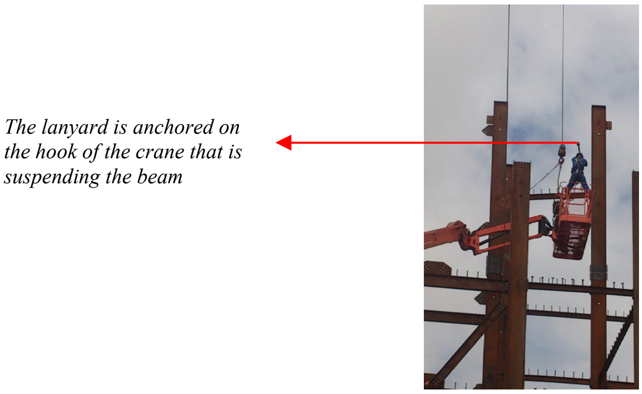

Figure 2: Example of making-do and resilience

TYPES OF VARIABILITY EMPHASIZED BY LC AND RE

So far, RE has been mostly a descriptive discipline, characterized by a proliferation of studies reporting stories of resilience (and the lack of), especially in sectors that involve hazardous technologies, such as aviation and healthcare. Such studies usually describe how the adoption of actions which had not been anticipated by standardized procedures supported recovery from challenging situations (Righi et al., 2014). Thus, RE studies describe how variability was beneficial to sustain operations, although the need for such variability is often taken for granted as inevitable. Although there is no widely accepted and formalized "RE classification" of variability types, in this paper we adopt the classification by Hollnagel (2012), who is one of the founders of RE as an academic discipline. He classifies the types of variability according to its association with three categories of functions: technological, which are carried out by various types of machinery; human, which are carried out by individuals or groups; and organizational, which are carried by large groups of people, where the activities are explicitly organized. According to Hollnagel (2012) the default assumption is that technological functions are stable, that human functions vary with high frequency and high amplitude, while organizational functions vary with low frequency but high amplitude. This means that the variability of human and organizational performance is of most interest. Hollnagel also proposes that the variability of the outputs of functions be classified with regard to time (too early, on time, too late, and not at all) and precision (precise, acceptable, and imprecise) (Hollnagel, 2012).

Similarly with RE, there is no "LC classification" of variability types. However, Koskela (2000) proposes seven categories of requirements that should be in place before starting a task, in order to reduce its variability: design, materials and components, labor, equipment, space, adequate external conditions, and absence of interference from other services. Nevertheless, core LC practices do not seek to understand *how*, *why* and *when* human performance varies. The emphasis of Last Planner is illustrative of this view, as it focuses on the stability and reliability of the flow of work packages. The assumption seems to be that if the Percentage of

Completed Work Packages (PPC) is high and stable, variability of the means to achieve that result is of little or no importance. While the description and measurement of making-do offers an opportunity for improving the understanding of all types of variability in construction, it has not yet been strongly used for that purpose. New insights on the variability of construction processes could be obtained through the use of cognitive task analysis methods, which are widely used in other sectors for knowledge elicitation, data analysis and knowledge representation (Crandall et al., 2006). However, such methods are still largely under explored by construction management academics and practitioners (Solis and O´Brien, 2014).

TOOLS FOR THE DESCRIPTION OF SYSTEMS

In this Section, two tools for describing systems are presented. For LC, Value Stream Mapping (VSM) was chosen as the representative method. Although VSM originated from lean production (Rother and Shook, 1999), several applications in construction have been reported (e.g., Leite and Neto, 2013). For RE, the Functional Resonance Analysis Method (FRAM) developed by Hollnagel (2004, 2012) was chosen, as it is, so far, the main tool for modelling CSS in line with RE premises. The name of the method is due to the assumption that, in CSS, accidents occur as a result of everyday variability, which through "functional resonance", amplifies and leads to unexpected outcomes (Hollnagel, 2012). The study by Ferreira (2011) is an example of using FRAM for modelling railways operations. To the authors´ knowledge, no application of FRAM in construction was reported in the academic literature so far, although an example of using it in the analysis of an accident in construction was identified from the 2013 meeting of the FRAM community of researchers and practitioners (see http://functionalresonance.com/framily-meetings/framily-2013.html). Figure 3 presents a comparison between VSM and FRAM, based on twelve criteria.

Criteria	FRAM	VSM
Origin	Studies of safety and resilience in CSS	Studies of lean in manufacturing
Typical situations of using the method	Risk assessment and accident investigation	Mapping the current state and designing the desired future state
Performance dimensions emphasized by the method	Safety and variability	Lead time and efficiency
Unit of analysis	Functions	Stages of the value stream
How is the unit of analysis described?	Six aspects of functions: input, output, preconditions, resources, time, and controls	Several data are required (e.g., cycle time, setup time, efficiency, number of workers, etc.), although there is no standardized set of data
Is visibility given to what exists between the units of analysis?	No, the method simply states that the units of analysis are connected to each other	Yes, the typical assumption is that there are queues/work-in-process between the units of analysis
Assumption on the nature of systems	Non-linear	Linear
How does the method capture the dynamics of production processes?	It captures fairly well	It does not capture the dynamics
Does the method require the use of quantitative data?	No	Yes
Degree of tacit knowledge required to use the method	High	Moderate
Degree of difficulty for obtaining insights from the method	High	Moderate or low
Degree of dissemination of the method among practitioners	Low	High, especially in the manufacturing industry

Figure 3: Comparison between VSM and FRAM

Figure 4 contrasts the graphical representations of how both methods describe a system. The edges of the FRAM hexagons represent the six aspects of each function while the lines connecting the hexagons represent the propagation of variability. In a parallel with making-do, five out of the six aspects (output is the exception) can be interpreted as the standard inputs for starting a task. If they vary, the output of the function may vary too, possibly causing making-do. In fact, FRAM may help to understand how making-do propagates throughout the value stream/functions, and how it can be amplified or dampened by the variability of other functions. Another insight is that the surplus of standard inputs is also a source of variability that may affect the output. The surplus is in itself a reduction of performance (e.g., more than the necessary money and time may have been used), thus causing making-do.

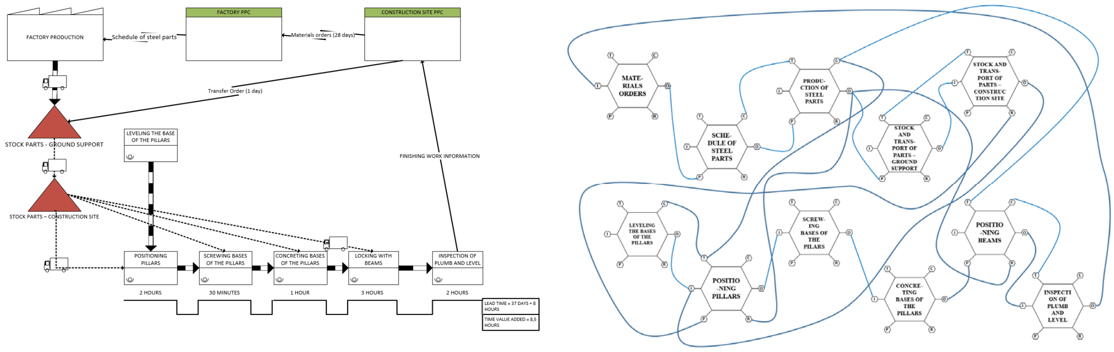

Figure 4: Left: VSM – the rectangles are the operations, the triangles are work-in-process, and the arrows indicate the flow of materials and information. Right: FRAM – the hexagons are the functions, the edges are the aspects of the functions, and the connecting lines show how variability propagates throughout functions

Overall, Figures 3 and 4 indicate that FRAM and VSM manage the trade-off between ease of use / simplicity and completeness in different ways. On the one hand, the relative simplicity of VSM has contributed to its widespread use among practitioners, especially in the manufacturing industry. Thus, as accumulated experience with VSM is substantial in some sectors, identification of solutions to streamline the workflow has been fairly straightforward (e.g., eliminating waiting times by using multifunctional workers and balancing processing times). However, VSM provides a snapshot of a CSS, conveying at least two misleading messages: (i) that the mapped value stream has no relevant interactions with other elements of the socio-technical system, provided there are no shared resources with other value streams, such as machinery and staff; and (ii) that small variations in relation to the graphical representation are unimportant - after all, processes vary all the time. Nevertheless, recent versions of VSM adapted to healthcare (Worth et al., 2012), which is regarded by many scholars as one of the most complex sectors, require the collection of maximum, minimum and average performance data, such as lead times, thus recognizing the importance of variability. Overall, both criticisms (i) and (ii) indicate that some assumptions of VSM are in conflict with the nature of CSS. Concerning (i), it conflicts with the facts that CSS are formed by a large number of dynamically interacting elements, that they are open systems, and that they are prone to non-linear interactions, in which small changes propagate throughout the system in unexpected ways (Cilliers, 1998). Although no resource is shared formally, sharing may occur by chance as a value stream is susceptible to a myriad of unplanned interactions, which is a well-known fact for construction academics and practitioners (Bertelsen and Koskela, 2005). Concerning (ii), it conflicts with the facts that CSS quickly evolve over time, and that small changes should not be overlooked due to the already mentioned non-linear interactions. In fact, these and other simplifications made by VSM should be explicitly recognized when this tool is applied in a CSS; it should not be taken for granted that they are not relevant. Furthermore, Rother and Shook (1999) do not recommend the use of any standard set of data to describe a system, and its resulting variability. While data such as cycle times and efficiency are usually collected, the tacit knowledge of those using the tool usually defines what counts as necessary data. This situation may be due to the fact that VSM lacks an explicit view of variability.

On the other hand, FRAM provides a more nuanced description of complexity, at the expenses of a difficult process for obtaining insights from the generated model. In fact, the use of FRAM is not recommended for trivial events (e.g., some well-known occupational accidents), as the same insights could be obtained from simpler methods (Ferreira, 2011). As a major difference between VSM and FRAM, the last is concerned with describing the propagation of variability throughout the value stream. The analyst using FRAM should identify the actual and the potential variability for the six aspects of each function. Then, it should be questioned how the variability of each aspect, for each function, may influence aspects of other functions, which are not necessarily those immediately upstream or downstream (Hollnagel, 2012). Technical knowledge of the domain, supported by cognitive task analysis, may provide a basis for understanding variability propagation. The leap from modelling variability propagation to designing effective control measures may also be difficult, as the envisioned actions to reduce variability may prove unpractical and produce side-effects, such as new forms of variability.

LEARNING OPPORTUNITIES FOR LC FROM RE

In this Section, examples of learning opportunities for LC from RE are presented, focusing on the management of variability. They are:

(a) LC could place more emphasis on the understanding of variability of individual and team performance across all hierarchical ranks, but especially at the level of front-line work. This may be useful for the design of more realistic and useful plans and standard operating procedures. In this respect, it is worth noting that the traditional lean production recipes for work standardization of front-line workers are conceptually limited, both for construction and other CSS. For example, Rother and Harris (2001) propose that standardized work should include the definition of takt time, cycle time, standard work-in-process, and the sequencing of operations. Such guidance is superficial to the extent that different types of plans and work standards may exist (Hale and Borys, 2013), and that the possibility of adaptations is neglected. Thus, innovative ways of designing standardized operating procedures in construction are necessary. Such procedures should not be separated by objective (e.g., safety, quality, etc.), as integration of all the rules directed at all of the objectives of a given activity is a more efficient option (Hale and Borys, 2013);

(b) While resilience is ubiquitous in construction sites, it is probably mostly reactive and dependent on workers´ initiatives, without adequate organizational support. This type of resilience may be closely associated with the high incidence of making-do in construction sites. As a result, LC should invest more on creating conditions that support resilient performance. Saurin et al. (2013a; 2013b) proposed some guidelines in this regard, such as designing slack, giving visibility to processes and outcomes, encouraging diversity of perspectives when making decisions, monitoring the gap between prescription and practice, and anticipating and monitoring the impact of small changes. Further investigation is required to understand how existing LC practices support the use of those and other similar guidelines;

(c) The modelling of variability propagation should be a greater concern for LC, rather than emphasizing the variability of isolated operations. However, short-term production planning illustrates how difficult that modelling can be, as work packages are recorded in the planning forms as discrete entities. As dozens of work packages may have been planned, the full comprehension of their dependencies is beyond the cognitive capabilities of any individual planner. In this respect, the use of FRAM in the context of production planning (e.g., work packages may be equivalent to the FRAM functions) as well as the development of new IT tools, could support the identification of dependencies and the impacts of variability propagation.

CONCLUSIONS

This paper presented a comparison between the LC and RE perspectives of variability. The concepts of making-do and resilience were useful for the comparison, as they represent manifestations of variability from each perspective. Making-do and resilience were found to have commonalities and differences, and therefore guidance was provided for the observation and measurement of both phenomena. Concerning the types of variability, RE seems to be relatively more concerned with the development of descriptive theory, as it places a stronger focus on understanding how work really happens at the front-line. LC and RE also adopt different assumptions for describing systems, as illustrated by the comparison between VSM and FRAM. However, attempts to use both tools jointly are encouraged, as they may be complementary.

Based on the comparison carried out in this study, learning opportunities for LC from RE were identified. Overall, renewed theoretical effort of the LC community is necessary to describe variability, including its different manifestations, possible classifications, identification of normal and acceptable thresholds, and mechanisms of propagation throughout functions and value streams.

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