# RESILIENCE ENGINEERING: A NEW PARADIGM FOR SAFETY IN LEAN CONSTRUCTION SYSTEMS

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## ABSTRACT

Achieving reliable workflow between construction operations is paramount to the success of Lean Construction implementations. In Lean Construction, as in lean production, workflow of operations is affected by waste (muda), variability (mura), and overburden to workers and machines (muri). It follows then that reliable workflow in construction operations cannot be achieved without safe work practices, which is the concern of this paper. The work of Jens Rasmussen was used previously as a foundation to propose a new cause and effect model for the way construction accidents originate and propagate to injury. The model provided a conceptual framework to help workers better detect where hazards may be released, better cope near the boundary beyond which work is no longer safe, recover if control is lost, and finally to minimize the effects if loss of control is irreversible. This paper presents a paradigm that investigates the ability of actors within an organization to anticipate and adapt *before* and *after* risk situations give rise to loss of control. The paradigm is dubbed "Resilience Engineering" in an attempt to signify that the ability to respond and adapt to unexpected changes can be engineered into organizational settings similar to how certain materials are engineered to be resilient – to recover to their original shape after being stressed. According to the pioneers of this field, a resilient organization is one that has mastered the art of managing and coping with unexpected events and following disruptive consequences. An underlying principle in Resilience Engineering is that understanding failure in order to prevent its reoccurrence is more profound when we understand how safety is created by people in workplaces with continually changing hazard sources and inevitable compromises between safe and productive actions. In this paper, the origins of Resilience Engineering are reviewed, focusing on what it is and what it isn't. The paper concludes with propositions for implementing Resilience Engineering in construction settings and offers pointers to future research.

## KEY WORDS

lean construction, safety theory, occupational safety, construction safety, construction accidents, resilience engineering

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## INTRODUCTION

Based on statistics alone, safety appears to be improving somewhat in the construction industry. The most recent version of the information rich "Construction Chart Book" (2008) reports that rates for construction overall work-related fatalities have decreased by 22% in the period from 1992 to 2005 and nonfatal injuries and illnesses with days away from work (DFW) dropped by 55% in the same period.

This is hardly cause for celebration – the raw numbers are more revealing. In the period mentioned 16,068 souls perished while working in the noble field of construction, an average of about 1,147 workers per year. Falls and electrocutions are the leading causes of death but have declined over the past 15 years. The "Chart Book" attributes this to focused efforts on prevention.

Other figures reveal the instance of elevated lead blood levels is disproportionally high in construction workers compared to other workforce sectors and about 41% of construction workers over age 55 were diagnosed with hypertension in 2005 (Chart Book, 2008). It would be difficult to argue that the safety, health, and well-being of the American construction worker is well-protected.

The loss and injury to construction workers is discouraging for other many reasons apart from the blatant disregard for humanity. The industry is aging and needs new workers. The average age of construction workers is 39 years old (the median is 41), up from 36 in 1985. By 2014, just six years from the date of this conference, 792,000 additional wage and salary jobs are expected to be needed.

Demographic trends indicate that young Hispanic workers are entering the construction workplace to fill this burgeoning need. In 2005, the U.S. construction workforce benefitted from the labor of 2.6 million Hispanics in a total pool of 11.2 million total workers. This phenomena places new demands on society and construction. Forty-two percent of Hispanic workers report that they can't speak English and, compared with their non-Hispanic counterparts, are younger, less-educated, less likely to be a labor union member, receive a lower-wage and fewer health care benefits, are more likely to be injured at worksites, and are about twice as likely die on the job (Chart Book, 2008). A skeptical person might speculate that safety and health risks are being transferred to a portion of society that is least able to bear the cost of the transaction and to "stand up for itself" rather than seek out new solutions to the chronic safety problem.

Another discouraging aspect of construction safety is that it is costly. In 2002 dollars the total (direct and indirect) costs of fatalities and nonfatal injuries was $13 billion. It is clear that safety issues places *demands* on the construction industry and individual firms that are dynamic and broad-ranging.

The lack of improvement in the safety record, or its stagnation, may be a reflection of a fundamental problem in understanding the accident process. Thus far, most efforts to understand the accident process have failed to recognize the dynamic and dependent nature of construction work (Howell et al. 2002). Moreover, the organizational pressure for productivity and the individual urge to minimize effort, push workers to work near the boundary of safe performance (Saurin et al 2004, Howell et al 2002, Rasmussen 1997). Safety programs create a counter pressure that aims to minimize exposure to hazards, and keep workers away from hazardous situations. In construction, worker training and motivation is assumed to be the key to preventing accidents.

A model that recognizes the pressures that push workers towards more risky behaviors is that advanced in Rasmussen's theory of cognitive systems engineering (Rasmussen et al. 1994). Howell et al. (2002) proposed a new approach to understand construction accidents based on Rasmussen's model wherein it is emphasized that workers need to receive training to make them more conscious of hazardous work environments and to engage the work with better planning and appropriate protection in a very similar way to how fire fighters engage hazardous situations.

This paper expands the discussion began in Howell et al (2002), Saurin et al (2004), and Saurin et al (2007) to encompass the region where demands placed on the production system force it out of its normal working range with regard to construction safety – novel and dangerous situations are encountered that were not possible to train for or anticipate. The paper will accomplish this with a foray into resilience engineering and its application to construction safety.

## RESILIENCE ENGINEERING

A proactive systems approach to improving safety, termed Resilience Engineering, is examined in this paper as a means to assess the adaptability of organizations in relation to the production demands encountered. Resilience engineering is grounded in sociotechnical systems (STS) theory. STS theory was developed at the Tavistock Institute in London in the late 1940's to relate social and psychological sciences to the needs of society. Researchers at the Institute studied coal mining production methods in the early 1950's to compare pre-mechanization methods; specifically the "shortwall method" approach that relies on multi-skilled teams of autonomous workers to the mechanized approach, the "longwall method" of coal mining, which was Tayloristic in nature, highly structured, and highly mechanized (Trist, 1951).

The study highlighted the fact that there are different ways to structure work, under the same umbrella of technological and labor constraints, with different social and psychological effects. The study also revealed that there are different ways available to organizations to design work. The design of production systems in the construction industry has largely been ignored (Ballard et al, 2001) as has the social and psychological aspects of the work. Correspondingly, so has organizational design, not just in construction but all industries. It is, in the words of Albert Cherns (1976), organizational design is "…simultaneously esoteric and poorly developed …" He further states that"… existing organizations were not born but "just growed."

Resilience engineering is discussed here as a new and extended outlook on safety for construction organizations. Lean construction as a backdrop is appropriate here because, as Woods (2006) states, examples are needed of how people at the workface fill gaps in specifications to create safety day-to-day in the face of increasing production demands. The term 'resilience' has different meaning across many disciplines (Saurin et al 2007). In nature one thinks of a resilient entity as one that absorbs extreme events, such as high winds or a toxic shock (e.g. a red tide event), and is able to draw upon reserves in the system to withstand the attack. An example would be a willow tree bending in high winds and gracefully returning to its original position. In humans resilience is the ability to absorb the slings and arrows of life and lead a normal life or adapt to the changes brought upon by the life altering event.

Inherent in resilience is the notion of adaptability to a perturbation. Woods (2007) defines resilience in a broad sense as the ability of a system to "…handle disruptions and variations that fall outside of the base mechanisms / model for being adaptive as defined in that system." However, as Woods (2006) points out, all systems adapt even though the adaptation may be slow and difficult to recognize. Of course, adaptability is finite and sometimes trees, humans, and organizations reach a breaking point.

Resilience engineering is concerned with how organizations manage unexpected events and how people in these organizations become prepared to cope with surprises (i.e. events that fall outside of planned for events and that are unforeseeable). It views resilience as a systems property and moves away from the linear cause and effect thinking that is prevalent when analyzing construction accidents. It looks to organizational factors instead of human errors or machine malfunction as conditional contributors to accidents (Hollnagel and Woods, 2006; Woods, 2007).

In resilience engineering, safety is not viewed as a system property but "…as something a system or organization *does*, rather than something an organization *has*" (Hollnagel and Woods, 2006). In other words, safety is not something placed into a system through rules and standards that will remain in place but rather safety is a reflection of how a system performs. This perspective on safety means that it should not be demonstrated by the absence of accidents from a system, but rather by the existence of certain system characteristics.

System resiliency should not be confused with system reliability, which is often used as a measure of safety. A system that is reliable and has a probability below which failure will occur is not resilient unless it has the ability to recover from infrequent and unexpected perturbations and disruptions to expected working conditions (Hollnagel et al 2006). Moreover, system resilience cannot be simply integrated in using more procedures, guidelines, personal protective equipment, and barriers. As advocated in Lean Construction, system resilience is achieved through continuous monitoring of system performance and "how things are done". Hollnagel and Woods (2005) state that resilience is "tantamount to coping with complexity, and to the ability to retain control."

In today's construction industry firms are generally well-aware of the demands that may be imposed upon them in the course of normal working condition. For instance, construction schedules typically include contingences for inclement weather that may delay production activities (Hinzie, 2008). The contingency is typically derived from data obtained from weather authorities, dictated by the owner, or based on the best guess of the construction manager(s). By including weather as a planned event the project team has (at least in theory) anticipated a perturbation to the production schedule. If the duration of the weather event occurs within the anticipated timeframe no extraordinary efforts will have to be extended to meet the demand to finish on time. In other words, the organization is adaptable to the perturbation – *in this range*.

Now envision that a 100-year rain occurs in the course of the project (say during the excavation phase), an extreme event not anticipated by anyone. Not only are company resources stretched to the limit but supporting resources throughout the region are stretched to the limit as other contractors in the same boat, perhaps both figuratively and literally, need rental equipment and labor resources that are exhausted (perhaps both physically exhausted from overtime work and exhausted in the sense that there are no additional labor sources available) as production resumes.

Resilience engineering is concerned with the behavior and reaction of the organization as it moves from this anticipated working range (i.e. an accounted for disruption to work) to a state outside of the normal working range (i.e. the 100-year rain). Now the firm must pick up the tempo of work and increase capacity to meet this new demand. The firm must stretch existing resources to meet the new demands as it exits the normal working zone and ramps up production to 'make-up' for lost time. Research has shown that when this situation occurs firms are apt to sacrifice safety for production concerns and that individuals, especially those removed from the workface (i.e. higher level managers) aren't aware that they are operating outside of the bounds of built-in adaptability and are jeopardizing safety (Woods, 2006).

The scheduling example illustrated is fairly straight forward. However, there are multiple instances in construction that have the potential to sacrifice safety for production that aren't nearly as well delineated. For instance, production parameters can quickly change when an associate is unexpectedly absent from work or a critical piece of equipment is out of operation (i.e. a crane). Murphy's Law can't be ignored here; it is not unimaginable that both events could occur simultaneously. Production demands don't diminish just because someone stays home or a crane is broken. Field managers often devise 'work-around's' to compensate for missing production component in order to maintain production schedules. These actions have the potential to move the firm from the normal working realm where adaptability is anticipated to an area that stretches the firm's ability to adapt. In the worst case scenario events could unfold that expose the firm or project to failure, such as a fatality or serious accident.

Resilient engineering has multi-faceted uses. One is to provide indicators that allow firms to recognize when they are moving to an area outside of its normal working capacity and into the area where production demands impinge upon safety so that an intervention can be made to stay out of dangerous working situations. Here the firm is better prepared and not surprised by perturbations to the system, resources that add capacity to the firm are located and at the ready if needed. Another goal of resilient engineering is to help the organization to become, as expressed by Woods and Wreathall (2008), well-calibrated. A well-calibrated firm knows, adaptability-wise, when it is in the normal working zone, when it is changing, and knows its limits, thus allowing it to invest in extra capacity or other means of adaptation when extraordinary events are encountered. Finally, resilience engineering deals with providing graceful transitions between the normal zone to the extraordinary zone, and a possible zone of extreme restructuring.

### STRESS-STRAIN ANALOGY FOR RESILIENCE ENGINEERING

Woods and Wreathall (2008) borrow the concept of stress-strain plots from material science to characterize and assess the resilience of a system. The following is adapted from that discussion (unless otherwise noted) and is related to typical construction scenarios where applicable. Figure 1 illustrates a typical stress-strain plot. Varying demands placed on a project (e.g. production and labor demands as described above) stand-in for stress (normally on the y-axis) on the plot. Strain is analogized to describe how the system adapts (or stretches), using available capacity (e.g. working overtime, renting additional excavation equipment) to the stress applied. Strain is plotted on the x-axis. The defining characteristic (i.e. parameters and regions) of the typical stress-strain plot, also known as the state space, distinguishes the organization as resilient, or its opposite *brittle*, in terms of adaptability. The state space also acts as a harbinger for management so that they can calibrate the organizations true status with perceived status. Typically, managers overestimate the state of safety, in other words firms believe that they are safer than reality indicates.

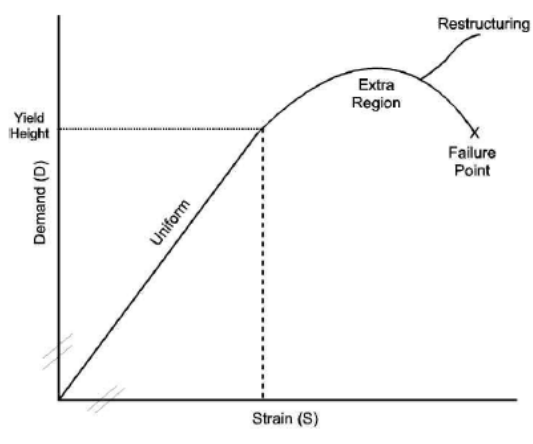


Figure 1: Stress-strain state-space (from Woods and Wreathall, 2008)

The uniform portion of the curve (the elastic region) corresponds to times and situations where the organization handles demands easily, stretching to accommodate them. Here the risks are anticipated by building in capacity to avert extraordinary failure or disruption. In other words, the company has adequately foreseen disruptions that may impact disruptions. An example would be accounting for weather delays as mentioned above. Plans, procedures, and flexibility in operations are the bellwether of the uniform region – in general, demands are well-known and accounted for, making stretching easy in this region. The yield height (the inflection point of the curve where elasticity ends and plasticity begins) of the uniform response curve captures the first-order adaptive capacity of the firm. This is the *on-plan* performance area.

The yield height can be adjusted by adding capacity in the uniform region or by changing the range of demands the curve can accommodate. One example could be additional training such as high-rise rescue training, drills, and simulation on a multi-story building. This is similar to enlarging the safe zone in the Rasmussen model. In fact, the entire yield region is captured in the dynamics of the Rasmussen model as presented in Howell et al (2002).

Thinking in terms of adaptation and capacity can help the construction manger foresee risks and adapt plans accordingly. Alas, being successful at anticipating and building-in capacity in the first-order also turns out to place another demand on the firm that is to improve even further. This is sometimes characterized as doing things 'faster, better, and cheaper.' Woods and Hollnagel (2006) call this the 'Law of Stretched Systems' where managers will try to gain a competitive advantage over rivals by exploiting the new capacity to increase the tempo, efficiency, complexity, and performance of work.

This holds interesting implications for Lean systems where practitioners constantly look for ways to increase throughput by eliminating waste at the system level in complete avoidance of local optimization. System-level optimization will actually help system resiliency, while local optimization might move a system toward brittleness. Woods and Wreathall (2008) report that most adaptation models assume that efforts to optimize systems does not affect system resilience or brittleness. However, research in biological systems has found that this assumption is incorrect; "…instead, efforts to make systems perform more optimally on some dimensions and demands will increase the systems brittleness when it encounters situations or demands that fall outside that design envelope."

Beyond the uniform region lies what Woods and Wreathall call the extra region (x-region for short). In material science this is known as the plastic region. This is where things get interesting. This is not where workers consciously step into the hazard zone as described by the Rasmussen model. Rather, now the demands encountered become more difficult to accommodate and the firm does not stretch in predictable ways. Demands are imposed upon the firms that go beyond what was anticipated in the on-plan performance area. In this region safety and production efficiencies may be compromised as 'gaps' appear in the organizations that exceed the first-adaptive capacity.

Resources, or second-order adaptive capacity, must be garnered to avoid reaching the failure point. Commonly, experienced groups or individuals at the sharp-end (workers) can recognize when they are operating in the plastic region and take actions to cope with increasing demands - in other words they begin to fill in the 'gaps' caused by lack of capacity. These actions are indicators that the firm is in the x-region. In the 100 year rain event mentioned above, the prime contractor might subcontract another excavator to work in parallel with the original excavator. This is reflected in the upswing portion of the x-region that corresponds to extra capacity added to meet demands. This action is fraught with potential problems. Other bottlenecks and constraints may appear and the tempo of the project increases. For instance, adding a second crew will incur more supervision. If additional superintendents or other supervisors are not included in the second-order adaptation then safety might suffer. Opportunity cost cannot be ignored here. Keeping a watchful eye on the second excavation crew means that other activities on the site are ignored that could impact safety and production.

If the demands imposed in the x-region begin to exceed second-order adaptive capacity then the curve begins to acquire a negative slope and heads toward the failure point. To avoid failure, the firm may decide to *re-structure.* The re-structuring occurs at a point in the x-region, prior to failure but at a location where there is time to rally the requisite resources to rescue the project. This could entail discarding the baseline schedule and re-planning the project. Resilient firms will anticipate the re-structuring phase and adjust capacity accordingly. Brittle firms will go bankrupt or worse, erode safety margins and endanger personnel. This highlights the importance of calibration, or knowing where a firm is situated with respect to the state space system. Mis-calibrated firms don't realize that they are in the x-region or perhaps heading toward failure. Those at the blunt end, distal from the work, usually mis-calibrated the region that the firm is in on the state-space plot.

## DISCUSSION

Woods and Wreathall (2008) are clear that the first-order region is not the focus of resilience engineering. Resilience should be reserved for perturbations that are outside of the system's base mechanism for adaptation (Woods, 2006 RE). There are a few options, at this point on the emerging field, to define what constitutes resilience in the stress-strain state space. One view is to use the plot in its entirety to gauge the resilience of the organization and to adjust its parameters (i.e. yield height, second-order capacity, etc.) in order to become better calibrated, and to develop indicators of resiliency / brittleness. Another definition might focus on how adept an organization is at mustering the troops and materiel to quickly react in the x-region. A resilient firm would be able to get its hands on resources quickly and with little effort, brittleness might imply the lack of this skill. Woods and Wreathall (2008) suggest the best definition, given the present state of research, is to characterize a resilient organization as one that make transitions between regions easily (e.g.

uniform to x-region) and sub-regions (e.g. x-region to re-structuring). Resilient organizations would make these transitions easily, while brittle organizations might by-pass, say the x-region, and fail.

All analogies have flaws and limitations and the stress-strain view is no different. Woods and Wreathall (2008) freely admit the flaws in this outlook. For instance, many demands with different disruptive characteristics are mapped onto a single dimension. Work is needed to classify demands and how they should be mapped. The analogy does not address the design problem - how should work be designed to be more resilient in terms of safety? Finally, the plot does not take advantage of advances in the modeling of complex adaptive systems.

Resilience engineering offers a fresh approach to construction safety, especially in a Lean Construction context. Some particularly interesting research questions include:

- To better understand how humans and machines interact to complete work. Overburdening (muri) poses safety problems.
- Resilience engineering takes a more realistic view of humans in the workplace. Instead of components of the system that are viewed as a liability they are the most flexible component of a system that can correct design flaws, are adaptable to the conditions at hand, apply the right procedure at the right time, and can detect when failure is about to occur.
- How to determine when elimination of essential non-value adding work (muda Type II) will affect safety? Some waste may serve as additional capacity that aids resiliency.
- Resilience engineering principles are readily applicable and, in many cases are already in use, for other concerns to the Lean community. For instance, supply-chain management uses resilience engineering to spot vulnerabilities and threats in the supply-chain.

## CONCLUSION

In this paper, the origins of Resilience Engineering were reviewed, focusing on what it is and what it isn't. The Rasmussen-Resilience model presented in this paper provides means to better understand the range of reaction and adaptability of organizations in relation to encountered production demands. The model encompasses regions where organizational and individual pressures push people to choose to work in hazardous but elastic situation, and regions where organization and individuals unexpectedly find themselves in a dangerous "plastic zone".

A resilient organization is one that has mastered the art of managing and coping with unexpected events and following disruptive consequences. An underlying principle in Resilience Engineering is that understanding failure in order to prevent its reoccurrence is more profound when we understand how safety is created by people in workplaces with continually changing hazard sources and inevitable compromises between safe and productive actions. The paper concluded with propositions for implementing Resilience Engineering in construction settings and offers pointers to future research. Additional research is needed to develop the Rasmussen-Resilience further and use it to investigate the relation between production and safety in construction settings.

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