PHYSICAL DEMANDS OF CONSTRUCTION WORK: A SOURCE OF WORKFLOW UNRELIABILITY

Tariq S. Abdelhamid[1] and John G. Everett[2]

ABSTRACT

Improving workflow reliability is paramount to the success of lean-based production operations. Unreliable workflow results from variability in performance. In the construction industry, sources of variability include late delivery of material and equipment, design errors, change orders, equipment breakdowns, tool malfunctions, improper crew utilization, labor strikes, and environmental effects. Another important source of variability, which is often overlooked in research and practice, is worker physical performance degradation. This degradation is caused by long term physical fatigue resulting from physically demanding work that remains ubiquitous in the construction industry. This research was motivated by the need to investigate the physical demands of construction work as an indirect source of workflow unreliability. Using work physiology principles, physiological measures of energy expenditure, including oxygen consumption and heart rate data, were collected for 18 construction laborers performing actual construction work. The results reveal that some workers routinely exceed one or more published guidelines for acceptable levels of physiological demands. The research points to the need to promote concepts of work physiology at the workplace to better the occupational safety and health of the construction workforce while simultaneously reducing performance variability and enabling lean conversion efforts.

KEYWORDS

Occupational Ergonomics, Work Physiology, Construction Safety

---

[1] Assistant Professor, 207 Farrall Hall, Construction Management Program, Michigan State University, East Lansing, MI 48824-1323. Email: tabdelha@msu.edu

[2] Assistant Professor, 2352 G. G. Brown, Dept. of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI 48109-2125. Email: Everett@umich.edu

INTRODUCTION

The minimization of waste in a production system is one of the cornerstones of lean construction. According to Womack and Jones (1996), waste results if resources are consumed with no creation of value. For example, excess inventories, unnecessary process steps, and idle workers are all examples of waste. Taiichi Ohno, one of the masterminds behind the Toyota Production System or Lean Production as it is now popularized, devoted much effort and energy to reduce and eliminate waste from the production process. In fact, he named seven sources of waste in a production process and tirelessly worked on eliminating them. This same maxim is emphasized in the lean construction literature (Everett 1992, Koskela 1993, Howell and Ballard 1994, and Howell 1999).

In lean construction, similar to lean manufacturing, workflow unreliability causes downstream workers to be idle resulting waste. Workflow refers to the release of work from one production process (not activity) to another. A fluctuation in the release of work, as committed to by one production process to another, is an indication of workflow unreliability (Ballard 1999). This unreliable workflow is a result of variability stemming from single or multiple causes that need to be targeted separately or collectively.

Under a lean paradigm, variability is controlled through the use of material and plan buffers, and/or flexible capacity (Ballard and Howell 1998). Material buffers could be in the form of raw and/or processed material. Plan buffers refer mainly to having a backlog of work for crews. Flexible capacity is the third way of combating the effects of variability and refers to the ability of using a resource in multiple ways. A common example of flexible capacity is cross-trained workers. Other examples of flexible capacity can be found in Hopp and Spearman (2000). The common element between these three approaches to tackle production process variability is that they are all attempts to combat the effects of variability and not to eliminate variability altogether. Eliminating or reducing the variability that plague production processes requires the removal of the root causes of variability –a difficult but not impossible task.

While variability has many causes, in construction or other industries, it manifests itself mainly in the form of poor intra-process and inter-process performance. Intra-process performance refers to the ability of a production process to meet its ***assigned*** work. Inter-process performance refers to workflow reliability between production processes. Clearly, a poorly performing intra-process will affect inter-process performance. In turn, inter-process performance will affect overall project performance.

In the construction industry, sources of variability include late delivery of material and equipment, design errors, change orders, equipment breakdowns, tool malfunctions, improper crew utilization, labor strikes, and environmental effects. Another important indirect source of variability in construction is the physical demand of work. Physically demanding work leads to physical fatigue which in turn leads to decreased productivity and motivation, inattentiveness, poor judgment, poor quality work, job dissatisfaction, accidents, and injuries (Brouha 1967, Janaro 1982, National Safety Council 2000).

The main focus of this paper is to present a work physiology perspective on workflow reliability and propose that worker physical performance degradation is an indirect source of workflow unreliability. It is suggested that this degradation is caused by long-term physical fatigue arising from physically demanding work. The results of a field study, conducted on 18 randomly selected construction laborers while they were engaged in actual construction work, is presented and discussed.

The following is a brief overview of the scientific discipline of work physiology. A detailed treatment may be found in Abdelhamid (1999) and Abdelhamid and Everett (1999).

BACKGROUND

Work physiology is the scientific discipline that is concerned with understanding metabolic and physiological responses to manual work. The main objective of work physiology is to make it possible for individuals to perform their work tasks without objectively or subjectively developing feelings of physical fatigue resulting from physiologically demanding work (Astrand and Rodahl 1986).

Different researchers have approached the measurement of physical demands and assessment of physical fatigue in a multitude of ways. The most common methods of measuring physical demand are those of measuring the oxygen consumption or oxygen uptake (usually measured in liters of oxygen per minute) during work or exercise, and/or recording the heart rate (measured in beats per minute) associated with the performance of an activity. Oxygen uptake data from direct measurements or estimates from heart rate have also been used to indirectly estimate energy cost of performing various human activities, which in turn is used to assess potential for physical fatigue.

METHODS

In the study reported in this paper, oxygen uptake (VO_2) and heart rate (HR) measurements for 18 construction laborers from 3 different sites were collected while construction work was being performed under normal work conditions. For each subject, VO_2 and HR data were collected at 20-second intervals for a period ranging from 30-60 minutes. Data was collected long enough to ensure that steady state VO_2 and HR had been reached and that several typical work or work-rest cycles had been completed.

Oxygen uptake measurements were made using indirect calorimetry techniques. The AeroSport KB1-C ambulatory metabolic analysis open-circuit spirometery-based system (AeroSport, Inc., Ann Arbor, Michigan) was the system chosen for measuring oxygen uptake (VO_2) and other physiological attributes. Energy expenditure was later derived from the measured VO_2.

The KB1-C metabolic system contains electronic instrumentation, battery, oxygen and carbon dioxide sensors, and telemetry connections to a microprocessor that permits radio transmissions of up to 300 meters (1000 feet) to a receiver and computer. The KB1-C is compact (7.5 x 15 x 5 cm) and lightweight (1.13 kg) making it easy to transport during physical activity. The data module and batteries may be worn with a three point vest or a contoured waist belt. With this system, subjects are also required to wear a mouth piece and a nose clip or a face mask. In either case, subjects breathe ambient air. The KB1-C can be programmed to measure oxygen uptake at 20, 40, or 60-second intervals.

A separate heart rate monitor system (Polar Vantage XL) was used for measuring heart rate. With this system, the HR is measured using a chest band fitted with a sensor/transmitter that measures the HR and transmits it to a microprocessor in the AeroSport KB1-C unit.

METHODS FOR EVALUATING MEASURED WORKLOADS

Measured physiological demands are evaluated against various criteria to determine whether the physical demand of a certain task is excessive, and whether the worker performing the task may suffer from physical fatigue. In general, the decrease in performance due to fatigue is widely accepted, but no agreement has been reached in trying to quantify this decrease, or in setting acceptable limits for it.

Workload evaluation techniques include classification of work severity based on published guidelines for oxygen uptake and heart rate (see Table 1), and evaluation of physical fatigue potential based on absolute energy expenditure and heart rate values. A widely used rule of thumb is that activities requiring less than 5 $\text{kcal} \cdot \text{min}^{-1}$ (approximately 1 $\text{liter} \cdot \text{min}^{-1}$ of oxygen uptake) can be performed continually for a work shift without overly taxing the worker. An activity requiring more than 5 $\text{kcal} \cdot \text{min}^{-1}$ can be performed for a limited time before the worker needs a rest to recoup energy from stores within the body (Oglesby at al. 1989).

Table 1. Severity of prolonged physical work and cardiovascular response [Source: adapted from Astrand and Rodahl (1986) and Christensen (1983)]

Work severity	Mean VO_2 ($\text{liters} \cdot \text{min}^{-1}$)	Mean HR ($\text{beats} \cdot \text{min}^{-1}$)	Peak VO_2 ($\text{liters} \cdot \text{min}^{-1}$)	Peak HR ($\text{beats} \cdot \text{min}^{-1}$)
Very light work	NA	NA	Up to 0.5	Up to 75
Light work	up to 0.5	up to 90	0.5 – 1.0	75 – 100
Moderate work	0.5 – 1.0	90 – 110	1.0 – 1.5	100 – 125
Heavy work	1.0 – 1.5	110 – 130	1.5 – 2.0	125 – 150
Very heavy work	1.5 – 2.0	130 – 150	2.0 – 2.5	150 – 175
Extremely heavy work	over 2.0	150 – 170	Over 2.5	Over 175

Brouha (1967) has suggested that an average HR of 110 $\text{beat} \cdot \text{min}^{-1}$ over an 8-hour shift should not be exceeded for industrial workers. Other researches have introduced different criteria by distinguishing between HR at rest and HR under physical work. The individual's general fitness level, duration of work, and level of work stress may all affect HR. Therefore, heart rate is considered as a non-specific measure of the response of the cardiovascular system. It still, nevertheless, has considerable value in assessing physically demanding work.

RESULTS AND DISCUSSION

Table 2 shows the workers' height, weight, age, and experience. Observed activities are described in Table 3. The average, standard deviation, peak, and minimum VO_2 and HR data for all workers are shown in Tables 4 and 5. In addition, columns [7] and [8] of Table 4 list the estimated average energy expenditure and average energy expenditure relative to body weight. This information is useful since it gives an order of magnitude of physical demands that could be expected when performing construction activities similar to those described in this paper.

Table 2. Subjects' information

Worker No. [1]	Number of Activities Observed [2]	Age (years) [3]	Height (cm) [4]	Weight (kg) [5]	Work Experience (years) [6]
1	1	30	180	79	6
2	1	29	183	85	4
3	1	40	170	95	25
4	1	23	173	79	8
5	2	18	185	90	1
6	1	50	185	99	27
7	3	37	183	75	14
8	2	32	183	77	12
9	1	47	179	102	23
10	1	44	191	86	24
11	1	30	178	81	5
12	1	24	173	70	4
13	1	45	163	68	27
14	1	32	173	68	2
15	1	23	191	106	4
16	1	29	178	93	6
17	1	39	191	86	12
18	1	47	173	70	16

Table 3. Observed construction activities

Worker No. [1]	Activity Number [2]	Work Duration (minutes) [3]	Description of work [4]
1	1	30	Transport concrete 22 times a distance of 40′ from concrete truck to sidewalk placing crew on a gas powered "concrete buggy".
2	2	58	Clean up: broom (300 sq. ft), lift and transport wood, welded wire fabric, paper, etc. to dump truck. Distances traveled ranged between 40′ and 110′. Shovel around footing to loosen buried trash
3	3	28	Operate a front-end loader and a "Bobcat" tractor during earthmoving as part of preparation work for concrete floor slab placement.
4	4	23	Place concrete using a "Come-Along" for a 100 sq.ft. concrete floor slab. Rest only while waiting for concrete buggy.
5	5	22	Carry six 2×4s 80′ for carpenter (twice). Hold rebar for ironworker to place ties. Stack 5 2′×4′ formwork panels (walking 20′ to get panels and carrying one panel at a time). Carry rebar with co-workers to clear path for concrete truck.
5	6	30	Remove ten layout/staking marks (20′ oc). One stake required extensive hammering (4 minutes) for removal.
6	7	22	Remove form ties for ten 2′×4′ formwork panels for concrete wall footing.
7	8	21	Remove form ties for five 2′×4′ formwork panels (in very tight space) for concrete wall footing.
7	9	25	Assemble formwork for a column footing (2′×2′×4′) using wood material.

Table 3. Observed construction activities (cont.)

Worker No. [1]	Activity Number [2]	Work Duration (minutes) [3]	Description of work [4]
7	10	21	Stack 20 40 lb. 2′×4′ wall formwork panels (walking 40′ to get panels and carrying one panel at a time).
8	11	23	Remove form ties for five 2′×4′ formwork panels. Strip ten 40 lb. 2′×4′ formwork panels for concrete wall footing.
8	12	22	Stack 25 40 lb. 2′×4′ wall formwork panels (walking 30′ to get panels and carrying one panel at a time).
9	13	21	Mason tending for two bricklayers laying blocks (worked on scaffold 6′ high). Bricklayers laying blocks.
10	14	21	Mason tending for masons installing a precast lintel. Work performed at ground level.
11	15	21	Mason tending for two bricklayers laying bricks (worked on scaffold three stories high). Carry bricks stored on scaffold at second story level to the scaffold at the third story level (twice). Remove 8 scaffold sections (35 lb. each) at third story level.
12	16	20	Mason tending for two bricklayers installing a 10′ wooden arch for a third floor window. Holding temporary steel shores in place. Carry material and power saw 30′ away. Carry electric generator 60′ away. Work performed at floor level.
13	17	21	Erect tubular steel frame scaffolding (10′ wide and 12′ high, using six 6′ high 35 lb. scaffold end frame sections).
14	18	28	Haul bricks and blocks using a Skylift (10 times).
15	19	21	Formwork carpenter tending and when not needed performed clean up: Remove wooden waste to dumpsite (60′ away); Stack four 2′×6′ formwork panels from work location to storage location (50′ away).
16	20	41	Wait for concrete truck to arrive (15 minutes). Guide concrete being poured for the 12′ concrete wall using a shovel.
17	21	20	Spread cleaning sand on a 6′×20′ area and a 15′×15′ area. Sweep the areas covered with broom. Shovel collected dirt into dumpster cart.
18	22	20	Spread cleaning sand on a 10′×15′ area and a 12′×15′ area. Sweep the areas covered with broom. Shovel collected dirt into dumpster cart.

Classification of the physical demand based on Table 1, and evaluation of physical fatigue potential for each worker based on the 5 $\text{kcal}\cdot\text{min}^{-1}$ limit, are shown in Table 6. At first glance, the results in Table 6 indicate the inconsistent nature of these guidelines. For example, a number of subjects (see worker 1 and 5) were performing “heavy” to “very heavy work” according to mean heart rate, but were performing “moderate work” according to mean oxygen uptake and were working at a rate that is not fatiguing when considering the 5 $\text{kcal}\cdot\text{min}^{-1}$ limit. These limitations of the guidelines are due to the wide variations among individuals. Table 7 provides a summary of the work classification results.

Table 4. *Worker oxygen uptake and energy expenditure data*

Subject [1]	Activity [2]	Mean VO$_2$ (liter · min^{-1}) [3]	Standard Deviation VO$_2$ (liter · min^{-1}) [4]	Peak VO$_2$ (liter · min^{-1}) [5]	Lowest VO2 (liter · min^{-1}) [6]	Estimated Energy Expenditure (kcal · min^{-1}) [7]	Estimated Energy Expenditure (kcal · kg^{-1} · min^{-1}) [8]
1	1	0.89	0.12	1.23	0.6	4.30	0.05
2	2	1.48	0.35	2.2	0.39	7.15	0.08
3	3	0.46	0.23	1.41	0.29	2.22	0.02
4	4	1.24	0.34	2.28	0.51	5.99	0.08
5	5	0.8	0.42	1.79	0.21	3.86	0.04
5	6	0.71	0.29	1.46	0.2	3.43	0.04
6	7	0.58	0.13	0.92	0.31	2.80	0.03
7	8	0.8	0.16	1.31	0.49	3.86	0.05
7	9	0.67	0.14	1.06	0.36	3.24	0.04
7	10	1.1	0.18	1.46	0.55	5.31	0.07
8	11	0.78	0.17	1.28	0.38	3.77	0.05
8	12	0.94	0.27	1.36	0.32	4.54	0.06
9	13	0.71	0.27	1.33	0.22	3.43	0.03
10	14	0.66	0.21	1.01	0.21	3.19	0.04
11	15	1.33	0.31	1.97	0.49	6.42	0.08
12	16	0.75	0.27	1.44	0.32	3.62	0.05
13	17	1	0.28	1.87	0.2	4.83	0.07
14	18	0.5	0.28	1.8	0.2	2.42	0.04
15	19	1.43	0.32	1.97	0.55	6.91	0.07
16	20	0.75	0.25	1.48	0.33	3.62	0.04
17	21	0.78	0.12	1.07	0.48	3.77	0.04
18	22	0.75	0.09	0.97	0.53	3.62	0.05

Table 5. *Worker heart rate data*

Subject [1]	Activity [2]	Mean HR (beats · min^{-1}) [3]	HR Standard Deviation (beats · min^{-1}) [4]	Peak HR (beats · min^{-1}) [5]	Lowest HR (beats · min^{-1}) [6]
1	1	113	6	129	102
2	2	131	11	156	93
3	3	106	6	126	96
4	4	109	16	150	78
5	5	131	11	159	111
5	6	124	16	159	66
6	7	107	10	135	78
7	8	131	5	141	120
7	9	116	6	129	102
7	10	117	5	129	99
8	11	137	12	153	102
8	12	129	11	144	108

Table 5. Worker heart rate data (cont.)

Subject [1]	Activity [2]	Mean HR (beats · min^{-1}) [3]	HR Standard Deviation (beats · min^{-1}) [4]	Peak HR (beats · min^{-1}) [5]	Lowest HR (beats · min^{-1}) [6]
9	13	87	9	108	69
10	14	98	9	126	72
11	15	142	14	165	102
12	16	94	11	117	75
13	17	123	12	159	102
14	18	107	9	154	93
15	19	126	13	156	96
16	20	101	9	135	87
17	21	94	16	123	69
18	22	115	4	120	99

Table 6. Evaluation of worker physiological data based on contemporary guidelines

Subject [1]	Activity [2]	Classification by Mean VO_2 [3]	Classification by Energy Expenditure [4]	Classification by Mean HR [5]	Classification by Peak VO_2 [6]	Classification by Peak HR [7]
1	1	Moderate	Not Fatiguing	Heavy	Moderate	Heavy
2	2	Heavy	Fatiguing	Very Heavy	Very Heavy	Very Heavy
3	3	Light	Not Fatiguing	Moderate	Moderate	Heavy
4	4	Heavy	Fatiguing	Moderate	Very Heavy	Heavy
5	5	Moderate	Not Fatiguing	Very Heavy	Heavy	Very Heavy
5	6	Moderate	Not Fatiguing	Heavy	Moderate	Very Heavy
6	7	Moderate	Not Fatiguing	Moderate	Light	Heavy
7	8	Moderate	Not Fatiguing	Very Heavy	Moderate	Heavy
7	9	Moderate	Not Fatiguing	Very Heavy	Moderate	Heavy
7	10	Heavy	Fatiguing	Heavy	Moderate	Heavy
8	11	Moderate	Not Fatiguing	Heavy	Moderate	Very Heavy
8	12	Moderate	Not Fatiguing	Heavy	Moderate	Heavy
9	13	Moderate	Not Fatiguing	Light	Moderate	Moderate
10	14	Moderate	Not Fatiguing	Moderate	Moderate	Heavy
11	15	Heavy	Fatiguing	Very Heavy	Heavy	Very Heavy
12	16	Moderate	Not Fatiguing	Moderate	Moderate	Moderate
13	17	Heavy	Not Fatiguing	Heavy	Heavy	Very Heavy
14	18	Light	Not Fatiguing	Moderate	Heavy	Very Heavy
15	19	Heavy	Fatiguing	Heavy	Heavy	Very Heavy
16	20	Moderate	Not Fatiguing	Moderate	Moderate	Heavy
17	21	Moderate	Not Fatiguing	Moderate	Moderate	Moderate
18	22	Moderate	Not Fatiguing	Heavy	Light	Moderate

In general, the classification results for all the construction activities indicate that on average construction work is classified as moderate to heavy work. The workload intensity classification results in Table 7 indicate the following:

- Based on mean oxygen uptake values, 27% of the observed construction activities were classified as heavy to very heavy work.

- Based on peak oxygen uptake values, 32% of the observed construction activities were classified as heavy to very heavy work.
- Based on mean heart rate values, 59.5% of the observed construction activities were classified as heavy to very heavy work.
- Based on peak heart rate values, 82% of the observed construction activities were classified as heavy to very heavy work.

Table 7. Summary of workload severity classification

	Based on:			
Percentage of observed construction activities classified as::	VO_{2avg} (%)	VO_{2peak} (%)	HR_{avg} (%)	HR_{peak} (%)
Very light work	NA	0	NA	0
Light work	9	9	4.5	0
Moderate work	64	59	36	18
Heavy work	27	23	36	45.5
Very heavy work	0	9	23.5	36.5
Extremely heavy work	0	0	0	0

The results clearly indicate that construction workers, or at least the workers in this study, are facing more problems with cardiovascular responses than with energy demands. These problems reflect a myriad of factors such as heat stress exposure, heavy static exertions, and/or general health problems.

It should come as no surprise that these workers are exhausted at the end of the day and may not be fully recovered at the beginning of the next work shift. Few workers can sustain this level of performance. Many burn out and seek alternative, less demanding, work. If alternative work cannot be found, the worker faces the dilemma of continuing at a job that causes excess fatigue, or perhaps dropping out of the workforce.

The implications of the above findings to companies on a lean conversion process are important and serious. As the results indicate, potentials of physical fatigue are high for construction workers. Understanding the physical demands of construction work is key to knowing what a worker can do safely and without suffering from performance degradation due to physical fatigue. Attempts to drive out variability from a production process by making workflow more reliable should consider the physical workload placed on workers.

Preempting the potential for physical fatigue arising from physically demanding work can be achieved by changing the work methods, including investment in more automated tools and equipment; providing appropriate work-rest cycles; or even adjusting expectations of what workers can reasonably be expected to accomplish. These and many other examples of administrative and engineering interventions to reduce physical demands and fatigue would provide endless opportunities to improve construction work today and enable lean conversion efforts.

The interventions mentioned above should be considered before construction operations commence. Specifically, they should consider during the Lean Design phase wherein the product and process are designed simultaneously (Ballard 2001). While the concept of Consrtuctability, as introduced in 1986 by the Construction Industry Institute (CII) based in Austin, Texas (CII 1986), is a critical part of the Lean Design phase, it is important not to assume that "Design for Safety" is implicit in design for constructability (akin to design for manufacturability in the manufacturing industries).

Underscoring the importance of "Design for Safety", in 1997, the Construction Industry Institute (CII), compiled and disseminated detailed guidelines for designers to help reduce safety issues during construction. Examples of such guidelines include avoiding roof edges and skylights as locations for rooftop mechanical equipment, scheduling night work sparingly, and designing slabs on grade and mat foundations with closely spaced reinforcement, which allows a continuous walking surface (Gambatese 2000). However, these guidelines are primarily concerned with safety issues that may lead to traumatic type injuries (e.g., cuts, bruises, lacerations, etc) and/or fatalities. As the results in this paper demonstrate, there is also a need to consider overexertion injuries (sprains, strains, etc) resulting from bad ergonomics. The following are sample guidelines to consider, using appropriate and available ergonomic tools and methods, during the lean design phase in an effort to avoid or reduce incidents of overexertion injuries – whether arising from physical fatigue or other ergonomic-based aspects of work such as biomechanical issues (Chaffin and Andersson 1991):

- Using mechanical handling aids like balancers, hoists and conveyors, where possible.
- Optimizing strength by proper positioning of tools, materials
- Keeping materials close at hand (horizontally) to avoid work with arms outstretched
- Avoiding overhead work.
- Using finger-padded handles to reduce vibration and contact stress
- Positioning work to optimize visual capabilities
- Evaluating need for anti-fatigue/anti-slip flooring
- Evaluating sit/stand options
- Maintaining a good work environment: consider lighting, temperature, and low noise levels

CONCLUSION

This paper investigated the physiological demands of construction work performed by construction laborers. Existing techniques for evaluating measured physical demand have been investigated in order to characterize work intensity and determine whether the demands are physically fatiguing to the workers. The findings reveal that some workers routinely exceed generally accepted thresholds for three physiological indicators of workload: oxygen consumption, heart rate, and energy expenditure, and can become physically fatigued. This may lead to decreased productivity and motivation, inattentiveness, poor judgment, poor quality work, job dissatisfaction, accidents, and injuries.

The methods described in this research have widespread applications in identifying excessively demanding construction tasks so the work can be better matched to the abilities of the workers. The research points to the need to promote concepts of work physiology (and occupational ergonomics) as part of lean-based Work Structuring as defined in the Lean Project Delivery System (Ballard 2001). Human-oriented work structuring will better the occupational safety and health of the construction workforce while simultaneously reducing workflow unreliability and enabling lean conversion efforts. Additional research is needed to assess the physical demands of other types of work and investigate other aspects of occupational ergonomics as they apply to construction work.

REFERENCES

Abdelhamid, T. S. (1999). *Measuring and Evaluating Physiological Demands of Construction Work.* Ph.D. Dissertation, University of Michigan, Ann Arbor, Michigan.

Abdelhamid, T. S., and Everett, J. G. (1999). Physiological demands of concrete slab placing and finishing work. *Journal of Construction Engineering and Management,* ASCE, 125(1), 47-52.

Astrand, P., and Rodahl, K. (1986). *Text book of work physiology, physiological bases of exercise*. McGraw-Hill, New York.

Ballard, G. (1999). Improving Work Flow Reliability. *Proceedings of the 7th Conference of the International Group for Lean Construction,* Berkeley, California, USA, 26-28 July 1999.

Ballard, G. (2000). Lean Project Delivery System. White Paper #8, Lean Construction Institute (www.leanconstruction.org).

Ballard, G. and Howell, G. (1998). What Kind of Production Is Construction? *Proceedings of the 6th Conference of the International Group for Lean Construction,* Guaruja, Brazil, August 13-15.

Brouha, L. (1967). *Physiology in industry*. Pergamon Press, New York.

Chaffin, D. B., and Andersson, G. B. (1991). *Occupational biomechanic*s. Wiley, New York.

Christensen, E. H. (1983). Physiology of Work. In L. Parmeggiani (Ed.), *Encyclopedia of Occupational Health and Safety.* Switzerland: International Labor Organization.

Construction Industry Institute (CII) Constructability Task Force. (1986). *Constructability, a primer*, Austin, Texas.

Everett, J. G. (1992). Let’s pass on Mass Production. *Construction Business Review* (CBR), 2(2), 13-14.

Gambatese, J. A. (2000). ‘‘Safety in a designer’s hands.’’ Civ. Engrg., June, 56–59.

Hopp, W. J., and Spearman, M. L. (2000). *Factory Physics.* McGraw-Hill, New York.

Howell, G and Ballard, G (1994). Lean Production Theory: Moving Beyond 'Can-Do. *Proceedings of the 8th Conference of the International Group for Lean Construction,* Santiago, Chile, September.

Howell, G. (1999). What Is Lean Construction. *Proceedings of the 7th Conference of the International Group for Lean Construction*, Berkeley, California, USA, 26-28 July 1999.

Injury Facts (2000). National Safety Council, Itasca, Illinois.

James Womack and Daniel Jones (1996). *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*. Simon & Schuster, New York, NY.

James Womack, Daniel Jones, and Daniel Roos (1990). *The Machine That Changed the World*, MacMillan Publishing, New York, NY.

Janaro, R. E. (1982). *The development and implementation of optimal multi-rest break scheduling models.* Ph.D. Dissertation, Florida State University, Florida.

Koskela, L. (1993). Lean production in construction. *Proceedings of the 10th ISARC*, Houston, Texas, May 24-26, 47-54.

Oglesby, C. H., Parker, H. W., and Howell, G. A. (1989). *Productivity improvement in construction.* McGraw-Hill, New York.