A Case Study into Task Variation and the Social Network of Construction Trades

Brad W. Wambeke[1], Min Liu[2] and Simon M. Hsiang[3]

ABSTRACT

Construction projects can be complex and managers are faced with the challenge of managing multiple trades working on a large number of interdependent tasks. When one trade or task experiences variation, defined as the time difference between what was planned and what happened for this research, additional trades or tasks can be impacted, the project schedule can be disrupted, and/or productivity can suffer. A case study involving a general contractor (GC) building a 150,000 square foot data collection center was conducted. Both starting time and task duration variation data was collected on approximately 1200 tasks performed by over 40 trades. A risk assessment matrix was used to determine which causes of variation posed the greatest risk to project performance. Pajek, a social network analysis software, was used to illustrate the organizational structure of the key trades throughout the project. The research is unique as it couples the quantitative variation analysis with the associated social network of trades to create a decision support system that can be used to target variation for reduction. The results of this research are repeatable and can be useful for managers in improving project performance.

KEY WORDS

Variation, risk assessment, social network, labor productivity, construction.

INTRODUCTION

Construction projects are often complex and full of uncertain and interdependent tasks that a project manager works to synchronize to the best of his/her ability. Crichton et al. (1966) found uncertainty to be one of the greatest challenges to the interdependent building process. These uncertainties can stem from numerous sources ranging from items like labor, equipment, and materials, to government departments, planning authorities, and even the general public (Crichton et al. 1966). Task variation, defined as the time difference in days between what was planned and what actually happened for this research, often occurs as a result of uncertainty. When one task experiences variation, it may cause another task to experience variation to their interdependency. The consequence can be poor project performance and waste.

[1] Academy Professor, Department of Civil and Mechanical Engineering, United States Military Academy, West Point, NY 10996; PH (910) 988-9488; email bwwambek@ncsu.edu

[2] Assistant Professor, Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, NC 27695-7908; PH (919) 513-7920; email min_liu@ncsu.edu

[3] Derr Professor, Industrial Engineering, Texas Tech University, Lubbock, TX 79409; PH (806)742-3543 email simon.hsiang@ttu.edu

Plausibly and arguably, there is an underlying social network of trades that exists and recognizing it can help succeed in this challenging environment. A social network is pattern of ties that exist between different entities (i.e. people, organizations, countries, etc.)

This research uses a case study involving a general contractor and over 40 trades to examine the variation and associated social network of trades during the construction of a $50M data center. Although this research is based on a specific case study, the analytical process is repeatable and can be used to develop decision support systems for other projects. The case study was used to address two primary objectives associated with this research:

1) Determine the causes of variation that pose the greatest risk of impacting project performance.
2) Develop a decision support system to target trades in an effort to reduce variation.

LITERATURE REVIEW

Several researchers have recognized the presence and importance of reducing variation in the construction industry (Howell et al. 1994; Ballard, 2000; Howell et al. 2002; Thomas et al. 2002; Horman and Thomas 2005; Wambeke et al. 2011a). The construction process is also highly interdependent; therefore, variation caused by one trade can likely impact other trades as well.

The interconnected nature is what led to the motivation to use social network analysis to study the interaction between the various trades. The concept of social network analysis (SNA) was first introduced in the 1930s and original studies focused on the social and political relationships between individuals (Moreno 1960). Barnes (1954) started using the term "social network" to denote patterns of ties, concepts usually used by social scientists: bounded groups (e.g., tribes, families) and social categories (e.g., gender, ethnicity). There has been limited research using social networks in the construction field. Thorpe and Meade (2001) used social networks to determine if project specific websites could be used to pull information and more effectively design & build complex projects. They surveyed members of the design and construction team to determine communications patters; more specifically, with whom and how often did the different teams members communication with each other. Their SNA identified key members of the team in terms of communication and illustrated the challenges that can arise when one of those key members does not participate (i.e. use the project specific website). Social networks have also been used in the development of a model for achieving high performance results from project teams. To reduce the uncertainty during construction, Chinowski et al. (2008) modeled the mechanics (i.e. what) and the dynamics (i.e. why) of information passed between the team members. Much like Thorpe and Meade (2001), Chinowski et al. (2008) surveyed team members and used SNA to determine a graphical representation of the communication architecture within the team. In their study, architects were in infrequent contact with the team during the majority of decision-making processes. They concluded that the isolation of key individuals contributed to over centralized decision making, a lack of information and knowledge integration, and a lack of trust (Chinowski et al. 2008). "In projects where trust and value sharing are not evident, the impact on information and knowledge sharing can be significant." SNA was also used in the construction industry to examine the mediating role played by individuals that share the same nationality as an international partner on a project (Di Marco et al. 2010). They studied the internal communications between two different project teams executing complex, reciprocally interdependent design projects in India. One team was comprised of Indians and Americans. The other team was identical, but also contained an Indian national who had studied and worked in the United States. Using SNA to represent the communication patterns, the Indian expatriate was found to play a cultural boundary spanning role by resolving cross-cultural knowledge system conflicts and increasing collaboration effectiveness (Di Marco et al. 2010).

METHODOLOGY

A general contractor (GC) overseeing 43 subcontractors, also referred to as trades, involved with the construction of a 150,000 square foot data center participated in the case study. The $50M project entailed the build-out of an existing warehouse building into a data center and white space computer labs. The scope included the construction of a new steel structure within the building, new mechanical and electrical systems, raised access floor computer labs with associated support spaces, and a general office component.

The GC held a weekly subcontractor meeting in which the foreman from each trade working on the site attended. The focus of the meeting was to identify and resolve conflicts (i.e. more than one trade working in the same area at the same time) by using a work breakdown structure. They also discussed material procurement for timely support of construction activities. Additionally, daily huddles were conducted to review the key tasks to be completed for the day. Data was collected for 28 weeks and included the planned and actual starting times and duration for each task on the work plan, as well as reasons for variation. Variation was tracked in terms of starting time and task duration for the tasks scheduled each week. The starting time variation is the time difference in days between the planned and actual task starting time and the duration variation is the time difference between the planned and actual task duration.

Initially, the GC intended to use the Last Planner System (LPS) ® to manage their weekly planning meetings (Ballard, 2000). The actual planning process encompassed some of the framework of the LPS®, but not all of it. For example, they reviewed the previous weeks' work and used a look-ahead process; however, the look-aheads were not conducted as intended by the LPS®. One of the key purposes of the look-ahead is to identify and remove constraints, which are items that need to be completed and/or addressed prior to a task being started (Ballard 1997). Once the constraints for a task have been removed, the task is "made ready" and the commitment to accomplish the task is more reliable (González et al. 2010). Look-aheads are an important aspect of the LPS® and Alarcón et al. (2005) found that PPC improved when companies included the use of look-aheads while implementing the LPS®. The project manager involved with this case study stated they did not work to identify and remove constraints to the extent they had envisioned during their look-aheads.

CASE STUDY RESULTS/ANALYSIS:

Objective 1) Determine the causes of variation that pose the greatest risk of impacting project performance.

In order to determine risk, both frequency and severity are required; therefore, the variation is tracked in those terms. There were 1183 tasks performed by the various trades working on the data center. If there was either starting time and/or task duration variation associated with a task, the GC attempted to capture the reason. The variation data was plotted in terms of frequency and severity in Figure 1. Each point in the figure represents one cause of variation. The horizontal axis is the normalized frequency, represented by the percent of variation that is accounted for by each cause. For example, "material delivery" accounted for 18% of the total starting time variation. The vertical axis is the mean magnitude (in days) for each cause of variation. Overcommitment by a subcontractor, incomplete prerequisite work, and a lack of materials were the three dominating causes of variation that comprise the risk frontier to project performance. Overcommitment accounted for almost all of the instances of task duration variation and was arguably the great risk to schedule compliance. When one trade over commits (i.e. plans to accomplish more than they actually do), it often affects the sequential trade(s) behind them; thus causing them to experience starting time variation due to the prerequisite work that was not completed. Two additional causes of variation to highlight were requests for information and problems associated with the design being incomplete.

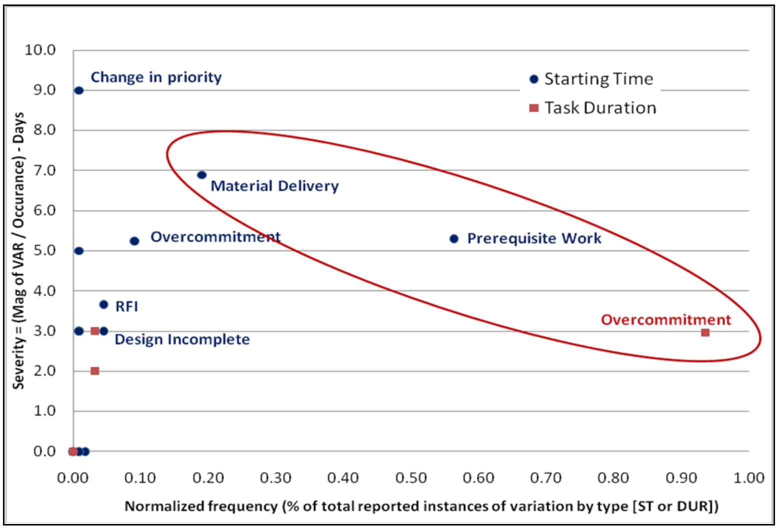

Figure 1: Starting Time and Task Duration Variation on Risk Assessment Matrix

In addition to understanding what the primary causes of variation are, it is important for project managers to understand where these causes are originating from and how the trades are related to one another. Figure 2 illustrates which trades are associated with the top three causes of variation. The horizontal axis of Figure 2 represents the percent of time each trade was associated with the frequency of variation occurences and the vertical axis represents the percent of variation magnitude a trade is associated with. Consider trade V and the data point that has the largest severity in Figure 2. This point is associated with the starting time variation due to material delivery for trade V. There were 21 instances in which material delivery impacted the starting time of a task during the entire project. Trade V accounted for four (i.e. 19%) of those instances. In terms of magnitude, there were 124 total days of starting time varation associated with material delivery during the entire project. Trade V accounted for 38 (i.e. 31%) of those days.

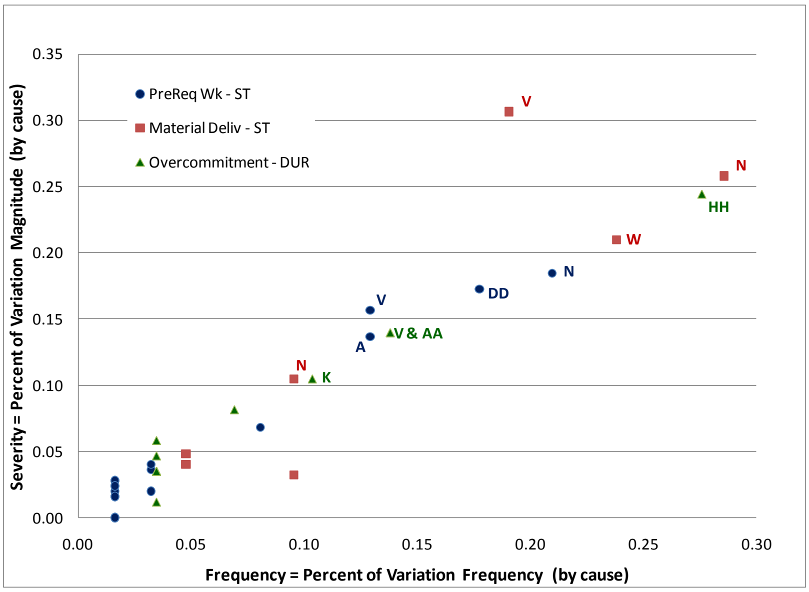

Figure 2: Trades associated with the top three causes of variation

While Figure 2 illustrates the trades that are associated with the greatest risk in terms of frequency and severity of variation, managers need to understand how the trades are related to each other. For example, how critical is it that the steel contractor is associated with the greatest frequency and severity of task duration variation due to over commitement? Pajek, a software used to analyze social networks, was used to examine the trade network. The project manager divided the project into 14 different areas / phases in an effort to deconflict the trades working in each of the areas.

An adjacency matrix [A] was created to indicate how many times trade worked with the others and is the basis for the social network (Table 1). Mathematically, an adjacency matrix is a means of representing which vertices of a graph are adjacent to which other vertices. Consider trade “N” in the first row of [A]. Trade “N” worked with “DD” one time, with “V” 13 times, with “K” and “B” one time each, etc. Zeros are placed along the diagonal because trades are not considered to work with themselves. The adjacency matrices in this research are undirected. In other words, the order of the pairings of trades is irrelevant. It indicates which trades are physically working in the same area, not whether the tasks they are performing are related in a sequential or simultaneous manner.

Table 1: Adjacency Matrix for "Site Work" Area

	N	DD	V	K	B	HH	Z	W	AA	P	II	O	CC	KK	MM	G	E
N	0	1	13	1	1	5	11	4	1	2	2	2	2	4	1	2	2
DD	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
V	13	0	0	1	1	4	8	3	1	1	1	2	2	4	0	0	3
K	1	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	1
B	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
HH	5	2	4	0	0	0	0	2	0	0	0	0	0	3	0	1	0
Z	11	0	8	0	1	0	0	1	0	2	2	0	0	0	1	0	1
W	4	0	3	0	0	2	1	0	0	0	0	0	0	1	0	0	0
AA	1	0	1	0	0	0	0	0	0	0	0	1	1	1	0	0	1
P	2	0	1	0	0	0	2	0	0	0	2	0	0	0	0	0	0
II	2	0	1	0	0	0	2	0	0	2	0	0	0	0	0	0	0
O	2	0	2	1	0	0	0	0	1	0	0	0	2	1	0	0	2
CC	2	0	2	1	0	0	0	0	1	0	0	2	0	1	0	0	2
KK	4	0	4	0	0	3	0	1	1	0	0	1	1	0	0	0	1
MM	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
G	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
E	2	0	3	1	0	0	1	0	1	0	0	2	2	1	0	0	0

The steps for creating a Pajek input file are fully outlined in Part I of De Nooy et al. (2005), but a partial listing of the "Site Work" area input file is shown below in Figure 3. Each of the vertices (19 of them in the "Site Work" area) are labeled and provided three dimensional coordinates, which are used by Pajek to initially locate the vertices. The second portion of the input files described the edges (or relationships) between the vertices. For example, the first three edges listed in Figure 3 indicates that the first trade (N in this example) is linked to trades 2, 3, and 4 (i.e. trades DD, V, and K) by strengths of 1, 13, and 1 respectively. Notice that this is the start of the first line of the [A] (Table 1).

```
*Vertices    19
1 "N"         0.7842    0.6742    0.5000
2 "DD"        0.2643    0.2643    0.5000
3 "V"         0.3724    0.8080    0.5000
--- vertices 4-16 omitted to save space
17 "E"        0.7842    0.3258    0.5000
18 "L"        0.4738    0.1677    0.5000
19 "M"        0.2158    0.3258    0.5000
*Edges
1 2 1
1 3 13
1 4 1
--- likewise for the remainder of [A]
```

Figure 3: Partial listing of Pajek Input File for "Site Work" Area

The adjacency matrix provides the majority of the input data that enables Pajek to create the graphical depiction of the social network (**Error! Reference source not found.**4). Graphically, a trade is represented as a vertex. Two vertices (or trades) are adjacent if they are two end-vertices of an edge (or a connection) and two edges are adjacent if they share a common end-vertex. The numbers next to the lines are line values and represent the strength of the relationship (De Nooy 2005). The trades with more ties to others are more centrally located and the stronger the tie. Topologically, trade N is located at the center of the network because N is the only trade that has ties to each of the other 18 trades.

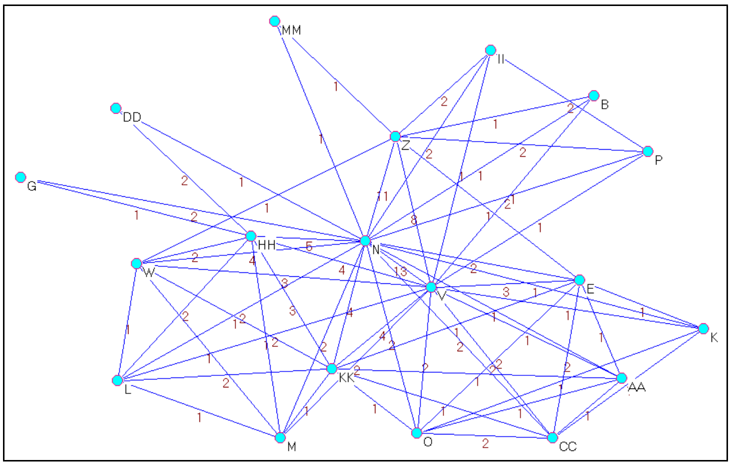

Figure 4: Social network for "Site Work" area of project

Exploring a network structure by calculation is much more concise and precise than visual inspection (De Nooy et al. 2005). Centrality is a key measure that reflects the distribution of relationships through the network. In a highly centralized network, a small percentage of the members will have a high percentage of relationships with other members in the network (Chinowski et al. 2010). Centrality analysis was performed by Wambeke et al. (2011b) using both degree and eigenvector based methods and the results for this case study are shown in Figure 5.

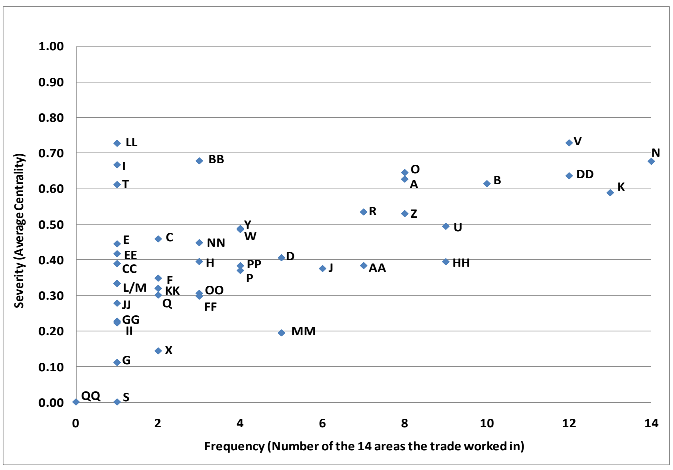

Figure 5: Trade centrality for all 14 project areas

Objective 2) Develop a decision support system to target trades in an effort to reduce variation.

The final analysis performed was to combine the social network results with those related to variation. A variation and centrality score was calculated for each trade by using the respective frequency-severity plots (Figures 2 and 5). The scores were determined by calculating a normalized distance from the origin for both the centrality and the variation. The results were plotted and initially separated into four quadrants (Figure 6). The respective trades are also listed for the corresponding code letters of the seven trades with the highest priority for reducing variation. Trades in the upper right hand quadrant of Figure 6 are the recommended to be the highest priority for a project management team to reduced variation as they both have high uncertainty (i.e. variation) and high centrality relative to the other trades in the project. There were no trades that fell in the lower right quadrant and the trades in lower left quadrant have relatively low variation and low centrality. While these trades are still important to the overall project, they are not likely to require the same level of attention from the project management team. There were several trades in the upper left quadrant; therefore, that quadrant was divided a second time and five trades (DD, K, A, R, and HH) were identified. Of those five trades, DD has relatively high variation and centrality; therefore, is the third overall priority for the project management team. The remaining four trades (K, A, R, and HH) should be considered to pose about the same level of risk for the project management team.

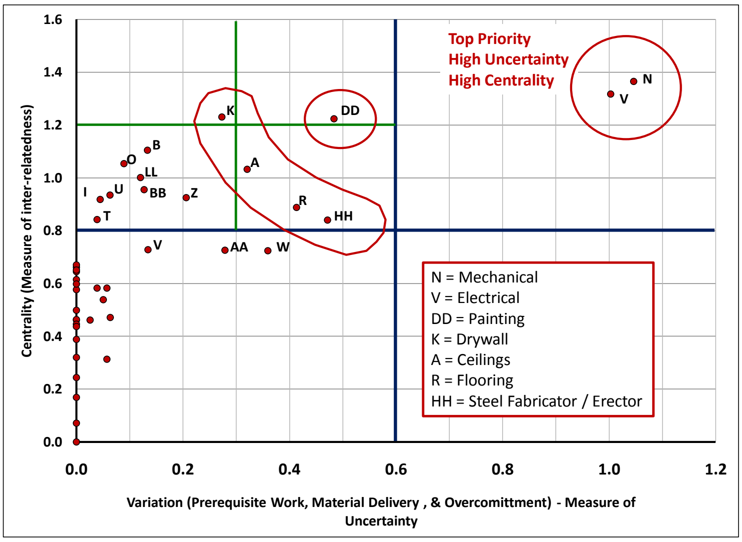

Figure 6: Variation vs Centrality summary for all trades

CONCLUSIONS

The frequency – severity characteristic associated with risk assessment matrices was used to examine approximately 1200 tasks performed by 43 different trades and identify the top three causes of variation. Material delivery and not having prerequisite work completed were the top two causes of starting time variation and overcomittement was the top cause of task duration variation. Pajek was used to identify a social network of trades for each of the 14 areas associated with the project in this study. Eigenvector and degree centrality analysis identified the key trades within the networks. Lastly, the results of the variation analysis and that of the social network analysis were combined to identify and prioritize the trades, in terms of their associated relative variation and how central they were to the overall project. The mechanical and electrical contractors were identified as the top two trades overall. The painting contractor was next in priority, followed by a group of four trades that were considered to be relatively equal in priority. Those four trades represented the drywall, ceiling, flooring, and steel fabricator/erector contractors. The project manager involved with the case study intends to use the results to reduce variation on an upcoming project by focusing on these specific trades and causes of variation during their weekly LPS® meetings.

The utility of the research may be limited due to the time it takes to collect the data. It may be less beneficial for construction companies, compared to the conventional use of the LPS®, in which the causes of planning failures are systematically identified, and the discussions at weekly meetings can be used for learning about the actual capacity of different crews.

Despite this potential limitation, this research is significant and contributes to the body of knowlege as it provides a means to identify and prioritize variation based on its frequency and severity. The research is also unique as it couples the variation analysis with the associated social network of trades to create a decision making system that can be used to target variation for reduction. While this research is based upon an individual case study, the apsects of this research can be applied to other projects and can be useful for a project management team as they strive to improve project performance and efficiency. The authors feel the repeatable nature of this research is one of its most valuable qualities.

REFERENCES

Alarcón, L.F. et al. (2005). “Assessing the Impacts of Implementing Lean Construction.” Proceedings of the 13th Annual Conference of the International Group for Lean Construction, July, Sydney, Australia, pp. 387-393.

Barnes, J. A. (1954) "Class and Committees in a Norwegian Island Parish", Human Relations 7:39–58.

Ballard, G. (1997). “Lookahead Planning: The Missing Link in Production Control.” Proceedings of the 5th Annual Conference of the International Group for Lean Construction, July, Griffith University, Gold Coast, Australia.

Ballard, G. (2000) *The Last Planner System of Production Control.* PhD thesis, Dept. of Civil Engineering, University of Birmingham, Birmingham, U.K.

Ballard, G., Koskela, L. J., Howell, G. A., and Tommelein, I. D. (2003) “Discussion of ‘Improving Labor Flow Reliability for Better Productivity as Lean Construction Principle’” ASCE, J. Constr. Eng. Mgmt., May/June, Vol. 129, No. 3, pp. 251–261.

Chinowski, P., Diekmann, J., and Galotti, V. (2008) “Social Network Model of Construction.” J Constr. Eng. and Mgmt., October, pp. 804-812.

Crichton, C. (1966). Interdependence and Uncertainty – A Study of the Building Industry. Tavistock Publications Limited, Great Britain.

Dai, J., Goodrum, P. M., and Maloney, W. F. (2009) "Construction Craft Workers' Perceptions of the Factors Affecting Their Productivity." J Constr. Eng. and Mgmt., Vol. 135, No. 3, March 1, pp. 217-226.

Di Marco, M.K., Taylor, J.E., and Alin, P. (2010) "Emergence and Role of Cultural Boundary Spanners in Global Engineering Project Networks." J of Mgmt. in Eng, July 2010, pp 123-132.

De Nooy, W., Mrvar, A., and Batagelj, V. (2005) Exploratory Network Analysis with Pajek. Cambridge University Press, New York.

Galbraith, J. R. (1977) Organization Design. Reading, MA, Addison-Wesley.

González, V., Alarcón. L.F., Maturana, S., Mundaca, F., and Bustamante, J. (2010) "Improving Planning Reliability and Project Performance Using the Reliable Commitment Model." J. Constr. Eng. and Mgmt., October, pp. 1129-1139.

Hagen, L. and Kahng, A.B. (1992) "New Spectral Methods for Ratio Cut Partitioning and Clustering." IEEE Transactions on Computer-Aided Design, Vol. 11, No. 9, pp. 1074-1085.

Horman, M.J. and Thomas, H.R., (2005) "Role of Inventory Buffers in Construction Labor Performance." J. Constr. Eng. and Mgmt., July, pp. 834-843.

Howell, G.A, and Ballard, G. (1994) "Implementing Lean Construction: Reducing Inflow Variation." 2nd Annual Conference on Lean Construction, Catolica Universidad de Chile Santiago, Chile, September.

Howell, G.A., Ballard, G., and Hall, J. (2001) "Capacity Utilization and Wait Time: A Primer for Construction." Proceedings of IGLC-9, Singapore, Korea, 6 – 8 August.

Howell, G.A., Ballard, G., Tommelein, I.D., and Koskela, I. (2004) "Discussion of 'Reducing Variability to Improve Performance as a Lean Construction Principle.'" ASCE, J. Constr. Eng. Mgmt., Mar/Apr, pp. 299-304.

Ibbs, W., Nguyen, L.D., and Lee, S. (2007) "Quantified Impacts of Project Change." J. of Professional Issues in Eng. Education and Practice, January, pp. 45-52.

Liu, M. and Ballard, G. (2009). "Factors Affecting Work Flow Reliability – A Case Study." Proceedings of the 17th Annual Conference of the International Group for Lean Construction (IGLC 17), 15-17 July, Taipei, Taiwan, pp.657-666.

Moreno, J. L. (1960). *The sociometry reader*, The Free Press, Glencoe.

Thomas, H. R. and Sakarcan, A. S. (1994) "Forecasting Labor Productivity using Factor Model." J. Constr. Eng. Mgmt., Vol. 120, No. 1, March, pp. 228-239.

Thomas, H. R., Horman, M. J., Lemes de Souza, U. E., and Zavrski, I. (2002) "Reducing Variability to Improve Performance as a Lean Construction Principle." ASCE, J. Constr. Eng. Mgmt., Mar/Apr, Vol 128, No. 2, pp. 144-154.

Wambeke, B.W., Hsiang, S.M., and Liu, M. (2011a) "Causes of Variation in Construction Project Task Starting Times and Duration." J Const. Eng. Mgmt., 10.1061/(ASCE)CO.1943-7862.0000342

Wambeke, B.W., Liu, M., and Hsiang, S.M. (2011b) "Using Pajek and Centrality Analysis to Identify a Social Network of Construction Trades." J Const. Eng. Mgmt., TBD