ANALYZING THE RELATIONSHIP BETWEEN PRODUCTION CONSTRAINTS AND CONSTRUCTION WORK FLOW RELIABILITY: AN SEM APPROACH

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ABSTRACT

The lack of an explanatory understanding of factors giving rise to low/high PPC highlights the importance of investigating the relation between production constraints and PPC as implemented in the Last Planner™ System. As production is cumulative in nature, that is, underperformances and deficiencies multiply as we move downstream it is important to investigate the combined effect of constraints and underperformances on the next production performance output, and develop an association between production constraints and percent plan complete. The overall goal of this research is to understand the relation between production constraints and workflow reliability, as measured by the PPC metric, at the production level in a construction project. To approach this goal, the research focused on developing a method to investigate such a relationship. The research has concluded that production constraints are mostly subject to constructivist interpretation, i.e., they form as a result of a collection of a set of measured variables and represent a collective existence of those variables. Therefore, it is recommended that future research focus on testing the relationships with formative latent variables. It was also found that studying the impact of all factors together is more insightful than in isolation. The framework in this paper can be used by industry professionals to measure the impact of production constraints on work flow reliability.

KEYWORDS

Lean Construction, SEM approach, Production constraints, Workflow reliability, Last Planner System

INTRODUCTION

A major contributor to improving workflow reliability has been the explicit application of production management techniques as inspired by Lean Construction principles. A key component in addressing work flow reliability is comparison between work planned and work performed on a weekly basis, or any other project appropriate resolution (Abdelhamid et al 2009).

The Last Planner™System (LPS™) is a tool of choice for project personnel implementing Lean Construction (from crewperson to project manager). It provides a regimented process of achieving reliable workflow on simple and complex

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construction projects. The system empowers front-line planners, the Last Planners, to schedule day-to-day production assignments according to the prevailing conditions on the site, as well as focuses coordination meetings on what is to come through a process termed “Lookahead Planning” (Ballard and Howell 1998; Salem et. al, 2005).

To measure the effectiveness of the production system to carryout assignments (commitments), the number of completed assignments is expressed as a ratio of the total number of assignments committed in a given week (or some other planning horizon). This ratio is known as the Percent Plan Completed or PPC (ranges from 0 to 100%) which is a metric reflecting the effectiveness of production planning and the reliability of workflow from one trade to another (Ballard 2000).

Currently, there is no mechanism to anticipate the impact of identified production constraints on workflow reliability prior to proceeding with the work (in effect until PPC is measured). In addition, not understanding the relationship between production constraints and workflow prevents the differentiation of the constraints based on high or low impact. This may be an underlying reason for why getting to 100% PPC values, in a given time period, is still not achieved in practice.

This paper posits that there is a need to understand the relation between production constraints and workflow reliability. The aim of this paper is to develop an approach to investigate the relationship between production constraints and their impact on workflow reliability as measured by the PPC metric. This approach would be implemented by the production control team to help identify which production constraints are more likely to result in low workflow reliability and work to remove them.

The hypothesis being tested in this research is that it is possible to understand the relation between production constraints and workflow reliability by using a Structural Equation Model (SEM). The research concluded that using SEM is plausible, albeit requires, as of yet, a lengthy analytical procedure. Specifically, we found production constraints are mostly subject to constructivist interpretation, i.e., they form as a result of a collection of a set of measured variables and represent a collective existence of those variables. Review of the factor loadings and error variance analysis indicated that diametrically opposed conclusions would be inferred if production constraints were examined individually with respect to workflow reliability. Therefore, it is recommended that future research focus on testing the relationships with formative latent variables. It was also found that studying the impact of all factors together is more insightful than in isolation.

There is no doubt that different production constraints will affect a project differently based on the phase the project is in and various other project attributes. Therefore, the procedure outlined here is best suited for project by project application. The research will mainly benefit parties who implement the Last Planner™ System in their projects by aiding them in improving their understanding of the relation between production constraints and reliable workflow on a project by project basis. The framework in this paper can be used by industry professionals to better understand the impact of production constraints on work flow reliability.

PAPER OVERVIEW

The overall aim of this research was to develop a procedure, in the form of a framework, which enables understanding the relation between production constraints and workflow reliability at the production level in a construction project. In order to achieve this aim, three objectives were pursued: (1) Studying production control tools implemented at the site level and documenting the production constraints encountered on construction sites (Dai et al. 2009, Jain 2010); (2) a generic survey instrument was created for assessing the level if impact different production constraints have on workflow reliability on a particular project - detailed accounts are available in Jain (2010); and (3) Developing a framework to allow examining the relationship between production constraints and PPC.

The developed framework has a number of steps to be performed to (1) identify production constraints specific to a particular project's conditions and (2) to empirically establish a correlation model between these production constraints and reliable workflow - detailed accounts are available in Jain (2010). Each step of the framework was supported by demonstrating it with an example, eventually leading to an SEM model. The model developed was accomplished using randomly generated hypothetical data. Software applications like EQS and Minitab were integral to the development of the framework; therefore, software input/output was an integral component of the framework demonstration.

BACKGROUND

CLASSIFICATION OF PRODUCTION CONSTRAINTS

Lean Construction scholars have typically referred to two types of failure in production work. The first type is planning failures or factors that essentially prevent a work (assignment) from starting. These factors are identified in LPS™ during the constraint analysis stage of the lookahead process, as well as during the weekly work planning sessions. It is proposed here that these fall into three broad categories, namely: Pre-Requisite Work, Directives, and Resources (the three elements of the ADM developed by Lean Construction Institute). These categories represent the exhaustive list of factors that if present will prevent the planned assignment/work from starting. Examples of these include coordination issues, regulatory inspections, unaddressed RFI's, unapproved submittals, lacking specifications, incomplete change order authorizations, availability of space, labor, material, and/or equipment (Mitropoulos 2005).

If all the elements covered under Prerequisite work, Directives, and Resources are satisfied and available, then the start of work is secured – there are no planning failures. However, this does not ensure the finish of the work that is started. This is because finishing a started assignment to its required conditions of satisfaction depends on having no execution failures. We propose here that execution failures come from three main types of elements. According to Koskela (2000) and Liker (2004), these are Muda (Unnecessary work/waste), Mura (Variation), and Muri (Overburden). Figure 1 illustrates the relation between these three elements relative to the crew capability (capacity) for work. For example, if the crew is working much below capability, then there is waste. Conversely, if the crew is working above capability, then there is overburden and likelihood of fatigue and accidents increases.

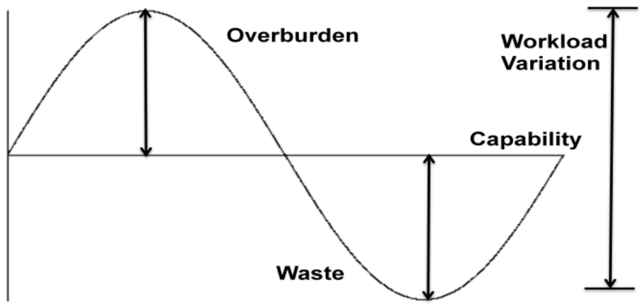

Figure 1: Relation between waste, overburden, and variation relative to crew work capability

Consequently, it is essential to view these three types of execution failures as they impact finishing work after it has resumed. Therefore, all the different types of factors that fall under Mura, Muri and Muda should be considered as important production constraints that lower workflow reliability. Table 1 below indicates the populated list of factors affecting work flow reliability and their classification suited to the LPS™.

Table 1: Classification of production factors suited to Last Planner™ System

Planning Failures (Factors that prevent the work from starting)	**Execution Failures (Factors that prevent the work from finishing)**
Pre Requisite Work	Non-value adding work (Muda)
Directives	Performance Variation(Mura)
Resources	Overburden (Muri)

SEM

This research explored a statistical tool called Structural Equation Modeling (SEM), which is an advanced form of regression analysis and has been extensively applied in psychological research and has the ability to include both measured and latent variables in a relationship model (MacCallum and Austin 2000). The goal of SEM analysis is to determine the extent to which such a theoretical model is supported by sample data. The paper posits that SEM could be a useful technique to arrive at some understanding of the relations between production constraints and reliable workflow. Specifically, with the use of SEM, we have an opportunity to look at these variables together and understand their degree of impact on reliable workflow.

It is critical to understand the type of latent constructs and indicators associated with them as they are critical to SEM model design and validation. There are two types of latent constructs that exist namely “Reflective” constructs and “Formative” constructs. Reflective constructs are the constructs that are usually viewed as producing behavior or phenomenon that is captured by their indicators, meaning that variation in a construct leads to variation in its indicators. In a reflective model, the latent construct exists (in an absolute sense) independent of the measures. Such indicators are termed reflective because they represent reflections, or manifestations, of a construct. For example, behavioral intention to use a system is often operationalized with three reflective indicators. Hence, an individual's change in the latent behavioral intention construct results in corresponding changes in each manifest indicator of intention (Coltman et al. 2008).

On the other hand, Formative constructs are the constructs viewed as being formed by their indicators. In a formative model, the latent construct depends on a constructivist, operationalist or instrumentalist interpretation by the investigator. Such constructs are formed or induced by their measures. Formative constructs are commonly conceived as composites of specific component variables or dimensions. For example, at an organizational level, knowledge embeddedness may be defined in terms of planning, analysis, design, and construction knowledge. Hence, indicators of planning, analysis, design, and construction knowledge form the latent variable 'knowledge embeddedness'. For more details the reader is referred to Jain (2010).

FRAMEWORK DEVELOPMENT

The first step in building an SEM model is establishing the hypothesis that is being tested or confirmed in the model. The hypothesis proposed in this paper is: *Workflow reliability is impacted by production constraints that come into action during construction*. Thus, the interest is in exploring the relationship between production constraints and reliable workflow.

The second step after formulating the hypothesis is to identify the key constructs and establish relationship between the constructs. Thus, the key research question here is: How do the key production constraints (Prerequisite Work, Directives, Resources, Waste, Variation and Burden) affect workflow reliability? We developed the following relationships (hypotheses) based on literature, survey results, and professional experience of the authors:

- 'Availability of Prerequisite Work' positively affects 'Work Flow Reliability'.
- 'Availability of Directives' positively affects 'Work Flow Reliability'.
- 'Availability of Resources' positively affects 'Work Flow Reliability'.
- 'Waste Reduction' positively affects 'Work Flow Reliability'.
- 'Variation Reduction' positively affects 'Work Flow Reliability'.
- 'Burden Reduction' positively affects 'Work Flow Reliability'.

After the constructs are specified, the next step is to identify the model in a form suitable for analysis. This step involves identifying constructs as endogenous or exogenous, followed by demonstrating the relationship visually in a path diagram. In other words, the directional relationships are established between the constructs.

The path model shown in Figure 2 provides the assumed relationship for the constructs. Because they are all latent constructs, i.e., they cannot be measured directly and represent a larger condition created by a myriad of factors, it becomes imperative to identify the variables that truly capture the constructs by direct measurement. These variables are better known as *indicators or measured variables*

(Hair et al. 2005). For example, variation in work cannot be measured so accurately as to eliminate it, but by measuring factors that influence or cause variation we can measure the variation to a greater accuracy.

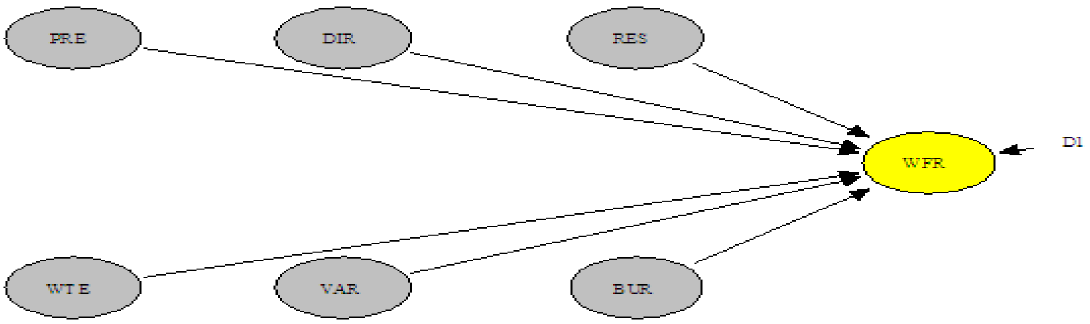

Figure 2: Path Diagram of the proposed structural model (1st Stage)

Thus, the next step in the process is to define the constructs and operationalize them by selecting their measured variables and their scale type. Identifying scale type is critical because it converts the qualitative data into quantitative data. The variables and definition are listed as follows:

- Work Flow Reliability (WFR): Work flow reliability concerns a state of consistency, dependability, and predictability, and improving reliability generates a more consistent, dependable, and predictable flow (Abdelhamid et al. 2009). It is therefore, the measure of consistency of flow of activities carried out for completion of a set of tasks in order to achieve a larger production goal in adherence with a plan. Two Likert items are provided as item indicators for this construct. These are (Table 2):

Table 2: Measured Variables for Work flow Reliability Construct

Measured Variables	**Scale**	**Scale Reference**
WFR1. The PPC is high; 90% or higher	1-10	(10-100% Agree)
WFR2. We are headed to a timely completion of the project	1-10	(10-100% Agree)

- Availability of Prerequisite Work (PRE): As suggested by the name it includes all the planning factors that make sure that the prerequisite work is available in time, desired quality, and in time, etc. It is difficult to measure precisely the 'availability of prerequisite work' without measuring the production constraints that together contribute to availability of prerequisite work. A sampling of the measured variables designed for this construct are (Table 3):

Table 3: Measured Variables for Availability of Pre Requisite Work

Measured Variables	Scale	Scale Reference
PRE1. Prior work is complete with desired quality.	1-10	(10-100% Complete)
PRE2. The pre-requisite work has been verified to meet current work needs (dimensions, locations, etc)	1-10	(10-100% Agree)
PRE8. Overall, the prerequisite work is complete.	1-10	(10-100% Complete)

In a similar fashion, Availability of Directives (DIR), Availability of Resources (RES), Waste Reduction (WTE), Variation Reduction (VAR), and Burden Reduction (BUR) were defined and given measured variables (see Jain 2010 for details).

Next, construct validity is investigated. There are four components of the procedure to establish construct validity. Three of those were used in this research, namely, components are convergent validity, discriminant validity, and nomological validity (Jain 2010). After validating the constructs, SEM analysis can move forward in two different ways. In this research the measurement model was specified estimated followed by specifying and estimating the structural model. In this approach, the relationships between various constructs are specified as originally proposed in the relationships (statements listed on page 5). The structural model that corresponds to the relationships in this demonstration example is shown in Figure 3.

In Figure 3, the red arrows indicate the fixed factor loadings on the reflective variable of each construct. For the WFR construct, since both its MVs are reflective, one can choose any one variable and fix its factor loading to 1. Once the model is specified it is checked for identification. The next step after specifying the structural model is to design a study and collect data for model estimation purposes.

The large sample size needed to feed the SEM model presented a challenge for the research (400 responses were needed, representing 400 projects). In consultation with the Statistics Center on campus, it was acceptable to consider a measurement as the PPC for 400 days instead of 400 projects. Realizing that most projects measure weekly PPC, and given the early stages of the research, it was decided to randomly generate survey responses. This data set was used for demonstration purposes and guidance for interpreting the results and their statistical significance once a model is developed. The demonstration illustrated the use of software like EQS and MINITAB for development of model as well as analysis of the results. In the demonstration, it was found that departure from standard method of developing an SEM model, as found in literature, is acceptable for purposes of exploring relationship between production constraints and reliable workflow (Jain 2010).

Review of the factor loadings and error variance analysis indicated that diametrically opposed conclusions would be inferred if production constraints were examined individually with respect to workflow reliability. The different analysis experiments confirmed the need for studying the impact of all factors together as compared to isolation studies. In addition, it is advisable to study management practices in a formative approach.

FUTURE WORK

The introduction of SEM analysis technique in construction management research is still in a nascent stage and offers a huge potential for implementation in studying cause-and-effect relationships, as was discovered during the literature analysis and framework development and demonstration stage.

Much of the applied SEM literature is characterized by inadequate understanding or acknowledgement of the limitations of single studies. Most often conclusions are limited to the particular sample, variables, and time frame represented by the study. The results are subject to sampling or selection effects with respect to at least three aspects of a study: individuals, measures, and occasions. The choice of individuals has an effect on sampling results, in order to account for such effects researchers may use expected cross-validation index (ECVI), which is computed from a single sample, as an index of how well a solution obtained in one sample is likely to fit an independent sample.

Therefore as a first potential research area, actual data should be collected and used for testing a particular investigator's model. Also, a good fit does not imply a universally true model for a set of factors; therefore, further research is required to produce models with better fit to the data and hence better prediction capability. In addition, the list of factors may not be exhaustive and only represent the pool suited to this research's purpose. More research is required to refine the list of production constraints to study workflow reliability.

Furthermore, the framework development focused on cross-sectional design in SEM. Cross-sectional designs allow only for the evaluation of relationships among variables at one point in time and do not allow for autoregressive effects or time lags. This causes problems in inferring causality or directional influence in cross-sectional studies. To posit such an inference as valid, it would have to be assumed that the time lag during which causal influence operates is essentially instantaneous, thereby justifying concurrent measurement of variables in a cross-sectional design (MacCallum and Austin 2000).

A framework for repeated measures designs will be more complex and require longer data observation times, which may limit the benefit of such modeling for explanatory purposes. However, SEM research using the repeated measures design aimed at studying the cumulative impact of production constraints on workflow reliability over the entire duration of the project has the benefit of establishing higher predictive capability. Such a study will be especially helpful to create models designed to understand production planning effectiveness for each type of construction project classified according to the characteristic of its sector such as industrial, commercial, healthcare, nuclear, etc.

Construction is a global activity. As such, it is executed by people from different cultures all across the globe. Given that culture provides a behavioral context especially when there is a huge presence of human interaction, it is important to examine the weighted value of production constraints that involve direct human involvement, such as burden and variation in this case. Therefore, a third potential area of research is to investigate the extent to which particular production constraints carry more impact in overall performance and assign those weights and study the cause-and-effect relationship in cultural context as well.

CONCLUSIONS

This research provided a framework for studying the relationship between production constraints and workflow reliability. The framework components were inspired from literature review and input from practitioners steeped in the Last Planner™ System. The framework involves constructing an SEM model to analyze the relationship between workflow reliability and production constraints. Data for the model building activity is obtained using a survey instrument.

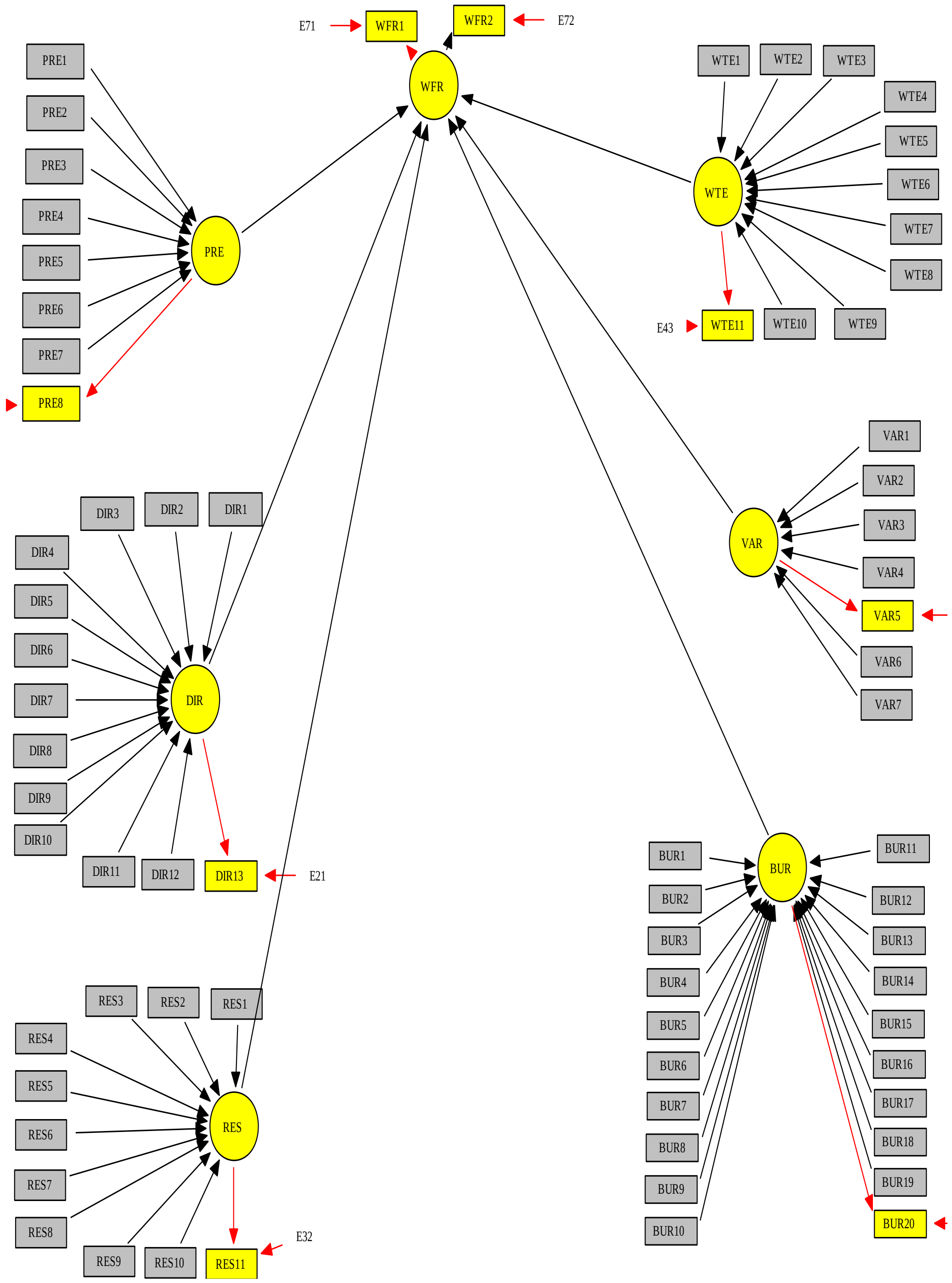

Figure 3: Diagram showing the Structural Model of the proposed Hypotheses

This research will primarily benefit construction contractors especially those who implement the Last Planner™ System. This approach provides an opportunity to researchers to revisit earlier studies, and study the impact of factors on the respective end result in a manner more suitable for construction management practices. In general, this framework is expected to aid contractors to bring a scientific structure in their evaluation of construction site performance based on a set of project-specific production constraints.

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