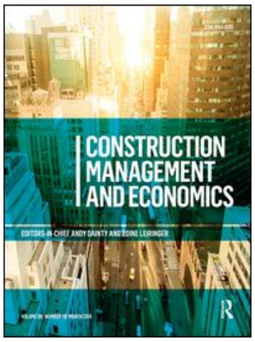

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Construction flow index: a metric of production flow quality in construction

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ABSTRACT
A new, process-oriented approach is needed in construction management. Lean construction emphasizes the concept of flow as a way to understand production in construction, yet there is still no accepted metric for measurement of flow quality. This has hampered research and practice. The proposed construction flow index (CFI) is a composite measure that reflects the quality of production flow in repetitive construction projects. It incorporates measures of work continuity for crews, processing continuity for locations, production rate variation, amounts of work in progress, interference and operation sequence logic. Expert knowledge was acquired to establish weights for the CFI parameters, and its use was tested in evaluating the planned and actual production flows for a number of projects. Project managers can use the CFI to evaluate the quality of their construction plans and to measure and communicate production flow quality status to trade crews, enabling management and improvement of production flow. The CFI is also a valuable tool for construction research. The CFI challenges traditional construction management by measuring flow, where standard practice only measures transformation (earned value). It challenges lean construction practice using the Last Planner System, suggesting that the percent plan complete measure of plan reliability is insufficient.

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Introduction

Lean construction emphasizes the concept of flow as a way to understand production in construction (Koskela 2000, Bertelsen *et al*. 2007, Sacks 2016). The flow view is complementary to the traditional concept of transformation, and with the perspective of value generation, it is a part of Koskela's Transformation-Flow-Value (or TFV) conceptualization of construction (Koskela 2000). The transformation view underpins the traditional and predominant "results-oriented" approach to construction management, whereas the flow view emphasizes a new "process-oriented" direction.

Perhaps the main practical significance of the flow view is that it shines a spotlight on the waste of time from the perspective of both construction "products" (typically well-defined locations, i.e. zones or spaces in a building) and construction crews. Wasted time is manifested as time spent on non-value adding activities, such as inspections, waiting, or moving from place to place. Crews wait for materials, information, equipment, space, completion of preceding activities, etc., whereas products wait for crews. Locations where no productive activity is taking place are considered analogous to products in a production line that accumulate in front of a machine before they can be processed.

In lean implementations in factories, flow is monitored continually using a variety of metrics (Fernando and Cadavid 2007, Davidson 2013). Many of the production metrics are derived from or closely related to the parameters of Little's Law, which relates throughput (TH) to work in progress (WIP) and cycle time (CT) in the equation TH = WIP/CT (Hopp and Spearman 1996, Little and Graves 2008). WIP and throughput are easily measured: WIP by counting the number of products present in a production line, and TH by measuring the rate of output of the last machine in the line. These reflect the flow directly. Other common metrics measure aspects that impede flow (e.g. setup times, waiting and inspection times, batch sizes).

In construction, however, flow is more difficult to measure. There are three key differences between manufacturing and construction in this regard. First, in construction, the work crews move while the products are stationary. Thus there is no apparent physical flow of products that can be observed or measured. Instead, the status of work locations must be monitored (Bertelsen and Sacks 2007).

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Second, construction is by its nature production within projects (Ballard and Howell 2003, Forbes and Ahmed 2011). A construction project encompasses more than producing the finished product; it extends to planning, assembling and disposing of the production facilities. In a manufacturing context, this is akin to designing, building and demolishing the factory as well as manufacturing the products. The first activities in building construction – such as structural works – are generally completed well before the last activities are begun, with the result that the proportion of WIP within the total production quantity is very high and setup times have strong significance. Third, construction projects involve complex and temporary organizations made up of independent contractors who are not subject to a central authority and are considered providers of products rather than of labour or service. This is significant because it often leads to a management style that abdicates its responsibility for controlling production, preferring to transfer risk and manage contracts instead (Ballard 2000, Koskela 2000, Sacks and Harel 2006).

There are no direct metrics of flow in common use in lean construction. The percent plan complete (PPC) measure, an integral part of the Last Planner System™ (LPS) (Ballard 2000), is the most pervasive metric in lean construction, but it measures plan reliability, not production flow. It is at best an indirect measure of production flow. The absence of a direct measure of production flow quality in construction is a significant barrier to continuous improvement in industry and to effective research, because without a metric it is difficult to compare alternative production management and control strategies.

In response to the need for fundamental change in production control in construction, and recognizing the power of and need for a metric, the authors propose a novel measure called the construction flow index (CFI). The CFI is intended to provide construction project teams with a simple composite indicator with which they can determine whether their efforts are improving production flow or if production flow is deteriorating. Furthermore, the CFI is normalized such that it can be used to compare projects with one another, so that companies can establish target minimum standard production flow quality performance levels for planning and for control of their projects.

The next section provides the background to the notion of flow in construction and to the measurement of flow in manufacturing and in construction. The following section describes the goals and requirements for the CFI. Development of the index – methods, process and calibration – is detailed next. A section on testing and validation with other projects, smooth and chaotic, shows application of the index to different projects. The discussion section places the CFI within its research context, describes possible modes of application and defines some of its current limitations.

Background

Production flow in construction

One of the difficulties faced in developing metrics for production flow in construction seems to be the absence of agreement on the definition of what "production flow" means in this context.

In manufacturing, Shingo emphasized the differences between two axes of flow: *process flow*, which represents the progress of a product along a production line, and *operations flow*, which represents the individual actions performed on the product (Shingo and Dillon 1989). This is a fundamental distinction and enables focus on improvement of the flow of product (process flow) and on improvement of operations, including reducing setup time, rework, etc. Koskela *et al*. (2007, p. 216) adopt this distinction in the context of construction. They distinguish between operations, referring to the individual activities performed by crews and represented in activity networks, and process, referring to the flow of work (construction products). They explicitly refer to the latter as "work flow".

The construction metaphor for product flow is the flow of locations (Kenley and Seppänen 2010, Sacks 2016), which although they do not move, are analogous to the products moving down a production line, onto which incoming parts and materials are assembled in the operations performed by trade crews. This can therefore be understood to be the primary production flow. Where subsidiary engineered-to-order parts are fabricated and/or pre-assembled, as in precast concrete or steel construction, the process flow of these products are also part of the production flow.

Construction site trade crews function on the operations axis. Unlike the fixed workstations along a production line in a factory, the crews move through the project, and their flow can be readily observed. In contrast with Henry Ford's idea that "the thing is to keep everything in motion and take the work to the man and not the man to the work" (Ford and Crowther 2003), on a construction site crews and equipment move to the work. It is also possible for more than one trade crew to work in a single location. This is analogous to the imaginary scenario of multiple machines working simultaneously on a single product piece in a factory. In the industry it is known as "stacking of trades", and it usually reduces productivity (Koskela 1999, Serag *et al*. 2010).

Sacks (2016) proposed a model of production flow in construction with three axes, adding a portfolio axis to the process and operations axes. The portfolio, process and operations (PPO) model recognizes that construction projects produce *aggregated* products (e.g. a building composed of rooms). From the point of view of construction contractors in a regional economy, projects themselves are products that flow – they have cycle time and one can

Table 1. Ideal process axis conditions for good location flow in construction.

Optimal flow conditions	Production flow principle	Source
1. Balanced work: the variation of takt time across locations for all trades, measured as the standard deviation of the average number of locations completed per unit of time for each trade, is zero	Takt time variation	Emiliani and Seymour (2011), Schmenner and Swink (1998)
2. The batch size, measured as the number of locations occupied by a crew, is one	Little's law	Hopp and Spearman (1996), Little and Graves (2008))
3. The sum of the time buffers between trade operations is zero for all locations	Minimum cycle time; Little's law	Hopp and Spearman (1996), Little and Graves (2008)
4. The number of operations has been reduced to an essential minimum	Minimum waste	Ohno (1988)
5. There is no re-entrant flow	Re-entrant flow	Brodetskaia *et al.* (2013), Kumar (1993)
6. There is no rework	Minimum waste	Ohno (1988), Schmenner and Swink (1998)
7. The work flow is reliable: only work packages with matures[a] constraints are released to operations. This also ensures that "making-do" is prevented	Last planner system, waste of making-do	Ballard (2000), Koskela (2004)

Source: Sacks (2016).
[a]i.e. work packages whose constraints have been removed.

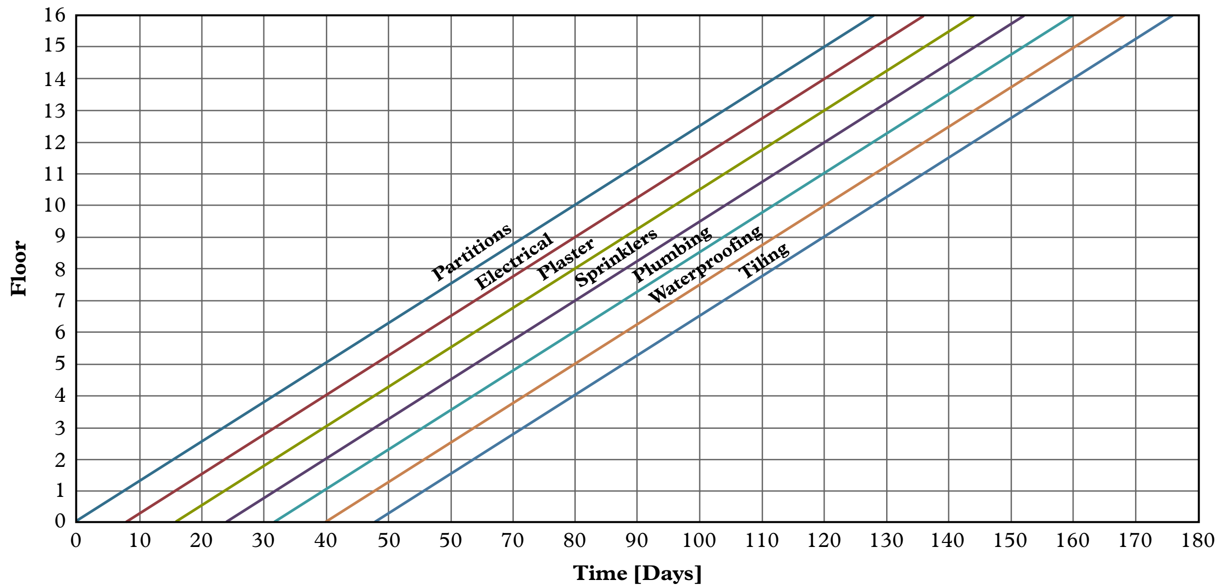

Figure 1. Flowline chart of a project with optimal production flow.

talk about the WIP of projects in a company's current workload and about project throughput. The model is cyclic, connecting operations to portfolio, to recognize that construction trade crews flow from project to project and not only from location to location within a project.

Thus production flow in construction has three primary aspects that can and should be measured – (1) the flow of trade crews from location to location and between projects, (2) the flow of locations through their production process and (3) the flow of projects viewed as unitary products.

Construction operations – trade crews performing activities – are also fed by ancillary flows. Materials, design information, process information (directives), equipment and cash must all flow into activities, and all can experience waiting, unnecessary storage and accumulation of inventory, buffering and other forms of waste. However, these are not part of the production flow that is the focus of the CFI.

Good production flow in construction

Sacks (2016) reviewed the literature defining conditions for achieving optimal flow in manufacturing and in construction. The conditions listed pertain to all three axes of the PPO model, but only those for the process axis, the flow of locations, are relevant for the CFI measure, because the CFI cannot measure the flow of a portfolio of projects and it does not measure the attributes of the operations (such as setup time and productivity). Table 1 below summarizes the working set of conditions for the process axis with the relevant production principle and the sources from the literature.

In summary, good location flow can be said to occur when locations and subassemblies are built continuously (with no waiting between operations), at stable production rates, and with minimized cycle times and minimal WIP. Figure 1 shows the flowline chart for an idealized project with optimal production flow. The process, or the location flow, can be seen by viewing the rows for the locations (in this example, the floors of the building). The inclined lines represent the flow of the trade crews as they progress from location to location. Each location experiences continuous flow, with smooth handovers from trade to trade. The project has single piece flow (each trade crew occupies only one location at a time), there is no waiting and no re-entrant flow.

Planning and controlling production flow in construction

Location-based methods for planning explicitly plan for better flow in construction. The first documented use of a method belonging to this group was the Empire State Building in the late 1920s (Willis and Friedman 1998, Sacks and Partouche 2010). Later, more systematic approaches, include Line-of-Balance (Lumsden 1968), Flowline (Mohr 1979, Peer 1974, Selinger 1973, 1980) and Representing Construction (Russell and Wong 1993) among several others.

The most recent additions to this group are the Location-Based Management System (LBMS) (Kenley and Seppänen 2010) and the adaptation of takt time planning (TTP) to construction (e.g. Frandson *et al*. 2013). Both methods use flowline diagrams for visualization but LBMS emphasizes the continuous flow of resources from location to location whereas TTP emphasizes the continuity of work in each location. LBMS allows the durations of operations to vary from location to location if work quantities change between locations, assuming the same crew working continuously. Time buffers are added between the tasks to account for variability (Kenley and Seppänen 2010). TTP uses capacity buffers to ensure that the takt time can be met consistently (Frandson *et al*. 2015).

In terms of controlling flow, both LBMS and TTP focus on crew-level metrics. In LBMS, managers forecast future progress based on actual production and productivity rates measured on site. Alarms are generated when buffers have been exhausted and there is a risk of interference and control actions are planned to prevent production problems (Kenley and Seppänen 2010, p. 254). Managers' attention is focused on preventing cascading delays (Seppänen 2009). TTP focuses control on achieving the hand-offs for every trade and every takt time (Frandson *et al*. 2015). As in LBMS, its control methods are based on controlling individual crews. Neither system has an overall metric of construction flow.

Measuring production flow in manufacturing and in construction

In lean implementations in factories, flow is monitored continually using a variety of metrics. Common metrics include: on-time delivery; manufacturing cycle time or production lead time; tool setup time; time to make changeovers (from one product to another); yield; rework; throughput; capacity utilization; WIP inventory or inventory turns; ratio of downtime to operating time; and cash to cash cycle time (Maskell 1991, Karlsson and Åhlström 1996, Fernando and Cadavid 2007, Davidson 2013).

Many of the production metrics are derived from or closely related to the parameters of Little's Law. WIP and throughput are easily measured: WIP by counting the number of products present in a production line, and TH by measuring the rate of output of the last machine in the line. These reflect the flow directly. Other common metrics measure aspects that impede flow (e.g. setup times, waiting and inspection times, batch sizes). In many lean implementations in manufacturing plants the status of flow is communicated to workers in the plant by displaying the current values and trends of the metrics on visual devices such as Andon boards (Liker 2003).

In traditional construction management, earned value management is the most common approach to monitoring production rates, cash flow and schedule compliance. However, its various measures – such as the schedule performance index (SPI) and the cost performance index (CPI) (Hendrickson and Au 1998) – do not tell managers anything about the quality of the production flow. Indeed, Kim and Ballard claimed that their use can actually undermine efforts to achieve good production flow (Kim and Ballard 2000).

With the exception of the most repetitive of construction projects, achieving optimal production flow is highly unlikely to coincide with achieving optimal productivity for all work crews. This is due to the variation in the content and quantity of work types required across locations that is common in almost all projects. Re-entrant flow - the return of the same crew to the same location for different aspects of the work - occurs in most construction projects (Brodetskaia *et al*. 2013) and also contributes to the disconnect between optimal production flow and optimal productivity. As such, measures of productivity or efficiency of labour allocation – such as the actual to planned labour ratio (APLR) (Miles 1998) – also cannot be considered as measures of production flow. In the manufacturing context, too, it has been argued that measures such as machine utilization or labour efficiency are not

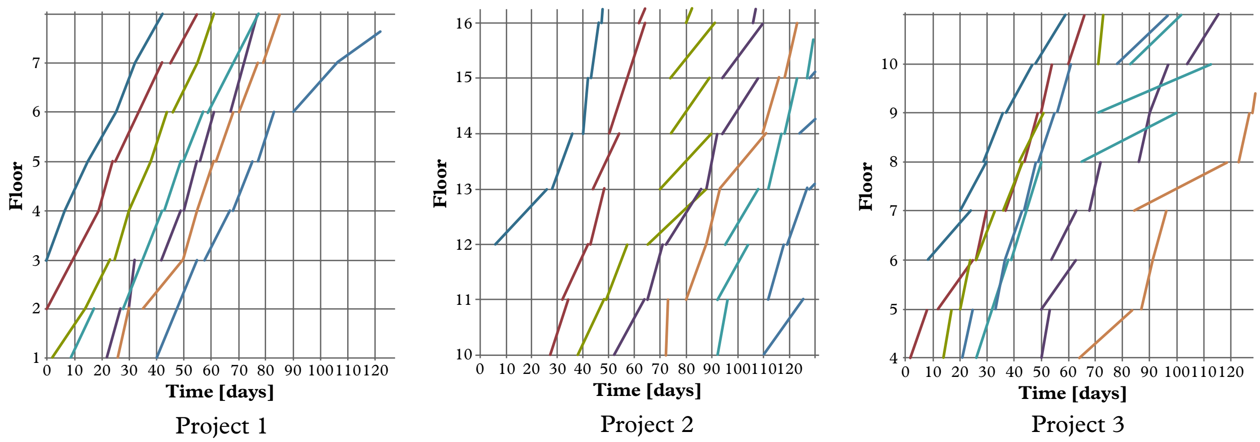

Figure 2. Flowline charts for three repetitive projects, showing actual progress of seven trade crews through seven locations.

measures of either flow or variability and that they should be abandoned (Schmenner and Swink 1998).

The most common metric in lean construction is PPC (Ballard 2000). However, PPC measures plan reliability, not production flow per se. Additional metrics have been proposed to support the make-ready process within the LPS, such as percent work ready (PWR) (Mitropoulos and Takis, 2005) and the similar tasks made ready (TMR) (Hamzeh 2009, Hamzeh and Aridi 2013) and percent constraints removed (PCR) (Jang and Kim 2007). Beary and Abdelhamid (2005) developed a metric for production planning process assessment for use in conjunction with the LPS in home-building companies. However, all of these, like the PPC itself, measure plan reliability and not production flow. They are good metrics for quality of planning, but not for the quality of production flow.

Indeed, projects which achieve high PPC may nevertheless have unstable production flow. Hamzeh explained how poor look ahead planning results in poor linkage between master plans and weekly work planning, with the result that PPC becomes a weak indicator of project progress (Hamzeh 2009). Empirical evidence, such as the comparisons of schedule performance indices and PPC values for two large projects conducted by Olano *et al*. (2009), and measurements by Priven and Sacks (2014), reveal that LPS improves production flow but that PPC can nevertheless be weakly correlated with schedule performance or characteristics of smooth production flow. This is particularly the case where PPC values are driven up by under-loading of tasks (goals set too low) (España *et al*. 2012), resulting in low capacity utilization. Similarly, over-ambitious task commitment or under-reporting of completion can result in artificially low PPC values. España *et al*. (2012) criticized PPC as "not a good indicator of performance capability or productivity", and proposed a set of 12 additional metrics. However, none of these measures the quality of production flow experienced by the work crews or the products directly.

Bølviken and Kalsaas investigated alternative approaches to understand and measure flow in construction (Kalsaas and Bølviken 2010, Bølviken and Kalsaas 2011, Kalsaas 2012). They concluded that productivity is a measure of production flow and proposed that it can therefore be calculated by the formula: "(Man hours at employer's disposal – Wasted time)/Man hours at employer's disposal". This definition disregards the distinction between the process and operations axes, i.e. between location flow and trade crew flow. Productivity measures may lead to local optimization, which can in some situations work against product flow.

Requirements for a CFI

To be of practical value, production flow metrics for application in a construction project must be based on easily measured data, relatively simple and quick to compute and easy to comprehend. To be useful for control during a project, it should be possible to compute their rate of change over relatively short periods (days or weeks).

Experience gained in earlier work provides a starting point for meeting these requirements. Bølviken and Kalsaas (2011) tested their method for measuring production flow as direct productivity by conducting waste measurements within pipe installation activities for an offshore drilling system. However, measuring waste by distinguishing value adding from non-value adding time is very time-consuming, essentially requiring continuous sampling of all crews. As Kalsaas (2013) concluded, this method is also rather suited for improving work than measuring total difference between two points in time, because the contextual framework is subject to change.

While a set of distinct basic flow measures may be useful for those skilled in production system design and operation, a single composite index that encapsulates the basic measures may provide simpler feedback for construction planners at the site level who have diverse skill sets. An

Table 2. Proposed production flow measures.

Symbol	Description	Unit of measure
RS_i	The square of the Pearson product moment correlation coefficient, for each trade *i*. This reflects the smoothness of the flowline	–
P_i	Duration per location for each trade *i*	Days/location
STD	Standard deviation of duration per location	Days/location
ND	Days of break for all tasks	Days
NB	Number of breaks for all tasks	–
TFP	Sum of all locations produced by all trades	Locations
NT	Number of tasks considered (active tasks)	Tasks
BP	Number of times a task is performed before its predecessor in a location (work out of sequence)	Tasks
BF	Number of times a crew works on location X before location $X - 1$ (location out of sequence)	Tasks
WIP	Work in Process (WIP) – number of locations with work in progress	Number of locations

Source: Priven *et al*. (2014).

additional advantage of a composite index is that it can be normalized across projects to set a comparative standard for performance. Ray *et al*. (2006) provided a good example of a composite index for lean operations in the wood products industry. They identified ten variables using factor analysis and computed weights for each normalized variable, adding the components to provide the scaled index.

Bertelsen and Koskela (2003) argued that production in construction projects is turbulent, which would make measurement of flow difficult. Kenley (2005) argued that the apparent complexity of construction is caused by activity-based planning and can be resolved by using location-based planning principles. Seppänen (2009) analysed the production phase of numerous projects and showed that complexity is partially caused by cascading delay chains of predecessors impacting successors and causing slowdowns, start-up delays and discontinuities. Seppänen *et al*. (2013) reviewed numerical evidence for accuracy of production forecasts and showed that forecasts work well in a non-chaotic project, but are virtually useless when a project has entered a chaotic state. Visual inspection of flowlines was proposed as a way to evaluate whether a project is in a chaotic state or not.

These results imply that the information represented in flowline charts are a potential direct source for the necessary data. Indeed, a practitioner skilled in the principles of lean construction can readily determine the quality of flow simply by observing the patterns of the flowlines in a chart. The three project flowline charts shown in Figure 2 illustrate the principle. A skilled practitioner can see that Project 1 has the best production flow of the three; that Project 2 has the longest cycle times and greatest WIP over much of the project duration; and that Project 3 has the most variation in the sequence of trade work in each location.

The CFI can therefore be composed of the properties of flow that can be measured and observed in flowline charts. In practical terms, the conditions for optimal flow in construction from Sacks (2016), including those presented in Table 1, require that production planners try to achieve the following:

(1) near equal takt times across all trades (i.e. the duration of work in each location is similar. This is achieved by balancing production rates and work quantities in locations),
(2) stable production rates for each trade crew (low variation),
(3) small batch sizes,
(4) minimized waiting/time buffers between operations,
(5) minimized non-value-adding time within operations (minimized layout/setup, waiting and inspection times),
(6) satisfactory quality to avoid delays for rework,
(7) minimized number of operations,
(8) just-in-time delivery at the junctions where subsidiary process flow meets higher-order flow (e.g. where prefabricated windows and doors are installed in a building),
(9) just-in-time delivery of raw materials.

Requirements 1–4 relate to the process (flow of locations), 5–7 to the operations (flow of crews) and 8–9 to the subsidiary flows. Numbers 1–4 and 7 are visible in flowline charts and can be measured relatively easily.

Development of the CFI

The CFI was developed in the following steps:

(1) Define a set of possible production flow measures and a CFI formula as a composite of the measures using a parametric polynomial function.
(2) Establish a calibration benchmark for the composite CFI values by surveying experienced lean construction practitioners for their evaluation of the production flow quality of eleven real and idealized projects.
(3) Calibrate the parameters of the function using the benchmark values.

Table 3. Parameters used to compute the CFI.

Parameter	Description
$P_1 = \prod_{i=1}^{n} \mathrm{RS}_i$	Product of all RS_i values, for *n* trades
$P_2 = \frac{\bar{P}}{\bar{P} + P\,\mathrm{STD}}$	Standard deviation of the duration *P* normalized using the average of *P*
$P_3 = 1 - \frac{\mathrm{NB}}{\mathrm{TFP}}$	Proportion of transfers from location to location for a crew that are continuous (i.e. percentage of the locations after which a crew will not have a break after finishing the location)
$P_4 = \frac{\bar{P}}{\frac{\mathrm{ND}}{\mathrm{TFP}} + \bar{P}}$	Normalized proportion of average actual working time to total time spent on site for all trades
$P_5 = \frac{\mathrm{NT}}{\mathrm{WIP}}$	Proportion of locations worked on in a given period to the total number of locations with work in progress over the same period
$P_6 = 1/e^{(10\times \mathrm{BP}/\mathrm{TFP})}$	Indicator of the proportion of work performed out of sequence
$P_7 = \frac{\mathrm{TFP}-\mathrm{BF}}{\mathrm{TFP}}$	Normalized proportion of locations performed out of sequence (a trade crew performing locations out of order or in parallel – not according to the plan)

Note: The symbols for the flow measures are defined in Table 2.

(4) Implement a software tool to compute the CFI.
(5) Test, validate and refine the CFI with legacy data-sets from large construction projects.Implementation of the first three steps is reported in Priven *et al*. (2014) and is briefly presented here. The proposed CFI formula has the form:

$$\mathrm{CFI}\,(t) = 10\sum_{i=1}^{7} W_i P_i^{X_i} \quad \text{where } X_i \in [1,2]$$

The period *t* is the time span over which the CFI is calculated. Table 2 lists the proposed set of production flow measures that are used to compute the parameter values and Table 3 lists the parameters of the formula. Note that all of the measures can be ascertained directly from the planned or as-built flowline data of a project. The formula is a polynomial function of either first or second degree: the values of the weights (W_i) and their coefficients (X_i), were determined by calibration with empirical data in the third step of the procedure.

Production flow evaluation survey

A survey was conducted to establish a benchmark for quality flow perceptions for a set of 11 representative construction projects. As-built flowline records for the 11 projects were shown to members of the lean construction institute (LCI) and the international group for lean construction (IGLC). Participants were asked to assess the work flow quality in each project on a scale from 1 to 10. Of the 39 responses, 24 were used (those with at least four years' experience in lean construction).

The 11 projects included three real and eight simulated projects (see Figures 3 and 4). Simulated projects were included in the survey because they can be configured to highlight particular aspects of interest – such as perfect flow (project 1), out-of-sequence work (project 5), and discontinuous work (project 11) – in isolation.

Calibration of the CFI function

The results of the survey were then used to calibrate parameter coefficient values in the CFI formula. Using a selective brute-force search algorithm, the weights of each parameter were calibrated subject to the average project production flow measures attained in the survey. The solution was obtained by minimizing the error between the calculated production flow indexes and the surveyed indexes subject to the following constraints: the sum of the weights is one, no negative weights, and ensuring that no index fell outside of the allowed range of 1–10. Two alternative minimization functions were tested for the sum of the errors: minimize the sum of errors for the whole sample and minimize the maximum single error. The former gives an average error of 9.0% and the largest single error is 21%; the latter gives an average error of 10.0% and the largest single error is 16.5%. The resulting calibrated CFI weights yield the following formulae:

$$\mathrm{CFI}\,(t) = 10\left[0.28\,P_2^2 + 0.38\,P_3^2 + 0.20\,P_5^2 + 0.14\,P_6\right] \quad (1)$$

$$\mathrm{CFI}\,(t) = 10\left[0.30\,P_2^2 + 0.32\,P_3^2 + 0.06\,P_4^2 + 0.24\,P_5^2 + 0.03\,P_6 + 0.05\,P_7^2\right] \quad (2)$$

Table 4 shows the results for the first formulation (Equation (1)) for all 11 survey projects, with the survey results, the computed CFI values and the differences between them.

The resulting formula was used to compute the CFI for three real projects (numbers 3, 6 and 10 in Figure 3). All three projects are high-rise residential buildings with similar typical floor and same construction methods. To illustrate the impact of the different parameters, Table 5 provides parameter values for the significant parameters of the three real projects. For all three projects, both the flowline and CFI was calculated over a time span of 7 months, to ensure good conditions for comparison.

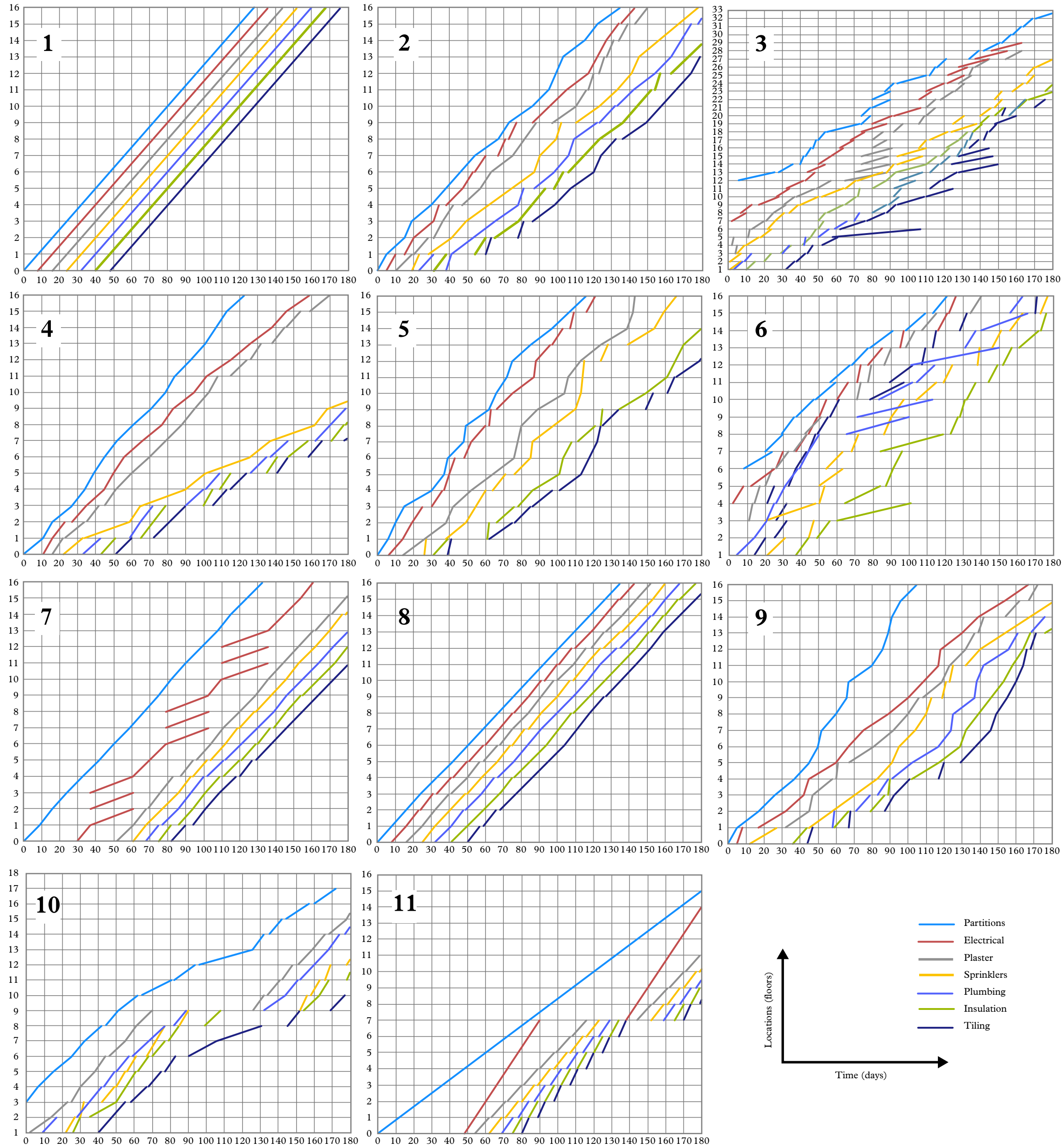

Figure 3. The eleven project flowline charts used for the survey. Each project had seven trades, as shown in Figure 4.

Table 5 shows that while Project 10 is the project with the most stops after a task has completed a floor (parameter P_3^2 in the table) its CFI is significantly higher than for Project 3 and Project 6 as it has lower WIP (P_5^2) and fewer crossings between tasks (P_6).

CFI implementation in software application

A software application was implemented to automate computation of the CFI and its component values using a Microsoft Excel spreadsheet and macro code written in Visual Basic. The input required includes: the number of locations, the number of trades, and the start and end dates for each trade in each relevant location. The application checks the data for internal consistency and then reports the project's CFI and all its composing parameters. Processing time, even for relatively large projects, is less than one minute. Although the prototype is a standalone application, the computation code could be easily embedded within commercial project management software that supports location-based planning and control. In such situations data entry specifically for CFI computation would be unnecessary.

Testing and validation

Three construction projects for which detailed production control records were available were used to validate

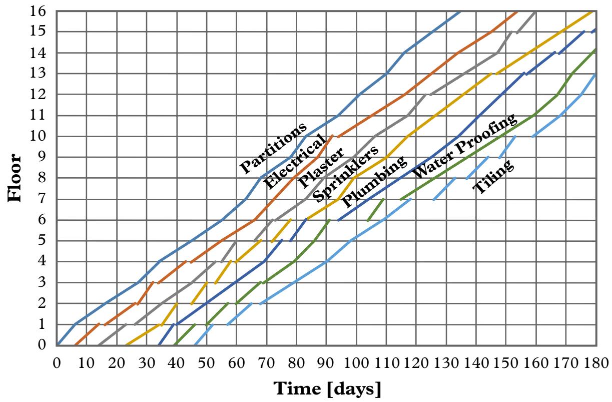

Figure 4. A flowline chart for a simulated project. Task durations were generated randomly using the distribution of durations from the three real projects, yielding a range of 5–11 days per floor with an average of 8 days. For simplicity, possible return delays due to subcontractors' unavailability when work is finally released are ignored (Kenley and Seppänen 2010).

Table 4. Survey results vs. computed CFI using Equation (1).

Project number	Survey average production flow score (1 … 10)	CFI (1 … 10)	Difference (%)
1	10	10.00	0
2	7.06	6.12	15
3	3.67	4.66	21
4	5.22	5.20	0
5	5.56	5.57	0
6	3.22	3.33	3
7	6.28	6.69	6
8	8.94	7.45	20
9	5.33	6.43	17
10	5.35	5.39	1
11	5.59	6.49	14

the CFI and test its generalizability to other contexts. The selected projects had significantly different characteristics from the idealized and the real projects that were used to calibrate the model. Two were hospital construction projects in California (H1 and H2) and the third was an office building in Finland (O). These project case studies were selected from previously documented case studies with full production data, allowing retrospective computation of CFI and comparison of the findings with previously documented results.

According to subjective feedback from the project team, project H1 had good production flow. On the other hand, project H2 had plunged into chaos. Thus H1 was expected to have a significantly better CFI than H2. Project O had a full set of production control data, including start and finish dates for all tasks in each location, PPC and the number of production problems (Seppänen 2009). It was thus possible to validate the CFI against these other metrics of interest.

The interior rough-in/finishes phase was used from each project, with roughly the same scope considered in the CFI calibration projects. In the hospital project with good production flow (H1), 11 systems and interior finish tasks were examined over all 34 project locations. In the chaotic hospital case (H2), 11 interrelated tasks over all 13 project locations were selected for the study. In the office building case (O), 18 tasks across all 10 project locations were used.

As is often the case when trying to validate against projects different from a calibration sample, the initial set of results was discouraging. The chaotic project H2 actually had the highest CFI although visually the flowline figure looks chaotic (Figure 5). One of the main reasons for chaos on this project was the management policy of starting tasks even though they could not be finished. The result was that many trades had unfinished tasks in each location (as can be seen in Figure 5), such that the WIP was in fact greater than the total number of locations. Each task had work ongoing in almost all locations in parallel, a situation that had not occurred in the calibration projects.

This behaviour was not reflected in the CFI because the denominator of parameter P_5 counted the number of locations with ongoing work regardless of the number of trades with ongoing work in each location. Thus P_5 reached a value of 1.0 and the project CFI of H2 was greater than it was for projects H1 and O. The anomaly was readily corrected by replacing the denominator of P_5 with a summation of the number of work-in-progress locations for each trade, thus:

$$P_5 = \frac{\mathrm{NT}}{\sum_{i=1}^{p} \mathrm{NTL}_i}$$

where NTL = number of active task locations for a *trade*.

The initial CFI measure for the hospital with good production flow (H1) revealed an error in the calculation of parameter P_3 (discontinuities in trade crew work) that arose from the assumption, which held for all of the calibration projects, that all trades followed the same sequence through all of the locations, from the first to the last. In project H1 three parallel crews worked in three sets of locations (Figure 6). Although most of the individual trades were able to work continuously, without breaks, the flowline does not look like the good production flow subjectively experienced by the project team. The odd pattern in the flowline chart results from missing design or design changes which did not impact the first task (fireproofing), but impacted several other tasks: the production flow bypassed these areas which were held up and therefore look out of sequence in the flowline diagram.

This error was corrected by sorting the locations of each trade task according to the start dates in each location for the computation of P_3, as can be seen in Figure 7. In this way parameter P_3 correctly reflects actual discontinuities

Table 5. Parameter values for three real projects.

Measurement	Project 3	Project 6	Project 10	Units	Weight (%)
P_1	0.85	0.74	0.68		
P_1^2	0.72	0.55	0.46		
$\overline{P\ STD}$	8.98	9.75	8.31	Days/location	
P_2	5.73	8.93	4.21	Days/location	
P_2	0.64	0.60	0.72		
P_2^2	0.41	0.36	0.51		28
NB	33	43	46	Breaks	
TFP	154	89	86	Locations	
P_3	78.54	52.49	45.06	%	
P_3^2	61.69	27.55	20.30	%^{2}	38
ND	227	306	447	Days	
P_4	85.90	73.93	61.53	%	
P_4^2	73.79	54.66	37.85	%^{2}	
Active tasks	7	7	7	Tasks	
$\overline{WIP}$	14.85	9.71	7.08	Locations	
P_5	0.47	0.72	0.99	Tasks/locations	
P_5^2	0.22	0.52	0.98	Tasks^2/locations^2	20
BP	9	15	1	Tasks	
NFP	140	86	78	Locations	
P_6	0.53	0.17	0.88		14
BF	63	24	6	Tasks	
P_7	59.09	73.03	93.02	%	
P_7^2	34.92	53.34	86.53	%^{2}	
CFI	4.68	3.33	5.39		

Note: That some of the rows provide the square of the parameter in the previous row (e.g. P_1^2 is the square of P_1).

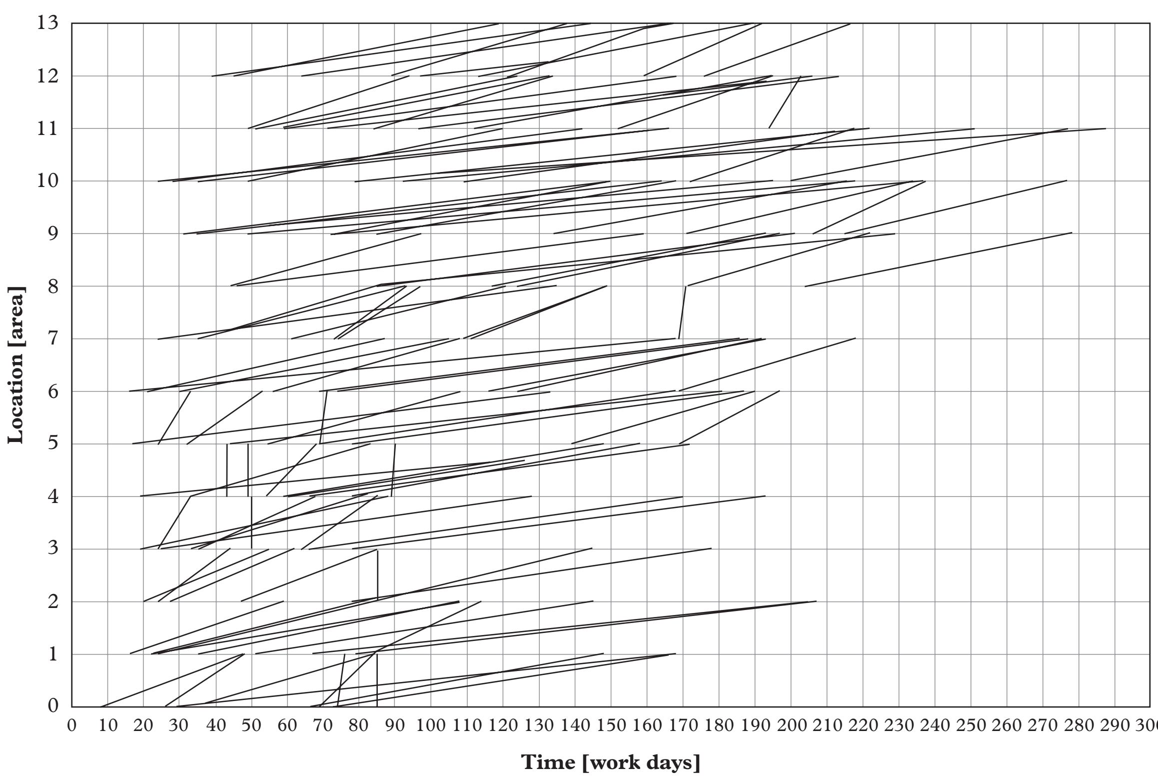

Figure 5. Flowline chart of project H2 (hospital project with chaotic flow).

in each trade's work. Computation of all other parameters remains unchanged, and the correction has no effect on the calibration.

In the office building project (project O) work in locations 1–5 was interrupted for some seven weeks, as can be seen in Figure 8, when the project managers decided to halt production in these locations to improve production flow after the two week summer break.

Table 6 shows the CFI scores and their constituent parameters for the validation case studies both before

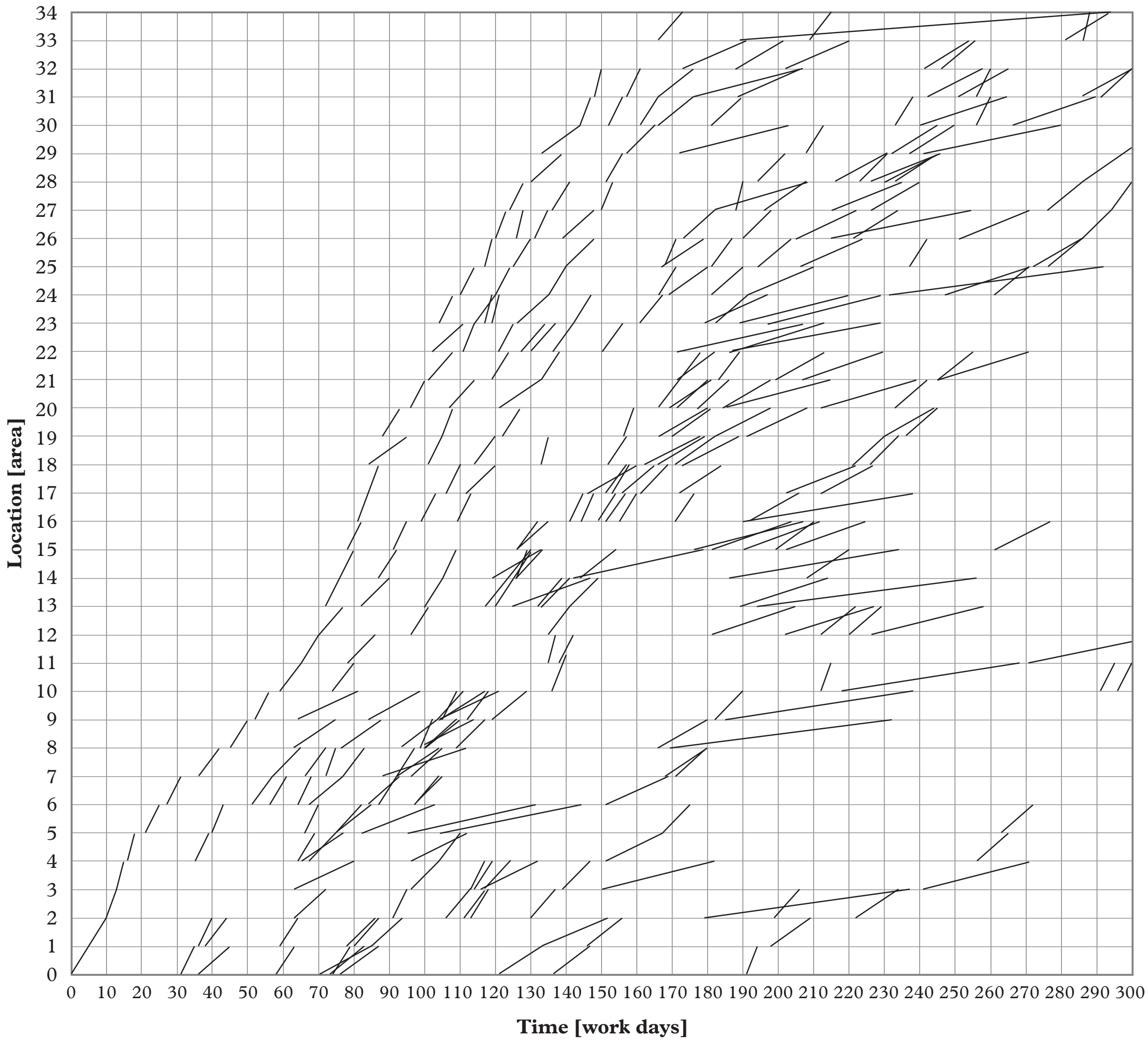

Figure 6. Flowline chart of project H1 (hospital project with good production flow).

and after the corrections noted above. The anomaly in the WIP scores (P_3) of all three projects before the correction is apparent. Project H2 has a high score for continuity of trade work, which given the high weight for this parameter results in a relatively low degree of differentiation of this project from the others. Project O has a low score due the planned discontinuity.

In summary, testing and validation revealed three main issues which were not apparent in the calibration case studies. Firstly, the WIP metric was based on the total number of tasks and total number of locations. It ignored the consequences of starting early and being unable to finish. The key to improving this parameter was the realization that WIP can manifest on project level or individual task level. Secondly, sequence changes due to missing design or change orders are common in construction and were not handled well in the original model as it ignored the intentional changes in location sequence. Thirdly, the CFI computation did not account for planned interruptions. The first two issues were resolved by correcting the CFI software. The third issue is discussed below.

Using CFI to monitor production flow status

Thus far, the CFI computation was shown considering the full lifetime of projects. However, in day to day project production control, it is useful to measure trends in production flow. This requires measurement of CFI over short time periods (days or weeks).

In the CFI software application, users can set the time interval over which they wish to calculate the index and how frequently the CFI should be calculated for a new interval. The system computes the CFI for all intervals and plots a graph showing the trend in production flow. Figure 9 shows the CFI trend for a time interval of 30 workdays with renewal of intervals every 10 workdays for the

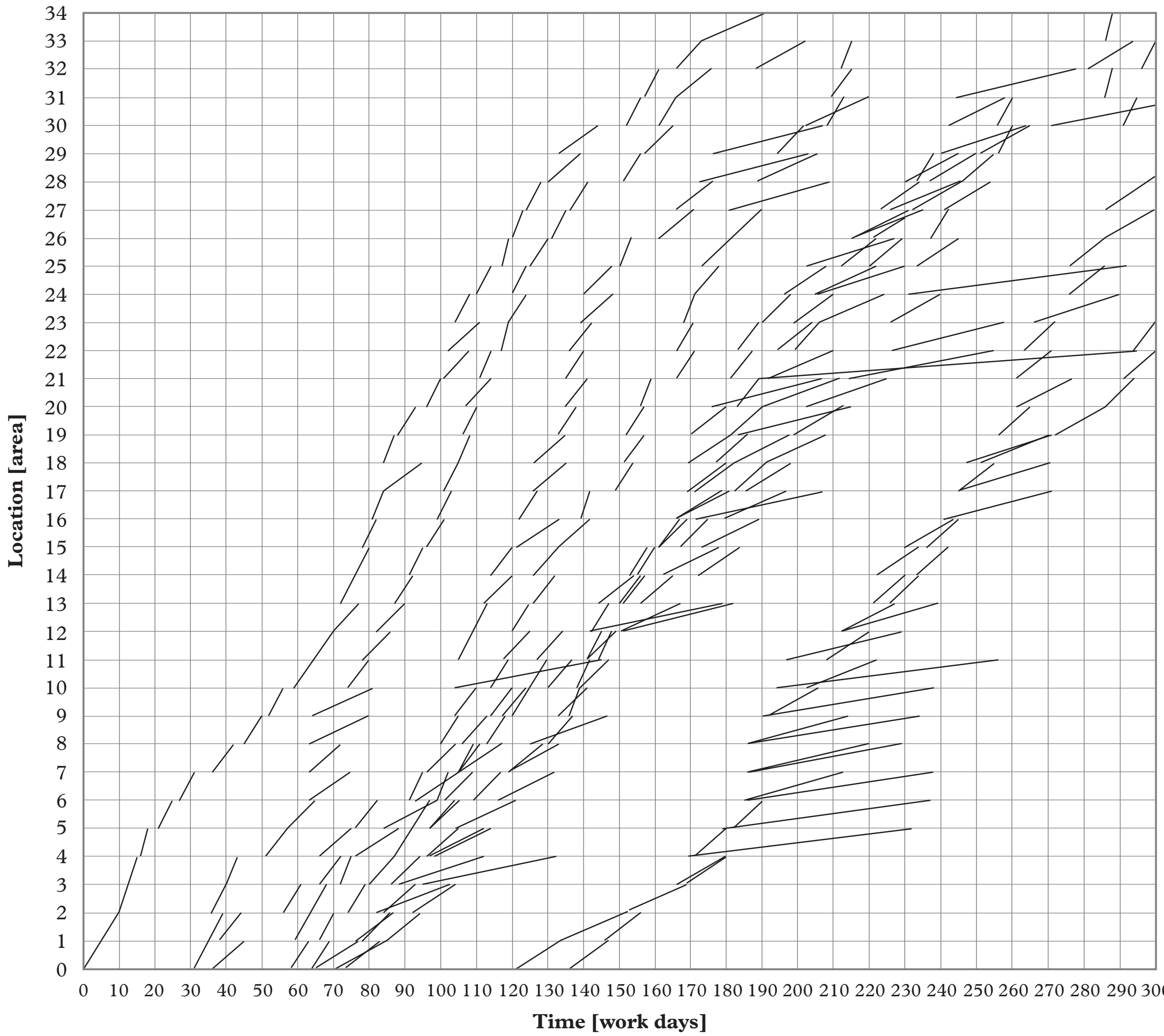

Figure 7. Flowline chart of project H1 sorted for computation of P3.

three real projects from the calibration set (projects 3, 6 and 10). As can be seen in the figure, there is no apparent correlation between PPC and CFI. Project 10 has the highest CFI and the lowest PPC.

The same function was applied to project O from the validation set. The project was analysed for correlations between CFI and PPC, and between CFI and production problems recorded on site (based on data from Seppänen 2009). In order to do this, the CFI was calculated at the same time points as PPC and production problems were reported in the data. The CFI was calculated based on intervals of 10, 20 and 40 days of history in order to evaluate the sensitivity of the measure to the interval. Figure 10 shows the results. There is no apparent correlation between the different PPC and the CFI for any of the three projects.

The Pearson correlation coefficients between these five variables are shown in Table 7. PPC and Production problems had a negative correlation, so they are partially measuring the same phenomenon. Production problems and CFI had a strong positive correlation when the span was long, indicating that evaluating the CFI based on longer spans may result in a measure that is not sensitive enough to be a useful measure for detecting real-time problems. As expected, CFI measures with different spans correlated with each other statistically significantly.

Finally, the CFI and parameter values of the Office Building were plotted together with the flowlines to visualize the contributions of the constituent parameters (Figure 11). Work continuity (P_3) is low and WIP quantity is low (reflected by high P_5) from days 40 to day 60, as theory would suggest due to starvation. However, this suggests that low WIP is not always good – when WIP dips below the critical WIP, the WIP parameter should likewise be reduced. Similarly, CFI and P_3 (continuous work) are at their lowest levels when the tasks begin to finish location 5 because most of the tasks had a planned break at that point. This was neither a production problem nor a reliability problem because the break was planned. CFI improves when the

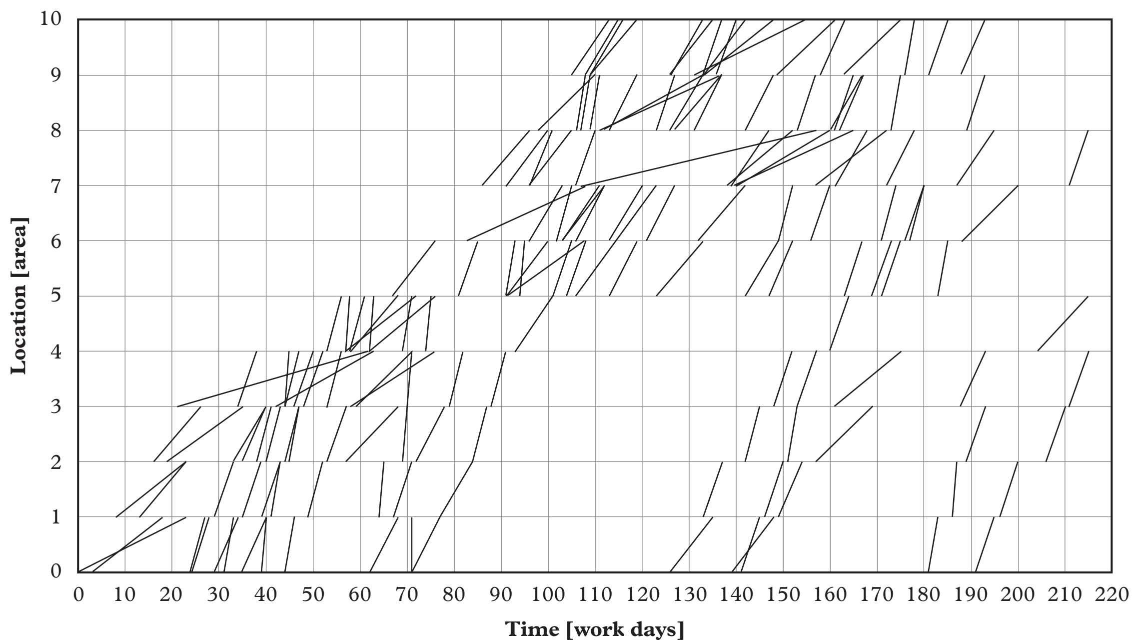

Figure 8. Flowline figure of office case study.

Table 6. CFI scores for validation case studies prior to and after corrections.

			Before correction			After correction		
Parameter	Subject	Weight (%)	H1	H2	O	H1	H2	O
P_2	Production rate stability	28	0.34	0.41	0.40	0.34	0.41	0.40
P_3	Continuity of trade work	38	0.55	0.86	0.34	0.76	0.92	0.42
P_5	Work in process	20	1.00	1.00	1.00	0.46	0.08	0.61
P_6	Interferences	14	0.46	0.03	0.55	0.46	0.03	0.55
CFI		100	5.69	6.46	5.18	5.42	4.85	4.70

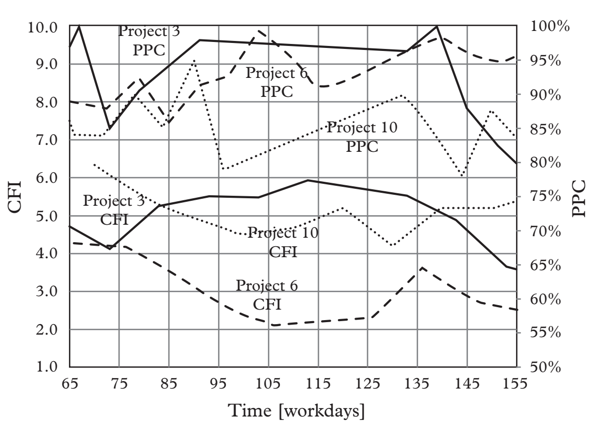

Figure 9. CFI vs. PPC of project 3, 6 and 10.

tasks start again and declines when the work becomes more chaotic around the summer holiday period (gap in figure). With the exception of the time of the planned break in the beginning of the project and the period when WIP is lower than critical WIP, the CFI reflects the project's production flow reasonably well.

Discussion

As proposed, the CFI has potential applications in both practice and research, but its development, validation and testing also reveal a number of aspects that require further consideration and development.

When measured during the life of a project, the CFI can give advance warning when a project's production flow measures begin to deteriorate. The composite CFI can raise a general alarm, and the component values can indicate the symptoms of the problems. The CFI can be presented as a radar graph, which would illustrate not only the composite value but the component values too. If the metric works well, management will be able to take action to help the site team to improve production flow and avoid chaos. In research, an objective and quantitative measure of work flow quality is an essential tool for investigators whose research methods require measurement in the field or evaluation of simulation outcomes.

Yet before CFI can be introduced in practice, further research is needed to establish appropriate modes of

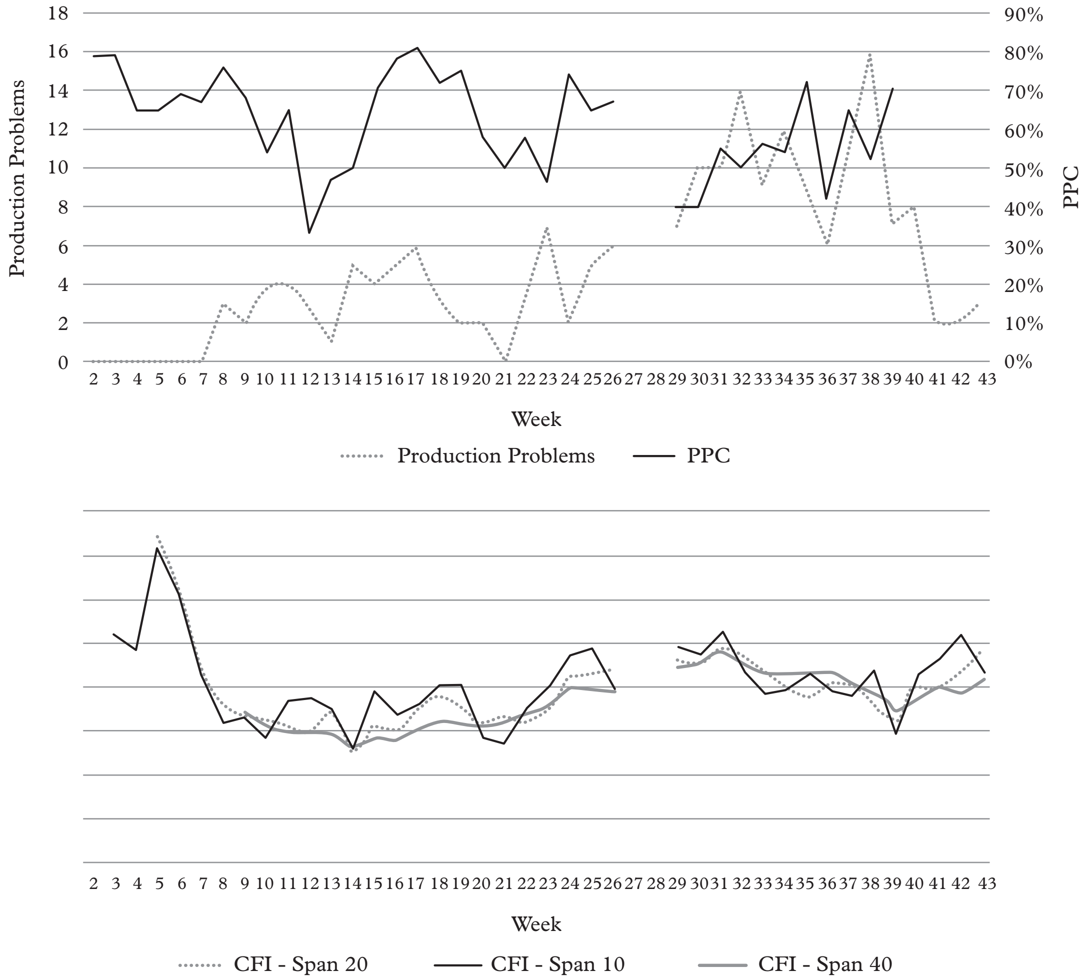

Figure 10. PPC, production problems and CFI with different time spans for project O.

Table 7. Pearson correlation coefficients for project O for PPC, number of production problems and the CFI calculated with different spans.

		Correlations				
		PPC	Problems	CFI_span10	CFI_span20	CFI_span40
PPC	Pearson correlation	1	−0.348*	−0.089	−0.070	−.308
	Sig. (2-tailed)		0.037	0.612	0.699	0.104
	N	36	36	35	33	29
Problems	Pearson correlation		1	−0.069	−0.208	0.493**
	Sig. (2-tailed)			0.676	0.216	0.004
	N		40	39	37	33
CFI_span10	Pearson correlation			1	0.846**	0.480**
	Sig. (2-tailed)				0.000	0.005
	N			39	37	33
CFI_span20	Pearson correlation				1	0.724**
	Sig. (2-tailed)					0.000
	N				37	33
CFI_span40	Pearson Correlation					1
	Sig. (2-tailed)					
	N					33

*Correlation is significant at the 0.05 level (2-tailed); **Correlation is significant at the 0.01 level (2-tailed).

use. The meaning of a composite index value to a user is dependent on that individual's understanding of the notion of flow and it may obscure the relative importance of its components. The cumulative aggregation of the components proposed in Equation (1) above is only one of many possibilities. For example, variation of trades' production rates is measured in both parameter P_1 and P_2 (P_1 is dependent on the number of locations, P_2 is not). P_1 was

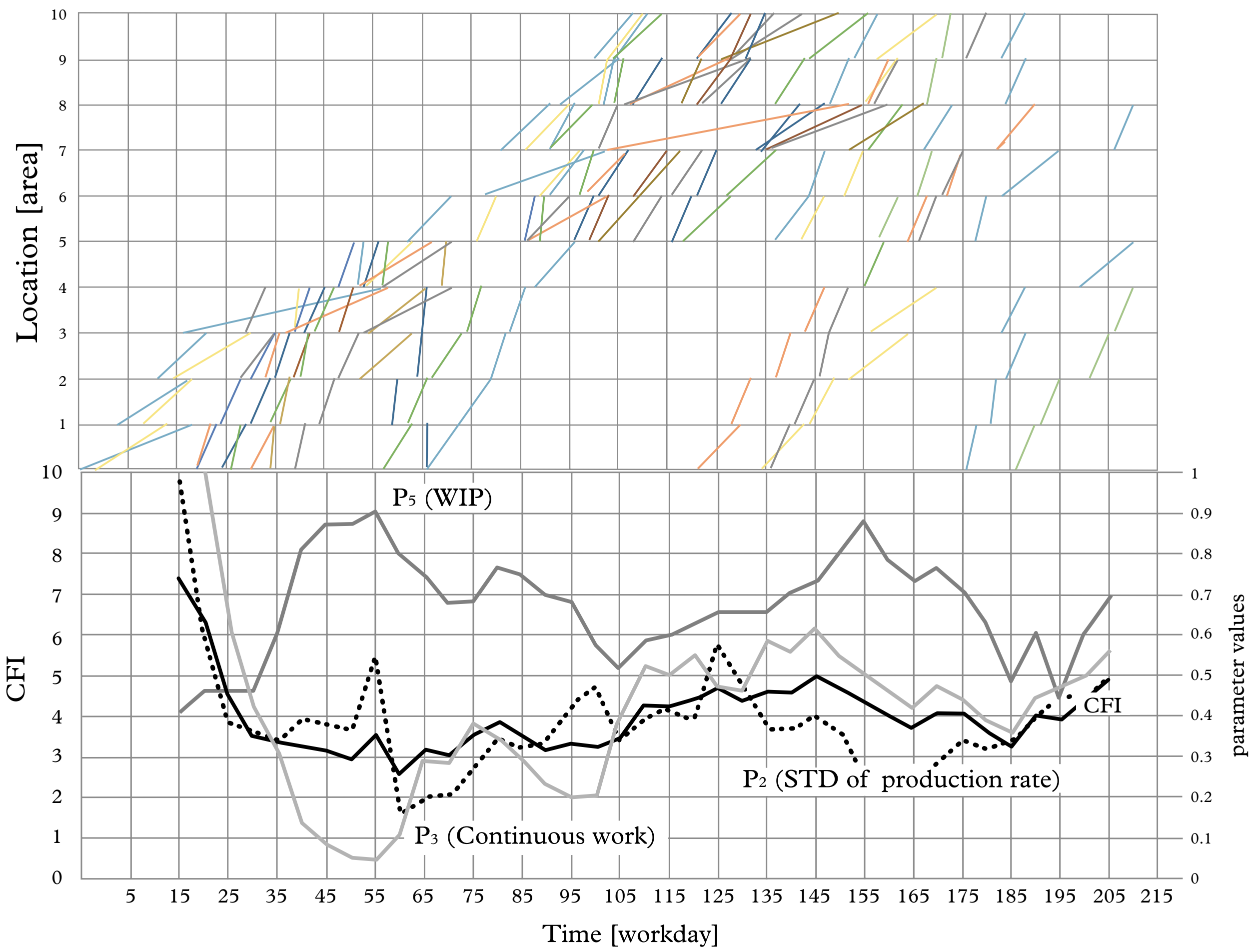

Figure 11. The flowline, CFI (span 20 days) and parameter values of project O.

Table 8. Alternative formulations of the composite CFI.

Parameter		Weight (%)	Project		
			O	H1	H2
P_2	Production rate stability	20	0.40	0.34	0.41
P_3	Continuity of trade work	20	0.42	0.76	0.92
P_5	Work in process	40	0.61	0.46	0.08
P_6	Interferences	20	0.55	0.46	0.03
CFI cumulative weighted			5.17	4.97	3.04
CFI multiplicative			5.58	5.51	0.09

given zero weight, normalizing the CFI to be independent of the project size. Table 8 illustrates two additional possibilities for aggregation: (1) use of a differently calibrated set of weights, and (2) direct (unweighted) multiplication of the four component values. Adjusting the weights places more or less emphasis on each aspect, and this can be tailored according to the characteristics of specific production systems or their modes of control. The weights could be calibrated to reflect the preferences of a particular company or project type. For example, applying 40 and 20% weights to P_5 and P_6, respectively, emphasizes the problems of project H2 (CFI = 3.04). Multiplication gives lower values dominance in the composite CFI, resulting in a wider range of values and greater sensitivity to any particular flow problem. Using the formula CFI $(t) = \prod_{i=1}^{7} P_i^2$ for project H2 yields a very low CFI (0.09), strongly highlighting its' flow problems.

Regardless of the way in which the composite CFI is computed, inspection of the values of the component parameters provides a richer and more useful assessment of the state of a project's flow. Observing the low value for production rate stability (P_1) for project H1 in Table 8, for example, shows that this is the primary problem plaguing the work flow, revealing a potential focus for improvement efforts. While the simplicity of a single composite index value may be useful for obtaining an overview of a project's performance, the component parameter values should be provided with it.

An important benefit of any production flow measure lies in its ability not only to reflect current performance, but to support management learning (Neely and Najjar 2006, Barth and Formoso 2008). The CFI supports learning because it directly reflects the impact of managers' policy decisions. For example, managers can set targets for controlling WIP, knowing what the expected impact on the CFI result will be. Consideration of its component measures and the way in which they raise or lower the CFI value should help managers learn how to improve production flow. In other words, the CFI makes production flow, and the impacts of their efforts to control it, visible and tangible.

Although the case studies focused on the measurement of actual flow during production, the CFI could also be used to measure the theoretical flow of a plan before implementation. All the CFI components, except Interference which is calculated based on breaking planned dependency relationships, can be calculated for planned production before implementation. This raises interesting new research questions, such as: Will planning for flow result in better actual flow in the project? If the planned CFI is small, is it still possible to achieve a high CFI during implementation? Can the planned CFI be used to set a target for actual CFI during implementation?

Additional research steps will also be needed to validate the CFI. Its ability to correctly reflect expected trends can be evaluated by collecting empirical data and evaluating CFI trends for predicted situations. Some examples:

(1) The cascading impact of interruptions to flow from the first trade crew in a project to the last means that earlier trades should have smoother flow than later trades. CFI values per trade should reflect this degradation for most projects.
(2) Where projects are repetitive and production rates are unstable, lean theory predicts that WIP, cycle times and the number of interruptions will rise. Measurements of the CFI components for these four parameters should reflect positive correlation.
(3) Where trade crews have numerous locations in which their work is incomplete, the ratio of general contractor and/or other supervision hours worked to trade crews' hours worked is expected to be higher than in situations where trade crews occupy a single location at a time. The WIP parameter should exhibit positive correlations with the amount of supervision overheads consumed.

As can be seen from Figures 9 and 10, no correlation was found in these cases between the CFI and PPC measured over time. This is expected, but it also calls for, and indeed the CFI enables, further research to explore the nature of the relationship between plan reliability and production flow. A hypothesis worth testing would be to look for correlation between PPC and CFI with a time delay between the former and the latter to account for the effects of planning to manifest in production flow.

There are several documented case studies where the LBMS forecasts have been used to inform control actions to prevent production problems from causing cascading delays (for example Seppänen 2009, Seppänen *et al*. 2014). The forecasts worked reasonably well in standard circumstances but were virtually useless when the project had plunged into chaos (Seppänen *et al*. 2013). Seppänen *et al*. (2013) proposed visual inspections of flowlines to detect chaotic projects. CFI could conceivably be used to detect chaotic projects using a numeric measure, which could allow managers to detect potential problems without having to analyse the flowlines of each project.

In the form proposed, the CFI also has a number of limitations:

(1) The CFI computation considers interruptions to crews' work between locations, but it does not consider breaks within locations. The input data is the start and end of work in each location – what occurs between those two dates is ignored.
(2) Application of the CFI is limited to repetitive projects, where work content variation across locations is small. Where location sizes or work contents vary significantly, production planners may specifically plan breaks in workflow for crews or fluctuations in crew sizes. Future research and development of the CFI must consider monitoring planned interruptions and fluctuations in crew size on site over time, and incorporation of these values in reporting CFI and its components.

Measures influence the ways in which people behave. When teams are measured by the PPC index, they usually try to improve their planning and their execution of tasks. Some teams may also try to improve the measurements artificially by approving tasks as done before they are completely "done-done" or by planning fewer tasks. The CFI will likely have a similar effect: once measurements begin, teams will try to improve production flow by paying attention to the components of the CFI – interruptions, stability, sequential work, etc. However, the CFI is also subject to "gaming". To avoid the problem of subjective evaluation, CFI and PPC should be measured using an independent means to determine tasks that are "done-done", and a minimum required production rate should be set to avoid plans with too few tasks.

Conclusions

Invention of the CFI was motivated by the understanding that the prevailing "results-oriented" approach to construction management is inhibiting the industry's performance. A new direction with a "process-oriented" approach is needed to bring production management back into the practice of construction management. The CFI is designed to support process-oriented planning and control actions by measuring production flow quality. It challenges the paradigm of traditional construction management practice by offering an alternative to measures of earned-value. Production control using flow concepts seeks global optimization, whereas earned-value control promotes local optimization.

The CFI also challenges a commonly held view in the context of lean construction. The results reported show that the PPC measure, the primary measure of the Last Planner System®, is insufficient for achieving good production flow.

From a practical standpoint, the CFI has the potential to fundamentally change construction management practice because (1) it is the first metric that measures production flow in construction directly, (2) it uses easily measurable quantities and is thus relatively easy to implement, (3) its use does not presuppose understanding of flow but rather educates through "learning by doing", and (4) people tend to behave according to the way they are measured.

The composite CFI is a weighted sum or product of the values of component parameters that measure flow aspects such as continuity of work, accumulation of WIP, variability of production rates, etc. The CFI enables monitoring of project production flows in real-time so that construction teams can be continuously aware of their performance and in can be used to compare alternative production plans**.** Unlike PPC, which has a scale that is relative to the number of tasks committed to, CFI has an independent scale, so that values can be compared across projects. In most implementations of the Last Planner® System in construction, PPC is used to measure plan reliability, but it does not specifically nor necessarily engender smooth production flow. The CFI can complement PPC, adding impetus to achieve smooth and stable production flows.

The CFI can also be a useful tool for research, enabling evaluation and comparison of the production flow quality achieved in sets of experimental results, whether from measurements made of live projects or from computer simulations. Up to now, research of construction production control systems has been hampered by the tools available for measuring efficacy – such as WIP, location cycle time, ratio of value-adding time to total work time, etc. Most of these enable comparison within sets of simulation runs but not across projects. The CFI can be compared directly across simulation samples and across projects.

Several issues with CFI still need further research and development. To begin with, alternative formulations for the composite CFI could be considered. Thus far a weighted polynomial function of either first or second degree has been tested, but a multiplicative formula could be considered. Secondly, the current method works for repetitive projects without major planning changes or interruptions. For non-repetitive projects with significant interruptions, an additional component of the CFI is needed to account for interruptions. Finally, the formulae for calculating the component parameters of the CFI should be refined by collecting empirical evidence and evaluating their fluctuation over time, with a view to improving their ability to reflect flow quality.

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