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A LEAN WORKFLOW INDEX FOR CONSTRUCTION PROJECTS

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ABSTRACT

Traditional monitoring methods for construction project control based on the earned-value method provide measures of cash flow and schedule compliance. However, they do not tell managers anything about the quality (stability, continuity) of the workflow, and the results are not timely enough for effective control. In order to improve workflows where lean production control is applied, direct measures of workflow are needed. Kalsaas and others have proposed measures of daily or weekly workflow for specific tasks, but their measures cannot be used for real-time project control and they were not tested or calibrated over complete project life-spans.

The Lean Workflow Index (LWI) that we propose directly reflects the smoothness and continuity of workflow lines in flowline charts. In the first stage we define a set of possible tracking parameters and propose the lean workflow index formula as a combination of them. A survey of lean experts was conducted in which they graded workflow quality for as-built flowline records for 12 projects. The results of the survey were then used to calibrate parameter coefficient values in the LWI formula by using a goal seeking algorithm. The resulting formula was used to compute the LWI for three high-rise residential projects.

The major advantage of the proposed lean workflow index is that it monitors project workflows in real-time so that construction teams can be continuously aware of and improve their performance in the areas that are measured.

KEYWORDS

Workflow, lean construction, flowline, production control

INTRODUCTION

According to Koskela (2000) there are six principles for flow in production processes: reduce waste (including waiting time), reduce cycle time, reduce variability, minimize the number of steps, maximize flexibility and provide transparency.

Anyone skilled in these principles can easily judge which project among the three shown in figure 1 below has the best workflow (in the figure, each line represents a different trade). In flowline charts such as these, waiting, cycle time and variability

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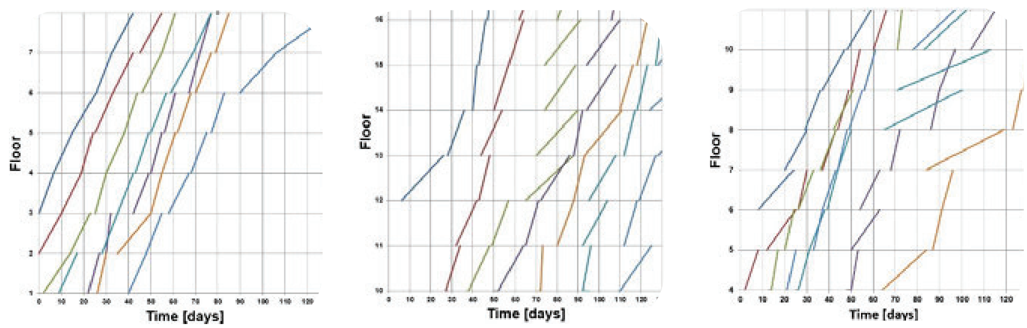
are clearly visible and the charts make the process transparent. But how can we measure it quantitatively?



Project 1 Project 2 Project 3

Figure 1: flowline charts of three real projects

Traditional monitoring methods for construction project control based on the earned-value method provide measures of cash flow and schedule compliance. However, they do not tell managers anything about the quality (stability, continuity) of the workflow, and the results are not timely enough for effective control.

Lean Construction researchers have debated notions of complexity and stability of production in construction. Bertelsen and Koskela (2003) argued that production in construction projects is turbulent. Bertelsen (2003) hypothesized that construction is a complex system where project execution can be planned in detail only a few steps into the future. Kenley (2005) argued that this apparent complexity is caused by ignoring the fact that similar production can be carried out in the project continuously and this optimized workflow decreases the complexity. Seppänen (2009) showed that complexity is partially caused by cascading delay chains of predecessors impacting successors and causing slowdowns, start-up delays and discontinuities. The key to predictable projects was found to be taking control actions based on production alarms based on production forecasts. Sacks and Harel (2004) showed how lose-lose resource allocation behaviour was exacerbated by unreliability of planning, leading to increasing instability. Seppänen et al. (2013) reviewed numerical evidence for accuracy of these production forecasts. Their results show 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.

The majority of previous studies related to construction workflow have put much effort into trying to understand the variability of workflow (Tommelein et al. 1999) and in studying how to stabilize (Ballard and Howell 1997) or even improve workflow (Bertelsen 2004, Brodetskaia et al. 2013, Ballard and Hamzeh 2007, Hamzeh 2009, Simonsson et al. 2012, Hamzeh et al. 2012). However, the studies do not suggest how workflow should be measured. Moreover, in general this topic has not been developed.

One of the reasons behind the current lack of methods for measuring workflow in construction seems to be the fact that there is no common agreement on how to define the notion of 'workflow' in project-based production. According to Koskela the natural unit of flow in construction is time, rather than cost or quality, as reduction in lead time will result in reduced costs and improved quality. As Kalsaas (2010) pointedly explains, the relative definition of flow as a *continuous stream of something* has some essential intuitive characteristics which are sufficient for using in relation to improving construction projects' performance and therefore the notion "work flow" has become very popular among both lean construction practitioners and academics.

The *Percent Plan Complete* (PPC) index is the main and almost the only measure of stability in use in lean construction, but it is often misunderstood or misused because it measures planning stability and not production itself, which is the main goal. PPC is a good index for quality of planning, but not for the stability of workflow. We have observed projects with high PPC, but with unstable workflow. This fact was the initial reason that motivated the search for an index of workflow stability.

Nevertheless, Drucker (2009), like many others, has stated: "If you can't measure it, you can't manage" and "If you can't measure it, you can't improve it". Drucker suggests that the success of any activity can be identified only if it is possible to define and track its performance. Improvement depends on the ability to measure performance and the metric for success should be clearly defined. Harrington and Harrington (1995) state the same idea as follows: "Measurement is the first step that leads to control and eventually to improvement. If you can't measure something, you can't understand it. If you can't understand it, you can't control it. If you can't control it, you can't improve it." Thus in order to improve workflows where lean production control is applied, direct measures of workflow are needed.

Bølviken and Kalsaas had an ambitious goal of understanding and measuring flow in construction (Kalsaas 2010, 2011, 2012, Kalsaas and Bølviken 2010, Bølviken and Kalsaas 2011). For this purpose they listed a series of alternative approaches to its quantification. After years of extensive research and testing of different approaches they concluded that *workflow* is a measure of productivity and can be therefore be calculated by the following formula: "***(Man hours at employer's disposal – Wasted time) / Man hours at employer's disposal".***

Bølviken and Kalsaas tested their method by conducting waste measurements within pipe installation activities for an offshore drilling system over two one-week periods six weeks apart. However, even though this formula seems to be simple, it is actually not, due to the difficulty of measuring wasted time. Firstly, it cannot identify and measure the different types of wastes in construction. Secondly, measuring and documenting these wastes is a very time- and labor-consuming activity, even if it is performed through self-estimation by different trade crews. Considering the amount of time and effort put into this kind of rough estimation, which is recorded by documenting wastes that can be recognized and measured, then this approach is not very efficient in practical terms. As Kalsaas (2013) concluded, this method is rather suited for improving work than measuring total difference between two points in time, because the contextual framework is subject to change. In other words, the measures of daily or weekly workflow, proposed by Kalsaas and Bølviken, can work well for specific tasks, but their approach was not tested or calibrated over complete project life-spans and cannot be used for real-time project control.

Instead, we propose a novel measure that we call the **'Lean Workflow Index' (LWI).** The LWI gives advance warning before a project slides into a chaotic state. If the metric works well, management will be able to take action to help the site team to improve workflow and prevent chaos. Workflow stability is a root issue and one worth measuring, because it has a direct relationship with a trade's profit. According to Goldratt´s Theory of Constraints (1992) the overall throughput can be increased only by increasing flow through the constraints. Removing constraints means making the process more predictable, which will result in smoother workflow and higher productivity that, in turn, leads to bigger profit.

METHOD

In the first stage we define a set of possible tracking parameters and propose the lean workflow index formula as a combination of them. As a starting point of this research, we define ‘good’ or stable workflow as follows:

- Crews work continuously with no interruptions
- Crews have constant production rates, or production rates increase gradually with the learning curve effect
- Resource levels and consumption rates remain essentially constant or decrease gradually
- Time and/or space buffers between trades are kept to a minimum

However, no definitive statement was found in the lean construction literature about this definition. To establish consensus about the notion of good workflow, on the one hand, and to establish the relationship between notions of good workflow and their visualization on flowline charts, we conducted a survey of lean experts in which they graded workflow quality for as-built flowline records for 12 projects.

The results of the survey were then used to calibrate parameter coefficient values in the LWI formula by using a goal seeking algorithm. The resulting formula was used to compute the LWI for three real projects. The all three projects are high-rise residential buildings with similar typical floor and same construction methods. The survey is described in Appendix 1. Lean construction professionals were asked to rate each project’s workflow quality, based on their experience, on a scale from 1 to 10. The 12 projects were a mixture of real and generated projects, using a purpose-built computer simulation, so that specific features – out of sequence work, breaks in work, different WIP levels, etc. - could be compared directly.

WORKFLOW TRACKING PARAMETERS

Table 1 lists a set of possible workflow measures. All of these can be measured directly from the as-built flowlines of a project. Most, like production rate or work in process (WIP), can be measured directly; a few, like R^2, are more easily computed using software.

Table 1: Workflow tracking parameters

Symbol	Description	Units of measure
RS_i	The smoothness of the line. R^2 - the square of the Pearson product moment correlation coefficient through data points in known y’s and known x’s - for each trade	-

P	Production rate per floor for each trade	Days/floor
STD	Standard deviation of production rate per floor	Days/floor
ND	Days of break for all tasks	Days
NB	Number of breaks for all tasks	-
NFP	Number of floors produced	Floors
TFP	Sum of all floors produced by all trades	Floors
T	Number of tasks considered	Tasks
BP	Number of times a task is performed before its predecessor (Work out-of-logic)	Tasks
BF	Number of times a crew works on floor X before floor X-1 (space out of sequence)	Tasks
WIP	Work in Process (WIP)	Number of Floors

THE LEAN WORKFLOW INDEX FORMULA

The index is assumed to be a polynomial function of either first or second degree (X_i = 1-2).

$$LWI(t) = \sum_{i=1}^{7} W_i P_i^{x_i} \quad where\ P \in [A, B, C, D, E, F, G]$$

The parameters A to G are described in Table 2. The period t is the time span over which they are calculated. Each of the tracked measures from Table 1 are included in at least one parameter. The parameters are constrained to generate values between 0-1.

The formula is calibrated to result in a workflow index on a scale of 1-10. To achieve this, the parameters A-G are normalized so that all $P_i^{x_i}$ have values from 0-10. As a result, a project can technically receive a LWI below one, but for such a case, the LWI will be set to one.

Table 2: Parameters used to compute the LWI

Parameter	Description
$A = \prod_{i=1}^{7} RS_i$	Product of all R^2's
$B = \frac{\overline{P}}{\overline{P} + \overline{STD}}$	Standard deviation of the production rate
$C = 1 - \frac{NB}{FP}$	Percent of time a crew will not have a break after finishing a floor.
$D = \frac{Average(P)}{\frac{ND}{FP} + Average(P)}$	Percent of time crews are working
$E = \frac{Total\ number\ of\ tasks}{WIP}$	Work in progress
$F = \frac{NFP}{NFP + BP}$	Work out of sequence (crossings in the flowchart)

$G = \frac{TFP - BF}{TFP}$	Space out of sequence (a trade crew performing floors out of order or in parallel – not according to the plan)

COLLECTING EMPIRICAL WORKFLOW MEASURES

While real project data could be used for calibrating the workflow index, a mix of real and artificial projects is preferable. The reason is that artificial projects can be configured to highlight particular aspects of interest – such as perfect flow, out-of-sequence work alone, breaks only, etc. To generate these artificial projects we created a simulation in Excel, allowing us to both tune the index against an abundance of projects as well as letting us create projects that are outliers on the index spectrum. The Excel based simulation was inspired by the Parade of Trades (Tommelein, Riley et al. 1999), but has been adapted to fit our needs. The simulation user provides planned durations for each task and the simulation automatically provides a flowline chart, as shown in figure 2. The simulation also provides a table with all of the measurements needed for computing the LWI.

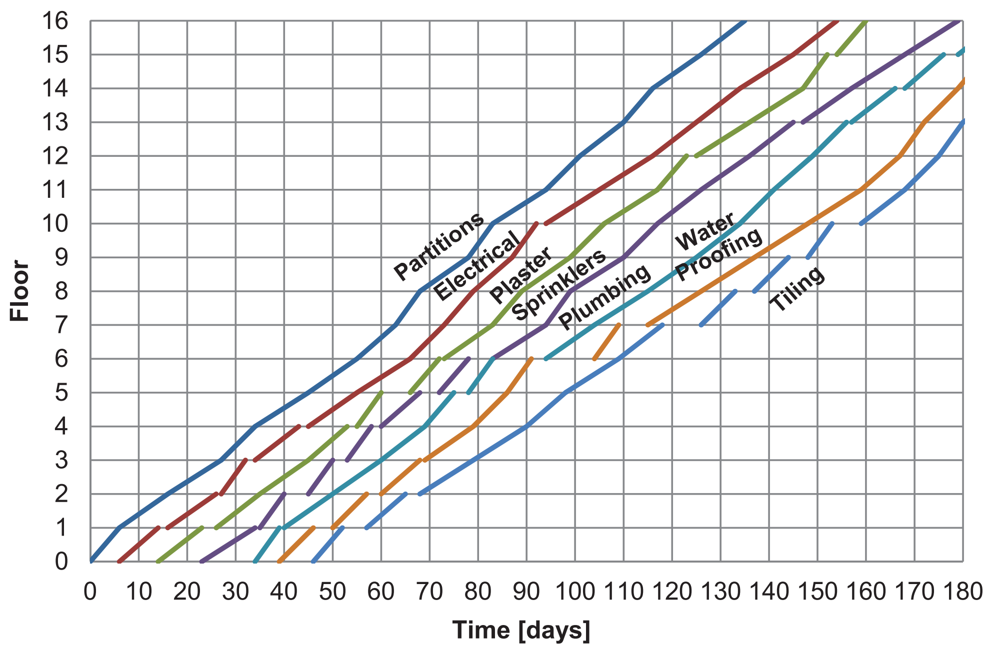


Figure 2: Example of flowline chart generated by simulation

In the example in figure 2, all 'as-built' durations were created randomly, giving durations between 5 and 11 days per floor (average of eight days per task per floor, which is the average duration of our three real projects). It should be noted that for simplicity, the simulation ignores the possible return delay related to subcontractors not being available to come back when work is finally released (Kenley and Seppänen 2010).

CALIBRATION OF THE WORKFLOW FUNCTION

We used a goal seeking algorithm to calibrate the weights of each parameter subject to the median project workflow measures that were attained in the survey. The solution was obtained by minimizing the error between the calculated workflow indexes and the surveyed indexes subject to the following constraints: ensuring the sum of the weights adding up to 1, no negative weights, as well as making sure no index is outside of the allowed region of 1-10.

Having calibrated the LWI weights, we received the following formula:

$$LWI(t) = 7\% \times A^2 + 33\% \times C^2 + 4\% \times D^2 + 31\% \times E^2 + 25\% \times F^2 \qquad \text{Eq. 1}$$

Using the weights, the LWI was calculated for all 12 survey projects. Table 3 shows the survey results, the computed LWI and the differences between them.

Table 3: Survey results vs. LWI

Project number	Survey median workflow [1..10]	Lean workflow index [1..10]	Difference [%]
1	10	10.00	0%
2	7.5	7.37	2%
3	3.5	3.49	0%
4	6	6.00	0%
5	6.5	6.84	5%
6	3.5	3.83	9%
7	7	7.25	3%
8	9	8.16	10%
9	6	7.92	24%
10	6	5.89	2%
11	6	6.52	8%
12	7.5	7.52	0%

To illustrate the impact of the different parameters, table 4 provides parameter values for the significant parameters of the three real projects whose flowline charts can be seen in figure 3. For all three projects, both the flowline and LWI was calculated over a time span of 7 months, to ensure good conditions for comparison.

Table 4: Parameter values for three real projects

Measurement	Sea Unik	Lagoon	Mishab	Units	Weights
A^2	0.53	0.72	0.54		7%
Average(P)	8.32	8.68	9.18	Days per floor	
Average(STD)	3.23	5.18	7.02	Days per floor	
ND	479	262	254	Working days	
NB	62	49	41	Breaks	
C^2	10.23	47.09	30.34	%	33%
D^2	37.68	70.08	52.82	%	4%
Average(WIP)	7.36	13.80	8.83	Floors	

E^2	0.90	0.26	0.63		31%
F^2	0.89	0.14	0.12		25%
LWI (1-10)	**5.89**	**3.49**	**3.83**		

It can be seen from table 4 and figure 3 that while See Unik is the project with the most stops after a task has completed a floor (parameter C^2 in the table); its LWI is significantly higher than for Lagoon and Mishab as it has lower WIP (E^2) and fewer crossings between tasks (F^2).

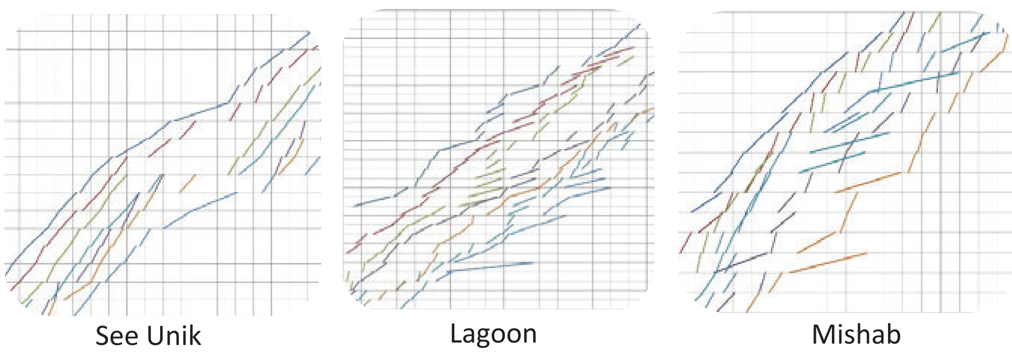


Figure 3: Flowline charts of three real projects

Practical implementation

The measures were then tested on as-built flowline records from three high-rise residential projects and the results were compared with subjective perceptions of workflow quality. As shown in equation 1 above, the LWI was computed as a weighted sum of a) the product of the root mean squares (r^2) values of all flowlines (r^2 is a measure of straightness of a line), b) percentage of total working time, c) the waiting times for each crew, d) the work in progress, and e) work out of sequence (crossings in the flowchart).

While the LWI was calibrated on full projects; for management to be able to carry out correcting measures it is desirable to receive the LWI for smaller time intervals that are updated as the project progresses.

User Defined Delta Time

With a macro created with Visual Basic in Excel, the project manager can set the time interval over which he or she wants the index to be calculated on. In addition, one can choose how frequently the LWI should be calculated for a new interval. The system computes the LWI for all intervals and plots a graph showing the trend in workflow. Figure 4 shows the LWI trend for a time interval of 40 workdays (1.5 months) with renewal of intervals every 2 weeks for Sea Unik, Mishab and Lagoon.

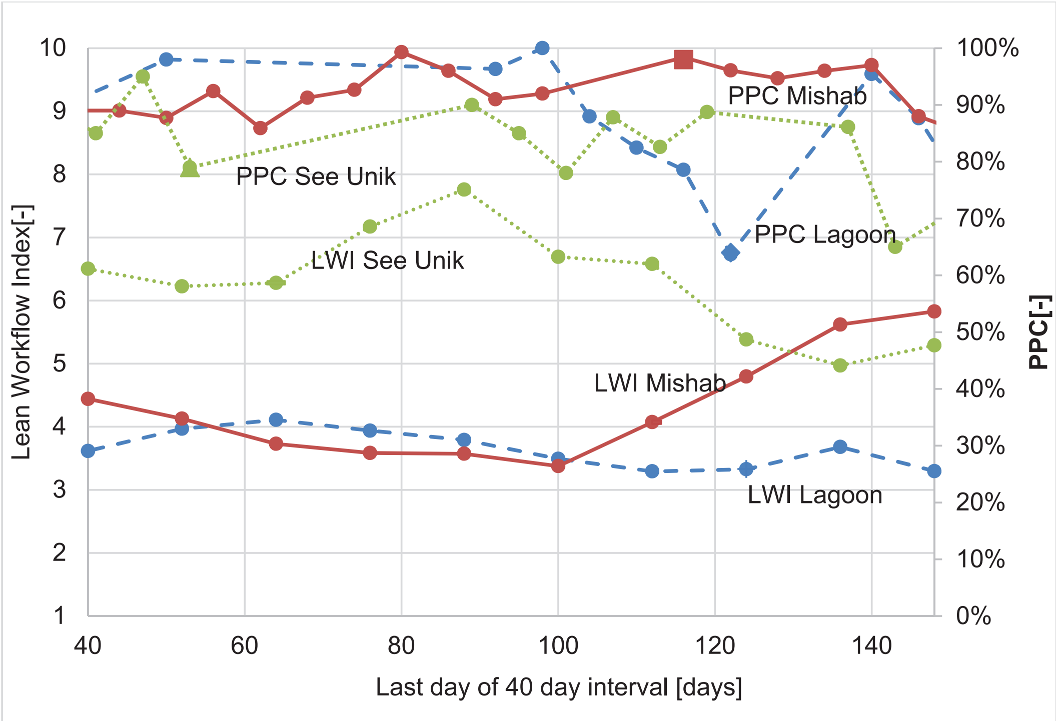


Figure 4: LWI vs. PPC of three real projects

DISCUSSION

As can be seen in figure 4, there is no correlation between PPC and LWI. See Unik has the highest LWI and the lowest PPC. It's also important to mention that high LWI can increase the chances of completion on schedule, but it does not imply or guarantee overall success in a project. Of course, there are two more corners of the gold triangle: cost and quality.

Measures influence the ways in which people behave. When teams are measured by the PPC index, they usually try to improve their planning. 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 LWI will likely have a similar effect: once measurements begin, teams will try to improve workflow by paying attention to the components of the LWI – interruptions, stability, sequential work, etc. However, the LWI is also subject to 'gaming'. To avoid this problem, LWI and PPC should be measured using an independent means to determine tasks that are 'done-done' and by setting minimum amounts of needed tasks in each period.

CONCLUSION

This paper describes the development of the LWI – a novel index for measuring construction workflow. The formula of LWI was generated by using a goal seeking algorithm based on expert survey results. The major advantage of the proposed index is that it monitors project workflows in real-time so that construction teams can be continuously aware of their performance**.** Therefore, LWI makes it easier for large construction companies to be aware of how their projects are being executed. This, in turn, will enable them to identify which projects are underperforming and seek remedial action where necessary.

Previously, PPC was the main and almost the only measure of stability in lean construction. However, although PPC does improve stability and predictability, it does not specifically nor necessarily engender smooth workflow. The LWI can complement PPC, adding impetus to achieve smooth and stable workflows.

Several issues with LWI still need further development:

A better algorithm can be used for formula calibration, such as a genetic algorithm. In this paper, the index was restricted to be a polynomial function of either first or second degree. Using other types of algorithms may allow us to get a more suitable formula.

Root cause analyses for losing index points can provide information for the project team, outlining how they might improve their score.

The calibration would be improved by increasing the sample of real projects in the expert survey.

ACKNOWLEDGMENTS

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APPENDIX 1 – SURVEY: LEAN WORKFLOW INDEX FOR CONSTRUCTION PROJECTS

The original survey form can be found at:

https://docs.google.com/forms/d/1khRpB8Ag9XwPYNoawYXp1M0V9DIPxWSieY6Jcg3MJ4Q/viewform

Dear Participant,

We are working to develop a way to quantify the quality of workflow in construction, and we need your help as a Lean Construction expert to calibrate our 'lean workflow measure'. Please look at the following project flowline charts and assess their workflow quality (on a scale from 1 to 10):

1 = very poor workflow, interruptions, waiting, out-of-sequence work, space conflicts, etc., for all or most crews

10 = excellent, smooth workflow for all crews

Please assess the project as a whole first, and then each trade in turn. Note that charts represent a record of workflow as it was performed (not as planned). Also note that for each trade, the amount of work in all locations is the same.

Thanks very much!

Vitaliy Priven, Rafael Sacks, Olli Seppanen, Jonathan Savosnick

Note:

- Some of the projects are from real projects and others from simulated projects.

- The results will be compiled and used by the Virtual Construction Lab at the Technion - Israel Institute of Technology.

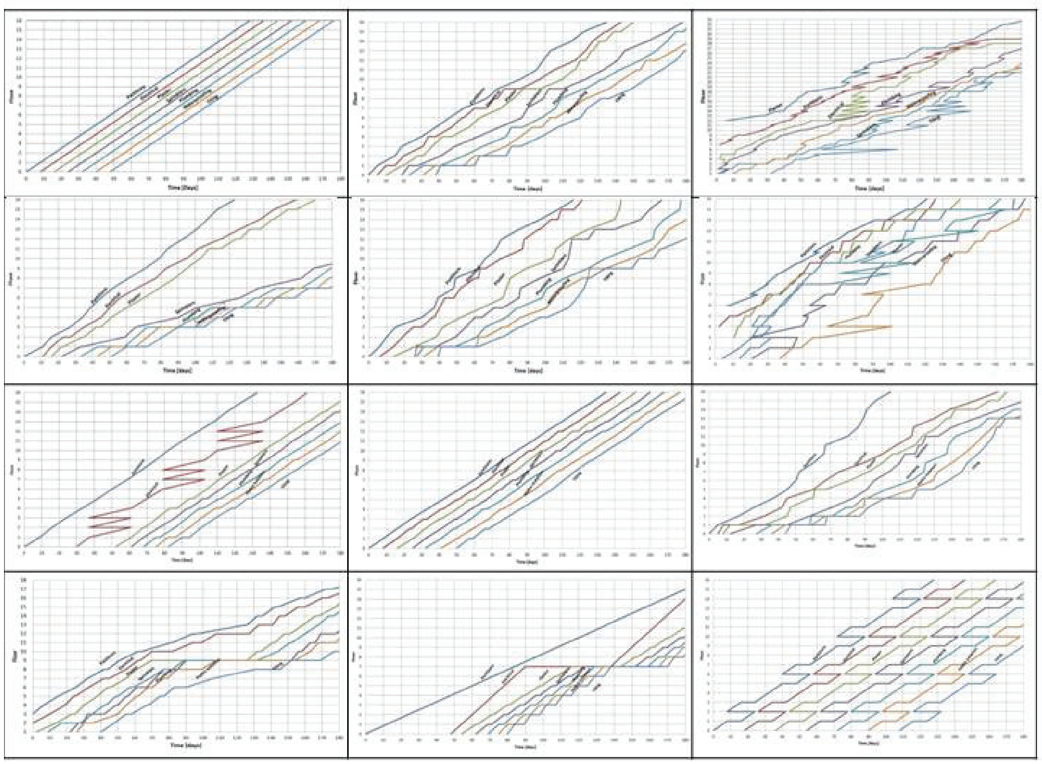

Figure 5: preview of survey's flowiline charts