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TOWARDS A FLOW-BASED DISRUPTION METRIC: A CASE STUDY

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ABSTRACT

Construction projects are inherently ad-hoc, meaning if disruptions arise, it can be hard to quantify the impact of the "damage" that has been done to the cost or timeline as a result of the disruption, as there isn't necessarily a nominal steady-state condition to compare it to. In this paper, we present a case study of an infrastructure construction project that was beset by over a hundred documented disruptions due to a politically charged project that had ongoing, active attempts to interfere. Traditional approaches to quantifying the impact of disruptions presume there is a baseline against which the disruptions can be compared, which is not the case in a unstable project. Also, they are inherently "transformation" in their approach, whereas a Lean Construction approach would recognize the importance of taking a more holistic view incorporating elements of Flow and Value. A WIP-based metric of the project outcome, called "WIP-Time" is proposed and assessed in the context of the case study.

KEYWORDS

Disruption analysis, Transformation-Flow-Value theory, contract disputes, production control

INTRODUCTION

Construction projects have long suffered from inefficiencies, leading to cost overruns and schedule delays (Egan 1998). When problems occur, project stakeholders (owners, project managers, contractors) naturally want to understand their nature, so that responsibility can be apportioned and parties "made whole" through compensation. To this end, the Society of Construction Law (SCL) publishes a "Delay and Disruption Protocol" (Society of Construction Law 2017) that is a widely-used framework for mediating disputes between the parties that may arise due to deviations from the agreed project scope.

The SCL defines a disruption as "a disturbance, hindrance or interruption to a Contractor's normal working methods, resulting in lower efficiency" (Society of Construction Law 2017). Disruptions are distinct from delays, though the two are linked and often lead one to the other. In this approach, disruption events are identified and quantified, using methods like the "measured mile analysis" (Ibbs and Liu 2005). In a measured mile analysis, periods of undisrupted work (the eponymous "measured mile") are compared to those suffering disruptions to assess the impact of the disruption event on the productivity of the work.

Underlying the measured mile analysis (and the other methods proposed by the SCL) is a transformation-centric paradigm. In Koskela's Transformation-Flow-Value theory (Koskela 2000), there are different approaches to conceptualizing and understanding production, of which the transformation approach is but one. The Delay and Disruption Protocol makes frequent references to work efficiency, lost productivity, and analyzing direct and indirect costs. All of these clearly indicate that they are solely focused on the actions of transforming the raw

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materials into finished products, which in turn implies they are not taking into account the Flow (how the products flow through the production system) or Value (how the value is created for the end customer, and conversely which elements do not add value and thus are waste) approaches.

In this paper, we present a case study of a project that had over a hundred disruptions, as well as a preliminary metric based on integrating Work In Progress (WIP) in order to assess the impact of the disruptions on the flow of the project and the capability of the project to generate the planned value. While there are Lean-related metrics that have made great improvements upon metrics like the measured mile, such as the Percent Plan Complete (PPC), used in the Last Planner System to evaluate the ability of the team to meet their weekly commitments (Ballard 2000), or the Construction Flow Index (CFI), which quantifies the quality of the production flow (Sacks et al. 2017), these were not found to adequately address the need of quantifying the impacts of disruptions on the project outcome.

PROJECT BACKGROUND

The case study project is a linear infrastructure project (a new rail line) that expands over 20 km, with a cost scope of US$200 million. The general work sequence for the project is presented in Figure 1. In the first stage, structural linear elements such as retaining walls were built (tasks A, B, and C in Figure 1) in parallel with the construction of structural elements in particular locations, such as bridges and tunnels (tasks D and E). After the structural elements, the superstructure of the transportation infrastructure was built (task F), followed by systems and finishes (task G), and handovers (task H). From an engineering point of view, this project was not particularly innovative.

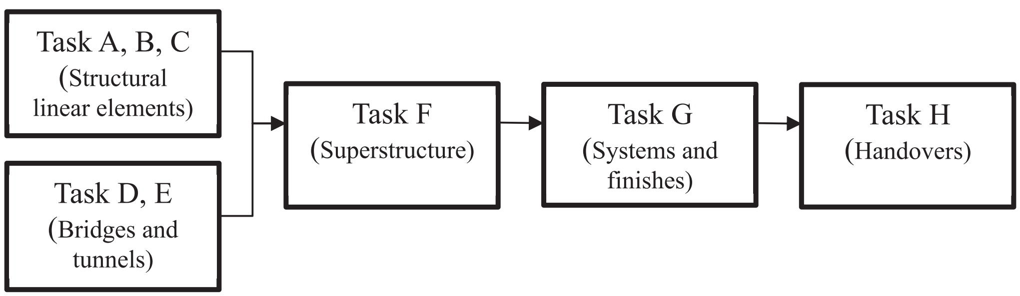

Figure 1: Process sequence for the infrastructure project

While this sequence seems fairly straight-forward, in practice, the project was subject to over one hundred documented disruption events in less than a year. These disturbance events were all caused by external parties, who were attempting to actively interfere with the project. The project was politically controversial, leading to objections, and it became a lightning rod of sorts through which political frustrations were vented through attacks on the project.

The disruption events recorded by the contractor, and categorized based on which type of "waste" (Ohno 1988) they caused:

- Disruptions leading to re-work: damages were caused to the product, as a result trades were required to return to previously-completed sites to perform repair or do the work again. For example, off-road vehicles were driven over graded substrates that had been smoothed and awaiting the next course. The tracks left by the vehicles meant the material had to be re-graded, effectively doing the work again. In other instances, sewage was routed into the work sites, which required drying them out and possibly disposing of contaminated materials.

- Disruptions leading to waiting and transportation: materials (such as steel) and equipment (such as concrete forms) were stolen. As a result, the workers would have to wait for a renewed supply, either from external suppliers or by additional transportation on of the materials within the project (and given the 20km extent of this linear project, this could be quite far).
- Disruptions leading to movement: in general, as WIP levels increased due to the disruptions preventing the closing out of work areas, trades were required to move back and forth from one location to another as they addressed the problem areas. In addition, due to damages to access roads to the site, work trades were sometimes required to travel via alternate (longer) routes. Finally, the project sites were used as illegal dumping sites for construction and other wastes, requiring the removal of more than a hundred thousand cubic meters of waste that had been deposited on the work sites.

While individual disruptions (like theft) might not be clearly political, their high rate of incidence relative to other similar projects made it clear that there was additional motivation beyond random opportunism. The impact of all of these disruptions was to greatly delay the completion of the project tasks, and as a result the entire project suffered, as well. Figure 2 and Figure 3 show the time-location diagrams of one section of the project, with each task shown as a diagonal line. Note that a time-location diagram, which is common in infrastructure projects, has swapped axes from a Line-of-Balance chart (Kenley and Seppänen 2010): time is on the y axis, progressing downwards, and the project locations are on the x axis. The actual project delivery took significantly longer for all tasks to be completed, due to the multitude of disruption events. In Figure 3, the disruptions events for 2022 are shown as small stars (those from earlier in the project were not sufficiently recorded), 120 disruptions in all during the period of a year. As the project (railway construction) was well-understood and relatively routine, it was clear that the disruptions were the cause of the delays, particularly when compared with similar projects that were not subject to the same barrage of disruptions.

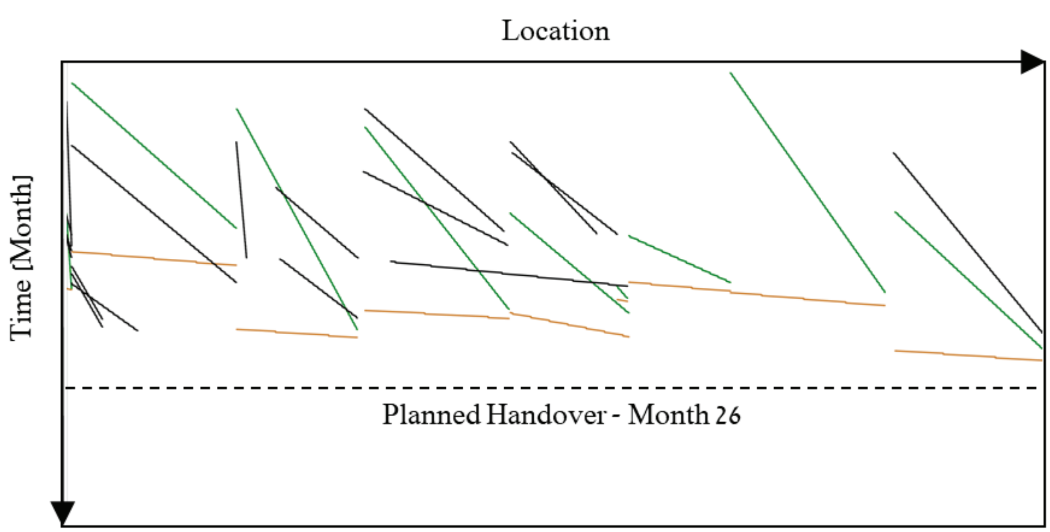

Figure 2: Time-location diagram of the planned schedule for one section of the project

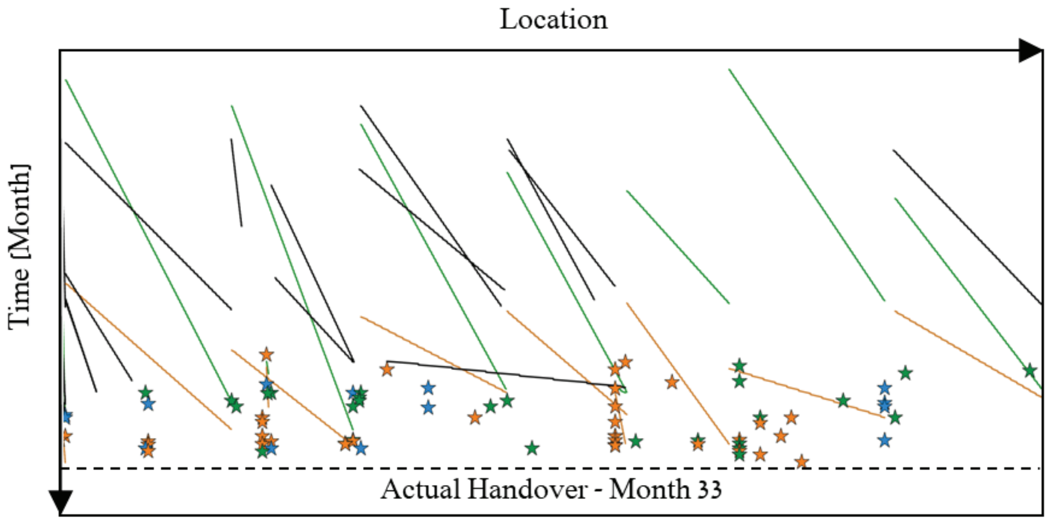

Figure 3: Time-location diagram of the actual schedule for one section of the project, including the 2022 disruption events (show as stars)

Table 1: Legends for Figure 2 and 3

Task/ Disruption	Legend
A, B, C	
F	
G	
Defects, Rework	
Waiting, Transportation	
Motion	

The picture in Figure 4 illustrates the scale of just one of the disruption events that the project encountered.

Figure 4: Illustration of one of the disruptions to the project

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LIMITATIONS OF EXISTING APPROACHES

As mentioned above, each of the disruption events was documented, using the SCL approach of trying to quantize the financial damage caused by each of the disruptions. For example, in the case of stolen material, the replacement cost of the material would be presented, or in the case of damage, the cost of the workers' time to repair the damage. But a harder question to answer remains what the impact on the overall project is of each individual disruption event.

For example, the missing material could mean that the work for a particular segment of the work would not be able to commence. So either the workers would be underutilized, or they might engage in "making do" (Koskela 2004), which could lead to further waste. And when the material does arrive, the tradespeople have to be scheduled away from what they were supposed to be doing at that point to return to the newly-arrive material.

One approach for trying to address this problem is reductionist in nature: for each disruption event, create an estimate of the delay caused by that one disruption. In the case of rework, how much time will it take to perform that rework. Or in the case of stolen material, how long will it take to source a replacement and have it delivered. Then, the time-impact of each individual event on the critical path can be assessed, enabling the quantification of the total time impact of all the events on the project duration.

This thinking is behind the approach suggested by the SCL, which recommends constructing a "Baseline", "Impacted", and "Accelerated" timeline for the project. The baseline is the plan, prior to any of the disruptions. The impacted timeline is calculated according to the critical path and reflects the total impact of all the individual events. And the accelerated timeline is what the contractor is capable of achieving (or has in practice achieved) if they work hard and bring on additional resources.

But a reductionist approach is flawed in this scenario, since it assumes that the individual disruptions and delays are sufficiently independent events (especially if they are not on the critical path). In practice, any construction project is a tightly coupled network, invalidating that assumption. A piecemeal approach to time delays doesn't necessarily reflect the system-wide impact of the total sum of the disruptions; in this case the whole is different than the sum of its parts. Even the necessity of starting tasks, then stopping when disruptions arise, then starting again can have costs, as fragmented work carries the cost of task switching.

A New Metric

To that end, a new metric was developed, that incorporates the Flow and Value approaches that are distinct from a pure-Transformation approach. The metric is based on an analysis of the level of Work in Progress (WIP) over the lifetime of the project.

As Little's Law (Hopp and Spearman 2011) describes, WIP is directly related to production throughput and the cycle time of products leaving the system. WIP has long been a focus of Lean thinkers, as WIP is inventory, which is a form of waste (Ohno 1988). Early pilgrims to Toyota factories described what we now call Lean as "Just in Time" production, as their attention was drawn to the low levels of WIP in the production system. In the world of software, the "Kanban" approach seeks to limit the WIP of work tasks, under the understanding that this will inherently improve the throughput of individual tasks.

In construction, particularly linear infrastructure projects, the concept of how to measure WIP is a bit more amorphous and up to the discretion of a planner. A unit of work might be a sub-area of a building, or a room, or in the case of a new road, a "roadel"(Haronian and Sacks 2020). The important aspect is not finding a globally accepted definition of what the "unit" is as much as being mindful of what is appropriate for the project in question and then studiously tracking the level of WIP throughout the lifetime of the project.

In the case study project, WIP was defined as sections of the train tracks of roughly equal length. Due to the differences in the nature of the different tasks, the WIP was defined differently for each.

The graphs in Figure 5 show the levels of WIP of the tasks over the lifetime of the project, both Planned and Actual. The WIP is the amount of "open" work areas, either according to the original plan or those that the contractor had to leave “open” due to the ongoing disruption events. The disruptions prevented the contractor from completing the works as planned and closing out work areas, leaving the WIP high. Trades were often forced to move the work teams among the various areas to address the problems as they appeared. Keeping many work areas open at the same time (high WIP levels) increased costs due to excess transportation of materials, equipment and tools, costs of damages, repair costs, and so on. In other words, WIP is both a waste and it leads to the other wastes, an insight as old as Lean itself.

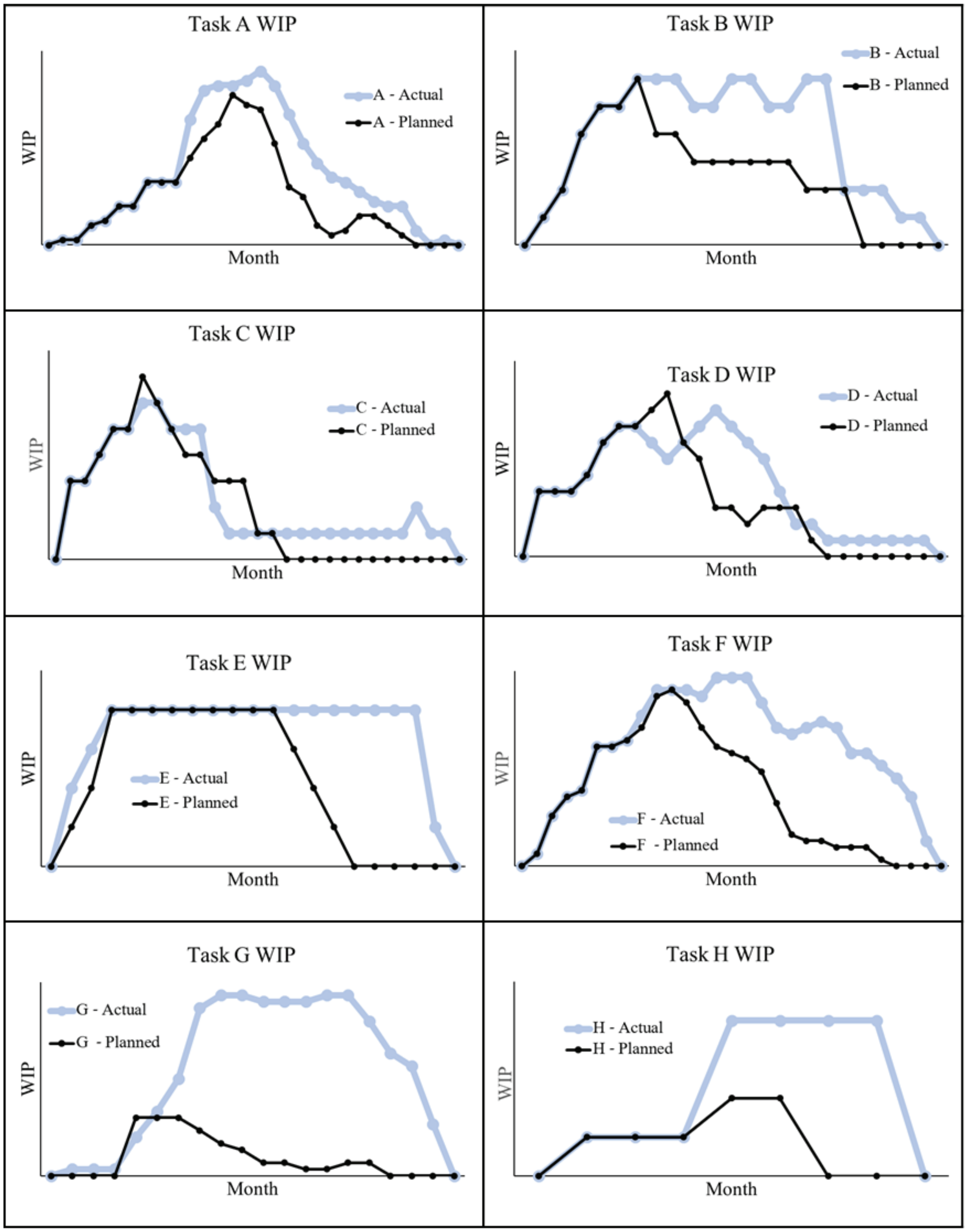

Figure 5: Planned versus Actual WIP for Each of the Tasks, over the Course of the Project

The proposed new metric integrates the WIP curve over the lifetime of the project, and compares the planned versus actual. In other words, the area under each of the curves, which has units of "WIP * time." For each time interval, the open WIP is summed, for both the plan and the actual. This metric is useful because it provides a concrete, flow-based measure of how the disruptions to the flow are leading to work areas that can't be close out and which continue to "gather" wastes. The metric is easy to compute (in this case, merely counting the number of open units each month) but also connects directly to the overall efficiency and effectiveness of the production system, in light of the disruptions.

RESULTS

For the case study, the new metric (WIP-Time) is shown in Table 2.

In this project, the WIP (and in turn the metric) was broken down by task, instead of looking at the WIP for the entire project all together. The reason this was done was in order to increase the fidelity of the measure. The WIP for the entire project jumps quickly to 100% and then stays there until the end of the project timeline, which means that the WIP-Time metric at the level of the project devolves into a proxy for the project timeline (both planned and actual). The project timeline, which a useful outcome measure, is less focused on the quality of the Flow. As the main goal of the proposed metric seeks to measure, in order to derive use from this indicator, it was computed at the task level.

Table 2: WIP-Time metric for each of the project tasks

Task	Planned WIP-Time (Unit-Months)	Actual WIP-Time (Unit-Months)	% Overrun
A	289	425	47%
B	55	87	58%
C	57	66	16%
D	90	113	26%
E	45	70	56%
F	318	533	68%
G	53	321	506%
H	7	19	171%

As can be seen, the WIP-Time overrun ranges from a modest 16% up to 506%. The latter was for Task G, which included laying the communication systems infrastructure for the trains. This was very precise and sensitive work, which was particularly vulnerable to interference and damage, as the disrupters soon learned. This was part of the reason that the WIP was planned to be so low, but in practice, the workers found it difficult to close out the work areas for this task.

In this case study, the metric has been deployed at project completion, as part of the efforts to quantify the scope of the disruptions that caused financial damage to the contractor. But it could also be deployed as a "live" metric, where the numbers are updated weekly or monthly throughout the project lifespan, to draw attention to the problem areas of the project where flow is currently suffering the worst.

CONCLUSIONS

This work presents a preliminary analysis for the impact of disruptions on production flow in construction projects. The proposed analysis and "WIP-Time" metric, as demonstrated on the case study, enables the evaluation of the impact of disruption events on production flow, as reflected by basic production parameters, for each type of activity and trade. The new metric has the advantage of simplicity of calculation while simultaneously connecting directly to the quality of the project value creation. The findings align with what was reported by the construction team on site, indicating that the disruptions prevented the completion of tasks and location handovers, forcing redundant movement, and making the work plans unreliable. The analysis presented in this paper is contrary to the traditional evaluation methods that view production exclusively through a "transformation" lens, without addressing aspects of production flow. The findings provide motivation for further work required to formulate a systematic methodology for evaluating the impact of disturbances on the production flow.

While this project was unique in the political landscape that it was developed and deployed in, there are other scenarios where there may be a number of disruptions, such as other parts of the world with political instability. But any project has disruptions and delays, even if not so many or from inimical third parties, and a proper measure of Flow can serve them, as well.

A large limitation of the work is the open question about the accuracy of the plan. Since the plan is the basis for comparison with the actual outcome of the project, if it is incorrect, then the metric in turn may be equally divorced from reality. Yet in the case of linear infrastructure projects, which tend to have more benchmarks and fewer engineering "surprises", it is possible that the planning is more accurate. Also, a flow metric such as this one does not apportion "blame" in the sense that the metric itself is agnostic as to the cause of the poor flow, be they external disturbances (as in this case study) or internal mismanagement or poor decision making.

Future work is required to turn this general metric into one that can be more directly translatable into financial terms, since as described above, it can be hard to put a monetary figure on poor flow. Likewise, it would be beneficial if the impact of external disruption events could be teased out from those of internal problems (i.e. inefficiencies that are due to or the fault of the project management/execution). And while this case study was a retrospective, the proposed metric could be deployed as a "live" measure of project performance in an ongoing project, with the impacts of its implementation being studied.

Another tack is to examine how worker morale due to a large number of disruptions can impact the project flow, as this project definitely struggled with a demoralizing effect in the face of repeated and ongoing interferences to the work, which took a toll on the workforce.

Ultimately, a Flow-based approach to measuring projects will have benefits, as the metric will in turn bring the focus of project management to the impact on the flow of the evolving nature of the project.

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