A Model for Managing Construction Activities and Flows

By

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Abstract

Construction field managers often struggle to keep projects on schedule, resulting in time and cost overruns. Schedule conformance depends on the construction activities starting and finishing on time. However, construction activities are often delayed because the construction flows necessary to start their execution are unavailable. Construction flows can be classified into: labor, equipment, workspace, materials, precedence, information, and external. Current construction models do not formally represent, measure, and track all the flows. Hence, field managers lack formal methods for managing flows and instead rely on their intuition and experience managing them. This report presents a construction model based on activities and flows, called the Activity-Flow Model (AFM). The AFM formally represents the activities, the flows, and their interactions. The AFM was validated prospectively through its implementation on three building projects that were in different phases (foundations, core and shell, and finishing), geographic locations (Bogota, Copenhagen, and Lima), and used different planning and control methods (master schedule and weekly planning, Last Planner System, and Location-based Management System). The AFM was able to represent all the activities and flows in the test projects, track the variations of the activities and flows, and quantify the activities’ and flows’ variability. Field managers can use the metrics enabled by the AFM to plan and control the project. Such proactive flow management can help field managers improve flow readiness, which should reduce activity delays and improve schedule conformance.

KEYWORDS: construction model, project management, flow, variability, control
1 Introduction

Although most construction owners rank schedule as the top factor associated with value in their projects, over 61% of typical construction capital projects are delayed (Mace et al. 2016). An important reason for explaining the prevalent delays is that tools available to represent the construction work going on at the site do not represent the construction flows, which is one of the key aspects of the work that field managers need to manage (Garcia-Lopez and Fischer 2016). Construction flows are inputs that activities need to be executed efficiently. Koskela (1999) classified these flows into seven types: labor, equipment, workspace, materials, precedence, information, and external flows. Once the activity is finished, some of the flows are released as inputs to downstream activities.

Current construction models focus on representing the construction activities, the resources that go into those activities, and the workspaces needed to execute them. They focus on allowing field managers to answer the question: who is doing what when and where. This information is formalized in construction schedules that represent the activities and the work logic dependencies connecting the activities. However, when field managers are creating schedules they also need to think about the flows needed to execute the activities, where those flows are coming from, and where those flows will go after an activity is executed. Therefore, field managers should be able to represent schedules as an interconnected network of activities and flows to answer questions like these: What flows are being utilized by what, when, where? Where will the flows come from? Where will the flows go next? Moreover, variations in upstream activities and flows lead to variations in downstream activities. Therefore, characterizing activity and flow variability is important for anticipating variation in downstream activities and for placing appropriate buffers during planning. Variability metrics and analytics should help field managers identify the most appropriate corrective actions during execution, should an actual delay occur. This report introduces a construction model that allows field managers to represent, update, and track construction activities and flows. The model supports field managers in keeping projects on schedule by characterizing flow and activity readiness through quantifying activity and flow variability.

This report is divided in five sections. The first section introduced the motivation for the research. The second section presents the problem tackled in this research, namely, the need to
formally represent and track the flows in addition to the activities to enable field managers to control the project. The third section introduces the main points of departure supporting the research. The fourth section presents the development and testing of the AFM. Finally, the fifth section outlines the conclusions and future work enabled by this research.

2 Problem statement

The construction industry has achieved schedule performance improvements due to the use of BIM, Lean Construction, and IPD (El Asmar et al. 2013; Azhar 2011; Gonzalez et al. 2008). However, field managers still face problems keeping projects on schedule (Jones and Bernstein 2014). On the other hand, the manufacturing industry has achieved breakthrough performance by managing flows and variability (Womack and Jones 1996). For example, General Motors’ NUMII plant achieved 50% higher labor productivity compared to similar General Motors’ plants and the highest quality of all GM’s plants in the USA after one year of implementing the Toyota Production System (Holweg 2007). One of the pillars of the Toyota Production System (TPS) is just-in-time production, which focuses on managing flows so that they are ready at the workstation in the right amount when they are needed (Ohno 1988). In construction, variability in the activities and flows has been associated with poor project performance, specifically, higher work-in-progress, longer activity durations, and project delays (Alarcón and Ashley 1999; Arashpour and Arashpour 2015; Tommelein et al. 1999). However, currently, field managers lack methods for managing the flows, which prevents them from managing and anticipating variability.

One of the reasons for the lack of methods for managing flows is that current construction models do not formally represent and track the seven flows that are needed to execute the activities, namely, the labor, equipment, workspace, materials, precedence, information, and external flows (Koskela 1999). Flows released by upstream activities become inputs for downstream activities (Bertelsen et al. 2007; Hamzeh 2009). Hence, if an upstream activity finishes late the untimely release of the related flows can lead to variation in downstream activities. A comprehensive survey investigating the factors that lead to activity variation revealed that all the factors can be associated with variation in one of the seven flows (Wambeke et al. 2011). In this research, we defined information flows following the Activity Definition
Model of directives that includes assignments, design criteria, and specifications (Ballard and Howell 2003a). Therefore, to reduce the impact of variability on project execution, field managers need better methods for managing the flows between activities and for understanding how variability affects those flows. However, since current construction models do not formally represent and track flows, it is not possible for field managers to quantify flow variability and manage flows appropriately.

The importance of managing flows to reduce variability is evidenced during the make-ready process. The make-ready process is an important aspect of the Last Planner System that is intended to increase planning reliability (Ballard and Howell 1998). During the make-ready process, field managers actively identify and remove the constraints that prevent an activity from starting. Activities that have no unresolved constraints are said to be “ready.” During the weekly meeting, field managers are encouraged to commit to “ready” activities since field managers should only commit to work that “CAN” be done instead of the work that “SHOULD” be done (Ballard and Howell 2003b).

During one of our case studies, we noticed that the field planners dedicated about 60% of the jobsite weekly planning meetings to the make-ready process. Field managers valued how the make-ready process allowed them to coordinate issues between different scopes and teams. However, one of the problems we observed was that the make-ready process was only tracking constraints related to off-site flows, which are flows that are brought into the production system in the form of deliveries, mobilizations, information, permits, inspections, etc. Constraints related to on-site flows were not tracked, which are flows that are released from a previous activity, such as the concrete crew that moves to the activity “Pour Columns A2” once it has been released by the activity “Pour Columns A1.”

Additionally, we recorded that 85.10% of the reasons for non-completion of activities for the project were associated with on-site flows (Figure 1). The reasons for non-completion were added by the field managers to explain why an activity was finished late. The reasons for non-completion are project-specific and reflect the field managers’ perception of what caused the delay. During the case study, we kept a record linking the reason for non-completion with the specific flow that caused the delay and whether it was an on-site or off-site flow. As an example, “Labor availability” was added as the reason for non-completion whenever labor was the
primary cause of delay due to late mobilizations (off-site) or late release from an upstream activity (on-site).

<table>
<thead>
<tr>
<th>Reason for non-completion</th>
<th>% related to flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predecessor</td>
<td>50.60%</td>
</tr>
<tr>
<td>Labor availability</td>
<td>4.50% 14.54%</td>
</tr>
<tr>
<td>Change of priority</td>
<td>13.90%</td>
</tr>
<tr>
<td>Equipment availability</td>
<td>8.23%</td>
</tr>
<tr>
<td>Equipment overcapacity</td>
<td>3.90%</td>
</tr>
<tr>
<td>Information unavailable</td>
<td>1.73%</td>
</tr>
<tr>
<td>Quality inspection failed</td>
<td>1.73%</td>
</tr>
<tr>
<td>Materials delivery</td>
<td>0.43%</td>
</tr>
<tr>
<td>Underestimated</td>
<td>0.43%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>14.89% 85.10%</strong></td>
</tr>
</tbody>
</table>

Figure 1. Distribution of the reasons for non-completion in the Ichma project during the 18 weeks of tracking. 85.10% of the reasons were associated with on-site flows, which were not tracked during the make-ready process.

An issue with tracking on-site flows is that their readiness status is highly dynamic since it depends on the status of the predecessor activities. Since field managers need to commit to the activities in the weekly plan ahead of time, they need to judge the readiness likelihood of the flows needed for each activity. Therefore, field managers commit to the activities based on their “perception” of readiness (Pikas et al. 2012). Field managers need methods that help them assess the likelihood that the flows needed for an activity will be ready. However, since current construction models do not formally represent and track flows, field managers have no way of quantifying flow variability and using that information to assess the flows’ likely readiness and future performance.

Field managers need construction models that support them to plan, execute the plan, track the actual versus planned execution, and update and adjust the plan based on the learnings and improvements. This cycle of planning, doing, studying, and acting (PDSA cycle), is essential to achieving continuous improvement (Sokovic et al. 2010). Field managers need to represent the plan including the activities, the flows, and their interactions. Work executed on site varies from the plan due to the occurrence of unexpected variability factors and natural variability related to the nature of construction projects (e.g., differences between workers’ pace, material quality
fluctuations, etc.). As a result, field managers need to update the plan based on the observed project performance (Levitt 2011). Furthermore, construction models need to support field managers in helping them understand the causes of variations in the planned and completed work, implement changes to avoid variations in downstream activities (Ballard 2000), and anticipate variations in downstream activities (Levitt and Kunz 1987). Therefore, a construction model needs to support field managers in four ways to achieve continuous improvement.

1. Planning the work: Represent the construction activities, the flows, and their interactions.
2. Tracking the work: Track the status of the construction activities and flows.
3. Updating the work: Update the activities, flows, and their interactions.
4. Adjusting the plan: Anticipate variations in downstream activities.

Current construction models do not support the representation of all construction flows. The two most important construction representations available are the activity-based and the location-based representations.

Activity-based construction models represent the construction plan as a network of activities connected via precedence constraints. The Critical Path Method (CPM) is based on this representation. Similarly, most commercial scheduling software uses the activity-based representation, e.g., Primavera P6, Microsoft Project. Some construction models have extended the activity-based representation by adding attributes to the activities to indicate what resources are working on the activity (e.g., resource-loaded CPM (Lu and Li 2003)) or where the activity is taking place (e.g., workspace representation (Akinci et al. 2000; Morkos 2014)). However, these models cannot represent the movement of the resources or handoff of workspaces between activities. Therefore, the only flow that can be fully represented by the activity-based models is the precedence flow.

Location-based models represent the construction plan as activities executed in a sequence of locations (Kenley and Seppänen 2009; Russell and Wong 1993). The location-based representation uses flowline diagrams to represent the schedule. Flowline diagrams are drawn in 2D graphs where the x-axis represents time, the y-axis represents the locations, and the activities are shown as diagonal lines whose slopes represent the velocity of the activity. A key difference between the location-based and the activity-based representation is the ability to formally represent the sequence of locations and the handoff of locations between activities. The location-
based representation argues that resource continuity between locations is important for maximizing project performance. Hence, it assumes that resources flow between locations executing the same type of activity. However, it does not represent how resources flow between activities. Analogously to the activity-based models, location-based models can represent the resources that are needed to execute the activities by adding this attribute to activities. Therefore, the location-based models can only fully represent the precedence and workspace flows.

This report presents the Activity-Flow Model (AFM), a construction model that represents and tracks the activities, the flows, and their interactions, and computes activity and flow variability.

The AFM extends the existing activity-based and location-based schedule representation into an activity and flow representation. The AFM formally represents the schedule as a network of on-site flows joining the activities and off-site flows feeding the activities (Figure 2). During production control, field managers track the status of the activities and flows, which are used by the AFM to compute the activity and flow variation metrics. The activity variability is calculated by aggregating the activity variation metrics at the activity type\(^1\) level. Similarly, flow variability is calculated by aggregating flow variation metrics at the flow class level. The AFM leverages the activity and flow data collected during production control to generate analytics and predictions about downstream activities that are most likely to face variations. Field managers

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\(^{1}\) An activity type is a `<Component, Action>` tuple aggregating activities, which are `<Component, Action, Workspace>` tuples. For example, the activities “Pour columns A1” and “Pour columns A2” belong to the activity type “Pour columns.”
can use the analytics and predictions generated by the AFM to manage the flows in look-ahead and weekly planning.

3 Point of departure

As shown in the previous section, field managers must be able to represent the construction activities, the flows, and their interactions, track the status of the construction activities and flows, update the activities, flows, and their interactions, and anticipate variations in downstream activities. This section reviews which of these needs are addressed in construction conceptualizations reported in the literature and, in doing so, introduces the main points of departure underpinning the research. The first section summarizes the transformation and flow views in construction, which highlight the need to develop models that take activities and flows into account. The second section presents the existing flow conceptualization, including the gaps that need to be filled to operationalize the flow conceptualization in a computational representation. Finally, the third section analyzes the impact of variability on production and the reasons why variability needs to be measured and tracked by the construction models to help field managers anticipate and mitigate its impact.

3.1 Transformation vs. Flow views

There are two main views in production, the transformation view and the flow view (Koskela 1992, 1999) (Figure 3). The transformation view represents production as a series of activities with inputs and outputs. Activities can be decomposed into smaller activities at higher levels of detail without losing any representation of the system. Production management focuses on optimizing the activities themselves, under the assumption that optimizing the individual activities will lead to overall system optimization (Hopp and Spearman 2011). Since construction firms get paid for producing the product (a building, a bridge, etc.) the owner ordered and since activities transform materials into the components and systems that make up the product, the transformation view, which uses the activity-based representation, is the traditional view adopted in project management and construction scheduling. Construction work is represented as a sequence of activities connected via precedence constraints (Aalami 1998; Chapman 1997; Darwiche et al. 1988; Echeverry et al. 1991). A limitation of the transformation model is its inability to explicitly represent resources and workspaces (Akinci 2000; Koskela 2000; Morkos
2014). The commonly used project management tools today, such as scheduling software based on the CPM representation, give field managers little visibility into the specific flows that are impacted by variability and into the downstream activities dependent on those flows. Field managers using the transformation-based tools can only rely on their personal experiences to implement specific measures to shield activities from variability.

![Diagram: Transformation versus flow views.](image)

**Figure 3:** Transformation versus flow views. The transformation view represents dependencies between activities using precedence constraints, while the flow view represents them as flows moving between activities.

The flow view represents construction work as a series of flows composed of transformation, inspection, moving, and waiting times (Koskela 2000). Managers should aim to optimize both the activities and the flows feeding the activities (Ohno 1988). In construction, activities are assembly-type operations that require a large number of flows to be ready for an activity to start execution (Koskela 1999). Hence, construction activities are particularly vulnerable to variability because all the flows need to be available for an activity to be executed efficiently, which is also known as the matching problem (Tommelein 1998). The flow view is preferred in Lean Construction (Ballard 2000; Hamzeh et al. 2012; Koskela 1992, 2000), and has been partially formalized by some simulation models (Akbas 2003; Brodetskaia et al. 2011; González et al. 2009; Tommelein 1998; Tommelein et al. 1999). However, these models cannot support planning, updating, and controlling the work at the jobsite.

In manufacturing, the flow view was first introduced by the Gilbreth brothers and later implemented by Henry Ford (Ballard et al. 2003). The flow view was also embraced by Toyota and embedded in the Toyota Production System which formed the basis for Lean Manufacturing (Womack et al. 2007). The flow view was formalized by Shingo, who argued that manufacturing production is composed of process flows and operations flows (Shingo and Dillon 1989). The
process flows comprise all the actions that are performed on the product itself, while the operations flows comprise all the actions that are performed by the operators and equipment on the product. The process flows can be improved by removing non-value adding steps. The operations flows can be improved by balancing the work at the workstations and improving the operations themselves, such as improving the tools and methods (Sacks 2016). An important insight from Shingo’s framework is that both the process flows and the operations flows need to be considered simultaneously to improve the system, otherwise waste can result as an unexpected by-product. For example, consider the manufacturing process for a door shown in Figure 4. Suppose the cutting process is improved resulting in a lower processing time for the cutting workstation. If the moving process is not improved simultaneously the cutting workstation will likely be idle most of the time because the moving workstation is not able to supply it with enough materials. Similarly, the joining process must also be improved, otherwise there will probably be long queues of cut material waiting to be processed. Mapping the process flows and operations flows allows the managers to improve the efficiency of the whole system by identifying measures that improve the process flows and simultaneously formulating improvements to the operations flows.

![Diagram](image)

**Figure 4:** Production is composed of process flows (a) and operations flows (b).

Currently, the most complete construction flow conceptualization is the Construction Physics conceptualization, where the activities represent the process flows and the flows represent the operations flows per Shingo’s conceptualization. Construction Physics is “a theory based understanding of the nature of the flows and their interactions in the construction process” (Bertelsen et al. 2006). Construction Physics extends the seven-flow conceptualization introduced by Koskela (1999) by suggesting that the flows can be viewed as physical entities feeding the activities. Hence, physically-based queuing models could be developed to describe the behavior of the construction production systems in a similar way as the Factory Physics body of work presented models for describing manufacturing production systems (Hopp and Spearman 2011). The researchers argue that, at any time, there is only one critical flow.
constraining an activity’s start (Bertelsen et al. 2007; Goldratt 1997). Therefore, a field manager’s focus should be on identifying and managing the critical flows. However, the Construction Physics conceptualization has not currently been operationalized into a model that can help field managers manage the flows.

This research leverages the Construction Physics conceptualization to develop a construction model that formally represents the activities, the flows, and their interactions. One of the most important aspects to consider when modelling the interactions between the activities and the flows is the effect that variability has on the system performance. In the next section, we will analyze the effect of variability on production system performance, as well as the mechanisms that cause variability, and the mechanisms that prevent variability.

3.2 Variability and its effect on production performance

Variability degrades the performance of a production system, leading to longer cycle times, higher work-in-progress, and schedule slippages (Alarcon and Ashley 1999; Arashpour and Arashpour 2015; Tommelein et al. 1999). Variability in upstream activities is propagated to downstream activities, causing cascading delays (Hopp and Spearman 2011; Koskela 2000). Variability is defined as a statistical measure characterizing the distribution of a variable of interest. In production, variability is mainly associated with the distribution of the rates of arrival to a workstation and with the distribution of the processing rates at the workstation (Hopp and Spearman 2011). In this research, we characterize variability at the activity and flow levels. The activity variability is analogous to the processing rate variability, whereas the flow variability is analogous to the arrival rate variability.

The Last Planner System of production control proposes to reduce workflow variability by increasing planning reliability (Ballard 1999; Ballard and Howell 1994). Although the Last Planner System has been successful at improving planning reliability (Alarcón et al. 2014; Ballard 2000; Gonzalez et al. 2008), it does not quantify the impact that variability at the flow level has on the activities (Bhargav et al. 2015).

To model activity and flow variability, construction models need to incorporate the mechanisms that cause activity and flow variability as well as those that prevent activity and flow variability. The following section explores these mechanisms.
3.2.1 Mechanisms that cause activity and flow variability

There are two main mechanisms that cause activity and flow variability: the occurrence of variability factors and the late release of flows from upstream to downstream activities. Variability factors are external shocks to the project that are outside of the control of the field managers. Examples of variability factors are: weather, labor strikes, and equipment breakdowns. On the other hand, late release of flows from upstream to downstream activities occurs when an activity finishes late. Therefore, the two mechanisms that cause activity and flow variability are interrelated: the occurrence of variability factors can cause the activity to finish late, which in turn leads to the late release of flows. Measuring both the occurrence of variability factors and the late release of flows can help field managers understand the underlying causes of variability.

Construction activities and flows are vulnerable to the occurrence of variability factors that affect the project performance. There are three main construction research areas that have focused on identifying and tracking variability factors and their impact on production. Firstly, delay analysis research has focused on identifying what factors cause delays at the project and activity level (Cisterna et al. 2013; González et al. 2014; Korde et al. 2005). Secondly, risk management research has attempted to quantify the impact that variability factors have on the project schedule (Akintoye and MacLeod 1997; Chapman 1997; Dawood 1998; Liu 2010; Tah et al. 1993). Finally, the Lean Construction research area has proposed to track the reasons for non-completion for activities to analyze their root causes and prevent their re-occurrence (Alarcón et al. 2014; Ballard 2000; Ballard and Howell 1998). Most research related to variability factors is focused on their impact at the activity level. However, research has shown that most of the variability factors can be associated with variation in one of the seven flows (Wambeke et al. 2011). Therefore, it is important to understand the impact that the occurrence of variability factors has at the flow level. This can only be achieved by measuring both the flow variations and the occurrence of variability factors.

The second mechanism that causes activity and flow variability is the late release of flows from an upstream activity to a downstream activity (Hamzeh 2009; Koskela 2000). This is the mechanism that transfers variability between activities causing cascading delays. This mechanism is shown graphically in Figure 5, where the late finish for the activity “Install slab
“Install slab rebar L1” results in workspace and labor flow variations. These variations delay the readiness of the flows for the downstream activities, leading to activity start delays.

![Diagram showing flow variations](image)

Figure 5: Flow variations often result from late release from upstream activities.

### 3.2.1.1 Mechanisms that prevent activity and flow variability

Buffers can be implemented by field managers to shield activities from variability (Ballard and Howell 1998). There are three types of buffers: inventory, capacity, and time (González et al. 2004). Inventory buffers increase the stock of the flows to ensure that there is an additional amount of what is needed to execute the activity (González et al. 2009, 2011; Horman and Thomas 2005). Inventory buffers can be used to shield the material, workspace, information, and external flows. The capacity buffers increase the capacity of the resources either by increasing their amount or their processing rate (Horman et al. 2003; Thomas et al. 2002). Finally, time buffers shield all the flows by absorbing their readiness variation (Hopp and Spearman 2011).

This research focused on quantifying the time buffers since they can be used to shield all the seven flows. Figure 6 extends the previous example by showing how buffers can shield flow variation. The “Install slab rebar L1” activity releases the workspace and labor flows two days late, leading to a flow readiness variation of two days. The labor flow has a two-day buffer built in. Therefore, the time buffer absorbs the flow readiness variation in the labor flow, leading to no impact on the downstream activity “Install slab rebar L2.” On the other hand, the workspace flow released from the “Install slab rebar L1” activity has no buffer. Therefore, the two-day flow readiness variation causes a two-day start-delay on the downstream activity “Pour slab L1.”

![Diagram showing buffers shield activities](image)

Figure 6: Buffers shield activities from flow readiness variation.
Buffers are expensive in terms of cost and time. Therefore, field managers need to optimize them to ensure that they fulfill their function of shielding activities from variability, but are not oversized. Previous research has shown that buffer sizes can be optimized by measuring the flows and optimizing the buffers as a function of their variability. For example, variability in the material flows has been used to optimize time buffers (González et al. 2011) and capacity buffers in projects with repetitive activities (Arashpour et al. 2013, 2014). Therefore, quantifying all the flows’ variability could enable better models for optimizing buffer sizing.

### 3.2.1.2 Existing construction models

Up to this point, we have presented the need to develop a construction model that can formally represent the activities, the flows, and their interactions. Field managers must be able to define the flows needed for each activity, track them, and update the plan based on activity and flow variability. This section reviews which of these needs are addressed in construction conceptualizations reported in the literature (Figure 7). The objective of this section is to provide a summary of the concepts from prior work that contribute to the AFM.

Figure 7: Point of departure canvas classifying the existing construction models according to the flows they model, their treatment of the variability factors, their quantification of variations, and the source of their inputs.
We grouped the exiting models into four groups: deterministic models, stochastic risk models, stochastic simulation models, and models based on project progress.

The first group of models are deterministic. These models are intended to represent and plan the construction work but not necessarily to track it. Most of the models use the activity-based representation and depart from the CPM representation (Fondahl 1961). Automated AI planners leverage the <Component, Action, Resource> representation of the activities by adding attributes that link activities to components in the product model and the resources executing them (Aalami 1998; Darwiche et al. 1988). Akinci (2000) extended the <CAR> representation by adding workspaces to the activities. Similarly, the Tri-Constraint Method added the workspace and resource attributes to the activities to generate thousands of feasible schedules (Morkos 2014). The line-of-balance models use a location-based representation that represents the activities in flowlines where each activity is repeated in different locations (Russell and Wong 1993). Finally, the Geometry-based Process Model uses discrete event simulation as well as the geometric properties of the product model to represent the construction activities (Akbas 2003). Since all the aforementioned models are planning models, they are not intended to measure or quantify the activity or flow variations. Similarly, they do not take variability factors into account.

The second group of models are stochastic risk models. These models are based on the activity representation and use the logic underlying the CPM ontology and algorithm to model the relationships between the activities. Therefore, they only represent precedence constraints. They leverage probability distribution functions and mathematical modelling to estimate the impact that duration variability at the activity level has on the project duration. Most of the models also account for the occurrence of variability factors and estimate the impact of their occurrence on the activity duration (AbouRizk and Halpin 1992; Dawood 1998; Liu 2010; Pohl and Chapman 1987). Stochastic models have not been integrated to support project control.

The third group are the stochastic simulation models. These models leverage discrete event simulation and can model flows as entities connecting activities (AbouRizk and Hajjar 1998; González et al. 2009; Martinez and Ioannou 1999; Tommelein 1998; Tommelein et al. 1999). Brodeskaia et al. (2011) proposed one of the most complete simulation models, modelling all of the flows as well as the occurrence of variability factors. However, one of the drawbacks of current simulation models is that they estimate the stochastic distribution for the inputs based on
time studies or statistical inference. This is both time consuming and based on a small number of samples (Arashpour and Arashpour 2015; Poshdar et al. 2014). Field managers lack an efficient method for measuring activity and flow variations in the field and for computing their variability on a daily basis. If simulation models had access to up-to-date activity and flow variations as well as variability data, they could be used by field managers to update the plan and explore the impact of different production management decisions, such as resource allocation and buffer sizing, on the overall schedule.

Finally, the fourth group are the models based on project progress. There are two main classifications within this group: models that quantify variation at the activity level, and those that quantify variation both at the activity and flow levels. There are three main models that quantify the variation at the activity level: the Last Planner System, the Location-based Management System (LBMS), and Platform I. The Last Planner System tracks activities and computes their variability factors by recording the reason for non-completion for each activity (Ballard 2000). The LBMS leverages the location-based representation and links activities with their associated product model components (Kenley and Seppänen 2009). Platform I estimates activity duration variation based on the activity’s risk factors and the impact those risk factors have had on activities executed earlier (Levitt and Kunz 1985). Platform I is an important point of departure for this research because we use the same underlying assumption that activities with similar attributes will be affected by comparable variations. The main difference is that this research does not require that the field managers identify the particular risk factors that are likely to affect each activity. Its estimation of activity variation is based on the flows that are needed by the activities and their record of past variability.

The second classification corresponds to those models that quantify variation at the activity and flow levels. There are two main models within this classification: The Flow Index and the Reliable Commitment Model. The Flow Index measures flow quality based on location and trade flow conditions (Sacks 2016; Sacks et al. 2017). One of the drawbacks of the Flow Index is that it is based on the location-based representation. Therefore, it can only fully represent variations in the location and precedence flows. Variations in the labor flows cannot be fully represented since the location-based representation only assumes trade continuity between locations for the same activity type, not between activity types. For example, in one of our case studies, the
concrete crew did not follow the same location sequence as the carpentry or steel crews. Rather, it moved between activity types executed in different locations. For instance, it first poured the tower slabs in workspace Level 11 zone 1, then poured the core slab on Level 14, then returned to workspace Level 11 zone 1 to pour the columns. This movement of crews between locations and activity types is cumbersome to represent using the location-based representation. The Reliable Commitment Model (González et al. 2010, 2011) uses the record of work-in-progress and activity variability to help field managers decide what activities to commit to and to determine the time buffers. To date, there are no models that base their inputs on project progress, quantify variations at the activity and flow levels, model all the flows, and consider variability factors. The AFM proposed in this research fills this gap.

3.3 Research questions and methodology
The two research questions tackled in this report are: 1) What is an ontology of a model that would allow field managers to represent activities, flows, and their interaction; and 2) What formalization enables a model-based quantification of activity and flow variability. The first research question is related to the representation problem, specifically, how to create a computer-interpretable model that can represent activities, flows, and how they are connected to each other. The second research question is related to how to measure variations during project execution and how to use these variations to characterize variability at the activity and flow level. Answering these two questions allows the representation of activities, flows, and their interaction (RQ1) and the quantification of activity and flow variability (RQ2).

We carried out a series of research tasks to answer these two research questions. First, we developed an ontology representing the activities, the flows, and their interactions. The ontology was developed based on theory and field observations. Then, we developed metrics for activity and flow variation based on measures used by field managers and by considering the ease of collecting data in the field. Following this, we formalized the ontology and the variation measures into a class diagram. Next, we developed a web application that implements the class diagram and that allowed us to collect the data required by the AFM. Finally, we validated the Activity-Flow formalization by implementing it on three building projects and testing the

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2 In this research, we define variation as the measure between two states of a variable. Variability is a statistical measure characterizing the distribution of a variable of interest.
model’s ability to a) represent activities and flows, b) represent, measure, and track activity and flow variations, and c) quantify activity and flow variability.

This research followed the CIFE horseshoe research method which consists of seven interrelated steps: observed problem, intuition, theoretical points of departure, research questions and methods, research tasks, research validation, contributions, and impact (Figure 8)(Fischer 2006).

![CIFE horseshoe research process](image)

Figure 8: CIFE horseshoe research process adopted from (Fischer 2006).

The AFM was developed iteratively based on existing literature, field observations made during the case studies, and the authors’ experience. Each of the modules of the AFM was tested for internal validity by using test cases and unit-tests built into the modules. The AFM was validated prospectively through its implementation on three construction jobsites. Prospective validation provides a higher degree of external validity than other validation methods, such as charrette experiments or test examples (Ho et al. 2009; Thomsen et al. 1999). Some of the advantages of prospective validation are: it supports the direct comparison between the proposed and existing method, predictions can be compared to actual data, the model can be tested on real data, practitioners can provide direct input on the model results, and the results of the model can lead to interventions. The three test projects were chosen because they were in different building phases (foundations, core and shell, and finishing), in different geographical locations (Bogota, Copenhagen, and Lima), and used different planning and control methods (master schedule and weekly planning, Last Planner System, and Location-based Management System). The validation criteria consisted of: 1) completeness of the activity and flow representation, and 2) ability to track and quantify activity and flow variations.

The following section presents the development and testing of the Activity-Flow Model.
4 Activity-Flow formalization

This section describes the Activity-Flow formalization, which provides the structure for collecting the data and formalizing the mechanisms that allow field managers to represent and track activities, flows, and their interactions. It is structured in five sub-sections. The first sub-section presents the development of an ontology representing the activities, the flows, and their interactions. The second sub-section develops the measures for quantifying the activity and flow variations. The third sub-section presents the Activity-Flow Model class diagram, which merges the semantic relationships outlined in the ontology with the measures for quantifying activity and flow variation. The fourth sub-section presents an overview of the web application that we developed to collect the model data and that allowed us to implement it in three building projects. Finally, the fifth sub-section analyzes the implementation results of applying the Activity-Flow formalization in the test projects.

4.1 Ontology representing the activities, the flows, and their interactions

The first step towards formalizing an ontology is to develop a conceptual model of how the activities and flows interact. As we outlined in a previous section, the construction flow view conceptualizes construction as assembly-type activities enabled by seven flows: labor, equipment, workspace, material, information, precedence, and external (Koskela 1992). The flows move between activities, are utilized by the activities, and are then released to downstream activities. Thus, variation in upstream activities leads to variation in the flows available for downstream activities (Hamzeh 2009). Additionally, the occurrence of variability factors can also cause flow and activity variations (Wambeke et al. 2011). To avoid variations in the flows from affecting the activities, field managers can implement buffers. There are three types of buffers: inventory, capacity, and time. Inventory buffers shield activities from variations in material flows by adding material stock on site (Alves 2005; Arbulu and Ballard 2004; Vrijhoef and Koskela 2000) or adding work-in-progress between activities (González et al. 2011). Information and external flows can also be shielded by using an inventory buffer, for example, by submitting more information than is strictly required in a plan or asking for a permit to cover a longer period of time than planned. Similarly, workspace flows can also be shielded using inventory buffers by having workspaces with work-in-progress where work can be redirected. Capacity buffers shield activities from variations in labor and equipment flows by adding more...
labor and equipment to avoid full capacity utilization (Arashpour et al. 2014). Finally, time buffers shield activities from variation in all the seven flows by adding time between when the flow is planned to be ready and when it is needed (planned start of the activity) (González et al. 2004; Horman et al. 2003). This research focuses on measuring the time buffer for two reasons. The first is that it is applicable to all the seven flows. The second is that during the field tests we found that measuring inventory or capacity buffers on site was extremely time consuming and prone to error. Some of the reasons for this were: lack of standardized ways to measure the inventory and capacity buffers, limited control from the general contractor over the flows due to subcontracting structures, and fragmented information sources.

Figure 9: Conceptual activity and flow model showing a construction activity, the seven flows, and their variation mechanisms.

Figure 9 shows a conceptual activity and flow model summarizing the concepts discussed in the previous paragraph. In construction, activities are defined as “resources acting on components” (Aalami 1998; Darwiche et al. 1988). For activities to start, they require that a certain set of flows are available at the planned start of the activity (Bertelsen et al. 2007; Koskela 2000). There are two mechanisms that can cause variation in the readiness of flows feeding the activities: the occurrence of variability factors such as bad weather, and the late release of flows due to delays in upstream activities. Time buffers can be implemented by field managers to shield activities from variation in the flows. If a flow’s readiness variation is larger than its time buffer, the flow delays the activity’s start. At any time, one or more of the flows needed by an activity can be experiencing variations. However, the activity’s start is constrained by the flow with the highest variation only, since even if the other flows were ready the activity would still be unable
to start. The flow constraining the activity’s start is called the critical flow (Bertelsen et al. 2006; Goldratt 1997).

There are theoretical gaps that need to be filled to formalize the conceptual activity and flow model into an ontology for representing the activities, the flows, and their interactions. First, the interactions between flows and activities needs to be defined; specifically, differentiating between how on-site and off-site flows interact with activities. Secondly, the function that flows have for an activity needs to be established. All the required flows must, of course, be available for the execution of an activity. Some flows, like permits, are simply prerequisites for an activity’s start; they are not further transformed or provide capacity to the activity. We call these flows “prerequisite flows.” Other flows are transformed by an activity, and others provide capacity for the execution of an activity. Finally, the characteristics of each of the flow types needs to be defined to represent them in a computational model.

4.1.1 Activity – Flow interaction

There are two flow sources: on-site flows and off-site flows (Figure 10). On-site flows are released from upstream activities and move between the activities. An on-site flow and an activity interact via the predecessor link. Off-site flows originate from outside the site. Examples of off-site flows are deliveries of materials or resource mobilizations. An off-site flow and an activity interact via the flow’s due date. Activities release the flows once they are completed, and the flows move to downstream activities. A released flow interacts with an activity via the successor link.

![Diagram of Activity – Flow interaction](image)

Figure 10: Interaction between the two flow sources and the activity.
4.1.2 Function played by the flows for an activity

Based on our field observations, we identified three functions that flows play for an activity (Figure 11). The first function is as prerequisites: the flow provides an input that is required by an activity but it does not take part in the transformation process. The second function is as transformation products: the flow goes into an activity, is transformed by the activity, and is released as a transformed flow. The third function is as a capacity provider: the flow goes into the activity, is utilized during the transformation, and is released unchanged.

Figure 11: Functions played by the flows for activities: prerequisite, transformation product, and capacity provider.

4.1.3 Flow characteristics

In this section, we explore the characteristics of each of the seven flows, discussing whether they can be off-site or on-site, and the function they play for activities. To guide the discussion, we classified the seven flows according to the flow framework introduced by Shingo (Shingo and Dillon 1989). Shingo argued that manufacturing production is composed of two interdependent flows: the process flow and the operations flow. The process flow describes the product progress along the production line, while the operations flow describes the processes performed by the resources at each workstation. In this research, the process flow is defined by the materials and precedence flows and the operations flow by the resource flows (labor, equipment, and workspaces). We added support flows which are information and external flows. We will refer to the operations flows as resource flows in this report because it is a more commonly used term in construction.

The characteristics of each of the flows are summarized in Table 1 and are later embedded into the ontology representation.
Table 1. Flow source and flow function classification for the different flow types.

<table>
<thead>
<tr>
<th>Flow category</th>
<th>Flow type</th>
<th>Flow source</th>
<th>Flow function in the activity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>On-site</td>
<td>Off-site</td>
</tr>
<tr>
<td>Process flows</td>
<td>Material</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Precedence</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resource flows</td>
<td>Labor</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Equipment</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Workspace</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Support flows</td>
<td>Information</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>External</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.1.3.1 Process flows (materials and precedence flows)

The process flows describe the processes performed on the product. In construction, we can view the products to be the components, which are transformed from raw materials to the finished building via the activities. The material and precedence flows define the process flows. The material flows represent the raw materials and work-in-progress flows that move from activity to activity. The precedence flows represent inflexible sequencing constraints that are imposed either by physical relationships between the components or process constraints from the construction methods themselves (Aalami 1998; Echeverry et al. 1991).

4.1.3.1.1 Material flow characteristics

The material flows can be either off-site or on-site. Off-site material flows include the delivery of raw materials or assemblies. On-site material flows represent the work-in-progress shared between the activities. Activities transform the material flows and then release them to downstream activities.

4.1.3.1.2 Precedence flow characteristics

Precedence flows constrain the relationships between two activities. Therefore, they can only be on-site flows. Similarly, precedence flows act as prerequisites constraining the activity from starting, but are not actively involved in the transformation process.
4.1.3.2 Resource flows (labor, equipment, and workspace flows)
Resources are characterized by having a limited capacity (Hamzeh 2009). If an activity is using a resource, another activity cannot simultaneously use that resource. Field managers determine the flow of resources between activities. Decisions regarding the order of the flow of the resources determine the sequencing of the activities at the production level (Echeverry et al. 1991). Resource flows can be regarded as “disjunctive constraints,” meaning that two activities with overlapping time intervals cannot use the same resource at the same time (Morkos 2014).

4.1.3.2.1 Labor and equipment flow characteristics
Labor and equipment have essentially the same characteristics. Both flows can either be on-site or off-site flows. The first occurs when an activity uses the flows and releases them to downstream activities, while the later occurs when there are mobilizations to the site. An activity temporarily utilizes the flow’s capacity and then releases it unchanged to downstream activities.

4.1.3.2.2 Workspace flow characteristics
Workspace flows are always on-site flows. An activity temporarily utilizes a workspace and then releases it to downstream activities.

4.1.3.3 Support flows (information and external flows)
Construction production has three important particularities compared to manufacturing production: one of a kind production, site production, and temporary organization (Koskela and Ballard 2003). Support flows are extremely important in construction due to its one-of-a-kind production. In manufacturing, there are few changes to the product (i.e., information flows), and few external permits or inspections need to support production (i.e., external flows). Therefore, it is not surprising that Shingo’s manufacturing conceptualization did not include support flows (Shingo and Dillon 1989). However, failing to include them in a construction model would incur a representation simplification problem, since it would not account for one of the main characteristics that differentiates construction from manufacturing (Sacks 2016).

4.1.3.3.1 Information flow characteristics
There are two main sources of information: directives and design specifications (Ballard 2000). Directives encompass the agreements, instructions, and decisions made by the field management team regarding the scope and schedule of the activities. The design specifications supply critical
information about the scope of the activities and how they should be executed. During a project, design changes or requests for information can give rise to information flows that constrain the activity. For example, suppose the rebar subcontractor encounters conflicting information in the drawings for placing the rebar in column A1. The rebar subcontractor will send a request for information to the field engineer who will forward it to the structural engineer for clarification. In the meantime, the activity “Place rebar in column A1” will be constrained pending a response from the structural engineer. Currently, most requests for information and change orders are managed using either spreadsheets or specialized software that time-stamp the communications between the stakeholders. The problem with these solutions is that they are not linked to the on-site activity schedule. Therefore, it is difficult for the stakeholders to understand the impact of a delay on downstream activities in the request for information response. By linking an information flow directly with an activity, it is possible for stakeholders to understand what activities the information is delaying and to prioritize information responses. Similarly, they can see how much time they have left to supply the information flow before impacting the activity’s planned start date. One of the problems we have seen on site is that designers lack clarity of when the site needs the information and why they need it. Therefore, it is not easy for them to prioritize information requests based on the impact that they have on site production. Rather, they tend to prioritize their work based on other considerations, such as which requests for information are easier to answer or who is asking more loudly for the information. Lean construction tells us that we must wait for the last responsible moment to allow designers to make changes so that value is maximized for the client (Ballard et al. 2003). However, it is generally difficult for field managers to determine when the last responsible moment is. A model that links the information flows directly to the activities alleviates this problem.

Most of the information flows come into a site as a response to a request for information or a change order. Thus, they are off-site flows with a due date attached to the activity. However, it is also possible to have on-site information flows. For example, consider the case where the location of an in-wall plate is slightly modified due to interference with other in-wall pipes. This as-built information needs to flow to downstream activities that depend on the new location of the in-wall plate, such as the casework activities. Failing to deliver this information to downstream activities could lead to rework. If the as-built information was not updated and the casework was placed in the initial place, not only would it lack support, it might hit an in-wall
pipe, leading to rework and extra cost. As the previous example shows, information flows interact with the activity, are transformed by it, and released to downstream activities.

4.1.3.3.2 External flow characteristics
External flows comprise inputs that are required by the activity to start, but are not under the control of the project team. For example, an activity might require a parking permit that is issued by the municipality or it needs to pass an inspection carried out by the city inspector. By definition, external flows are always off-site and function as prerequisites to the activities.

4.1.4 Activity-Flow interaction ontology
The previous section summarized the characteristics of the seven flows, discussing their flow source (on-site and off-site) and the function they play for activities (prerequisites, transformation of the product, and capacity provider). This section formalizes the semantic relationships between activities and flows based on the characteristics described in the previous sections.

“An ontology is an explicit specification of a conceptualization” (Gruber 1993). Ontologies are typically composed of classes, relations, and functions. In construction, ontologies have enabled the formalization of construction models that support the generation of 4D production models (Aalami 1998), activity workspace types to uncover workspace conflicts (Akinci et al. 2002), and the relationship between building features and activities to support estimating (Staub-French et al. 2003), among others.

Figure 12 shows our proposed ontology representing the construction activities, the flows, and their interactions. The ontology represents 12 classes, their internal characteristics, and their external relationships to other classes. An activity belongs to an activity type. For example, the activities “Pour columns A1” and “Pour columns A2” belong to the activity type “Pour columns.” Specifying this relationship enables the aggregation of the activities’ performance at the activity type level, allowing field managers to understand the behavior of groups of activities by further aggregating their performance metrics at different Unisformat levels. An activity is enabled by its flows. A flow can be of the class: material, precedence, labor, equipment, workspace, information, or external. Aggregating flows into their respective class standardizes the flow name library for the project and enables the aggregation of flow behavior across the
project. A flow can only be released from a predecessor activity if it is an on-site flow and if it is not a prerequisite flow. An activity and a flow are assigned a stakeholder that is responsible for their execution. Finally, an activity and a flow can be affected by the occurrence of variability factors. When this occurs, a reason for variation is associated with either the activity or the flow, which is analogous to the Last Planner System’s reason for non-completion assignment (Ballard 2000). The Activity, Activity Type, and Stakeholder classes (shown in blue) and their interactions were adopted from the <Component, Action, Resource> activity definition (Aalami 1998; Darwiche et al. 1988). Similarly, the seven flow classes (colored in gray) were introduced by Koskela (2000, 1999). The Flow class and the interactions with the other classes (shown in red) were introduced and formalized in this research.

Figure 12: Ontology representing the construction activities, the flows, and their interactions.

An example of the ontology representation for an activity-flow network connecting the activity “Pour column A1” and its flows is shown in Figure 13. In this case, the activity “Pour column A1” has three flows enabling it. The first is an off-site flow delivering concrete to the activity. This flow is of type “Material,” and the flow name is “Concrete.” Since it is an off-site flow it cannot be released from a predecessor activity. The second flow is an on-site flow providing the concrete crew to execute the activity. This flow is of type “Labor” and the flow name is “Concrete crew.” Since it is an on-site flow and the labor flow type provides capacity for the
activity (function played by the flow for the activity is different from “Prerequisite”), then the predecessor activity “Pour slab 1” releases the flow. The third flow is also an on-site flow providing the workspace “A1” needed by the activity. This flow is of type “Workspace” and the flow name is “A1.” Since flows of type workspace are always on-site and provide capacity for the activity, then the predecessor activity “Rebar col A1” releases the flow.

Figure 13: Ontology representation of the activity-flow network representing the Pour Column A1 activity and its flows.

The ontology presented in this section formalizes the semantic relationships between the classes, constraining the activity-flow interaction based on the flows’ characteristics. However, the ontology is not able to represent the activities’ and flows’ execution deviation from the plan. In the next section, we will present the metrics developed to track the activities’ and flows’ variations.
4.2 Metrics for tracking activity and flow variation

Construction projects are highly dynamic, the actual work performed rarely follows the plan. To deal with this dynamic nature of construction, field managers need models that can measure and track the activities’ and flows’ variations.

4.2.1 Activity variation metrics

Activity variation can be measured by tracking the activity’s start variation (delta start), duration variation (delta duration), and finish variation (delta finish) (Wambeke et al. 2011). In this research, we refer to these metrics (delta start, delta duration, and delta finish) as the activity variation metrics. The delta start is measured by comparing the actual start minus the planned start for the activity. The delta duration is measured by comparing the actual duration minus the planned duration for the activity. Finally, the delta finish is measured by computing the actual finish minus the planned finish for the activity. The activity variation metrics are linearly dependent: the delta finish is equal to the delta start plus the delta duration. Figure 14 summarizes the activity variation metrics.

![Activity and flow variation metrics](image)

Figure 14: Activity and flow variation metrics.

4.2.2 Flow variation metrics

While there have been methods that enable construction models to measure and track variations at the activity level, measuring and tracking flow variations has not been operationalized before. In manufacturing, measuring flow variations allowed their variability to be quantified, enabling the generation of queuing models to analyze the production system’s performance and evaluate it under different production scenarios (e.g., different queuing rules, batching sizes, etc.) (Hopp and Spearman 2011).
In construction, the main characteristic that defines flow variation is whether the flow is ready for the activity at the activity start date or not. If a flow is delayed (i.e., released late from a previous activity or delivered late to the jobsite), it will push the downstream activity if the flow delay is greater than the buffer that the field managers had set. Hence, flow variation can be characterized by the following three metrics: flow delta ready, flow buffer, and flow push. Flow readiness variation (delta ready for short), is defined as the difference between when the flow is ready and when it was planned to be ready. For off-site flows, delta ready is calculated as the difference between the date delivered and the due date. For on-site flows, delta ready is calculated as the difference between the predecessor’s actual finish minus the predecessor planned finish. Field managers place time buffers to shield activities from variation in the flows’ readiness. For off-site flows, the time buffer is calculated as the difference between the activity planned start and the due date for the flow. For on-site flows, the time buffer is calculated as the difference between the activity planned start and the predecessor planned finish. If the flow readiness variation is larger than the time buffer set by the field managers, the flow pushes the activity’s planned start date. The flow push metric is defined as the difference between the flow delta ready minus the time buffer. Figure 14 summarizes the flow variation metrics.

4.2.3 Reasons for variations of activities and flows

As mentioned previously, the occurrence of variability factors leads to variations at both the flow and activity levels. Measuring the variability factor’s impact at the flow level is difficult because a variability factor can affect several flows simultaneously and it can affect both the flow’s time dimension (which was measured in this research) and quantity dimension (which was not measured in this research). To abate this limitation, we represent the variability factors at both the activity level and at the flow level. A ‘reason for variation’ was added at the activity level if the variability factor affected more than one flow, for example, the occurrence of bad weather. On the other hand, if it was clear what flow was affected by the variability factor, the ‘reason for variation’ was added at the flow level, for example, an equipment breakdown or a worker absence. For variability factors at the activity level, the variability factor’s impact can be quantified at the activity level (i.e., measuring the activity’s variation metrics). For variability factors at the flow level, a variability factor’s impact can be quantified both at the activity level as well as on the other flows required by the activity. For example, we were able to quantify the
number of days that the labor flow was idle as a result of the occurrence of an equipment breakdown.

4.3 Activity-Flow Model class diagram

In this section, we present a class diagram formalizing the Activity-Flow Model by merging the ontology representation presented in section 4.1 and the activity and flow variation metrics presented in section 4.2 (Figure 15).

The class diagram contains the following classes: Activity, ActivityType, Stakeholder, Flow, LaborFlow, EquipmentFlow, MaterialFlow, WorkspaceFlow, InformationFlow, ExternalFlow, and ReasonForVariation. The Activity class is aggregated at the ActivityType class, which enables the aggregation of activity measures at the activity type level. The Activity class is also related to the ReasonForVariation class. The ReasonForVariation class contains a project-specific database of the reasons for variations used by the project team. If an activity is not completed as planned, the field managers can add a reason for variation to explain what variability factor caused the variation (Ballard 2000), enabling field managers to learn from previous variations. The Activity class and Stakeholder class are related via the actStakeholder
property that identifies the stakeholder responsible for executing the activity. The Activity class aggregates the Flow class since flows belong to an activity.

The Flow class is also related to the Activity class via the predecessor property. The predecessor property represents what upstream activity releases that specific flow. Hence, the existence of the predecessor property is contingent on the flow being on-site and not a prerequisite. If the flow is off-site or a prerequisite, the predecessor property is set to null and the dueDate property is required. If the flow is on-site and not a prerequisite, the predecessor property is required and the dueDate property is set to null. The Flow class is related to one of the flow type classes, namely: LaborFlow, EquipmentFlow, MaterialFlow, WorkspaceFlow, InformationFlow, or ExternalFlow classes depending on the Flow class’ property flowType. Each of the flow type classes has a database containing the flow names for the project. There are two reasons for this. The first is that it allows aggregating the flow variation metrics at the flow name level, allowing the characterization of the variability of a specific flow class (e.g., characterizing the flow push variability for the concrete crew). The second is that it standardizes the flow names across projects, allowing field managers to compare flow performance between projects. Notice that there is no precedence flow database. Precedence flows are identified solely by their flowType being set to “Precedence.” The Activity class contains the activity variation metrics and the Flow class contains flow variation metrics (see section 4.2 for a description of these measures). The Activity and the Flow class are versioned. This means that if a property of the class changes, a new instance of the class is created to reflect this change. Therefore, the AFM keeps a record of the variation changes for a specific activity and flow. For example, field managers can query the system and retrieve the different instances of the activityName “Pour Column A1” to understand how the activity changed through its use-cycle: from when it was created to when it was finished.

Darwiche et al. (1988) defined an activity as resources performing actions on components. The component-action tuple <CA> is represented by the activityName property contained in the Activity class. The resource <R> is represented at the stakeholder level and at the flow level. At the stakeholder level, the <R> component is represented by the stakeholderType property contained in the Stakeholder class. At the flow level, the <R> is represented by the labor and equipment resource flows associated with the activity.
4.4 Web application for collecting model data

We developed the Activity-Flow application to implement the Activity-Flow formalization on the test construction projects. The web application was developed using Google App Engine. The back-end of the application used python, while the front-end used Google Polymer’s framework. The web-application’s back-end implemented the Activity-Flow Model class diagram presented in section 4.3 in addition to the functions necessary to create and update the construction activities and flows. Internal consistency was ensured by creating unit-tests for each of the functions and testing the app’s results using a test project.

![Figure 16: Snapshot of the Activity-Flow application developed to collect the Activity-Flow Model data.](image)

Field managers need to specify the following information to create an activity: activity name, activity type, planned start, and planned finish. Field managers update the status of the activity by adding the actual start, actual finish, and assigning a reason for variation. The system automatically calculates the activity status based on the activity’s variation metrics. Additionally, the field managers can define the flows that are needed to execute the activity. Each flow contains the following information: flow type, flow name, flow description (optional), flow predecessors (if on-site flow and not prerequisite), due date (if off-site flow or prerequisite), and flow management description (optional). If the flow is on-site, the system automatically updates the flow status based on the status of the predecessor activity. If the flow is off-site, the flow status needs to be updated by the field managers to specify when the flow was delivered on site.
Figure 16 shows a snapshot of the web application showing the list of activities and the activity detail window.

4.5 Implementation results
We tested the Activity-Flow formalization by collecting data about the activities and their flows on three building projects. These projects were chosen because they had different scopes, were in different phases, and used different planning and control methods (Table 2). We tested whether the model could: a) represent the activities and the flows, b) represent, measure, and track the activities’ and flows’ variations, and c) quantify the activity and flow variability.

Table 2. Characteristics of the three projects used to test the AFM.

<table>
<thead>
<tr>
<th>Test project</th>
<th>Ichma</th>
<th>Equilibrium</th>
<th>Frederikskaj</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of building</td>
<td>Office building</td>
<td>Residential building</td>
<td>Residential blocks</td>
</tr>
<tr>
<td>Location</td>
<td>Peru</td>
<td>Colombia</td>
<td>Denmark</td>
</tr>
<tr>
<td>Project scope</td>
<td>21 floors, 11 basements</td>
<td>25 floors, 3 basements</td>
<td>4 blocks, 68 apartments</td>
</tr>
<tr>
<td>Project phase</td>
<td>Structural phase</td>
<td>Foundations phase</td>
<td>Finishes phase</td>
</tr>
<tr>
<td>Planning method</td>
<td>Last Planner / Takt</td>
<td>Critical Path Method</td>
<td>Line-of-balance</td>
</tr>
<tr>
<td>Control method</td>
<td>Last Planner / Daily plan</td>
<td>Traditional CPM update/ Weekly planning</td>
<td>Location-based Management System</td>
</tr>
<tr>
<td>Test period</td>
<td>8 weeks on site, 10 weeks remote (18 total)</td>
<td>4 weeks on site</td>
<td>4 weeks on site</td>
</tr>
</tbody>
</table>

4.5.1 Activity and flow representation
The main criterion for testing the Activity-Flow formalization was to ensure that it could accurately represent the activities and flows in building projects. To achieve this, we collaborated with the field managers to transform the look-ahead schedule they had for the project into an activity and flow representation. We uploaded the activity and flow representation into the web application and used the web application to update and track the activities and flows during the week. After each week, we updated the look-ahead plan to match the field managers’ plan and proceeded to track the activities and flows.
Table 3. Number of activities represented and tracked by each of the test projects.

<table>
<thead>
<tr>
<th></th>
<th>Ichma</th>
<th>Equilibrium</th>
<th>Frederikskaj</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td># Activity Types</td>
<td>26</td>
<td>11</td>
<td>34</td>
<td>71</td>
</tr>
<tr>
<td># Activities</td>
<td>1,153</td>
<td>149</td>
<td>343</td>
<td>1,645</td>
</tr>
<tr>
<td>Avg. # Activities/week</td>
<td>64.1</td>
<td>37.3</td>
<td>85.8</td>
<td>62.4</td>
</tr>
<tr>
<td># Activities unable to represent</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

In total, we represented 71 activity types and tracked 1,645 activities (averaging 62.4 activities per week) for the three projects. Moreover, we did not encounter any activities that we were unable to represent using the formalization (Table 3). Since the three projects were in different phases, the activities covered all the main types of work encountered in building projects: foundations, structure, interiors, MEP, and equipment and finishing (Figure 17).

![Number of activity instances according to UNIFORMAT L3 classification](image)

Figure 17: Distribution of the activities represented and tracked by their Unisformat Level 3 classification.
Similarly, we tracked a total of 326 flow classes\(^3\) representing 5,843 flows (average of 224.7 flows per week). The percentage of on-site flows and off-site flows was similar for the three projects, where approximately one in every four flows is an off-site flow. The Ichma project had the highest percentage of on-site flows (79%), followed by the Frederikskaj (76%), and the Equilibrium project (67%). Analogous to the activity case, we did not encounter any flows that we were unable to represent using the Activity-Flow formalization (Table 4).

Table 4. Number of flows represented and tracked by each of the test projects.

<table>
<thead>
<tr>
<th></th>
<th>Ichma</th>
<th>Equilibrium</th>
<th>Frederikskaj</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td># Flow Classes</td>
<td>192</td>
<td>44</td>
<td>95</td>
<td>-</td>
</tr>
<tr>
<td># Flows</td>
<td>4,192</td>
<td>449</td>
<td>1,202</td>
<td>5,843</td>
</tr>
<tr>
<td>Avg. # Flows/ week</td>
<td>232.9</td>
<td>112.3</td>
<td>293.8</td>
<td>224.7</td>
</tr>
<tr>
<td># On-site flows</td>
<td>3312</td>
<td>301</td>
<td>914</td>
<td>4527</td>
</tr>
<tr>
<td>% On-site flows</td>
<td>79%</td>
<td>67%</td>
<td>76%</td>
<td>77%</td>
</tr>
<tr>
<td># Off-site flows</td>
<td>880</td>
<td>148</td>
<td>288</td>
<td>1,316</td>
</tr>
<tr>
<td>% Off-site flows</td>
<td>21%</td>
<td>33%</td>
<td>24%</td>
<td>23%</td>
</tr>
<tr>
<td># Flows unable to represent</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The flows also represented all the different flow types (Table 5). However, it is important to note that some of the flow types were underrepresented in the test. The information flows were only represented by three flow classes: “RFI structural detail,” “Quality inspection,” and “Material submittal approval.” Similarly, the external flows were only represented by two flow classes: “Loading permit” and “Occupancy inspection.” The information flows and the external flows accounted for only 0.4% and 0.3% of the total flows, respectively. There are two main reasons for this low representation. The first is that it is normal for information and external flows to be outnumbered by the other flow types. Whereas every activity requires labor, equipment, materials, and workspaces, fewer activities need additional information flows or need external flows. Since we were interested in understanding flow variations, we limited the tracking of information flows to just those involving exceptions, such as missing information (e.g., RFIs).

---

\(^3\) A flow class is an individual flow name, e.g., concrete crew (labor), concrete (material), concrete pump (equipment).
information changes (e.g., change orders), submittals, and inspections. We did not track regular information flows, such as directives, plans, etc., because tracking them would have provided very little management insight while requiring a higher time burden to represent and track them. The second reason is that we did not start tracking the projects at the beginning of the phase, but in the middle of the phase. Hence, many of the information requirements and external permits for the phase had already been acquired.

Table 5. Distribution of the number of flow classes and number of flows by flow type.

<table>
<thead>
<tr>
<th>Flow Type</th>
<th>Number of Flow classes</th>
<th>Number of Flows</th>
<th>% of total number of flows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor</td>
<td>33</td>
<td>1,647</td>
<td>28.19%</td>
</tr>
<tr>
<td>Materials</td>
<td>21</td>
<td>584</td>
<td>9.99%</td>
</tr>
<tr>
<td>Workspace</td>
<td>254</td>
<td>1,668</td>
<td>28.55%</td>
</tr>
<tr>
<td>Equipment</td>
<td>12</td>
<td>919</td>
<td>15.73%</td>
</tr>
<tr>
<td>Information</td>
<td>3</td>
<td>22</td>
<td>0.38%</td>
</tr>
<tr>
<td>Precedence</td>
<td>1</td>
<td>988</td>
<td>16.91%</td>
</tr>
<tr>
<td>External</td>
<td>2</td>
<td>15</td>
<td>0.26%</td>
</tr>
<tr>
<td>Total</td>
<td>326</td>
<td>5,843</td>
<td></td>
</tr>
</tbody>
</table>

4.5.2 Tracking activity and flow variations

The second criterion for testing the Activity-Flow formalization was whether it could represent, measure, and track activity and flow variations.

The activity variation metrics are: delta start, delta duration, and delta finish. The variation metrics are calculated based on the activity planned start, planned finish, actual start, and actual finish. If the activity does not finish on time, it is assigned a reason for variation (Table 6). We developed unit tests to ensure the internal consistency of the calculation of the activity variation metrics.
Table 6. Snapshot of the activity variation metrics for the Frederikskaj project.

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Planned Start</th>
<th>Planned Finish</th>
<th>Actual Start</th>
<th>Actual Finish</th>
<th>Delta Start</th>
<th>Delta Finish</th>
<th>Delta Duration</th>
<th>Reason for Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2M ST-2 - FLOOR RADIANT HEAT</td>
<td>11/9/16</td>
<td>11/14/16</td>
<td>11/17/16</td>
<td>11/22/16</td>
<td>6</td>
<td>0</td>
<td>6</td>
<td>MATERIAL AVAILABILITY</td>
</tr>
<tr>
<td>2N ST – ELECTRICAL FLOOR</td>
<td>11/10/16</td>
<td>11/11/16</td>
<td>11/10/16</td>
<td>11/10/16</td>
<td>1</td>
<td>-1</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>2N 1 – ELECTRICAL FLOOR</td>
<td>11/14/16</td>
<td>11/15/16</td>
<td>11/18/16</td>
<td>11/21/16</td>
<td>4</td>
<td>0</td>
<td>4</td>
<td>CHANGE OF PRIORITY</td>
</tr>
<tr>
<td>4G 1 - GYPSUM</td>
<td>11/15/16</td>
<td>11/16/16</td>
<td>11/17/16</td>
<td>11/22/16</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>LABOR AVAILABILITY</td>
</tr>
</tbody>
</table>

The flow variation metrics are: flow delta ready, flow buffer, and flow push. For on-site flows, the flow delta ready is calculated based on the difference between the predecessor activity’s planned finish and its actual finish (predecessor delta finish). For off-site flows, the flow delta ready is calculated as the difference between the ready date and the due date. The flow push is the difference between the delta ready and the flow buffer. Table 7 shows an example of an on-site flow and how its variation metrics are calculated. Table 8 shows an example of an off-site flow and how its variation metrics are calculated. We developed unit tests to ensure the internal consistency of the calculation of the flow variation metrics.

Table 7. Example of an on-site flow and its variation metrics.

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Flow Type</th>
<th>Flow Name</th>
<th>Flow Status</th>
<th>Flow Pred.</th>
<th>Pred. DF = Delta ready</th>
<th>Flow buffer</th>
<th>Flow Push</th>
<th>Reason for Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2M ST-2 - FLOOR RADIANT HEAT</td>
<td>PREC.</td>
<td>PREC.</td>
<td>FAILED</td>
<td>2M ST-2 - FLOOR THERMOZELL</td>
<td>7</td>
<td>1</td>
<td>6</td>
<td>PREDECESSOR</td>
</tr>
</tbody>
</table>

Table 8. Example of an off-site flow and its variation metrics.

<table>
<thead>
<tr>
<th>Activity Name</th>
<th>Flow Type</th>
<th>Flow Name</th>
<th>Flow Status</th>
<th>Flow Pred.</th>
<th>Due Date</th>
<th>Ready Date</th>
<th>Delta ready</th>
<th>Flow buffer</th>
<th>Flow Push</th>
<th>Reason for Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>4G ST - GYPSUM</td>
<td>MAT.</td>
<td>GYPSUM BOARD</td>
<td>READY</td>
<td>NA</td>
<td>11/15/16</td>
<td>11/16/16</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>LATE DELIVERY</td>
</tr>
</tbody>
</table>
4.5.3 Quantifying activity and flow variability

The third test criterion is whether the Activity-Flow formalization supports the quantification of the activity and flow variability at the project, activity type, and flow class levels. The following statistical measures are typically used to describe variability: the mean, median, standard deviation (SD), minimum, maximum, and interquartile range (75th and 25th percentile measures) (Hopp and Spearman 2011). The values taken by the different statistical measures reveal the shape of the variability distribution. For example, if the mean is greater than the median the distribution is skewed to the right, meaning that the right tail of the distribution is longer than the left tail.

Table 9 summarizes the statistical measures for the activity metrics the three test projects. The same underlying data for the activity variability can be seen graphically in the box plots in Figure 18. Of the three projects, the Equilibrium project exhibited the lowest activity variability (average activity delta finish was 0.18 days), while the Ichma and Frederikskaj projects had similar levels of activity variability (average activity delta finish was 1.89 days and 1.46 days, respectively).

![Distribution of activity delta start, delta duration, and delta finish by project](image)

Figure 18: Distribution of delta start, delta duration, and delta finish for the three test projects. The median is represented by the solid line and the mean is represented by the dotted line.
Table 9. Summary of the activity and flow variation metrics for the three test projects.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Flow</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Delta Start</td>
<td>Delta Dura.</td>
<td>Delta Finish</td>
<td>Delta ready</td>
<td>Flow buffer</td>
<td>Flow push</td>
</tr>
<tr>
<td>Ichna</td>
<td>Mean</td>
<td>1.61</td>
<td>0.28</td>
<td>1.89</td>
<td>2.14</td>
<td>1.55</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>1.0</td>
<td>0.0</td>
<td>2.00</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>2.16</td>
<td>1.19</td>
<td>2.41</td>
<td>2.40</td>
<td>2.02</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-8.0</td>
<td>-7.0</td>
<td>-9.0</td>
<td>-9.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>25%</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>75%</td>
<td>3.00</td>
<td>1.00</td>
<td>3.00</td>
<td>4.00</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>12.0</td>
<td>6.0</td>
<td>12.0</td>
<td>9.00</td>
<td>13.00</td>
</tr>
<tr>
<td>Equilibrium</td>
<td>Mean</td>
<td>0.14</td>
<td>0.06</td>
<td>0.18</td>
<td>0.27</td>
<td>2.38</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>0.74</td>
<td>0.68</td>
<td>0.93</td>
<td>0.87</td>
<td>2.71</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-3.00</td>
<td>-2.00</td>
<td>-3.00</td>
<td>-3.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>25%</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>75%</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>3.00</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>5.00</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
<td>13.00</td>
</tr>
<tr>
<td>Frederikskaj</td>
<td>Mean</td>
<td>0.64</td>
<td>0.94</td>
<td>1.46</td>
<td>1.55</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>0.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>1.96</td>
<td>1.44</td>
<td>2.54</td>
<td>2.21</td>
<td>1.72</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>-5.00</td>
<td>-3.00</td>
<td>-5.00</td>
<td>-5.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>25%</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>75%</td>
<td>2.00</td>
<td>2.00</td>
<td>3.00</td>
<td>3.00</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>6.00</td>
<td>5.00</td>
<td>6.00</td>
<td>6.00</td>
<td>10.00</td>
</tr>
</tbody>
</table>

Table 10 shows the distribution of activities with respect to their delta start, the causes for the delta start (either due to variability factors or flow push), and the number of activities for which critical flow buffer was smaller than the critical flow delta ready. On average, 63% of the activities were started late, 27% were started on time, and 10% were started early. The percentage of activities with a positive delta start was very similar for the three projects, 63% for
the Ichma project, 66% for the Equilibrium project, and 64% for the Frederikskaj project. The percentage of activities that started on time and early varied slightly for the three projects. The Ichma project had the highest percentage of activities that finished on time (29%), followed by the Frederikskaj project (23%), and the Equilibrium project (19%). Additionally, the Equilibrium project had the highest percentage of activities that started early (15%), followed by the Frederikskaj project (13%), and the Ichma project (8%). On the other hand, 87% of the activity start delays were caused by flow delays, while only 13% were associated with the occurrence of variability factors.

Table 10: Distribution of activities with respect to their delta start, and the causes of delta start.

<table>
<thead>
<tr>
<th></th>
<th>Ichma</th>
<th>Equilibrium</th>
<th>Frederikskaj</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td># Activities</td>
<td>1,153</td>
<td>149</td>
<td>343</td>
<td>1,645</td>
</tr>
<tr>
<td># Activities with delta start &gt; 0</td>
<td>726</td>
<td>98</td>
<td>219</td>
<td>1,043</td>
</tr>
<tr>
<td>% of activities with delta start &gt; 0</td>
<td>63%</td>
<td>66%</td>
<td>64%</td>
<td>63%</td>
</tr>
<tr>
<td># Activities with delta start = 0</td>
<td>334</td>
<td>28</td>
<td>79</td>
<td>441</td>
</tr>
<tr>
<td>% of activities with delta start = 0</td>
<td>29%</td>
<td>19%</td>
<td>23%</td>
<td>27%</td>
</tr>
<tr>
<td># Activities with delta start &lt; 0</td>
<td>93</td>
<td>23</td>
<td>45</td>
<td>161</td>
</tr>
<tr>
<td>% of activities with delta start &lt; 0</td>
<td>8%</td>
<td>15%</td>
<td>13%</td>
<td>10%</td>
</tr>
<tr>
<td># Activities with delta start &gt; 0 caused by variability factors</td>
<td>91</td>
<td>15</td>
<td>28</td>
<td>134</td>
</tr>
<tr>
<td>% of activities with delta start &gt; 0 caused by variability factors</td>
<td>13%</td>
<td>15%</td>
<td>13%</td>
<td>13%</td>
</tr>
<tr>
<td># Activities with delta start &gt; 0 caused by flow push</td>
<td>635</td>
<td>83</td>
<td>191</td>
<td>909</td>
</tr>
<tr>
<td>% of activities with delta start &gt; 0 caused by flow push</td>
<td>87%</td>
<td>85%</td>
<td>87%</td>
<td>87%</td>
</tr>
</tbody>
</table>

Flow variation metrics enable field managers to understand how flow variations affect activities and how buffers can be implemented to shield activities from flow variations. An activity will be impacted by a flow if the flow’s delta ready is greater than the flow buffer placed by field managers. The amount an activity is impacted is measured as the flow push, which is the difference between the flow delta ready and the flow buffer. The statistical measures for the flow metrics for the three projects are summarized in Table 9 and can be seen graphically in Figure 19. The Ichma and Frederikskaj projects had similar levels of flow delta ready, flow buffer, and flow push. The Ichma project had an average flow delta ready of 2.14 days, an average flow buffer of 1.55 days, and an average flow push of 0.64 days. The Frederikskaj project had an
average flow delta ready of 1.55 days, an average flow buffer of 1.00 days, and an average flow push of 0.37 days. On the other hand, the Equilibrium project had very low levels of flow delta ready and flow push, but higher levels of flow buffers. The Equilibrium project had an average flow delta ready of 0.27 days, an average flow buffer of 2.38 days, and an average flow push of -2.17 days. The high flow buffers implemented on the Equilibrium project help explain why it exhibited the lowest activity variations of all the projects, even if the percentage of activities that experienced delta start was the highest.

Both the activity and flow variation metrics are skewed to the right for all the projects. This is evidenced by the mean being larger than zero and the maximum being larger than the minimum for all the projects.

![Figure 19: Distribution of flow delta ready, flow buffer, and flow push for the three test projects. The median is represented by the solid line and the mean is represented by the dotted line.](image)

Table 11 shows the distribution of flows with respect to their delta ready, the causes for delta ready, and the suitability of the flow buffers to absorb flow delta variations. On average, 70% of the flows had positive readiness variations, 23% had no variation, and 7% had negative readiness variations (were ready earlier than planned). Most of the flow delays (90%) were caused by the predecessor activity finishing late or due to late deliveries to the jobsite. Only 10% of the flow delays were caused by the occurrence of variability factors. Finally, the distribution of flows with positive flow push, zero flow push, and negative flow push reveals how well the field managers sized the flow buffers to absorb the flow delta ready. The field managers on the Ichma project undersized the flow buffers 57% of the time (delta ready higher than flow buffer), sized them correctly 15% of the time (delta ready equal to flow buffer), and oversized them 28% of the time.
(delta ready lower than flow buffer). The field managers on the Equilibrium project undersized the flow buffers 10% of the time, sized them correctly 2% of the time, and oversized them 88% of the time. Finally, the field managers on the Frederikskaj project undersized the flow buffers 52% of the time, sized them correctly 22% of the time, and oversized them 26% of the time.

Table 11: Distribution of flows with respect to their delta ready, the causes of delta ready, and the distribution of flow buffers with respect to the delta ready.

<table>
<thead>
<tr>
<th></th>
<th>Ichma</th>
<th>Equilibrium</th>
<th>Frederikskaj</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td># Flows</td>
<td>4,192</td>
<td>449</td>
<td>1,202</td>
<td>5,843</td>
</tr>
<tr>
<td># Flows delta ready &gt; 0</td>
<td>3,102</td>
<td>134</td>
<td>830</td>
<td>4,066</td>
</tr>
<tr>
<td>% of flows delta ready &gt; 0</td>
<td>74%</td>
<td>30%</td>
<td>69%</td>
<td>70%</td>
</tr>
<tr>
<td># Flows delta ready = 0</td>
<td>797</td>
<td>301</td>
<td>264</td>
<td>1,362</td>
</tr>
<tr>
<td>% of flows delta ready = 0</td>
<td>19%</td>
<td>67%</td>
<td>22%</td>
<td>23%</td>
</tr>
<tr>
<td># Flows delta ready &lt; 0</td>
<td>293</td>
<td>14</td>
<td>108</td>
<td>415</td>
</tr>
<tr>
<td>% of flows delta ready &lt; 0</td>
<td>7%</td>
<td>3%</td>
<td>9%</td>
<td>7%</td>
</tr>
<tr>
<td># Flows with delta ready &gt; 0 due to variability factors</td>
<td>304</td>
<td>39</td>
<td>78</td>
<td>421</td>
</tr>
<tr>
<td>% of flows with delta ready &gt; 0 due to variability factors</td>
<td>10%</td>
<td>29%</td>
<td>9%</td>
<td>10%</td>
</tr>
<tr>
<td># Flows with delta ready &gt; 0 due to late release or delivery</td>
<td>2,798</td>
<td>95</td>
<td>752</td>
<td>3,645</td>
</tr>
<tr>
<td>% of flows with delta ready &gt; 0 due to late release or delivery</td>
<td>90%</td>
<td>71%</td>
<td>91%</td>
<td>90%</td>
</tr>
<tr>
<td># Flows where delta ready &gt; flow buffer</td>
<td>2,389</td>
<td>45</td>
<td>626</td>
<td>3,060</td>
</tr>
<tr>
<td>% of flows where delta ready &gt; flow buffer</td>
<td>57%</td>
<td>10%</td>
<td>52%</td>
<td>52%</td>
</tr>
<tr>
<td># Flows where delta ready = flow buffer</td>
<td>629</td>
<td>9</td>
<td>264</td>
<td>902</td>
</tr>
<tr>
<td>% of flows where delta ready = flow buffer</td>
<td>15%</td>
<td>2%</td>
<td>22%</td>
<td>15%</td>
</tr>
<tr>
<td># Flows where delta ready &lt; flow buffer</td>
<td>1,174</td>
<td>395</td>
<td>312</td>
<td>1,881</td>
</tr>
<tr>
<td>% of flows where delta ready &lt; flow buffer</td>
<td>28%</td>
<td>88%</td>
<td>26%</td>
<td>32%</td>
</tr>
</tbody>
</table>

The Activity-Flow Formalization also enables the aggregation of the variation metrics at the activity type level. Figure 20 shows the average activity variation metrics for the twenty activity types with the most number of activity instances. The “Install rebar wall” activity type experienced the highest total variability, while the “Form stair” experienced the lowest variability.
Figure 20: Average activity variation metrics (delta start, delta duration, and delta finish) for the twenty most common activity types across the three test projects.

Similarly, the Activity-Flow formalization enables the aggregation of flow variation data at the flow class level to understand how the flow performs across different activities. Figure 21 provides evidence of this ability, by showing the average flow variation metrics for the labor flows on the Frederikskaj project. The figure shows that the field managers over-sized the flow buffers for some of the flows, such as the carpenters crew, cleaning crew, concrete crew, and electrical shaft crew, since the flow buffer is much greater than the flow delta ready. On the other hand, the field managers under-sized the flow buffers for other flows, such as the electrical crew, electrical floor crew, and floor thermozell crew, since the flow buffer is much smaller than the flow delta ready. Hence, analyzing the flow variation metrics for the different flows can allow field managers to evaluate their flow buffer decisions.
Conclusions and future work

The following sections describe the conclusions and future work enabled by this research.

5.1 Conclusions

This report presented the development and validation of the Activity-Flow Model (AFM) which represents and tracks construction activities, flows, and their interactions. Current construction models depend on an activity-based representation that does not fully support the representation of the construction flows. This research extends current knowledge of construction model representation by providing: an ontology representing activities, flows, and their interactions; metrics for tracking activities’ and flows’ variations; and an activity and flow-based computational construction model.
Prior to this research there was a lack of understanding of how to formally represent each of the flows needed to execute the activities, how each of the flow types interacts with activities, and how to represent from where the flows originate. We developed an ontology that represents the semantic relationships between the activities, their flows, and their interactions. We found that the interaction between activities and flows depends on two factors: (1) flow source (on-site or off-site); and (2) function played by the flow in the transformation process (prerequisite, transformation, or capacity). We developed a taxonomy of the flow types specifying what flow source they could represent and the function they could play for the activity. We embedded this domain knowledge into the ontology representation by constraining the interaction between the activities and flows according to the characteristics of the flow types. The ontology developed in this research encapsulates the domain knowledge needed to represent the activities and flows in a construction model.

In addition to representing activities, flows, and their interactions, a construction model must also support tracking the variation of activities and flows. Currently, construction models support tracking variations at the activity level by measuring the activity’s delta start, delta duration, and delta finish. We developed metrics for tracking the flows’ readiness variation, which is defined as the difference between the “flow ready date” and its “planned ready date.” The flows’ readiness variation can be aggregated at the flow class level to characterize the flow class’ variability. Field managers can leverage the flow class’ variability to manage the flows proactively, for example, by increasing the time buffer between activities releasing a flow with a high readiness variability.

Finally, the construction model must help field managers to represent and track the large amount of activities and flows needed to plan and control projects. We found that, on average, a four-week look-ahead schedule contains 249.6 activities and 898.8 flows. Hence, we operationalized the ontology and the variation metrics into a computational model, called the Activity-Flow Model (AFM), and implemented it in a prototype software.

The AFM supports field managers in managing activities and flows proactively, which means that they are informed about the variations and variability of the activities and flows. Therefore, we validated the AFM prospectively on three construction sites. We worked with the field managers planning and controlling the activities to turn their activity-based schedules into
activity and flow representations so that we could test whether the AFM can represent all the activities and flows on the sites and track their variation and variability. In total, we represented 71 activity types corresponding to 1,645 activities, and 331 flow classes corresponding to 5,816 flows for the main phases of building construction from foundation work to finishing. There were no activities or flows that we were unable to represent using the AFM. The activity types that were recorded covered all the categories of the Uniformat Level 3 classification, providing further evidence of the generality of the approach.

5.2 Future work
The AFM can be extended to represent additional characteristics of the flows that are key for helping field managers to understand and manage them proactively. There are two flow characteristics that need to be formalized: measuring the quality and quantity of the flows and measuring and understanding the components of flow cycle time.

A limitation of the current AFM representation is that it only measures the time readiness variation, but does not measure the variation in the quality or quantity of the flows. For example, if the planned crew composition for the concrete crew has three workers, but only two are available because one got sick, the crew readiness variation is zero, but the quantity variation is one. Similarly, if the planned crew composition includes skilled workers with experience on similar projects, but only less skilled workers are available due to workforce availability, there is variation in the flow quality. This limitation prevents the AFM from estimating the cost associated with the flows and from quantifying the capacity and inventory buffers. Our initial plan was to measure both time and quality flow variations. However, this was very difficult in practice because there was no centralized information source that had the information about the planned flow quantity and actual flow quantity. We had to ask each of the subcontractors for this information, which was extremely time-consuming and error-prone. To extend the AFM representation to measure variations in the quantity and quality of flows, it will be necessary to develop methods for obtaining this information accurately and rapidly. A potential avenue for pursuing this line of research is to leverage sensor and IoT data that are currently being developed to track labor, equipment, and materials on site. Quantifying the flows’ time, inventory, and capacity buffers will enable researchers to develop methods for optimizing buffer sizing.
Another characteristic of the flows that needs to be measured at a higher level of detail is the flow cycle time, which we define as the time from when the flow is ready to when it is released by the activity. This definition is analogous to the cycle time definition in manufacturing, which states that the cycle time for a single station is defined as “the time from when the job is released to when it exits the line” (Hopp and Spearman 2011). Cycle time is composed of moving, queueing, set-up, processing, and batching times. Since throughput is equal to work-in-progress (WIP) divided by cycle time (Little’s Law), reducing cycle time while keeping WIP constant allows field managers to increase throughput. Hence, it is important for manufacturing managers to measure and understand each of the cycle time components to work systematically towards reducing it. To extend these methods to construction, we will need to understand the components of flow cycle time (i.e., are they the same as manufacturing or are there other components?), and how to measure them systematically.

6 References


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